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102

50 Years of cosmic ray research in Tasmania

Edited by Marc Duldig

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50 YEARS OF COSMIC RAY RESEARCH IN TASMANIA

SPECIAL SESSIONS

TWELFTH NATIONAL CONGRESS
OF THE AUSTRALIAN INSTITUTE OF PHYSICS

1–5 JULY 1996

Back, left to right:
A. Vrana, B.R. Dawson, J.E. Humble, K.G. Mc.Cracken,
K.B. (Peter) Fenton, A.G. Fenton, R.M. Jacklyn, N.R. Parsons,
M.L. Duldig *and* H.V. Cane

Front, left to right:
R.J. Francey, J.L. Cramp, Sir Arnold Wolfendale, P.G. Law
and R.M. Thomas.

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50 YEARS OF COMIC RAY RESEARCH IN TASMANIA

Edited by M.L. Duldig

Australian Antarctic Division
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Kingston, Tasmania, Australia

PREFACE

The papers in this collection were presented at the Twelfth National Congress of the Australian Institute of Physics held at the University of Tasmania, Hobart between 1 and 5 July 1996. This anthology consists of papers presented in the special session on "50 Years of Cosmic Ray Research in Tasmania". The papers in this session demonstrate the foundation and continuing impact that Tasmanian cosmic ray research has had on Antarctic research in the discipline. The anthology comprises historical accounts of the establishment of various research programs, papers describing some of the major achievements of those programs, reviews of aspects of the field at the time of the conference and papers looking to the future needs and directions of cosmic ray research. The anthology also includes the opening address to the Congress by the Lieutenant-Governor of Tasmania. A few papers from the special session could not be included in this anthology.

The editor thanks all those researchers who were able to provide manuscripts for this volume. For some of the authors this was not an easy task but some latitude with deadlines has allowed an important historical document to reach a satisfying conclusion. The editor is particularly grateful to Judy Whelan for transcribing and preparing the manuscriptst, redrafting many of the diagrams and coping with author delays and a change of publication software package late in the process.

OPENING ADDRESS

by

THE HONOURABLE Mr JUSTICE W.J.E. COX, RFD, ED.
CHIEF JUSTICE and LIEUTENANT-GOVERNOR OF TASMANIA

Professor Delbourgo, ladies and gentlemen, I would like to extend a very warm welcome to you all to this the twelfth Congress of the Australian Institute of Physics. In particular I welcome to Tasmania all our visitors from interstate and overseas.

We are delighted that Hobart has been chosen as the venue for this Congress which incorporates the 16th Australian Institute of Nuclear Science and Engineering conference and is also associated with the 20th Meeting of the Australian Society for Biophysics. Certainly, you have a very prestigious selection of speakers presenting papers at this Congress and you are particularly fortunate to have Sir Arnold Wolfendale, President of the Institute of Physics and a former Astronomer Royal, and Dr Jones the Chief Executive of the Institute of Physics, not only attending this Conference as official representatives of the Institute of Physics but also presenting papers.

The aim of this Congress is of course to provide an opportunity for presentation and discussion of the most significant developments in Physics and I am sure you will derive a great deal of professional benefit from the scientific program of the Congress. I also hope that while you are in Tasmania you are able to take advantage of our magnificent scenery, our gourmet produce and our exhilarating July weather.

I fear that Physicists may have suffered in the past from something of an image problem, with the popular misconception about physicists being that all physicists resemble Professor Julius Sumner Miller and spend a disproportionate part of their lives either tucked away in a laboratory somewhere, rarely seeing the light of day, or bounding around a television studio with an assortment of balloons, eggs and wooden ice cream spatulas, conducting experiments incapable of any application whatsoever to the practical needs of the rest of the members of society. Nothing of course could be further from the truth. Physicists are employed by a variety of different organisations, such as schools, universities, government and private research establishments and by companies in private industry. Physicists are involved in developing new techniques for diagnosis and treatment in the health field, can contribute greatly to our understanding of the environment, make significant contributions in industry to their companies and in numerous other ways make a significant contribution to society. It is also becoming increasingly more apparent that 'pure' scientific research often gives rise to results which are of significance to everyone.

The popular misconception of a physicist I have referred to earlier also fails to recognise that female physicists comprise approximately 10–20% of today's physics community and this percentage looks set to increase, particularly since the formation of the Women in Physics group at the Brisbane AIP Congress in 1994. It is essential to have a group such as this to promote the interests of women in the field and to identify and remove any barriers which may exist to discourage or prevent women from pursuing a career in Physics. This group is also able to address important issues such as the need to be able to balance careers in physics with other commitments. For example I believe that at this congress it is the first time that child care facilities have been offered. Without such facilities women physicists may well have been discouraged from attending this Congress.

You are very fortunate to have such an extensive and stimulating program ahead of you at this Congress. I imagine it can be quite difficult to choose which sessions to attend, although some groups such as the Nuclear and Particle Physics and Solar and Terrestrial Physics groups have a full program in their specialist areas. One interesting session that attracted my attention is that devoted to the major national research facilities program with papers being presented on the Australian Synchrotron Research Program, the National Plasma Fusion Research Facility and Airborne Research Australia. This latter facility in particular sounds like a tremendous development with a large range of potential research areas such as air quality and pollution monitoring, severe weather monitoring and forecasting, marine sciences, and disaster monitoring and response to name but a few, requiring a fleet of specialist research aircraft. The establishment of these facilities through the Federal Government's MNRF program is important not only because these facilities will provide research opportunities for Australian researchers but also because they will strengthen Australia's science and technology base, thereby ensuring that our reputation as a scientifically advanced nation is maintained.

One important initiative of this congress is the plenary session and follow-up forum addressing the issue of career prospects for young physicists. I think that the concerns young physicists have for their future are shared by other young graduates in different disciplines who often find themselves upon graduating unable to secure employment in the area of their choice. Also, job security, particularly as one becomes older and acquires more financial and family commitments, is an important concern.

I think that the approach you have taken at this Congress will be very productive and the follow-up forum in particular provides an excellent opportunity to identify the important issues and draft recommendations and suggestions which can then be referred on to the appropriate parties for action.

As you may be aware, the astrophysics group is conducting a celebration of 50 years of cosmic ray research in Tasmania and I urge you all to take some time to look in on these sessions which I am sure you will find very interesting. This is a very important area of research and we Tasmanians are very proud of the achievements of the Tasmanian cosmic ray groups.

Cosmic rays are very high energy charged particles, mostly protons which arrive from outside the solar system with speeds close to the speed of light. Cosmic rays are so abundant, I was astounded to discover that about 300 cosmic rays pass through a person's body every second.

Cosmic ray transient events are observed, so I am informed, by surface detecting systems such as neutron monitors and muon telescopes and by shallow underground muon telescopes. The two major transient events are Ground Level Enhancements (GLEs) and Forbush decreases.

Ground Level Enhancements are rare events in which a sudden rise in the cosmic ray flux is followed by an approximately exponential decay back to pre-increase levels. Fifty two GLEs have been observed since reliable observations began in the 1940s.

Forbush decreases are sudden decreases in the number of cosmic rays arriving at the Earth. They are invariably associated with sudden commencement magnetic storms which can have an enormous impact on human activity. The Canadian power grid was damaged by power surges resulting from such a storm a few years ago. There was a large scale blackout which lasted many hours with an estimated economic loss of hundreds of millions of dollars and there were also severe communication disruptions. It would obviously be of tremendous economic benefit to have a forecast ability and warning service to enable the shutdown of sensitive equipment to avoid damage induced by these magnetic storms.

While GLEs do not generally pose a hazard to human activity, passengers and crew flying high altitude polar routes may be exposed to significantly higher radiation environments during GLEs. While crossing the poles at high altitude much of the protection ordinarily provided by the Earth's magnetic field and the atmosphere in deflecting cosmic ray particles is lost. Consequently, Concorde which flies between London and Washington directly over the north magnetic pole, carries radiation monitoring equipment to warn pilots of increased radiation during such events and to allow the pilot to fly to lower altitudes for greater protection if necessary. Also, Lufthansa does not allow pregnant crew to fly high altitude routes during their 8th to 12th week of pregnancy when the foetus is most susceptible to radiation damage.

GLEs pose a much greater risk in space as is evident from documented accounts of satellite damage. Further study therefore of GLEs is needed so that it becomes possible to predict the onset of these events and issue a warning in order to minimise the potential radiation risks associated with high altitude and proposed sub-orbital mass transport and thus protect passengers and crew.

Tasmania's cosmic ray research groups have been world leaders in the field for 50 years and the University of Tasmania is responsible for a large proportion of the World Wide Neutron Monitor Detector Network. The University of Tasmania has the second largest latitude coverage of any group in the world and is the only one with equatorial as well as polar latitude observing sites.

The Tasmanian cosmic ray research group was founded by Dr Geoff Fenton 50 years ago. Dr Fenton, his brother Dr Peter Fenton and Dr Bob Jacklyn have been the backbone of Tasmania's cosmic ray team for most of this 50 year period.

Dr Nod Parsons founded the Mawson experiments and Dr Jacklyn instigated construction of the underground detector system at Mawson in 1971. This is the only underground observatory at polar latitudes and is a unique part of world-wide observatories of this type. In 1987, Dr Jacklyn was appointed a member of the Order of Australia in the General Division for service to science, particularly in the field of cosmic ray research.

Many other individuals have contributed to the success of Tasmania's cosmic ray program and their efforts as well will be recognised in these special sessions being held to mark the anniversary of the program.

While a great deal has been achieved in cosmic ray research there is still much to be done and it is essential that Tasmania's cosmic ray researchers are able to continue their work in this field.

I am glad to see that in addition to your very extensive daytime congress program activities you have a number of interesting evening activities on your agenda. Tomorrow night Professor Snyder, the winner of the Harrie Massie Prize will speak to you about the Unification of linear and non-linear waves and then Dr Wiseman, the winner of the Bragg Medal, will present his talk on Quantum Trajectories. These are prestigious awards indeed and it is always important that there exists some mechanism to promote and reward excellence in a particular field of endeavour.

I hope that you find this congress both productive and stimulating and that you enjoy your visit to Tasmania.

I have much pleasure in declaring this Congress open.

1. COSMIC RAY STUDIES BEFORE 1946

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ABSTRACT

An account is given of cosmic ray studies from early this century, when researchers studying radioactive substances identified a persistent residual conductivity in their electroscopes, to the end of World War II when the existing Hobart cosmic ray program began. Nostalgic comments are made about the Physics Department at the University of Tasmania from the late 1930's, and about its contributions to Australia's war effort from 1939 to 1945.

Reference is made to early reports by C.T.R. Wilson and others about background ionisation, and to the proof of its external origin by Hess in 1912, and also to the work of Clay, Compton, Millikan, Johnson and others showing that the primary rays are mainly atomic nuclei of very high energy.

Brief mention is made of the beginning of particle physics in the 1930's and 1940's, when Anderson discovered the positron, Anderson and Neddermeyer the muon, and Blackett, Rochester, Butler, Powell and associates set the stage for a rich harvest of sub-nuclear phenomena including the pion, discovered in 1947.

The observation by Compton and Getting in 1935 that the primary cosmic rays appear to be isotropic, whereas they expected to find an anisotropy due to the rotation of the galaxy, marked the beginning of the use of cosmic rays as a branch of astrophysics studying the high energy phenomena associated with the Sun and the interplanetary and interstellar regions, which are of current interest to the Hobart cosmic ray groups.

1.1 INTRODUCTION

It gives me much pleasure to have been invited by the conference organisers to present the first paper at the opening session of the contributed papers. I shall give a rather nostalgic account of the circumstances which led me to begin cosmic ray observations at the University of Tasmania in the mid 1940's. It may be appropriate to make some anecdotal comments on the situation as I recall it in the Physics Department at the University of Tasmania following my enrolment in Physics 1 in 1938. I shall also outline the history of our knowledge of cosmic rays from 1900 to the early 1940's.

1.2 THE PHYSICS DEPARTMENT IN THE LATE 1930'S

The year 1938 was a normal teaching year, with Professor A. Leicester McAulay (ALM) and Mr Fletcher D. Cruickshank the only physics academic staff, assisted by a laboratory/workshop technician. Descriptions of the laboratory experiments were handed out and it was left to the students working in pairs to select or assemble their apparatus from items in an adjacent store (and to return them afterwards!). Experiments usually lasted about three weeks and a minimum of six experiments complete with reports was expected. These ranged over the whole first year lecture topics, and with ingenuity and care one could achieve a reasonable experimental backup for these topics.

Second year students worked either alone or in pairs on the laboratory experiments, depending on the experiment, which were closely related to the lecture course. Ingenuity was encouraged (recall Rutherford's sealing wax and string approach to physics experiments conducted at the frontiers of knowledge, for which no standard equipment had yet been developed) and some of the students were given developmental projects for equipment to be added to the list for either Physics 1 or 2.

As a young student I did not consider it out of place or odd that the Vice-Chancellor, Professor Edmund Morris Miller, was also the librarian as well as teaching in his own department (philosophy and psychology). It was no surprise to me that he seemed to know all the students (about 450 total enrolment) by name, or that when coming face to face with him in the grounds one would be interrogated in a friendly way about studies and university life generally. It was obvious to me that with one exception (a chemistry lecturer who openly admitted his greater interest in horse racing than in organic chemistry) all the academics I encountered at University were very dedicated to their subject and devoted a great deal of time to their studies and research. Because of this and their cooperative and helpful attitude towards the students they were highly respected. At that time, some teaching classes were held on Saturday mornings but Wednesday afternoons were free from teaching to facilitate faculty or other meetings, student sport, etc. (some cynics would add academic golf!). There was an informality about the place, with an attendant feeling of responsibility, so that for example a student could arrange to do out of hours library studies or additional experimental work.

1.3 CONTRIBUTION TO AUSTRALIA'S WAR EFFORT

By 1939, war seemed imminent and the Department, along with Chemistry (Dr E.E. Kurth) investigated producer-gas (formed by passing air and water over red hot charcoal, giving a mixture of N_2, CO and H_2) as a substitute for petrol for motor vehicles. It was asserted that the best training and experience comes from tackling real problems under guidance, and students were encouraged to assist. I recall that I did a series of experiments with a bomb calorimeter to measure the energy output of a range of producer-gas mixtures with air. The calorimeter consisted of a thick-walled metal tube about 30 cm long by 10 cm diameter, fitted with appropriate pipes and taps, plus a spark plug and pressure gauge. The idea was to fill the tube with the gas-air mixture, ignite it with a spark and quickly read the gauge pressure. One was advised to stand back or shelter behind a screen when pressing the ignition button, but although very high pressures were observed, the tube did not explode! After about one year, the practical problems associated with the type of wood, the design of pits for burning it to charcoal, and the design of the producer units carried by vehicles had mostly been solved and handed over to commercial groups. At this point we turned our attention to acquiring glass grinding and polishing techniques for making components for optical instruments.

In 1940, Australia had no optical instrument industry and was desperately short of gunsights for guns being built in Australia as part of our self-sufficiency program, nor could these be purchased from anywhere in the world at that time. The Director of Ordnance Production (Mr L.J. Hartnett, seconded from his position as general manager of General Motors, Australia) sent telegrams in July 1940 to all physics departments in Australia asking whether they had any optical experience. Leicester McAulay immediately discussed this request with F.D. Cruickshank and with Eric N. Waterworth (ENW), a Hobart engineer-inventor, whose father and brother Philip ran 'Waterworth and Ross', a prominent Hobart optometrist business. He also spoke to third year students and several MSc students (there were no Honours or PhD students until after the war) and then responded to the telegram, saying that if they agreed to provide £100 for expenses we would see what we could do. Hartnett wired back saying to get on with it!

Initially, using techniques described in a book 'Amateur Telescope Making' and equipment constructed by ENW, (I shall use initials when referring to people already identified or well known – this was customary in the Department at the time, although ALM generally used family names only) we taught ourselves and each other how to grind and polish pieces of glass (some mastered the techniques more quickly than others). The objective was to make 'optical flats', which were flat to better than one wavelength of light (5×10^{-5} cm) over a piece of glass 5–10 cm diameter, and 90 degree angles to similar accuracy. If we could do this, we felt confident that we could tackle prism making. No sooner had this been achieved than a request came, in February 1941, from the Optical Munitions Panel, which had been set up in Melbourne to coordinate work at the participating universities (Western Australia, Adelaide, Melbourne and Sydney as well as Tasmania, plus munitions supply laboratories). This was a request for us to try to make roof prisms, so named because of their shape. These were notoriously difficult to make. ALM made our first one himself and took it to the next Optical Panel meeting. At this meeting discussion around the table is said to have centred on how to set up an industry to make roof prisms, whereupon ALM pulled this one out of his pocket and said "will this do"? We were given an order to go into production!

By mid 1941 we had set up a small production line in a Physics laboratory with about ten girls, mostly just finished at secondary school, and had produced the first monthly delivery of 25 roof prisms. New orders soon followed for other types of prisms and by the end of 1941 when I completed my studies for the BSc degree, the first stage of a new building in the University grounds was under construction for an Optical Munitions Annexe. This was completed in May 1942 and almost immediately a second storey was added, so rapid was the increase in staff and production. I joined the staff of the Annexe as head of a small Research and Development unit, set up to tackle day to day problems, and to devise testing and quality assurance procedures for the production sections. Also in 1942 with the Pacific war becoming very serious for Australia, ALM began to consider making photographic lenses for the RAAF. That is another success story about the Annexe, too detailed to recount here. Those interested are referred to a catalogue produced by the Queen Victoria Museum and Art Gallery, Launceston (1990) entitled: 'Eric Waterworth – An Inventive Tasmanian'. See also, 'Tasmania's War Effort' by the Department of Premier and Cabinet, Hobart, Tasmania, 1995 (reprinted from the 1945 edition).

1.4 TRANSITION TO PEACETIME

At the end of 1944 it was evident that both Germany and Japan were 'on the run' and optical production was progressing strongly with about 200 staff operating two and sometimes three shifts a day (in 1943 we had an order for 10 000 prisms for the USA and we were now making large camera lenses for the RAAF). As always, ALM was looking ahead and at this time asked me to join the teaching staff of the Physics Department. It was recognised that after the war there would be an influx of mature age students who had served in the armed forces and would now wish to continue their studies (the Commonwealth Reconstruction Training Scheme, CRTS) and the University was preparing for this.

So by 1945 I was back in Physics full time, preparing lecture courses and laboratory experiments in modern physics. During the war we were aware that nuclear physics research was progressing in the US (we had the Physical Review in our library) and that radio location (radar) had been developed to a sophisticated level in the UK and Australia. Hence it seemed that the basic physics in these areas should be included in our courses. I recall that a few weeks before the first atom bomb was exploded over Japan (August 6, 1945) I gave a lecture on 'Atomic Energy' to the Hobart Apex Club. We knew about uranium isotopes but had no knowledge of the new element, plutonium, until after the war. Soon we had radio and electronics experiments and nuclear physics experiments involving radioactivity. I taught myself glassblowing and proceeded to construct our first Geiger Müller (GM) counter tubes. I was assisted in this by reference to the book 'Procedures in Experimental Physics' by J. Strong (Prentice-Hall Inc., 1942) and with advice from John Trowbridge who had worked with me in the Optical Annexe and had been trained in glassblowing and in the use of vacuum pumps by Claude Neon Signs.

1.5 THE MOVE TO SANDY BAY

During 1945, plans were drawn up for the move to the Sandy Bay site in early 1946, first by Physics, then later by Mathematics, Botany and Zoology.

Accommodation was in wooden huts vacated by the Army and located along the side of a former rifle range! These temporary buildings were our 'home' until 1964 when we occupied the present more permanent quarters. We were not aware of any serious disadvantages of these buildings, which were more spacious and comfortable than those on the Domain and could be extended or modified readily when desired. Most of us actually liked them!

Chemistry remained in the city, where it was associated with the Hobart Technical College, a situation which caused difficulty for students studying chemistry along with other science subjects (at that time and for some years afterwards it was a requirement for first year science students to study at least two subjects from Physics, Chemistry and Pure Mathematics).

By mid 1946 we had GM counters and associated electronics equipment in operation at the Sandy Bay site to detect any fallout or other radiation effect due to the US nuclear weapons tests in the Northern Pacific at Bikini Atoll. We satisfied ourselves and assured the media that no fallout reached Hobart. I recall that there had been predictions that an underwater explosion would be likely to amplify the effects by fusing some of the hydrogen and deuterium in the vicinity.

My work with GM tubes led me to a practical interest in cosmic rays, which make up a large fraction of the naturally occurring background radiation. In fact GM tubes at the time were regarded as very temperamental devices, so that it was common to joke that the background counts were made up from 50% cosmic rays, 50% due to local radioactivity and 50% due to something else!

1.6 McAULAY'S VIEW OF ACADEMIC TEACHING AND RESEARCH

My interest in cosmic rays was encouraged by ALM who insisted that physics teaching staff should also do personal research: A teacher who does research is more likely to inspire students, while a researcher who teaches, benefits from being questioned by bright students about the basic concepts. This attitude evidently came from Rutherford, with whom ALM studied at Manchester for his PhD, and then at Cambridge for his MA when Rutherford transferred there in 1919. Another view attributable to Rutherford, sometimes forcefully expressed by ALM when grant-giving bodies asked for progress or annual reports, was that the best report is a published paper in a refereed journal. He also had a strong dislike of bureaucratic moves to direct or otherwise influence the progress of teaching or research. In his view, academics should be as free as possible to get on with their main job of teaching and research with few distractions from committee work or administration. He could not abide what he called 'woolly thinking' in any field, not only physics, and would ask penetrating questions which would oblige others to get to the basic principles involved in a discussion. Those confronted by this approach were not likely to forget the encounter and were often forced to re-assess their basic premises or knowledge of the subject. Although his lectures were regarded by many students as impossible to follow, or to take notes from, ALM was an inspiration to those who were intending to make a career in physics. His lectures were normally delivered without reference to notes and continuity from one lecture to the next, even if a week apart, appeared as if no break had occurred. In fact, he would have come directly from research or other absorbing activity without any evidence of preparation. He disliked doing lengthy mathematical proofs or derivations during lectures (often mistakes would occur) as he regarded maths as a means to an end, insisting that students work through these themselves and see him about any difficulty. To him, physics was the basic science underlying everything in the world and everybody should have an appreciation of the concepts of the subject. This attitude is not surprising as Rutherford is said to have made remarks such as – 'Physics is the basic science, the others are like stamp collecting'.

From the above it should be clear that ALM provided considerable enthusiasm, inspired confidence and produced numerous ideas for those around him. This situation appears to have existed throughout his appointment at the University of Tasmania, first as Lecturer (1922–1926) and as Professor (1927–1959) during which he had a breadth of interests, including nuclear physics, cosmic rays, metal surface electrochemistry, biophysics and the wartime projects. As a mark of their appreciation and respect, many of his former students and associates contributed to the purchase of the 1963 portrait of him by J. Carrington-Smith, which hangs on the wall near Physics Lecture Theatre 2.

1.7 POST-WAR FACILITIES IN THE PHYSICS DEPARTMENT

It may be of interest to describe the facilities available in Physics immediately following World War II. Pre-war, Physics had one laboratory technician who used the workshop equipment set up by Engineering to train mechanical engineering students in workshop practice. During the war, Physics had its own small workshop built close to the large red brick building jointly occupied by Physics and Engineering on the old (Domain) site of the University. This was essential for the Department's war work – first the producer gas trials and then for the optical munitions. When the Optical Munitions Annexe was built, a larger dedicated workshop with many more machines and staff was included there to construct and maintain its production line equipment.

By 1945 the Annexe was being prepared for peacetime private ownership and the Physics Department was reverting to its peacetime role, preparing to move to the Sandy Bay site and to cater for the expected influx of CRTS students. Thus, we had the luxury of owning a small but well equipped machine shop with three technicians. On the other hand there were no facilities, anywhere in the University, for glassblowing or for electronics. These I had to learn from books and journals, and practice. In the case of electronics, it was a new technology not generally understood at a time when 'radio' was more often called 'wireless' and valves (vacuum tubes) were usually thought of in their radio context. Mostly, the technology which later became Electronics, was developed by physics experimenters who were using valves as switches, binary dividers and pulse amplifiers. At about this time we acquired our first cathode ray oscilloscope. It had a two inch screen and a synch control but no trigger, so it required very careful adjustment to display pulses on it! Before long, I was able to make some minor changes to enable better triggering from random pulses, such as those from GM tubes.

1.8 DISCOVERY OF COSMIC RAYS

I shall now give a brief discussion of the studies early this century which culminated in the discovery that ultra rays are entering the atmosphere from outside. This is followed by an account of the state of knowledge about these cosmic rays in the mid

1940's, at the time I was considering what would be a suitable research project to tackle in this field.

The first clue that an additional source of ionising radiation may be present, apart from that due to local radioactive materials in the Earth's crust and in the atmosphere, came from studying the residual ionisation present in electroscopes. First reported by C.T.R. Wilson (1900) in England and by J. Elster and H. Geitel (1900) in Europe, the residual ionisation was an annoying background which had to be subtracted out by experimenters studying radioactive substances. Investigation of the background radiation itself was inconclusive for about ten years when Gockel (1910) reported a slight increase in the residual ionisation with an electroscope carried by balloon to an altitude of 4500 m, at which height any radiation from the Earth's surface should have been absorbed by the atmosphere. This prompted others notably Hess (1912) and Kolhorster (1913a, 1913b) to repeat the observations using better equipment with improved accuracy and extending to 5200 m and 9000 m respectively. These flights gave an initial decrease in ionisation to about 700 m, followed by a steady increase to the highest altitudes reached. Hess reported that the ionisation was the same during night and day and suggested that an extremely penetrating radiation, which is not coming directly from the Sun, falls continuously on the atmosphere from outer space.

Years later (1936) Hess was to share the Nobel Prize with Anderson for his part in the discovery of Cosmic Rays. Now-a-days, it is customary to invite a prominent person to deliver a public Hess Lecture at International Cosmic Ray Conferences. Studies of these 'ultra rays' ceased during World War I and resumed again in the early 1920's, notably by Millikan and associates who strongly favoured the idea that the primary radiation consisted of gamma rays more energetic than any observed from radioactive materials. This idea persisted throughout the 1920's during which the ionisation chamber was essentially the only instrument available, usually sophisticated improvements on the electroscopes used by the discoverers of ultra rays. At the California Institute of Technology, Millikan's group developed sensitive electroscopes with spring driven film recording that could be employed for a series of unmanned balloon flights and underwater intensity measurements. The ionisation chambers were still of the integrating type, with charge collection times of the order of minutes, so they were unable to detect individual charged particles.

During the 1920–30 decade, most of those who were convinced that the ultra rays had their origin either in the upper atmosphere or in outer space also accepted that they were gamma rays of extremely short wavelength and investigators measured absorption coefficients in air and water to determine the nature of these rays. Although there were many researchers making measurements, Millikan and his associates were notable for the sophistication and extent of the observations. From their measurements in the atmosphere with sounding balloons and underwater in lakes, they concluded that no single absorption coefficient could be attributed to all the rays falling on the upper atmosphere. Papers by Millikan and Cameron (1928) were important at that time. From measurements in two lakes, one at altitude 3595 m and the other at 1555 m, they found that all the readings in the lower lake were matched by those 1.8 m deeper in the upper. Since the atmosphere between these two altitudes is equivalent to 1.8 m of water, they concluded that no rays originated in this part of the atmosphere and that they probably were coming from outside it. Also, Millikan and Cameron (1928) proposed that the different absorption coefficients suggested different components amongst the rays, possibly originating in the annihilation of matter or in the creation of the light and medium atoms from their components, which would release mass-energy. It is interesting to recall that at this time the only known elementary particles were the proton and the electron, with the neutron, positron and muon still to be discovered.

Another point of interest is that Millikan and Bowen (1926) appear to have been the first to rename the penetrating radiation 'cosmic radiation'. At the end of their paper submitted for publication on December 24, 1925 they refer to 'cosmic radiation of extraordinary penetrating power'. By 1928 Millikan refers to 'new precision in cosmic ray measurements'.

1.9 EARLY MEASUREMENTS AT HOBART

Some readers may not know that in 1924, when physicists around the world were encouraged to measure the local intensity of this radiation, A.L. McAulay and Miss N.L. Hutchison (1924) published a paper entitled 'The Penetrating Radiation in the Atmosphere at Hobart'. They used a cast iron spherical ionisation chamber, 20 cm internal diameter and wall thickness 1.5 cm, with a small spherical central electrode supported by a sulphur insulator-plug and connected to a sensitive Compton type quadrant electrometer. The chamber was filled to pressures up to four atmospheres with radon-free oxygen. By taking measurements at different pressures it was possible to discriminate against at least some of the local radioactive contamination because the latter tended to give a constant ionisation, whereas the penetrating component ionisation increased linearly with pressure. The results were comparable to those measured elsewhere and varied between 1.3 and 3.5 ion pairs cm^{-3} s^{-1} at normal pressure. Over an observing period of a few weeks, the data suggested a small daily variation with larger erratic and sometimes rapid changes superimposed. They did not look for any atmospheric pressure effect, although they discussed the results of other researchers during 1920–23. As the readings had to be taken manually, the observations were soon terminated.

1.10 NEW TECHNIQUES

By the 1930's, new researchers and vitally important new techniques were entering the cosmic ray field. At this time, very few people doubted the existence of cosmic rays of origin outside the atmosphere, but their energy, composition and interactions in the atmosphere were not at all clear. In particular, the assumption that the cosmic rays were extremely energetic, short wavelength gamma rays was becoming more difficult to reconcile with the results of many observations around the world.

In 1928, Geiger and Müller (1928) reported the development of a cylindrical charged particle detector, the GM counter, which enabled large detector areas to be exposed to the cosmic rays. Soon afterwards, Bothe and Kolhorster (1929) invented the coincidence circuit, which was refined by Rossi (1930) and others, who quickly developed the first electronic pulse circuits using radio valves. These techniques showed that cosmic rays contain charged particles as well as gamma rays. Directional intensity measurements were soon being made with counter telescopes, the intensity being expressed in s^{-1} cm^{-2} $ster^{-1}$ instead of in ion pairs cm^{-3} s^{-1}, as for the omnidirectional ionisation chambers.

1.11 THE LATITUDE-INTENSITY VARIATION

At about this time, Clay (1927) discovered a difference in intensity between Holland and Java, and investigated this further by taking an ionisation chamber on three sea voyages between Europe and Java via the Suez Canal during the period 1928 to 1932, finding a consistently lower intensity near the equator (Clay, 1934). After some doubts were expressed by several other researchers, the finding was confirmed by Compton (1933) in a paper entitled 'A Geographic Study of Cosmic Rays'. Compton arranged for measurements to be made at about 70 locations world-wide with improved ionisation chambers and calibrated at each site with a standard radium source. The latitude effect can be explained if the primary cosmic rays are mostly charged particles, not gamma rays as had been thought earlier. Lemaitre and Vallarta (1933) calculated the deflections of particles carrying one electronic charge as they pass through the geomagnetic dipole field and showed that a particle must have a minimum energy E_{min} if it is to reach the upper atmosphere in a vertical direction at geomagnetic latitude λ, where E_{min} is given approximately by the well known expression:

$$E_{min} = 15 \cos^4\lambda \text{ GeV.}$$

Discovery of the latitude effect stimulated further research by a number of people and groups, until most of these projects ceased at the outbreak of World War II. The latitude-intensity measurements by Compton's group were probably the most detailed and extensive at this time. Under the auspices of the Carnegie Institution, the Carnegie Model C Cosmic Ray Meter was developed (Compton et al., 1934). It was a 19.3 litre spherical ionisation chamber filled with pure argon to 50 atmospheres pressure, shielded by lead shot poured into an outer spherical shell, equivalent to 10.7 cm of solid lead. The average ionisation current was balanced by an opposing or compensating steady current produced in a small balance chamber inside the sphere and which contained a radioactive source consisting of a piece of uranium metal whose beta particles from daughter products could reach the gas in the small chamber but not that in the main chamber. The position of the uranium was adjustable to alter the balance current. This method of compensating automatically balances any changes due to pressure or temperature variations in the gas filling, while achieving high sensitivity to changes in the cosmic ray intensity. A clockwork operated film strip continuously recorded the position of the Lindemann electrometer needle and also the atmospheric pressure and room temperature. The cosmic ray meter could operate unattended for about one month.

During the 1930's one of these cosmic ray meters was sent across the Pacific Ocean on at least 27 voyages between Vancouver and Sydney. During the period 29 January to 13 July 1937, the meter was transferred to the SS Talune for several return trips between Newcastle, NSW and Hobart, Tasmania. The reason for these latter trips was to extend the southern hemisphere latitude-intensity curve to higher latitudes than that of Sydney. These surveys showed significant seasonal effects attributable to temperature changes in the atmosphere, which had probably caused difficulties for some other less extensive surveys. After allowing for these, the intensity was found to be symmetrical within the experimental errors between the two hemispheres (see Figure 1).

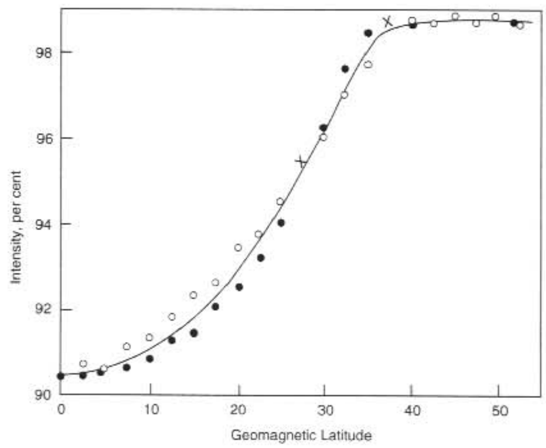

Figure 1. *Latitude-intensity curve, obtained from ship-borne surveys with an ionisation chamber across the Pacific during the 1930's. Seasonal atmospheric effects have been eliminated by the author to obtain this curve. Note that it is symmetrical about the geomagnetic equator (from Gill, 1939). Open circles northern hemisphere, filled circles southern hemisphere and X= average.*

The magnitude of the latitude effect observed with 10.7 cm equivalent of lead shielding was 11.3% from the equator (in the Pacific) to the plateau at latitudes beyond the 'knee' in the curve. Later, a small longitudinal effect was observed. The knee, which occurs at about 40° geomagnetic latitude, was accounted for in terms of either a lack of primary particles of energy less than a critical value corresponding to this latitude or to the inability of these lower energy cosmic rays to produce secondaries able to reach ground level.

Of the many publications during this period, indicating the intense interest and activity in cosmic ray studies during the 1930's, I shall mention only a few which are of special interest in the context of this talk. Compton and Getting (1935) published a paper entitled 'An Apparent Effect of Galactic Rotation on the Intensity of Cosmic Rays'. This predicted what is now referred to as the Compton-Getting Effect whereby the motion of our galaxy combined with the rotation of the earth was expected to lead to a small daily variation in sidereal time, if the cosmic rays originate outside the Milky Way. Early observations seemed to support this idea but later results including those made by Compton and his associates suggested a smaller effect, if any, than predicted (e.g. Compton and Turner, 1937). In an address to the AAAS in January 1936, later published in the Review of Scientific Instruments, Compton (1936) with the title 'Recent Developments in Cosmic Rays', gave a comprehensive review of the field, stressing its importance in providing information about the origin and acceleration of the particles and their interactions in matter and with magnetic fields in space outside the atmosphere. He also suggested that we might learn about the ancient history of the universe and gave his opinion that 'it is not impossible that they play an important part in the spontaneous variations upon which evolutionary changes depend'.

Of considerable interest to the Hobart group, because of our later emphasis on cosmic ray intensity variations, were the observations commenced in September 1935 by A.R. Hogg at the Mount Stromlo Observatory, Canberra, ACT. Hogg used a cylindrical ionisation chamber of volume approximately four litres, filled with CO_2 at 10 atmospheres pressure, shielded with 10 cm of lead, compensated electrically and fitted with a continuously recording electrometer. Due to wartime conditions the observations were discontinued in August 1940, and the results were not published until nine years later (A.R. Hogg, 1949). The tabulated data in this compilation have been very useful for comparison with ionisation chamber results obtained at other locations, notably by S.E. Forbush of the Carnegie Institution, Washington, DC, and with more recent data obtained with solar cycle phenomena. Hogg also obtained the absolute intensity of cosmic rays at Canberra and investigated the atmospheric and geomagnetic effects, 27-day periodicities and diurnal variations of cosmic rays in solar and sidereal time.

1.12 HIGH ALTITUDE BALLOON FLIGHT MEASUREMENTS

The latitude effect is more dramatic when observations are made at higher altitudes using sounding balloons with self-recording ionisation chambers or GM counter telescopes and the flights are made at different latitudes. Notable in this field was the California Institute of Technology group at Pasadena, led by Millikan who continued their cosmic ray studies from the 1920's. They took into account the results obtained by other investigators, in particular the latitude effect and its significance for the nature of the primary cosmic rays. Important results were presented by Bowen, Millikan and Neher (1938) (see Figure 2).

The depths below the top of the atmosphere are given in metres of water equivalent (mwe), a follow-on from earlier absorption coefficient measurements, and the data show that maximum cosmic ray intensities occur at distances below the top of the atmosphere, ranging from 0.4 to 1.0 mwe on going from 60° N to 3° N geomagnetic latitudes. The cosmic ray intensity at the maxima in ion pairs cm^{-3} s^{-1} at normal temperature and pressure (NTP) in their small recording ionisation chambers changed by about 75% between high latitude and near the equator. It was also noted that most of the change occurs at latitudes below the knee of the sea level latitude curve, suggesting that the knee may not be due entirely to the atmosphere but points to a lack of field sensitive primaries of energy below that corresponding to the

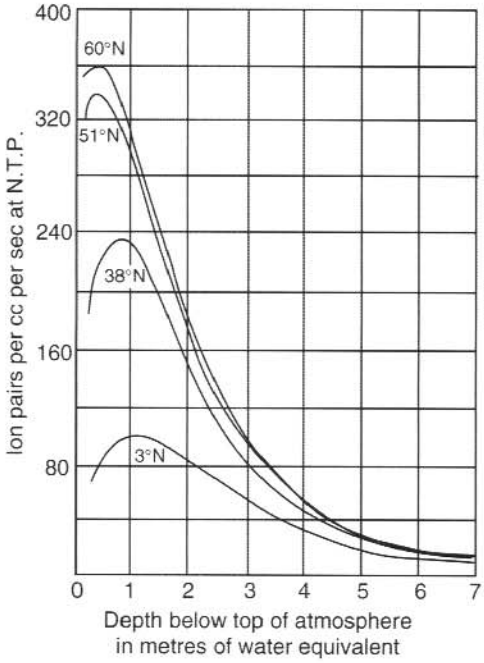

Figure 2. *Cosmic ray altitude-intensity curves at four geomagnetic latitudes by Bowen, Millikan and Neher (1938), using self-recording ionisation chambers carried by sounding balloon.*

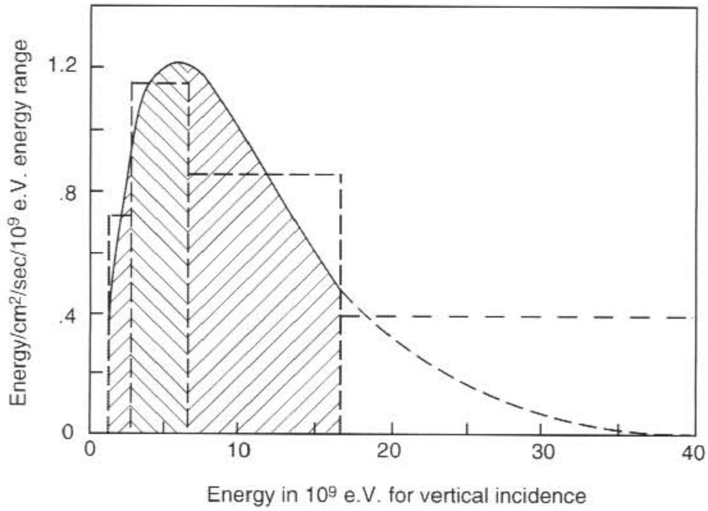

Figure 3. *Calculated energy distribution of the primary cosmic rays, made by Bowen, Millikan and Neher (1938), using data from balloon flights at various latitudes.*

knee latitude. Bowen et al., also calculated the energy distribution of the primary particles, using the energy deposited in the atmosphere at the various latitudes of the balloon flights together with the cut-off energies calculated for each latitude. The peak of the energy distribution was found to be at about 6 GeV, with the curve above this energy following a power law of exponent about -2.5. This result is reproduced in Figure 3.

Two papers by Schein et al. (1940, 1941) were of interest at the beginning of the 1940's in that they concluded that cosmic ray muons (then called mesotrons) are produced in the upper atmosphere by the primaries, which are most likely to be protons. They came to this conclusion using results from a series of free balloon flights with several layers of GM counters, coincidence circuits, up to 16 cm of lead absorber and photographic recording of the data.

1.13 PARTICLE PHYSICS BEGINS

It was pointed out by Swann (1934, 1936) that if the primary particles are electrons, protons or alpha particles of energies needed to reach the upper atmosphere through the geomagnetic field then they should not lead to latitude or altitude effects as large as are observed, if the only energy loss process is that of ionisation of the atmosphere as the particles pass through it. To explain this large discrepancy, Swann proposed that the primaries interact with the atoms in the upper atmosphere, producing a succession of secondaries so that the energy of the primary is shared with a number of particles.

The Swann hypothesis pointed towards the advent of particle physics – the secondary cosmic rays at ground level and in the atmosphere up to moderate altitudes need not be of the same types as the primary cosmic rays, but may be derived from the interactions of the latter. Thus it was important to investigate the primaries and their interactions and also to establish the nature of the secondaries.

The neutron was discovered by Chadwick (1932) during a nuclear physics experiment designed to study the penetrating radiation produced by bombarding certain light elements with alpha particles from a radioactive substance. It is interesting to note in passing that this radiation was initially thought to consist of very energetic gamma rays, just as cosmic rays were assumed to be until experiments proved otherwise.

The positron was also discovered in 1932, in ground level cosmic rays by Anderson (1932) who refined his experimental technique to make the observation more convincing and reported it the next year (Anderson, 1933). This project involved photographing, at random expansion, a large Wilson cloud chamber in a very strong magnetic field, a project initiated by Millikan's group at the California Institute of Technology for the purpose of studying ground-level cosmic rays. The discovery of the positron was quickly confirmed by Blackett and Occhialini (1933), who had arranged GM counters to trigger their cloud chamber on selected events instead of random expansion and clearly demonstrated electron pairs emerging from absorbers located in or above it. A few years later Anderson and Neddermeyer (1936) discovered the mesotron, the name meaning intermediate between electron and proton. Later, the name was shortened to meson, then changed to mu-meson, and later still to muon, as its place in the particle physics scheme became known. The muon was soon identified with the hard component of cosmic rays which had been known for some years from the absorption curve in lead, using GM counter telescopes, which had also enabled the determination of the zenith angle dependence (the well known $\cos^2\theta$ law). During this period also, the soft component was found to consist of electrons, positrons and photons produced in a cascade process. A number of research groups contributed to evidence about the properties of the muon: The mass was determined at about 200 electron masses, they occur about equally with positive and negative charge and they are radioactive with a mean life of about two microseconds. Also, these particles were found to interact very weakly with matter (from their ability to penetrate great depths of air, water or rock) and therefore it seemed unlikely that they could be identified with the Yukawa particle which had been predicted in 1935 to account for the binding together of neutrons and protons in nuclei. This problem was not resolved until 1947 when the pion was discovered in the upper atmosphere and soon identified as a strongly interacting meson.

The discovery by Auger et al. in 1938, of what became known as extensive air showers, was of considerable interest because it pointed towards extremely high energies among the primary particles and provided the means by which these infrequent primaries could be investigated. The coincidence counting rate plotted against counter separation in a horizontal plane, the de-coherence curve, was soon related to the spreading of the electron-photon cascade particles as they progress downwards through the atmosphere. It was a surprise to find that these showers were spread out over the ground to distances of at least 300 metres.

1.14 THE EAST-WEST DIRECTIONAL EFFECT AT GROUND LEVEL

There are many references in the literature of the 1930's to this E-W effect, which was found when GM counter telescopes, recently invented, were used to measure the intensity of cosmic rays reaching ground level from various directions in azimuth and at various zenith angles. For a given zenith angle it is found that there is a greater intensity from the geomagnetic west than from the east. At near sea level locations close to the geomagnetic equator the asymmetry, defined by the expression:

$$\text{asymmetry} = (W-E)/0.5(W + E),$$

amounts to about 0.15 or 15% for the total cosmic ray intensity at 45° zenith angle, while for the hard component it is close to 30%.

The magnitude of the E-W asymmetry has been used by a number of researchers, notably by T.H. Johnson and associates at the Bartol Foundation (1933, 1940, 1941) to conclude that most of the primary cosmic rays coming to the upper atmosphere through the geomagnetic field must be positively charged and are probably protons. There would be no asymmetry if there were equal numbers of positive and negative primary particles.

1.15 THE HIGH LATITUDE EAST-WEST EFFECT

There is a small but definite E-W asymmetry at latitudes beyond the knee of the latitude curve, whereas at first sight this should be zero if there are no field sensitive particles at these latitudes which would be energetic enough to produce effects at ground level. Johnson (1941) has explained the high latitude asymmetry in terms of the deflection of the muons in the Earth's field while they traverse the atmosphere, giving a difference in the path length of positive and negative particles, together with the positive excess found in these secondary cosmic rays, with a consequent difference in energy loss for muons arriving at a given zenith angle. Measurement of the E-W asymmetry by Seidl (1941) at Troy, New York, at 54° N geomagnetic latitude gave a value of less than one percent.

1.16 HIGH LATITUDE E-W ASYMMETRY OBSERVATIONS AT HOBART

In 1945, it seemed to me that a measurement of the type described by Seidl (1941) would be an achievable initial objective, as our first post-war cosmic ray research project. The data presented by Seidl had low statistical accuracy and did not fit Johnson's theoretical curve particularly well and I thought we could improve on that. Also, we would be making a measurement in the southern hemisphere at a similar high geomagnetic latitude (52° S) for comparison with the northern result.

Assisted by ALM, a grant was obtained from the Electrolytic Zinc Company (Risdon, Tasmania) for materials and apparatus, most of which was constructed in the Physics workshop, and later a grant for a PhD studentship was received from the CSIR. The latter was given to D.W.P. (Peter) Burbury, who, in 1952, received the second PhD awarded at the University of Tasmania (Burbury, 1951).

The equipment contained two trays, each with three GM counter tubes in parallel, plus a two-fold coincidence circuit forming a cosmic ray telescope. This was mounted in a yoke supported by a turntable so that both zenith and azimuth angles could be adjusted. The counting rate was low enough (about 180 coincidences per hour with no lead absorber between the trays) for direct registration by a post office call meter mounted on a panel along with a clock, direction indicator and aneroid barometer. This panel was photographed automatically with a single-shot 16 mm camera, usually at intervals of four hours. The timing unit also controlled the rotation of the turntable from one setting to the other. Statistically significant results at zenith angle 45° were obtained after the equipment had been in continuous operation for several months.

The first paper on the Hobart results, 'Measurements of the East-West Asymmetry of Cosmic Rays at Hobart, Tasmania' by A.G. Fenton and D.W.P. Burbury was submitted to the Physical Review during April 1948 and published in September that year (Fenton and Burbury, 1948).

The cosmic ray research program at Hobart had resumed after an interval of more than 20 years, and our first ALM style 'report' had been presented!

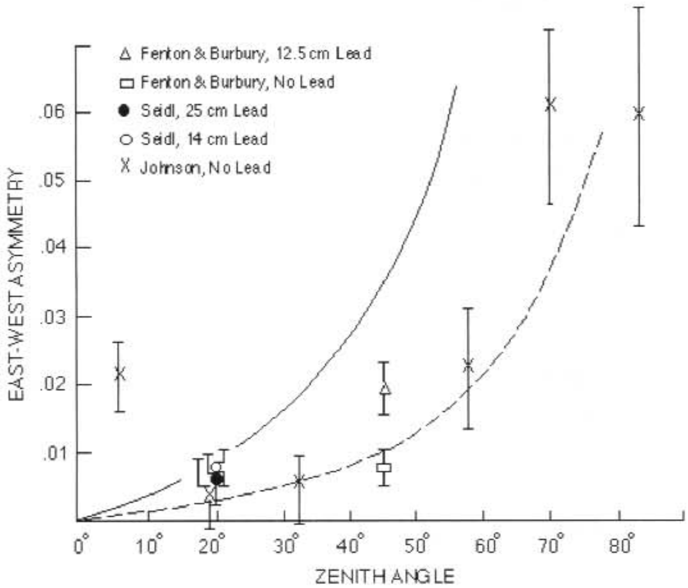

***Figure 4**. The first cosmic ray East-West asymmetry results at 45° zenith angle, from observations at Hobart, compared with data from the northern hemisphere and with predictions based on Johnson's theory for the hard component (solid curve). The broken curve represents the empirical asymmetry for the total radiation.*

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2. COSMIC RAYS IN THE ANTARCTIC – LAYING THE FOUNDATIONS

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In 1946 Professor Leslie Martin, in the Physics Department of Melbourne University, appointed a team to study cosmic radiation. Led by Dr Henri Rathgeber, it included me and several post graduate students – David Caro, Fred Jacka, Ken Hines, Charles Speedy, John Prescott and Joe Jelbart.

Apparatus was designed to measure the meson component of cosmic rays at ground level, comprising sets of geiger counters in 'coincidence circuits', mounted beneath blocks of lead which would absorb electron, proton and X-ray components of the radiation. The equipment served two purposes, to detect respectively the direct vertical radiation and that resulting from cosmic ray 'showers' slanting in at various angles over a wide area. When the geiger counters 'fired', they produced electrical impulses that operated mechanical counters whose registers were photographed each hour by 16 mm cine cameras, whose films were later developed and their counts transcribed manually onto record sheets. By today's standards, the equipment was primitive, time consuming and subject to repeated breakdowns as various thermionic vacuum tubes failed. Each failure demanded a search to determine which valve had blown.

A further piece of equipment was an ionisation chamber designed to detect and record the total cosmic ray intensity both meson and other radiations. The chamber was of spherical shape, about 38 cm in diameter, made of steel 1.5 cm thick and weighing around 80 kg. This, together with its associated electrical and recording gear, comprised a heavy and clumsy package.

In 1947, when the Australian National Antarctic Research Expeditions were established by the Commonwealth Government, Professor Martin requested that his Department's cosmic ray research be included in the scientific program of the ANARE. Accordingly, three sets of the equipment were built – one to go to each of Macquarie Island and Heard Island for a year, and one to voyage to the Antarctic on board the expedition ship 'Wyatt Earp'. Hines and Speedy were to go to Macquarie Island, Jacka and Jelbart to Heard Island, and I was to travel on the 'Wyatt Earp', accompanied by Ted McCarthy, a geophysicist from the Commonwealth Bureau of Mineral Resources.

As a lecturer in the Physics Department, I was given the responsibility of arranging the year's complex program, while the others I mentioned proceeded with the construction of the equipment. We planned to complete one set of apparatus by August so that it could be thoroughly tested. With my skiing experience on

Mount Hotham, I proposed that the testing should be carried out there. So, in April, Rathgeber and I visited Hotham and chose a site for a cosmic ray hut. A contract was let with a builder in Bright who managed, in execrable weather, to build a hut to our design before the winter snow blocked the Hotham road.

In August we had an adventurous time transporting the heavy equipment by sledges through snow, up and over Mount Hotham to the hut. Then, in August and September, various pairs of our group spent periods in the hut trying out the equipment. These tests were concluded and the equipment was returned to Melbourne by 20 September.

A detailed account of this period is given in my book, The Antarctic Voyage of HMAS 'Wyatt Earp'.

We were young, we were adventurous and we were all interested in skiing and snow and ice. We tackled the considerable transport difficulties of this Hotham exercise with boyish enthusiasm. Two incidents illustrate this.

We hired Eric Johnson and his twelve pack horses to transport our cases of meson equipment from Harrietville up the Bon Accord track to the Bon Accord hut above the snowline. So far so good. The next sector comprised a steep pinch from this hut on to Johnson's Hut, half buried in snow Johnson had shown considerable skill in steering the horses past the tree trunks and rocks at the sides of the trail, despite the way the clumsy cases projected sideways from the packsaddles. One horse, however, slipped in the slushy snow, its load hit a tree and the horse was thrown off balance, it fell heavily off the track and rolled and slithered 20 metres down the steep slope, neighing shrilly and scrabbling with its hooves at the scrub-covered terrain. The pack came apart and the two heavy cases hurtled on, tumbling and sliding in the snow bashing against the trees and bushes.

We plunged down through the snow, our feet tangled in buried bushes and broken branches, and began the difficult task of man-handling each case more than 30 metres up to the trail. With two men straining above, hauling on a rope tied around a case, and two on their knees in the snow pushing from below, it took a lot of time and effort. We hated to think what might have happened to the delicate apparatus within the cases!

The ionisation chamber equipment was too heavy and clumsy to be transported by packhorse. Instead, it was man-hauled on a sledge up the Omeo – Mt Hotham road, which was deep in snow. Over the final section to the hut, the road was obliterated by snow and the sledge could not be handled proceeding on a traverse across the steep slope, so the men were forced to haul the heavy sledge up and directly over the top of several hills leading up to the hut. To do this half of the sledge cargo was unloaded and relayed on a second trip. This whole exercise took two whole days of exhausting work.

In December 1947 the ANARE set up the Heard Island station and, early in 1948, the Macquarie Island station. During the year, Ken Hines had a lucky escape at Macquarie Island. While crossing a frozen lake with a companion, Charlie Scoble, the ice broke and the men were plunged into the freezing water. Scoble drowned but

Hines managed to break his way through the ice to the shore and struggle across the plateau and down the steep escarpment to the station on the isthmus.

The 'Wyatt Earp' cosmic ray project aimed to determine the variation of the sea-level meson intensity with latitude. The voyage was most demanding, the ship being quite unsuited for the purpose. It rolled abominably and leaked freezing sea water into the cabins.

On 19 February there was a Force 9 storm and the ship was rolling heavily about 35° each side of the vertical. I went to the cosmic ray lab on the boat deck at 10 am and was horrified to find, on opening the door, that the cosmic ray equipment in its enveloping aluminium chassis, was bashing from side to side of the cabin along the top of its bench. It was making horrible crashing and grinding noises. The retaining wooden 'fiddles' had been torn loose.

I looked around for some object to wedge into the 50 cm space between the equipment and the bulkhead, in order to control the sliding chassis. Since there was nothing available, I used my forearm, hoping that the 'throw' of the weighty apparatus would not break it. I stood there with my palm pressed against the chassis and my elbow several centimetres off the bulkhead and took the force of the sliding, bulky object on my forearm on each roll. I called for help but no one could hear me. After half an hour of this when I was wondering how much longer I could hold out, I attracted the attention of a passing sailor, who rushed off to get McCarthy. Ted found a baulk of timber to wedge in to place so I could withdraw my arm. We then surveyed the damage with sinking hearts.

All the connecting power leads had been sheared off. Worse, the heavy lead slabs, placed above the geiger counters to absorb unwanted 'soft' radiation, had become displaced and fallen onto the counters, smashing the delicate glass tubes. Two power transformers had torn loose and crushed some of the valves and circuits. Working hard over the next 24 hours we repaired most of the damage and set the gear operating again.

After my return at the end of March I was able to arrange to take the equipment on a voyage from Sydney to Japan on the troop ship 'Duntroon' to extend the latitude study across the equator. I was assisted by post graduate student Colin MacKenzie.

Back in Melbourne in September I settled down to analyse the results, set out on a great stack of record sheets listing thousands of figures. I was working on these in a temporary shed erected outside the physics building at Melbourne University.

One morning I arrived to find that the building had burned down during the night. It seemed that two years work had gone up in smoke.

Disconsolately, I picked my way through the charred timbers and ashes to the cabinet containing my records. I found blackened stacks of water-soaked paper. However, after peeling off the top sheets, I found that, although the edges of the pages were charred inwards to about a couple of centimetres, the major central portions were undamaged.

MacKenzie and I peeled the wet sheets apart and spread them over the floors of two laboratories to dry. We then used scissors to trim off the burnt margin. We were able to salvage more than 90% of our records!

Ball point pens had just been invented and I had used them on the voyage because a bottle of ink for a fountain pen might spill on a rolling ship. This was fortunate, for the ink of a ball-point is waterproof!

As a result of all this, two papers were published in the Australian Journal of Scientific Research.

In 1949 the two sets of cosmic ray equipment were brought back from the islands for overhaul and modification. Then, in 1950, Professor Martin decided to discontinue cosmic ray research in his laboratory. By this time I was directing the work of ANARE and was forced to find another home for this research.

I approached Professor Lester McAulay in Hobart, whom I had worked with on the Optical Munitions Panel during the war. He agreed to take over the work, so it was transferred to his Department of Physics in the University of Tasmania.

Geoff Fenton was put in charge and I will leave later speakers to go on form there.

As a postscript to all this, I must mention that when Bob Jacklyn retired recently from the Antarctic Division, he was clearing out his work space in the Physics Department of the University of Tasmania and found a box of records. They were the sheets of charred-edged paper with columns of figures that I had salvaged many years earlier from the burnt-out hut in Melbourne. He sent them to me and they now lie with my other personal archive material, which will finally go to the National Library in Canberra.

3. COSMIC RAY OBSERVATIONS AT MACQUARIE ISLAND IN THE 1940'S AND 1950'S

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ABSTRACT

The first cosmic ray measurements at Macquarie Island were made in 1948 by a group based at the University of Melbourne. The work of this group was expanded in 1950, which was also the year in which the University of Tasmania extended to the Island measurements of the high latitude East-West asymmetry of cosmic rays, commenced earlier at Hobart. Cosmic ray measurements continued on the island until 1959.

This paper gives a brief outline of the original objectives of the program and refers to some of the difficulties encountered in carrying them out as well as to the main findings. The emphasis is on the work done for the 1950–51 program although reference is also made to the subsequent years before the Cosmic Ray Hut was destroyed by fire in 1959. Brief references are included to the observations of the Aurora Australis in 1950–51 and to the balloon flights made in the early 1960's.

3.1 INTRODUCTION

Macquarie Island, some 1600 km SSE of Hobart, is situated in the sub-antarctic region of the Southern Ocean at latitude 54.5°S and longitude 159°E. Its geomagnetic latitude was taken to be 60.7°S in the 1940's, which placed it well above the knee of all the latitude vs cosmic ray intensity curves which had been obtained at sea level at that time. This fact implied that the primary cosmic ray particles which produce the secondaries observable at sea level at the island would have energies above the geomagnetic cut-off, and thus arrive essentially isotropically at the top of the atmosphere above the island. It was thus a very suitable site for the study of topics of interest to cosmic ray investigators at that time, several of which were concerned with meteorological effects. It must be remembered that this was a time before the major solar effects on cosmic rays of which we are now aware were clearly recognised and long before the solar wind was predicted or discovered. It was just at this time that the early experiments at Manchester and Chicago on cosmic ray neutrons were being conducted, which led to the development by the University of Chicago of the neutron monitors, with their profound effect on the study and identification of the solar effects. It was also just before this time that the π–meson (pion) was discovered and was accepted as the parent of the dominant particle among the cosmic rays at sea level, the μ-meson (muon) which constitutes the penetrating component. These discoveries heralded the beginning of the main era of high-energy particle physics, and the splitting of cosmic ray physics into the two more or less separate branches of astrophysics and particle physics, a split which, to a large extent, persists to the present day.

3.2 THE EARLY PLANNING

I have encountered difficulties in locating the documentation, which undoubtedly exists, as to the precise objectives of the planners of the research program of the Australian National Antarctic Research Expeditions (ANARE) of 1947–48. It is clear that the political climate was right for Australia to take a direct and active interest in the sub-antarctic and antarctic regions to our south, and that it was appropriate that scientific investigations in several areas should form the basis for that interest. Among the scientists who demonstrated enthusiasm to participate in such a program were members of the Cosmic Ray Group at the Physics Department, University of Melbourne, in particular, the head of that Group, H.D. Rathgeber, and his younger colleagues, D.E. Caro and P.G. Law. It was beyond the logistic capabilities of Australia at that time to consider an expedition to the antarctic continent, but expeditions could be contemplated to the sub-antarctic Macquarie and Heard Islands, over which Australia claimed jurisdiction. A voyage to measure the intensity of cosmic rays vs latitude using a Geiger-counter telescope was also planned over as large a range of latitudes as possible, including high southern latitudes. All such previous surveys had used ion-chambers. An account by P.G. Law of the voyage of The Wyatt Earp is included in this volume, and is also given by Caro et al. (1948).

The Melbourne group prepared three similar sets of equipment consisting of trays of Geiger counters arranged in 'telescopes' to measure the total vertical intensity from a narrow angle as well as the vertical intensity of the hard component (particles capable of penetrating 10 cm of lead) from a narrow angle and also the total intensity from a wide angle (essentially the full upper hemisphere). Valve electronic circuits handled the pulses from the Geiger counters and the recording was by mechanical registers of the type then used in telephone exchanges to count telephone calls made by subscribers. These registers were photographed every hour, the timing being with a ship's chronometer. One of these sets of equipment was for the latitude survey, the other two were destined for Heard and Macquarie Islands, supplemented by a high pressure ion chamber as well as an additional Geiger counter array which could be moved to various points up to 200 m away from the main arrays to record extensive air showers.

Some idea of the scientific objectives of this equipment, as conceived when the expeditions were planned, may be seen in the following statements extracted from a handbook entitled Australian Antarctic Expedition 1947–1948, Cosmic Ray Research Equipment, Heard and Macquarie Islands: "The equipment consists basically of an ionisation chamber and Geiger counter equipment. The ionisation chamber records bursts and the total ionisation produced by cosmic rays. The Geiger counter equipment provides facilities for recording the total intensity of cosmic rays, the meson content, the number of showers produced over a one metre base and the number of showers extending over a wide base of up to 200 metres. (This latter facility is not provided on the Wyatt Earp)." Also in this handbook are the following statements under the heading "Analysis and Correlation of Results": "...cosmic ray intensity is a function of barometric pressure, the temperature function through the atmosphere, the magnetic field of the Earth and possibly other as yet unknown variables... The purpose of the correlation calculations is to find from the observed data (a) the regression coefficients and (b) the closeness of the link between the cosmic ray intensity and the various independent variables."

3.3 THE BEGINNING OF ANARE OPERATIONS AT MACQUARIE ISLAND

The Macquarie Island equipment was taken South by C.L. (Leigh) Speedy and K.C. (Ken) Hines, physicist members of the 13-man wintering party which arrived at the island on 7 March 1948. At that time, only derelict huts remained from Mawson's Australasian Antarctic Expedition (AAE) of 1911–14, and the new party's first priority was to establish a new base and quarters on the narrow isthmus at the North end of the island. The Australian naval vessel (later to be named the HMAS Labuan) which brought the party to the island, departed on 25 March 1948, leaving the 13 men alone to complete the construction work, establish a suitable water supply, install the Diesel generators for electric power, erect radio masts and install radio equipment for communication back to Australia and to commence the scientific program (for further details of these early days, see the account in Bowden's book (Bowden, 1997).

The building to house the cosmic ray equipment (approximately 2.7 m x 2.7 m) was completed about 20 April and the first entry in the Macquarie Island Cosmic Ray Log Book kept by Speedy and Hines, dated 21–28 May 1948, gives an indication of the problems which were to plague the work: "The rack (main) had been assembled the previous week and tests carried out. At the beginning of this week the three mechanical counters and allied circuits were functioning satisfactorily and it was proposed to commence continuous recording immediately and a cable to that effect was sent to Melbourne. We received a reply the following day in which it was stated that the Wyatt Earp trip had proved the lifetime of the mechanical counters was very short, that our circuits would have to be rebuilt to cut down the counting rates and not to commence continuous recording but to continue with testing of ionisation chamber and showers. A few days later full details of the new circuits and modifications were received (it took three hours for the radio operators to take down the Morse Code message, as noted by Speedy (1999) in his personal diary). Work was commenced at once on the new circuits, which provided for drastic reductions of count rates by the insertion of scaling pairs. The shower section was to be temporarily laid aside and new circuits for this to be constructed later. A preliminary filling of the ionisation chamber was made this week but a small leak was present and the chamber was laid aside pending rebuilding of the principal circuits." (I have slightly changed the wording of this extract from the Cosmic Ray Log in order to insert the comment from Speedy's diary.)

The cosmic ray equipment was designed to run from car batteries which were charged either from a portable petrol-operated generator or from the island electric power system. Once the equipment was running, a set of batteries would last for about eight hours before being interchanged with a newly charged set. Speedy's diary has frequent references to the problems encountered because of this necessity, and also to the problems encountered with the main Diesel generators for the island power system. It is also evident from his diary that several failures among the valves in the electronic circuits and also failures of some of the Geiger counters occurred.

A tragic accident occurred on 8 July 1948, in which the Diesel engineer (Charles Scoble) was drowned following a mishap while skating across a frozen lake (now known as Scoble Lake) on the plateau South of the main base. In spite of valiant efforts, Ken Hines, who was with Scoble on this exploit, was unable to save him. Because of the critical importance of the Diesel generators for the provision of electric power at the base, the ANARE Headquarters in Melbourne arranged to send a replacement engineer to the island. This was achieved in a very hazardous winter-time undertaking by using a RAAF Catalina flying boat, equipped with JATO (jet assisted take-off) rockets to assist in its take-off from the island, after leaving the new engineer, Frank Keating. The Catalina also brought some replacement Geiger counters.

Problems with the equipment, and with the Diesel generators, continued for the rest of the year and into the next. Among other things, it proved to be impossible to repair the leak in the ionisation chamber with the facilities available on the island and no useful results were obtained with it. Geiger counters continued to fail and there were mechanical problems with the cameras used to record the data. The final entries in the Cosmic Ray Log tell the story:

"1–7 February 1949. Two additional checks of all Geiger counters showed that only 6 were satisfactory and these were arranged with three in each of trays 5 and 6. A new set of valves was put into the scale-of-32 circuits and extensive adjustments to the camera were necessary. Power difficulties interfering with battery charging precluded the commencement of continuous operation until 8th.

8 February 1949, after a run of only 1 day it was found that consistent results were not being obtained and a further check of Geiger counters showed that only two operable ones remained. It was thus impossible to continue the operation of the equipment and further efforts in this direction were consequently abandoned."

After this state of affairs was reached, packing up began for the return of the party to Australia. The HMAS Labuan arrived at the island on 25 March 1949 with a relief party which did not contain any cosmic ray physicists.

Although there are several references in Speedy's diary to the correlation work he was doing, I am unaware of any compilation of the data or results from the statistical calculations among the records held by the Antarctic Division. It may therefore seem that the frustrating efforts made by Speedy and Hines did not advance cosmic ray knowledge. However, their work did help appreciably in the planning of a new set of equipment at Melbourne for the next phase of Macquarie Island investigations. These experiences were also helpful to the Hobart group in designing the equipment which it planned to send to the island.

3.4 PLANNING THE NEXT PHASE

The objectives of the University of Melbourne program for the future remained the same, namely to obtain a long run of reliable data on the cosmic ray intensity with which to study the factors which cause the intensity to vary with time, particularly the meteorological factors. Surface and upper atmospheric measurements in 1948 and 1949 had verified that, although the surface temperature varied in only a narrow range, there were large changes in the atmospheric pressure and in the upper atmospheric variables, thus confirming that the island was very suitable for the proposed cosmic ray investigations. It was decided that a completely new set of recording equipment should be built and this was done during 1949 by N.R. (Nod) Parsons who had joined the Melbourne group from Hobart. Among other improvements which were decided upon, it was planned that the equipment would be operated from one set of lead-acid batteries which were to be continuously charged or 'floated' on a battery charger operated from the station mains supply. This was to avoid the problems encountered by the 1948 parties at Heard and Macquarie Islands in maintaining two separate sets of batteries. It was also decided to use a modular construction for the racks of electronic circuits and Geiger counter telescopes to simplify transport and assembly of the equipment and also to make it easier to service once in operation. The details of the equipment, which became known as 'Set A', are given by Parsons in his University of Melbourne MSc Thesis (Parsons, 1952) and also by Jacka et al. (1959). The basic design was virtually the same as that used on the Wyatt Earp and that sent to Macquarie and Heard Islands in 1948. The trays forming the telescopes had sensitive areas of 20 cm x 20 cm, made from six counters in parallel, trays 1, 2, 3 and 4 being vertically above one another with a separation of 15 cm, with 10 cm of lead between trays 3 and 4 to absorb the soft component. Trays 5 and 6, with negligible separation, were separated from trays 1, 2, 3 and 4 by a horizontal distance of 1 m between their centres. This combination of trays allowed measurements to be made of the total intensity of cosmic rays and of the penetrating component arriving from a narrow angle about the vertical, as well as the total intensity from a wide angle, together with showers over a short base length of 1 m, both total and penetrating. Trays 7 and 8, separated by an adjustable vertical distance, formed a wide-base shower unit which could be moved to various distances of up to 200 m from the main rack for observation of extensive air showers.

The Hobart group commenced a cosmic ray research program in 1946 and, as noted in the Preface to this volume, this collection of papers celebrates the 50th anniversary of this beginning. During 1948, discussions were held with ANARE about the possibility of extending to Macquarie Island measurements of the high-latitude East-West asymmetry of cosmic rays which the group had been making at Hobart. This was a topic chosen by A.G. Fenton as one in which useful results could be obtained from the beginning in the difficult process of building up a research program in Hobart in a field which had attracted many workers elsewhere in the world. The topic had the support of the then Head of the Department, Professor A.L. McAulay, who some 20 years earlier had led the first cosmic ray observations at Hobart (McAulay and Hutchison, 1924). The views were also sought of Professor T.H. Johnson of the cosmic ray group at the Bartol Research Foundation of the Franklin Institute, Pennsylvania, who had discovered the effect and had proposed an explanation of it. Johnson agreed that measurements at another site and with improved statistics would be of great interest.

Briefly, the explanation is that, although the primary cosmic rays which produce the secondaries observable at sea level in latitudes above the knee of the latitude curve arrive isotropically at the top of the atmosphere (as noted at the beginning of this paper) and that therefore there would not be an East-West asymmetry of the primaries, the secondary muons do undergo deflections in the geomagnetic field as they lose energy in the atmosphere. The path length of positively charged muons arriving from a given zenith angle from the East is longer than those arriving from the same zenith angle from the West and therefore there are more losses from the East due to absorption and decay. Because there are more positive than negative muons, a greater intensity is expected from a given zenith angle to the West than from the same zenith angle to the East. The measurements at Hobart had confirmed the existence of the effect (Fenton and Burbury, 1948), but, because Hobart was believed to be not far from the knee of the latitude curve, it was felt that similar measurements should be made at a higher latitude. ANARE agreed with the proposal and supplied the funds to build the necessary equipment to take to Macquarie Island.

Work on the design and construction of the equipment, which became known as 'Set B', commenced at Hobart early in 1949. Two narrow angle Geiger counter telescopes were to be mounted on a horizontal platform, rotatable about a vertical axis, with one telescope pointing to the East, the other at an equal zenith angle to the West. The platform was to be rotated every hour through 180°, thus interchanging the East and West pointing telescopes. In this way, over a period of time, each telescope would record for the same length of time in each direction and slight differences in the geometries of the two telescopes would be irrelevant. The work was divided between Drs A.G. Fenton, D.W.P. Burbury and myself, although we kept in close touch with one another, and also kept ourselves informed on the plans being developed by the Melbourne group.

Dr A.G. Fenton made the Geiger counters using methods he had devised in previous years. The counters were of the Maze external cathode type in which a cylindrical soda glass envelope with a fine tungsten wire anode along its axis is used to contain the argon-ethyl ether mixture, the cathode being colloidal graphite painted on the outside of the glass. It had been found that long-lasting counters with good plateaus could be produced simply and reproducibly with this technique. The sensitive length of the counters was 20 cm and the telescope trays used 11 such counters arranged with a layer of six counters, the remaining five filling the gaps between the six. By overlapping the counters in this way a uniformly sensitive area of 20 cm x 20 cm was produced, such that, if it became necessary to change a counter with another of the same length, the sensitive area would remain unchanged. The top and bottom trays in each of the two telescopes were separated by 75 cm, giving a half angle of ~15° in both the zenith and azimuthal directions. By using narrow angles in both directions, the particles detected could be assumed to travel essentially in a vertical plane and thus be subject to deflections due to the horizontal component of the geomagnetic field. Lead of thickness 12 cm was placed in each telescope to filter out the soft component.

Dr Burbury was responsible for many of the mechanical features of the equipment. The rotatable platform to support the telescopes was originally the base of a 'predictor unit' used during the Second World War for calculating the settings required for artillery units. Besides being sturdily constructed with a ball-bearing mount, it had a slip-ring contact system which was suitable for bringing power from the batteries to the electronic circuits needed for the telescopes and to the circuits needed to control the rotation and the recording system. As with the Melbourne group, electro-mechanical registers of the non-resetting type for recording telephone calls were used to record the telescope count rates and a panel of such registers was photographed every hour. Since no suitable camera was available either commercially or as ex-military equipment at that time, Burbury designed one specifically for the purpose. It was based on the then well-known Leica camera design which used a focal-plane shutter but the body had to be modified to hold enough 35 mm film to last for over a week, with two half-frame photographs (~25 mm x 19 mm) every hour separated by one minute (one before and one after each rotation of the platform). An external gearbox was bolted onto the camera body the purpose of which was to make a single turn of a shaft to open the shutter and advance the film for the next photograph. A Waterworth f/3.5 5 cm 'Centaur' lens, which was still in production in Hobart at that time, was used and a section at the back of the camera body could be screwed out to allow for focussing. About 15 of these cameras were produced by the Physics Department workshop, covering the needs at Hobart as well as at Macquarie Island. One was also made available for the Melbourne equipment for the island, and enough spares were provided for both projects. Burbury also designed the system of electric motors, relays and switches required to control such functions as the rotation of the platform as well as the operation of the camera and the lights to illuminate the register panel and clock. The switches were of the mercury-in-glass type which had to be tilted for electrical contact to be made, this type of switch being less likely to produce electrical noise than other types.

My own part in preparing the equipment was largely concerned with building the electronic circuits, including the high voltage supplies (~1100 V) for operating the Geiger counters and ~250 V for the pulse circuitry. The pulse handling circuits, in the main, used valves which were readily and cheaply available at that time as ex-military items, namely EF50 valves, although some other types were also used, including thyratrons for operating the mechanical registers. As with the Melbourne equipment, the power for all the circuits was derived from lead-acid batteries continuously charged by battery chargers at a current a little higher than that required by the circuits. The high voltages were produced using mechanical vibrator units, of a type then commercially available, connected to appropriate transformers.

The HMAS Labuan, carrying the Melbourne equipment together with most members of the wintering party and more than a year's supply of provisions left Melbourne on 3 April 1950. It called at Hobart a few days later to pick up Nod Parsons and me along with the Hobart equipment, suitably packed to withstand the expected hazardous landing at Macquarie Island, much of it in watertight containers. The Geiger counters were protected from severe mechanical shock by using car seat springs to support inner boxes containing the counters inside larger outer packing cases. The ship arrived at Macquarie Island on 10 April 1950.

3.5 GETTING ESTABLISHED IN 1950

After unloading the ship, transporting the equipment ashore using amphibious craft and storing it under tarpaulins near the place where it would be put into operation, the first task confronting Nod Parsons and myself was to construct a new Cosmic Ray Hut. A site on the West side of the narrow isthmus at the North end of the island had been chosen before we arrived, based on the requirements of the projects. It was about 3.7 m above sea level and was such that the hills to the North and South of the site would subtend the smallest possible angles at the equipment, about 8°. The prefabricated hut had dimensions of about 11 m x 3.7 m. The wall and roof panels, each about 1.8 m x 1.8 m, had an outer layer of 5-ply wood separated from an inner layer of 3-ply by about 5 cm of an insulating material known as Onazote. The frame onto which these panels were bolted was of oregon pine. Construction of this hut commenced before the ship left the island, use being made of the manpower available from the crew. In an attempt to speed this task, one group of men started erecting the frame for one end of the building while another group started at the other end. Unfortunately, either the prefabricated pieces were different from the specifications, or the tape measures used in Melbourne for their construction were different from those used by the sailors, with the result that Nod and I had to saw several centimetres off the lengths of the central wall, floor and roof panels after the ship had departed. It was also necessary to use a caulking material to block up the inevitable gaps which resulted from such construction methods.

With the aid of other members of the wintering party, we cut a square hole in the middle of the floor of the Cosmic Ray Hut to permit the construction of a concrete block about 60 cm x 60 cm set into the rock below to support the East-West asymmetry equipment. This was essential to ensure a stable foundation for the equipment which had to rotate about an axis vertical to within less than 10 minutes of arc. Among our other early tasks were the laying of an underground power cable from the Diesel generator about 200 m away and the construction of a second smaller hut, of galvanised sheet iron, to house the batteries and chargers. The power cable, sheathed in lead, was laid underground to help protect it from the elephant seals which were present in large numbers at various times of the year and moved at will across the isthmus.

The final building may be seen in the distance in Figure 1 with the main camp in the foreground near the foot of Camp Hill. A close-up photograph is shown in Figure 2.

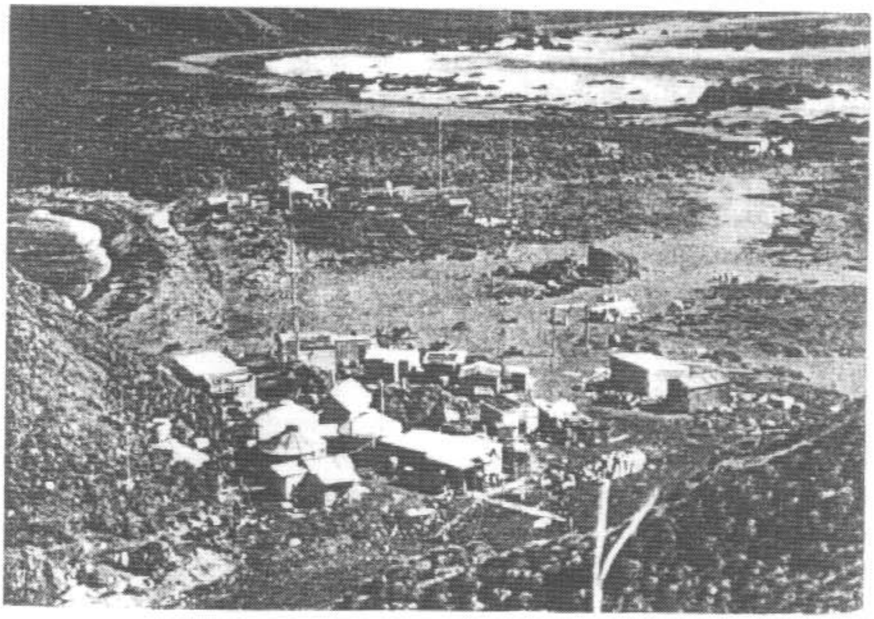

Figure 1. *The Cosmic Ray Hut at top right, near the shoreline of Hasselborough Bay. Two magnetic huts are further along to the left.*
(ANARE photograph taken from the slopes of Wireless Hill.)

Figure 2. *The Cosmic Ray Hut viewed from its northern end, with the battery hut in the foreground and, behind it, packing cases under a tarpaulin.*
(Photograph: Nod Parsons 1950.)

3.6 THE 1950 COSMIC RAY MEASUREMENTS WITH 'SET A'

The construction tasks and the assembly of our equipment were completed by about the middle of May 1950. Full operation of the Melbourne equipment was commenced on 28 May, although the preparation of sites for the wide-base shower unit delayed the commencement of observations of extensive air showers until 28 June.

Preparations for the observations of extensive air showers entailed the construction of a wooden framework for carrying the shower unit and its two lead-acid batteries to sites situated 10, 27.5, 75 and 200 m from the main rack in the Hut. At each site a piece of tin-plate was buried in the sandy/peaty soil to provide as efficient an earth-connection as possible for this unit, which was housed in a galvanised iron bin and covered with a small tarpaulin for maximum protection from the weather. During the early months of operation the batteries were charged using a small 300 watt 'Chorehorse' petrol-powered generator, with one of the batteries being charged while the other operated the equipment. Provision was made for interchanging the batteries without interruption of the current to the rack. The generator was run for about eight hours each day. This procedure was a constant source of trouble, with maintenance of the generator and a spare taking up considerable time. Several breaks in data collection occurred due to difficulties in the maintenance routine brought about by the weather conditions and the short periods of daylight during these early months. When word was received that a frigate, HMS St Austel Bay, would be visiting the island in September 1950, Nod Parsons decided that the opportunity should be taken of having two small mains-operated battery chargers sent down from Melbourne. These duly arrived on the ship and were put into operation, thus solving the problems, even though a very long power cord was needed to provide mains power at the shower unit.

Unfortunately, the station chef, Norm Figg, took the opportunity to leave the island on the same ship. However, his duties were capably assumed by the assistant cook/storeman, Fred Doutch, for the next three months until another ship, the British oceanographic vessel Discovery II, called at the island, bringing a replacement chef, Ron Knightley.

The shower unit continued to operate without much difficulty for the remainder of our stay, although constant attention had to be given to its protection from damage by elephant seals. Barricades formed of fuel drums and wooden railway sleepers were reasonably effective but had to be repaired frequently, particularly during the breeding season when the whole camp area was heavily populated by eager seals. Fortunately, the coaxial and power cables back to the main Cosmic Ray Hut suffered no damage from the incessant seal traffic.

Throughout the period of our stay on the island, which extended until May 1951, 'Set A' (as shown in Figure 3), operated without serious breakdown and an excellent set of data was accumulated which, in my opinion, was as good as any which had been obtained anywhere in the world up until that time. The main problems which did arise related to failure of Geiger counters but the weekly routine of checking all counters individually with a cathode ray oscilloscope and replacing or rejuvenating any which showed signs of deterioration kept the loss of data to a very few hours. The total number of Geiger counters in use in 'Set A' was 48 and 72 spares were taken to the island. At the end of our stay, the number of spares was reduced to about six.

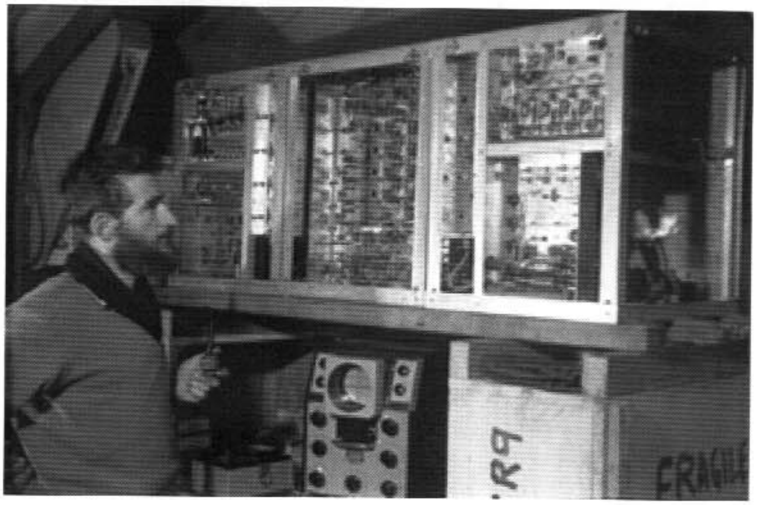

Figure 3. *Nod Parsons with 'Set A' in the Cosmic Ray Hut, 1950.*
(Photograph: W. Nutt, ANARE Photographer).

3.7 RESULTS OBTAINED WITH 'SET A'

It is of interest to note the counting rates observed with this equipment. The average counting rate obtained with 'Set A' at Macquarie Island from June 1950 to May 1951 was approximately 4800 per hour for the total intensity, i.e. coincidences (1, 2, 3), while the hard component intensity was approximately 3400 per hour, i.e. coincidences (2, 3, 4). The wide angle rate over nearly the full upper hemisphere was about 21 400 per hour, i.e. coincidences (5, 6). The total rate of showers over a 1 m base was about six per hour and of penetrating showers over the same base about 1.7 per hour. The rates of the wide-base showers are given in Figure 4 taken from Nod Parsons' thesis (Parsons, 1952).

This figure demonstrates the closely parallel variations of the total and penetrating shower rates with base length, with the ratio between the two rates being essentially constant over the whole range. The fact that the ratio of the rates of total to penetrating showers (2.61–2.94) is appreciably less for all base lengths ≥10 m than for the 1 m shower base, for which the ratio is 3.53, is probably due to the prevalence of locally produced soft showers. The evidence is consistent with the idea that only one type of shower is involved over the four different base lengths ≥10 m, a conclusion reached previously by Cocconi (1949), viz. that all extensive air showers contain penetrating particles and all extensive penetrating showers are accompanied by extensive electron showers.

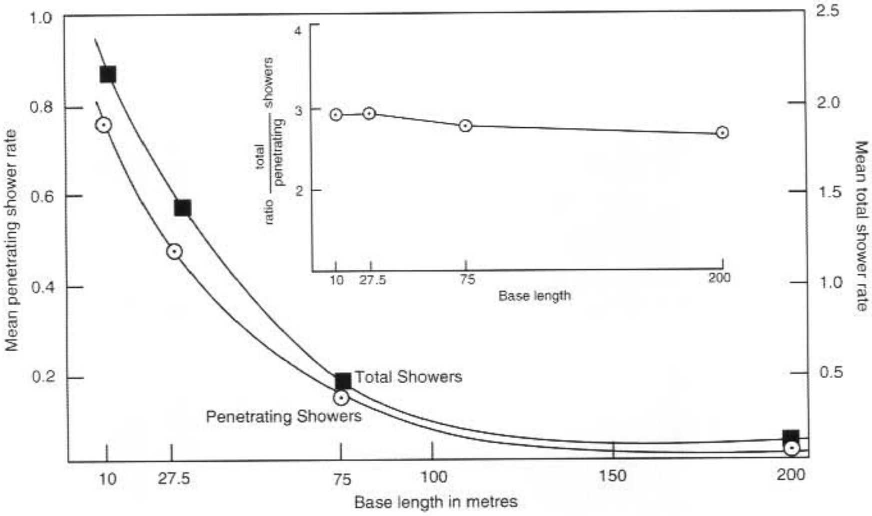

Figure 4. *Variation of Extensive Shower Rates with Base Length Observed with 'Set A' (Parsons, 1952).*

One of the main objectives of the program was to examine the meteorological effects on the intensity of cosmic rays. Consequently, an important part of our work was the collection of the meteorological data from the Bureau of Meteorology staff stationed on the island a few hundred metres from the Cosmic Ray Hut. This group of four highly competent people, headed by Jack Windsor, took great pride in keeping their instruments in good condition and in checking their calibrations wherever possible. They provided us with charts from which we obtained hourly values of surface pressure and temperature. They also provided us with the upper atmosphere data obtained from radiosonde balloon flights made daily at 0800 UT and, in the latter part of the year, they provided us with the data from 30 additional flights which they conducted when the station-level pressure was 1006 ±1 millibar (hectopascals). These additional flights were made in the hope of enabling a distinction to be made in later analyses between effects on cosmic ray intensity due to the total atmospheric pressure and the upper atmosphere parameters. In addition to the meteorological data we collected data from records obtained on the island of ionospheric, radio, magnetic and auroral disturbances, to permit investigations to be made of possible causes of fluctuations in cosmic ray intensity not related to meteorological variations.

3.8 'SET A' DATA ANALYSES AND CONCLUSIONS REACHED

These analyses were carried out by Nod Parsons in Melbourne in the latter part of 1951 and during 1952 and his results are included in his MSc Thesis (Parsons, 1952). Results are also given in ANARE Reports by Law and Burstall (1956) and by Jacka et al. (1959). In his thesis, Parsons gives a very comprehensive review of previous attempts to understand how the meteorological effects arise. It is not appropriate to refer to all the details here, but it is relevant to note that many of these attempts were frustrated by the lack of knowledge of the fundamental properties of the particles which constitute the secondary cosmic rays. This knowledge remained hidden until 1947 and the discovery of the pion (Lattes et al., 1947) and the immediate few years thereafter as the pion's properties were more fully understood.

Prior to this, it had been known for many years that the barometric pressure is the dominant factor, with the cosmic ray intensity decreasing as the pressure increases, an effect assumed to be due to ionisation energy loss and consequent absorption of the particles by the mass of air above the equipment. Towards the end of the 1930's, after the discovery of the particle we now call the muon as the penetrating component of the cosmic rays at sea level and the discovery that it is unstable with a mean lifetime near 2 μs, investigations began to be made of the effects of upper atmospheric parameters. The work of Duperier in the early part of the 1940's was of importance (e.g. Duperier, 1944) in that he began to attach significance to the height of the 100 mb level in the atmosphere as the assumed level of production of most of the muons. With the subsequent discovery of the pion and the realisation that, in addition to being the parent of the muon, it is also a nuclear active particle which reacts strongly with nuclei, Duperier examined whether the effect of competition between loss of pions in the upper atmosphere via nuclear interactions and decay to muons could be observed through a correlation between the intensity of muons at ground level and the density of the upper atmosphere. As a result of multiple correlation analyses, he concluded (Duperier, 1949) that the density of the air in the region 200 to 100 mb is a factor additional to the barometric pressure and height of the 100 mb level in controlling the sea level muon intensity, the intensity increasing with increasing temperature (i.e. decreasing density) in this region.

Parsons' thesis presents the results of a very large number of multiple regression analyses aimed at determining whether the Macquarie Island data support Duperier's conclusions. His conclusion was that the data provided little evidence in support of the idea that the bulk of the muons observed at sea level are produced in the vicinity of the 100 mb level. The values of the multiple correlation coefficient were found to be large at all heights up to that of the 80 mb level and showed no significant systematic variation with height. This was so even for the data from the flights conducted under standard surface pressure conditions. In view of this he concluded that the attachment of any great significance to the partial correlation coefficients is not justifiable.

Additional analyses showed a significant diurnal variation of cosmic ray intensity with an amplitude of about 0.2% and with a maximum shortly after local noon. No significant semi-diurnal variation was present. These results were consistent with the similar results obtained elsewhere and which were available at that time. This is a field in which a great deal of work has been done subsequently as much higher counting rates have become available and as knowledge of the structure of the heliosphere has evolved.

3.9 MEASUREMENTS WITH 'SET B'

Mention should be made of some of the criteria which had to be met in setting up this equipment. As noted earlier, it was essential that the axis of rotation of the turntable be vertical. Since the prime objective of the measurements was to obtain values of the East-West asymmetry at various zenith angles, it was important that the equipment itself should not introduce any spurious asymmetry. It was known that the muon intensity at sea level varies approximately as $\cos^2\theta$ where θ is the angle between the axis of an inclined telescope and the vertical. It could be shown easily that, if a small error, ϕ, were present in the verticality of the axis of rotation of the telescopes, an apparent asymmetry of $4\phi \tan\theta$ would result. Thus, at $\theta = 45°$, an error of 0.0025 radian (~10 arc minutes) would produce an apparent asymmetry of 1%, comparable in magnitude with the expected true asymmetry. The precision spirit levels used in adjusting the turntable were sufficiently sensitive to allow an error of about 1 arc minute to be detected. The results themselves, obtained later, indicated that any error present in the levelling must have been quite negligible.

It was also necessary to take into account the magnetic declination at the site, since the objective was to observe effects due to the deflection of particles in the East-West vertical plane. The declination at Macquarie Island at that time was 24° East of geographic North and the long side of the Cosmic Ray Hut had been determined to lie 12° East of North. Hence it was necessary to orient the equipment a further 12° East of North with respect to the walls of the Cosmic Ray Hut. Its operation commenced on 1 June 1950.

Figure 5 shows the final arrangement of 'Set B' in the middle of the Cosmic Ray Hut, with me standing and Nod seated at his desk and with bound Volumes of Physical Review on the shelf at the end.

Although all parts worked as expected from the beginning, the eight-day clock which controlled the timing of the rotation and the operation of the camera was found to be unsatisfactory, with its rate varying with spring tension. Fortunately, it was possible to determine the error in its rate and to correct for it by daily comparisons with time signals from the radio station WWV in Honolulu and also by frequent checks against the chronometer used in 'Set A'. The unsatisfactory nature of the clock was discovered very soon after operation commenced and the Hobart group was able to send a chronometer down on the HMS St Austel Bay which called at the island in September 1950. This was quickly put into operation in place of the original clock.

It emerged during the first several months of the operation that the rate of accidental coincidences resulting from using only two trays of Geiger counters per telescope was too high. This weakness in our design had probably come about because of simply adapting the design of the original Hobart East-West asymmetry telescope to that of 'Set B' and overlooking the fact that the background rate of the Maze type counters would be higher than that of the smaller internal cathode counters used in the original Hobart telescope, due to the radioactive potassium present in the soda glass of the Maze type counters. Fortunately we had provided enough spare counter assemblies for me to build a third tray for each telescope using sheet metal from the Station workshop and to build the necessary additional circuitry from spare components to produce three-fold coincidences in each telescope. This work was completed by February 1951 and proved very satisfactory. The makeshift circuitry was replaced by properly constructed new circuits built at Hobart when the personnel changeover occurred in May 1951. By using the new three-fold coincidence rates it was then possible to work out adequate corrections for the previously obtained two-fold coincidence data. It is of interest to note that in the current large-area telescopes in use at Mawson and at our Cambridge Tunnel Observatory two-fold coincidences are used together with additional circuitry to determine the accidental rate routinely.

Figure 5. *'Set B' in the Cosmic Ray Hut, 1951.*
(Photograph: W. Nutt, ANARE photographer)

Another matter worthy of mention is that a large rock to the East of the Cosmic Ray Hut subtended an angle of about 5° at the equipment. Since the half-angle of the telescopes was 15°, when the axes were set at 70° to the zenith muons arriving from the East would just graze the top of this rock. Since the rock was of a conglomerate type which was not difficult to chip, it was decided to blast the top off it. The station engineer, Cyril Park was eager to try his blasting experience and enthusiastically accepted the challenge of setting sticks of gelignite into the rock and reducing the angle subtended by a degree or so. It is of interest to note that in later years the now-flattened top of the rock was used as the foundation for an auroral observing post.

The data obtained with 'Set B' proved valuable not only for helping to verify the existence of the high-latitude East-West asymmetry but also for studying the meteorological effects on cosmic rays arriving from non-vertical directions. Few studies of this type had been made previously and they opened the possibility of assisting in the task of unravelling the complicated relationship between cosmic ray intensity and the structure of the atmosphere. Details of the analyses resulting from this work and carried out during the latter part of 1951 and during 1952 are contained in my thesis (Fenton, 1952). A discussion of the East-West asymmetry studies is given by Burbury and Fenton (1952) and Figure 6 shows the Hobart and Macquarie Island data in comparison with values expected from a modified version of the theory, represented by the smooth curves, worked out while I was on the island.

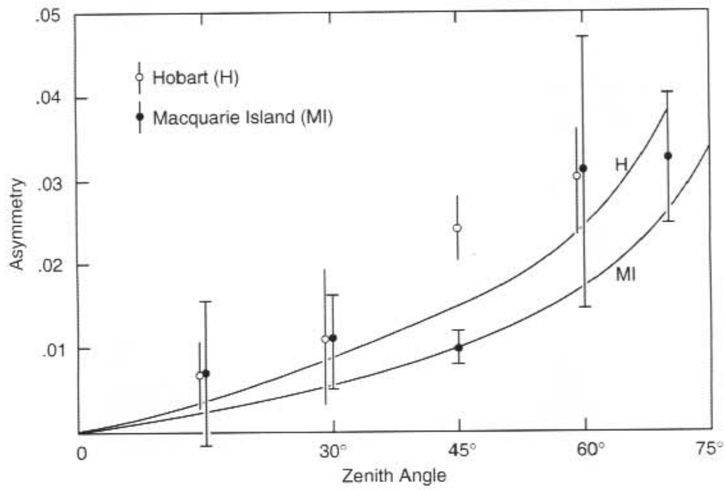

Figure 6*. East-West Asymmetry at Hobart and Macquarie Island (Fenton, 1952).*

All preliminary calculations carried out on Macquarie Island on data from both 'Set A' and 'Set B' were made using a small Facit mechanical hand calculator. Although an electric version was available at the time we left for the island, it was felt that the hand version would be more easily repaired by us if repairs became necessary, but, in fact, very few difficulties were encountered with the hand operated machine. Most of the calculations made after our return were carried out at ANARE Headquarters in Melbourne using Hollerith punched card machines.

As far as I know, a solution to the problem of completely accounting for the variations of cosmic ray intensity at sea level in terms of variations in atmospheric parameters has not yet been achieved.

During the course of our work on Macquarie Island, we began to realise that changes due to other factors than those related to the terrestrial atmosphere were occurring, as did others elsewhere. Our knowledge of solar system effects was far too rudimentary to begin to understand such variations. At the present time, with constant monitoring of solar parameters from the ground and from space, much progress is being made. The advent of the global network of cosmic ray neutron monitors, which are more sensitive to the cosmic ray changes due to solar effects than are muon telescopes, has led to a reduced reliance on muon observations for the study of several heliospheric effects, although for investigations of cosmic ray density gradients in the heliosphere advantage can be taken of the fact that the majority of muons are produced by primaries whose gyroradii are larger than those of the primaries responsible for most of the nucleonic component. Thus the muon intensity at sea level has a greater dependence on the cosmic ray particle density further out in the heliosphere than does the nucleonic component intensity. It is also worth reminding ourselves that the potential remains for benefit to be derived from a full understanding of the meteorological effects on muon intensity. Since, for a given intensity and spectrum of primary cosmic rays, it is processes in the atmosphere which determine the intensity of muons at the surface of Earth, it must be possible, in principle, from a combination of measurements of the primary and secondary cosmic rays and of the atmospheric parameters such as barometric pressure to determine important features of the atmosphere such as the temperature profile. Neutron and muon monitors on the ground as well as measurements such as will be possible on the Space Station would be needed for this task

3.10 AURORAL OBSERVATIONS

Nod Parsons and I made systematic visual observations of displays of the Aurora Australis during the period 1 May 1950 to 30 April 1951. A record of these observations is contained in a 338 page ANARE Report (Parsons and Fenton, 1953). During the first four of these months, while most of our attention had to be devoted to establishing the cosmic ray program, our observations ceased at midnight. But from September onwards we kept watch from sunset to sunrise on all nights. Nod usually did the sunset to midnight shift and I usually took over from midnight until dawn. Most of these observations were made from just outside the Cosmic Ray Hut, but at the end of February and in the early part of March 1951 some observations were also made from Lusitania Bay, about 20 km South of the main base.

Before leaving for the island, Nod and I together with Fred Jacka, who had spent a year at Heard Island (1948–49) and was then at ANARE Headquarters in overall charge of our observing program, had had a discussion with Professor Sidney Chapman who visited Australia during 1949. Chapman was a recognised authority on geomagnetism and related phenomena and we thought it would be useful to hear his views on what it would be sensible to try to achieve during our stay on the island. He concurred with our plan to make visual observations, probably realising that initially we would have no major equipment to do anything else.

I will not attempt to give a summary of our findings here. Nod has given a brief account in his thesis (Parsons, 1952) and further general comments are included in our report (Parsons and Fenton, 1953) in which some comparisons are made with the 1913 observations from the island by members of the AAE. Very briefly, although cloud cover made our observations difficult, we had a narrow aperture pocket spectroscope which made it possible to detect the presence of the green auroral line (wavelength 557.7 nm) on lightly overcast nights as well as during the long summer twilight periods and on moonlit nights. Auroral activity, either seen directly or revealed by the presence of the green line, occurred on 206 nights, or 56% of all nights. This frequency increased to 86% when continuously overcast nights were excluded. From this and the fact that about half of the displays extended into the Northern sky, we inferred that the island must be very close to the zone of maximum frequency of auroras, the auroral zone, which, at the time, was estimated to be a circle at about 18° from the South magnetic pole.

Two 35 mm Leica cameras with f/1.5 Waterworth 'Sirius' lenses were sent down to us by Fred Jacka on the HMS St Austel Bay in September 1950 and we began experimenting with them as soon as possible, using the fastest black and white film then available to us (sufficiently fast colour film had not yet been produced). One of the main purposes for these cameras was to attempt to estimate the height of the lower edge of auroral displays by taking photographs from each end of the island, using the background stars for triangulation. Stars are always visible through an auroral display on cloud-free nights. We took one of the cameras to Lusitania Bay in the early part of 1951 and used the other at the main base and we did our best to take photographs of the same part of the display simultaneously by using a portable half watt radio transceiver for communication. However, radio communication was very poor (probably because of the auroral displays) and we devised other means, including the use of chronometers, with time signals sent by the powerful transmitter at the main base to check them. About 20 pairs of simultaneous photographs were taken but these had not been analysed at the time of writing of the reports referred to above. Nevertheless, this work demonstrated the feasibility of such observations for future work. Macquarie Island did indeed become a very important base for later upper atmospheric research.

A couple of footnotes to this work are worthy of mention. Several years afterwards, when I was in the Boston area in connection with a US antarctic expedition, I was asked by a physicist associated with the Air Force Cambridge research group about our auroral observations. It was interesting to me that he had seen and read a copy of our Macquarie Island report. The other comment I wish to make is that, several years later, Nod Parsons, then working at the University of Calgary, made some very important studies of the Aurora Borealis using sensitive video cameras.

3.11 TRAGEDY STRIKES OUR PARTY

Just as 1951 began, a series of tragic incidents occurred which deeply affected and distressed our small party. The first was the illness of Jack Windsor, Officer-in-Charge of the meteorology team, which struck a few days after Christmas 1950. Our doctor, Kostos Kalnenas, suspected he had contracted appendicitis, a diagnosis which he confirmed after a few hours. He immediately began preparations for an operation, converting one of the sleeping huts into an operating theatre. Perhaps unfortunately, we had word that the French vessel Commandant Charcot was about 600 km West of the island, on its way to Adelie Land, and we believed that Jack was not willing to agree to surgery while there was the possibility of additional help arriving. There was also the possibility that a Catalina aircraft could be sent down to get him. ANARE Headquarters in Melbourne actively explored this option but the hazards involved were considered to be too great. Valuable time was lost while these options were explored but when it became clear to Jack that no help would come in time, he agreed to go ahead with the operation. 'Doc', as we knew our highly respected doctor, commenced the surgery at about 2 am on 2 January 1951, assisted by other members of our party. It was immediately obvious to Doc that the appendix could not be removed and that all he could do in the six hour operation was to drain the abscess which had formed, administer the then new wonder drug penicillin and hope for the best. During the next few days, many of us took it in turns to act as nurses to do whatever we could for Jack and, although it did indeed seem for a while that he was recovering, the final crisis came suddenly on the morning of 5 January while Doc was observing him. Surgeons in Melbourne and New Zealand from whom Doc had sought advice forbade further surgery. A Catalina was organised to fly down and we believed would have arrived within a few hours, but it was all too late. Jack Windsor died about noon on 5 January after oxygen had been administered for an hour and after Doc attempted to find a vein for a blood transfusion.

The whole camp was grief stricken and, after virtually no sleep for nearly a week, Doc was completely distraught, feeling that he had been an absolute failure when it came to the real test of his knowledge and skills. Several of us did our best to console him – this was in the days before the term 'counselling' was known – but he remained upset for a very long time.

Back in Melbourne, Phil Law, who himself had gone through periods of deep distress throughout these few days, had the sad duty of visiting Jack's wife and conveying the terrible news to her. She subsequently agreed that Jack's body should be buried on the island and our next task was to organise his funeral. A site for his grave was chosen on Wireless Hill, at the North end of the island, just above our Camp, the spot being not far from where the wireless masts of Mawson's 1911–14 expedition used to be. It had been through the aerial system supported by these masts that news from the Australasian Antarctic Expedition had been relayed from their main base at Commonwealth Bay back to the rest of Australia and the world, via Hobart, in the first real use of radio communication for antarctic expeditions, it being very few years after Marconi's pioneering demonstration of wireless transmission in the early 1900's.

Cyril Park and others set to work to construct a coffin from the timber available and a party was organised to carry it up the difficult slopes of Wireless Hill. I am sure we all had our own private thoughts during this melancholy event but mine probably included recollections of comments Jack had made to me after the operation about him being heavier than the sheep I used to help him round up on Wireless Hill on the occasions when we all felt the need to relieve our diet by having roast mutton. Jack had usually volunteered to 'dress' the sheep, a task at which he was quite adept. We were now all going to miss a very good and reliable friend and a highly competent meteorologist.

The next crisis befell our party in February when Cyril Park also began to have symptoms of appendicitis. His situation was further complicated by his high blood pressure and the fact that he also had symptoms of an inflamed gall bladder. Alarm bells rang both on the island and back in Melbourne. Arrangements were again set in motion to have a Catalina aircraft sent down to evacuate him, but, as it happened, the Commandant Charcot was on its way back from Adelie Land and was able to call at the island on 12 February 1951 to pick him up and bring him back to his home town, Hobart. Although I remember seeing Cyril some time after my own return later in the year, I cannot recall having heard whether he had had surgery or whether he simply recovered.

The next disturbing event to occur was the damage to the vessel HMAS Labuan which we had hoped would soon take us back home after about 12 months on the island. But in late January and during February 1951, on its way to resupply the base at Heard Island, it encountered very heavy seas and suffered severe damage. The Labuan was an LST (Landing Ship, Tanks), a ship of a type used in considerable numbers during World War II especially in the (usually) more tranquil waters of the Pacific islands. Although LST's had not been designed to withstand the pounding which the Southern Ocean could inflict, they had also been used on the Atlantic where occasionally they had broken in two. A vivid description of the events of the 1951 Heard Island voyage is given by Bowden (1997) but in brief, the steering failed on more than one occasion, a crack opened up right across the foredeck, sea water entered the fresh water tanks and the ship wallowed for several hours without engine power on 21 February. A tug reached her on 27 February and towed her back to Fremantle where some makeshift repairs were made. Although she was then able to limp back to Melbourne after several weeks, the thought of attempting to use her for the Macquarie Island run was not entertained.

On the island, we began to think of spending another year there, possibly after a new ship had been built. But the Australian Shipping Board was able to offer ANARE the 9000 tonne River Fitzroy, a BHP iron ore carrier, an offer which was gratefully accepted, even though it was not ideal for the purpose. The River Fitzroy arrived at the island on 4 May 1951 by which time the days were very short, making unloading more difficult. The Australian Army had provided two DUKW's, amphibious craft known to us as 'ducks', to assist with loading and unloading but one of these was wrecked on rocks while the ship was at Lusitania Bay at the South end of the island to land supplies for the 'hut' (actually, a large packing case) used there for field trips. Eventually, the resupply mission was completed, a new party was landed and our party, now down to 14 men, was returned to Port Kembla, NSW, towards the end of May 1951.

3.12 THE 1951–52 PARTY TAKES OVER

Nod Parsons and I were replaced in May 1951 by Peter Ford and Bob Jacklyn respectively. Both had been members of the Hobart cosmic ray group and, as employees of ANARE, had worked for a considerable length of time towards taking over the equipment on Macquarie Island.

Peter had spent some time with the Melbourne cosmic ray group learning about the methods used there for constructing Geiger counters of the type used in 'Set A'. He then helped make about 100 of them in Hobart, with the glass envelopes being supplied from Melbourne, but with all other steps being carried out in Hobart. He obtained another very good set of data with 'Set A' during his stay on the Island and, on his return, carried out detailed analyses searching for the solar and sidereal diurnal variations of intensity. In his Physics Honours Thesis (Ford, 1953), he reported having found significant effects in both solar and sidereal time, although he was inclined to believe that the sidereal effect was likely to be due to a solar component varying in phase during the year. He was also led to the suggestion that the Sun probably emits low energy cosmic rays. The fact that subsequent work has not confirmed this suggestion, except sporadically as an accompaniment of solar disturbances such as flares, merely indicates the problems encountered by cosmic ray physicists at that time in the quest for an understanding of the complex phenomena being studied.

As noted in the next section, it had been decided in Hobart and Melbourne that 'Set A' should be replaced by a simpler cosmic ray recorder at the end of the 1951–52 year. Hence, at the end of his stay, Peter had the task of packing up 'Set A' for return to Hobart. It is worthy of note that, apart from his work on data analysis in Hobart after his return, he made some progress towards developing a printing register. If successful, this would eliminate the need to photograph a panel of registers and it was clearly desirable to devise an alternative method of recording data. Peter attempted to produce a printing register by using a mechanical typewriter with electromagnetic solenoids to press the relevant keys. Electric typewriters were not yet available and it was long before line printers and the modern jet and laser printers were developed. He also developed a prototype printing register using solenoid activated vertical digit bars which printed when pressed onto carbon-copy teleprinter paper. This operated satisfactorily for a time in Hobart. However the resources were not available to produce a really successful device, with the cost of suitable solenoids being prohibitive.

Bob Jacklyn, who had returned to his studies after serving with the RAAF during World War II, completed qualifications for his degree in 1949, majoring in physics at the University of Tasmania. He joined the cosmic ray group in 1950. Prior to going to Macquarie Island he helped in building improved power supplies for 'Set B' and also the three-fold coincidence circuits needed to replace the makeshift circuits which I had built in the early part of 1951. He also helped in setting up a radio link which would be used for direct contacts between the Physics Department and Macquarie Island during his stay down there.

It had been decided that the main measurement to be made with 'Set B' during 1951–52 would be that of the East-West asymmetry at a zenith angle of 45° to obtain improved statistics. This would entail spending most of the time at this fixed setting which would, in addition, afford the opportunity of seeking evidence for any time variations of the asymmetry. If present, such an effect would suggest that changes were occurring which depended on factors other than meteorological ones. Bob did in fact achieve an East-West asymmetry value of excellent statistical significance, as represented by the 45° point for Macquarie Island in Figure 6. He was also able to prepare a preliminary report on the diurnal variation of the asymmetry at Macquarie Island in comparison with similar observations from Manchester. This work resulted in a paper presented by A.G. Fenton at the 5th International Cosmic Ray Conference held in Mexico in 1955 (Jacklyn, 1958). However, a successful study of time variations of the asymmetry had to await the later advent of East-West telescopes with sensitive areas of 1 m x 1 m and therefore much higher counting rates. Such observations of the asymmetry with these large telescopes, which Bob operated at Mawson in 1956, revealed significant changes, including 27-day recurrences, connected with solar activity. This prompted a study of changes in the annual E-W asymmetry observed at Hobart with the small telescopes over the years 1947–56, compared with changes in annual sunspot numbers. There were clear indications that they were in step. This resulted in a joint paper with A.G. Fenton (Jacklyn and Fenton, 1957). Further investigations into these effects were made in Hobart by Gary Webb using Hobart and Mawson data for the years 1956 and 1968. He confirmed the correlation with sunspot numbers and also found a seasonal effect and changes to the asymmetry accompanying Forbush decreases. His results and suggestions for possible mechanisms for the effects are given in his Honours Thesis (Webb, 1971).

Bob's final cosmic ray tasks on the island included packing up 'Set B' for its return to Hobart, where it would be used for obtaining improved East-West asymmetry values, and gathering meteorological data for a study of the effects on cosmic ray intensity of the passage of weather fronts across the island. He conducted this study back in Hobart and included 1950 data on fronts as well. The cosmic ray data were from 'Set A' and the number of well-defined fronts in the two years was 26. The analysis showed that an appreciable rise in cosmic ray intensity followed the passage of a front as cold dry air from Antarctica replaced the warmer moist air. This effect could be understood in terms of the lower altitude of production of muons in the cold air than in warmer air and hence the greater probability of survival to the ground. Bob also found that appreciably different barometer coefficients applied in the two types of air mass and that this could account for the variability found in the values of this coefficient in the monthly analyses carried out previously. These results are given in his paper (Jacklyn, 1954) and also in the ANARE Report (Jacka et al., 1959).

3.13 SOME HIGH LEVEL PLANNING DECISIONS

During 1950 the Australian Commonwealth Government had decided that a permanent station should be established on the part of the antarctic continent to which Australia had previously laid claim. This would occur when suitable shipping arrangements could be made, which, as it happened, was not until 1954 when the Mawson station was founded. During 1951, as part of the long-range planning, it had been decided that responsibility for the Antarctic Division's Cosmic ray research program, which would ultimately be extended to Antarctica, should be assumed by the Physics Department, University of Tasmania, and Nod Parsons had been appointed as the Division's officer in Hobart for this purpose. As part of the future Macquarie Island program, it had been decided that 'Set A' should be replaced by a simpler cosmic ray recorder and that 'Set B' should be returned to Hobart at the end of the 1951–52 year.

3.14 SUBSEQUENT DEVELOPMENTS

As noted above, 'Set A' was to be replaced by a simpler telescope system, it being felt that the extensive air shower observations had achieved their intended objectives. The new equipment, designated as 'Set A^{I}', consisted of two vertical telescopes made from four trays of Geiger counters, as for trays 1, 2, 3 and 4 of 'Set A', except that there was a total of 20 cm of lead, 10 cm between trays 2 and 3 and a further 10 cm between trays 3 and 4. Coincidences (1, 2, 3) and (2, 3, 4) were recorded. 'Set A^{I}' was designed and built in Hobart during 1951. The counters used were of the Maze external cathode type which had proved successful in 'Set B'.

The hourly totals of the coincidences were recorded on a bank of mechanical registers of the same type as used in Sets A and B, but rather than taking photographs every hour, there was a different register for each hour of a two-day period for each of the two telescopes, i.e., a total of 96 registers. Telephone exchange switches of the type known as uniselectors switched from one register to the next each hour, timed by a chronometer, over a 48-hour period. This procedure implied that, to obtain the hourly counting rates, the numbers registered by each register in half the bank had to be written down each day for subtraction of the number recorded by the same register two days previously. Separate non-switched registers for each telescope made it possible to check the daily totals. Much later, from the beginning of 1958, chart recorders of the multi-pen event type were also used.

'Set A^{I}' was taken to Macquarie Island in 1952 by Fred Strochnetter and its use was continued in 1953 by Jim Bishop, in 1954 by David Johns, by Peter Ford again in 1955, by Peter Trost in 1956, by John Steuart in 1957, Brian McInnes in 1958 and John Munro in 1959. The data obtained in some of these years have been published in an ANARE Report by McInnes et al. (1961). Possibly the most important single result obtained with this equipment was the record obtained of the giant flare increase observed world-wide in 1956, the subject of the last section of this paper.

Tragedy struck again when fire destroyed the Cosmic Ray Hut and all the equipment in it on 30 March 1959. A message to ANARE Headquarters in Melbourne the next day referred to vain attempts to extinguish the flames and to save the equipment but dense brown toxic smoke thwarted these attempts. Attempts were made to pull the Ionospherics Hut away from the Cosmic Ray Hut using a bulldozer but the steel rope burned through. An attempt was made to gain entry to the Cosmic Ray Hut by crushing the wall but the Hut exploded. A more detailed report of this event is held in the Archives, although I have not seen it. This loss brought an abrupt end to ground based cosmic ray observations on Macquarie Island. Rather than rebuild there, it was felt more advantageous to establish a cosmic ray neutron monitor at Wilkes and this was done in 1962. Balloons carrying detectors of auroral zone X-rays as well as charged particle and neutron counters were flown from the island during the 1960's. These flights in which Nod Parsons and John Phillips of the Hobart group collaborated with Professor R.R. Brown and his colleagues from the University of California, Berkeley, occurred in the summer of 1961–62 and were repeated in the summer of 1963–64.

3.15 FLARE INCREASE OF 23 FEBRUARY 1956

Along with many other cosmic ray recorders elsewhere in the world, the muon telescopes in 'Set A^{I}' observed the large increase due to a solar flare on 23 February 1956. As noted elsewhere, 'Set A^{I}' had four 20 cm x 20 cm trays of Geiger counters equally spaced in the vertical direction by 15 cm. The telescope had 10 cm of lead between trays 2 and 3 and between trays 3 and 4, numbering from the top. It was thus possible to determine the size of the intensity increase in the rate of muons which could penetrate 10 but not 20 cm of lead (i.e. those in the momentum range 235–340 MeV/c) as well as the rate of those, for instance, ≥235 MeV/c. With recording only hourly data, the peak intensity could not be observed, but, by assuming the increase commenced at the same time as that shown by the Hobart ionisation chamber, 0341 UT, a lower limit could be set for the peak intensity. For the narrow momentum band this lower limit was 360%, compared with 139% for the integral intensity above 235 MeV/c, showing, possibly for the first time, that the increase in a flare is greater at the low energy end of the spectrum than for the high energy particles. These results are contained in a paper by Fenton et al. (1956).

3.16 ACKNOWLEDGEMENTS

I am grateful to members of the Hobart cosmic ray group for discussions on various aspects of this paper, but especially to A.G. Fenton for sharing his recollections of the early activities of the group and for searching for records of those years. I am also grateful to Nod Parsons for checking my account of his work and for searching for appropriate photographs as well as to Bob Jacklyn and John Phillips for information on their work. I was also greatly assisted by Graeme Watt and Andy Smithies who searched the Antarctic Division Library for relevant information and by Rene Wanless who made painstaking searches of the Division's extensive collection of photographs to locate ones suitable for this paper. I am especially grateful to Judy Whelan for her patience in bringing all this material to the publication stage.

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4. COSMIC RAY OBSERVATIONS AT MAWSON – THE EARLY DAYS

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ABSTRACT

Aspects of the initial establishment and operation of the cosmic ray observatory in 1955 at Mawson, Antarctica are recalled.

4.1 INTRODUCTION

There are clearly two main thrusts to these special historical Sessions included in the conference program to celebrate fifty years of cosmic ray research based at the University of Tasmania. One is the important one of providing some background to later sessions concerned with current work and with the identification of future research objectives. The other is to provide an opportunity for some of the Tasmanian cosmic ray geriatrics to acknowledge that they are now genuinely part of history. I have been retired now for several years and out of the cosmic ray field for very much longer, so my contribution can be only a few nostalgic reminiscences.

I must take the opportunity to add my congratulations to Geoff Fenton, whose initial vision and long-term dedication inspired all those who played roles, large or small, transient or long-term, in the evolution of the Hobart-based programme over the last fifty years. I would also like to put on record my own personal indebtedness to the late Dr Fred Jacka, Senior Scientist with the Antarctic Division for very many years, for his support throughout my time on the Division staff from 1949–1964.

4.2 FROM THE BEGINNING

When proposals were given the green light for the establishment of a cosmic ray observatory at Mawson in 1955, in the second year of the Station's existence on the antarctic continent, we faced a major challenge to get two large meson telescopes designed, built, tested and then dismantled and packed in time for dispatch to Melbourne for loading on the small chartered Danish ice ship the 'Kista Dan'.

The telescopes were each to consist of three trays of Geiger counters, each tray with a sensitive area one metre square. Meson counting rates were to be of the order of 100 000 per hour. The telescopes were to contain 10 cm of lead absorber and to be supported on yokes to allow tilting to any required zenith angle. They were also to be mounted on large turntables to permit automatic rotation at hourly intervals between any chosen series of azimuths. Geoff Fenton will recall our visit with Fred Jacka to the Naval Ordinance Stores in Melbourne where we browsed through acres of mothballed and obsolete shipboard equipment and selected some very sturdy Bofors anti-aircraft gun mounts – they were ideal. I think the Navy was a little disappointed that we weren't keen to take more gear off their hands.

To place the construction phase in historical context, it took place while the Physics Department still occupied old army huts at the bottom end of this old rifle range site. And the electric circuitry involved scores of vacuum tubes, with scaled meson counting rates ticking up on electro-mechanical registers as then used in telephone exchanges.

I understand that Peter Fenton will later be making special mention of the fine contributions of technical support staff to the program over the years. Their excellent work and cooperation in meeting all the deadlines in preparing the equipment for Mawson was certainly greatly appreciated.

It took an incredible number of specially constructed boxes to pack all the gear for the long haul down to Antarctica. The lead absorber, nearly three tonnes of it, was in the form of accurately cast 20 x 5 x 5 cm blocks and at four blocks per box there were about 120 boxes of lead alone. Each one individually looked innocuous and it was amusing to see any uninitiated cargo handlers go to lift the small boxes first, only to discover that they seemed almost screwed to the floor. The dozens of long glass Geiger counters were carefully packed in lengthy coffin-like boxes which were then slung on networks of springs from all sides in considerably larger crates. On the voyage down, the little 1200 tonne 'Kista Dan' battled some mountainous seas, rearing up alarmingly on each huge wave with the bow crashing down into the next, each time shuddering and vibrating violently like a springboard when a diver leaves it. I had visions of those Geiger counter boxes shaking violently about on their springs for day after day and wondered whether any of the tubes would survive.

When we arrived at Mawson, everything had to be taken ashore in amphibious Army DUKW vehicles and manhandled over their high sides. The exposed rock site chosen for the cosmic ray hut was soon surrounded by all my equipment boxes together with daunting piles of foundation timbers and dozens of very heavy prefabricated floor, wall and roof sections for the building which was to be 36' x 15' x 10' high internally, with a flat roof. It was to have a clear space underneath to help prevent the build-up of leeside snowdrift.

The building was designed and prefabricated in Melbourne to provide a nearly uniform distribution of wall and roof material, without heavy beams or tresses which could introduce small artificial directional asymmetries into measured cosmic ray intensities. Every panel had a layer of chicken wire incorporated into it, with ragged wire edges protruding so that these edges on adjacent panels could ultimately be twisted together to enclose the building in a radiation shield – antarctic stations are notorious radio noise producers.

I shall not dwell on the many very frustrating construction difficulties, most of which were addressed and overcome during the twenty days of the ship's stay. Perhaps it is sufficient to quote from one of the progress reports radioed back to Melbourne by a well-known expedition leader – 'Physics hut an abortion'. During the ship's stay and in mostly favourable weather, the main work on twelve new buildings was well advanced, most of them fortunately involving few major problems. It used to be said by the manufacturers that to assemble their prefabricated buildings the only tool required was a spanner – expeditioners soon recognised that a spanner was fine as long as a sledge-hammer was close to hand.

Like all buildings, it was anchored down by an array of steel cables to large steel rods drilled into the rock surface and grouted in using molten sulphur which expands as it undergoes changes in crystalline structure on cooling to low temperatures.

The metre-square concrete pillars on which the telescopes were to be mounted were poured using high-alumina cement which sets very rapidly and which conveniently generates substantial amounts of heat itself in the process.

The ship left at the beginning of March and the telescopes were operational some time in May. Rather miraculously, everything that mattered had survived the rigours of transportation, unloading and frigid outdoor storage. I was able to settle into something approximating a daily routine, reading the counting rate registers and collecting and tabulating all the necessary surface and radiosonde meteorological data from the Met hut nearby. I still had to allow an hour or two each day to continue minor work on the building – like twisting chicken wire ends together and fully sealing the multitude of interpanel crevices where drift snow persistently penetrated. Along with a variety of general station responsibilities and chores I managed to fit in a few other physics-related activities – for instance keeping an eye on the Aurora Australis, making daily measurements with a sky-brightness photometer, relevant to the possible establishment of a program of solar coronal observations, and making regular test measurements for the Army on some experimental field telephone cable. The sidelines provided some interesting outcomes themselves.

Of course those were the days before the transistor revolution and the subsequent computer revolution. Repetitive Strain Injury was certainly not yet in vogue, otherwise I would surely have acquired it from the infinite number of times I wound the handle of a Facit calculating machine, processing all data manually.

I was well satisfied with the ten months or so of practically continuous data accumulated from both the vertical and inclined telescopes and pleased that I was able to hand over a good operating facility to Bob Jacklyn towards the end of the 1955/56 summer, in readiness for the International Geophysical Year. My one major regret was that I had spent lots of time over the months encouraging a chart recorder to perform satisfactorily and it was very frustratingly in one of its down periods from a day or two before that the very large solar flare-related increase in cosmic ray intensity of February 23, 1956, leaving only hourly totals during that event. Particularly for the Mawson observatory, finer time resolutions during that event would have been extremely valuable.

It is interesting to remind ourselves that the incredible wealth of knowledge that we have of the universe beyond the Earth has virtually all come from interpretation of the motley assortment of itinerant particles and photons which the Earth happens to get in the way of. In the early 1950's, cosmic rays offered unique types of information, at high particle energies, to supplement knowledge derived from visible light and from the relatively infant field of radio astronomy. X- and gamma-ray astronomy (and, of course, neutrino astronomy) were things of the future.

But the atmosphere itself introduced considerable complexity into interpretation of measured cosmic ray intensities and intensity variations at ground level. At that time, therefore, considerable effort was still going into the elucidation of atmospheric effects, notably those of total air pressure and of atmospheric mass distribution arising from varying temperature profiles. Only after satisfactory correction for these effects was it possible to address with any confidence the matter of small-scale modulations of the primary radiation.

I was particularly interested in the quite small solar diurnal and semidiurnal variations but there was considerable interest also in a possible sidereal daily variation as well as in Forbush decreases, solar flare-related increases and other manifestations of indirect solar influences. Dr McCracken will no doubt remember with affection his detailed studies of these various sporadic and transient variations.

In all these areas it was becoming increasingly important that one could, with some confidence, relate apparent arrival directions of the particles to primary particle trajectories unmodified by deflections in the Earth's magnetic field. Possible mechanisms involving speculative field structures in the general Sun-Earth environment could then be examined as potential causes of the various kinds of observed intensity modulations. 'Cut-off rigidities', 'coupling coefficients' and 'asymptotic directions' were essential parts of the latest terminology and were being calculated laboriously before computers had really come into their own. And it should be emphasised that at that time, knowledge of the configuration of the Earth's magnetosphere and its variability under the influence of a gusty solar wind, and of field structures within that wind, was really quite rudimentary. Sputnik, for instance, was still on the drawing board.

Naturally enough, all investigations of possible anisotropies and transient variations in the primary radiation benefit greatly from the availability of continuous and comparable records from a world-wide distribution of stations scanning different directions in space. For this reason both the Hobart and Mawson observatories have, over the years, been extremely useful components of the network of sites, most of which have been in the northern hemisphere.

Due in large part to the drive and energy of Ken McCracken, a neutron monitor was prepared in Hobart and installed in the Mawson laboratory in 1957. And significantly later, the massive task of burrowing down into the rock was undertaken to create an underground observatory. It seems ironic that in order to see out into space more clearly, one should need to go underground.

Cosmic rays have come a long way – in more ways than one. It is difficult to imagine what part they will be playing in astrophysical research after another fifty years but I would like to think that the Hobart and Mawson observatories will still be valuable contributors.

5. GEIGER MÜLLER COUNTERS BEFORE AND AFTER 1946

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ABSTRACT

Early methods for detecting nuclear radiation are described, including electroscopes, scintillation screens, ionisation chambers and Geiger point counters. The development by Müller of the tubular gas-filled detectors now called Geiger-Müller counters enormously increased the sensitive detecting areas for cosmic ray studies.

The beginning of the electronic age led to advances in the counting and recording of cosmic rays and development of the coincidence circuit by Rossi enabled muon telescopes to be constructed.

A review is given of the state of knowledge of the physics of gas-filled radiation detectors in the early 1940's followed by an account of the author's work at Birmingham in 1947–8.

A brief description of the construction methods for Geiger-Müller and proportional detectors for the Hobart cosmic ray program since its inception in 1946 is given.

5.1 INTRODUCTION

At the end of World War II in 1945, the Physics Department at the University of Tasmania made a rather rapid transition from its almost full-time commitment to the optical munitions annexe to an equally committed peacetime academic institution. The sense of urgency prevalent during wartime carried over to the new situation being experienced by staff and students. A rapidly increasing student enrolment was anticipated initially, and very soon realised, when ex-service personnel (mainly men!) enrolled as mature-age students. Also, recently de-classified information about nuclear energy and radar pointed to the desirability of including the basic physics behind these developments in physics courses. On the research side, there was a strong desire to employ the 'physics approach', which had been so successful during the optical work, to new topics. This view was promoted by Professor A.L. McAulay, head of the department, and three lines of research emerged: Biophysics, Optics (basic lens design, carried over from the Optical Annexe) and Cosmic Rays.

The rationale for beginning cosmic ray research was chiefly that the University would be unlikely to acquire a cyclotron or nuclear reactor for nuclear physics research, whereas there was a good prospect that radiation detection techniques could be acquired and used to study the free ubiquitous cosmic ray particles. Thus research and research training could be achieved with the limited resources likely to be available. It was clear that most of the equipment for teaching and research in the post-war Physics Department would need to be designed and constructed in-house or locally under our direction, as had occurred during the Optical Munitions Annexe period. At that time such items were either not available commercially or were too expensive.

The most important radiation detector then in use was the Geiger-Müller (GM) counter tube, so much of the following discussion will deal with this device – how the techniques for their construction were achieved and how the gas-discharge process in them became a research project. But first, it will be desirable to outline the state of knowledge about gas-filled radiation detectors, as reported in scientific literature prior to the commencement of the Hobart Cosmic Ray Research Program in the mid 1940's.

5.2 HISTORY OF RADIATION DETECTION

5.2.1 The electroscope, electrometer and ionisation chamber

In 1896 Henri Becquerel fortuitously discovered that uranium minerals emit rays able to penetrate materials opaque to light and blacken a photographic plate. Thus the photographic plate was the first detector of nuclear radiation, just as it had been involved a few months earlier in the discovery of X-rays by Wilhelm Roentgen. However, rather long exposures to the radiation from naturally occurring radioactive substances were necessary to demonstrate the effect and for further investigation of the phenomenon a more sensitive quantitative method was needed. It had been found that these new rays were able to discharge electrically charged objects such as gold-leaf electroscopes, so it was a logical step to use the latter to detect the presence of radiation and to measure its strength in terms of the loss of charge per unit time. It is interesting to recall that the nature of electricity was not clearly established until 1897 when J.J. Thomson measured e/m and proved the existence of the electron as an elementary particle. Gold-leaf electroscopes had been used since being invented by Bennet in 1787 to demonstrate static electrical effects, so it required some lateral thinking by physicists a century ago (A.L. McAulay's 'physics approach') to turn these into sensitive measuring devices. Various types of electroscopes were constructed, based on the principle of electrostatic repulsion of like charges but with the moving parts more robust than a pair of gold leaves, and observed using a telemicroscope with an eyepiece scale (Figure 1).

Another advance was to separate the indicating section from the region of ionisation, called the electrometer and ionisation chamber respectively. Provided good insulation could be achieved between the sensitive electrode and ground, it was then possible to use large volumes for the ionisation chamber or to operate at higher than atmospheric pressure and to try different gas-fillings. Lateral thinking leading to the introduction of guard-rings in the insulators was another technical development (Figure 2).

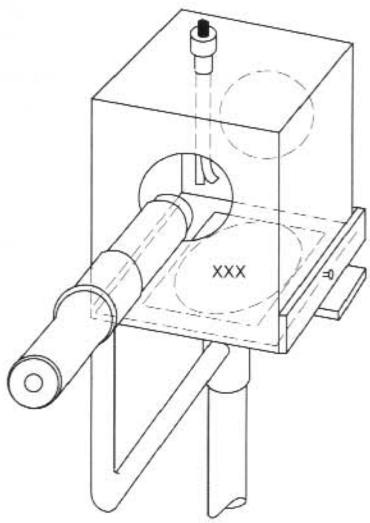


Figure 1. An electroscope, with telemicroscope for measuring the discharge of the gold-leaf due to ionisation caused by a radioactive source placed at xxx.

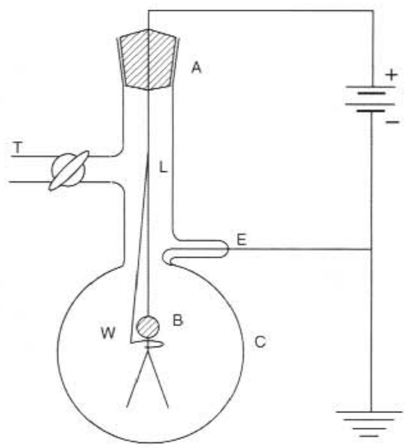


Figure 2. Gold-leaf electroscope used by C.T.R. Wilson in 1900 to demonstrate that gases conduct electricity due to residual ionising radiation. Note the use of a guard insulator B which has no potential difference across it after the leaves are charged by using the movable wire W.

5.2.2 Early scintillation detectors

Although the ionisation chamber with attached electrometer was used for early research on radioactive substances, and in 1912 enabled Victor Hess to verify the existence of cosmic rays, (see paper on Cosmic Ray Studies before 1946, this volume) the particle physics aspects of the radiation required the ability to observe evidence of individual particles instead of the integrated ionisation effects over many seconds which is a feature of the ionisation chamber. Initially, Rutherford and others used scintillation detectors consisting of a screen, coated with small zinc sulphide crystals, viewed by a low power microscope. With dark adapted eyes in a dark-room, the observer could see the flashes of light produced by individual alpha particles impinging on the screen. Geiger and Marsden (1909) used this method in their experiments on the scattering of alpha particles by thin foils of gold, silver and platinum which verified Rutherford's planetary model of the atom.

5.2.3 Gas-filled detectors

Counting the flashes of light was a very tedious process, so it was desirable to devise a less labour-intensive system, especially when more sophisticated nuclear physics studies were being planned. Rutherford and Geiger (1908) published a paper in which they described an electrical method for counting alpha particles. This detector consisted of a thin anode wire along the axis of a metal cylinder of length 25 cm. The alpha particles to be detected entered the tube through a thin mica window over a 1.5 mm hole drilled through one end-plate of the cylinder and travelled parallel to the wire. A tube attached to the other end enabled the air pressure inside to be reduced to about 5 cm Hg. A potential difference of about 1000 volts was applied between the anode wire and the cylindrical cathode and the anode wire was connected to an ordinary quadrant electrometer. The electric field strength around the wire was sufficient to cause a considerable multiplication of the ions produced along the path of each alpha particle entering the detector tube. The electrical capacity of the system, the high value of the recovery resistor used and the slow response of the quadrant electrometer limited the detection rate to about 5 alpha particles per minute. Four years later, Geiger and Rutherford (1912) achieved a detection rate of up to 1000 particles per minute by using a fast response string (quartz fibre) electrometer and recording the fibre deflections with moving photographic film. Instead of a cylindrical counter tube a hemisphere with a small anode sphere at its centre was used to keep the capacitance low.

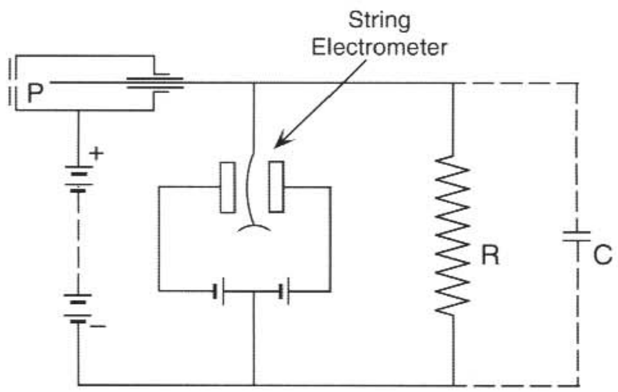


***Figure 3**. The original point counter and circuit used by Geiger.*

Geiger (1913) reported the development of a point counter of very high gas gain and very small sensitive region. This was a very useful detector of radiation from radioactive substances and could distinguish between alpha and beta particles (see Figure 3).

The next significant development of charged particle detectors was reported by Geiger and Müller (1928) and Geiger and Klemperer (1928) who investigated the mode of operation of cylindrical counter tubes. These tubes had much larger sensitive areas than the Geiger point counter and were quickly employed for studying cosmic rays (see Figure 4).

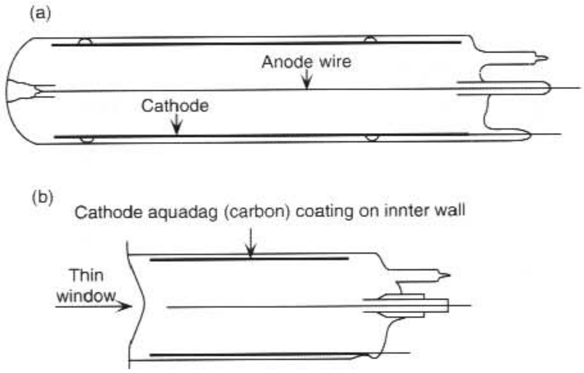


***Figure 4.** Two types of Geiger-Müller tube.*

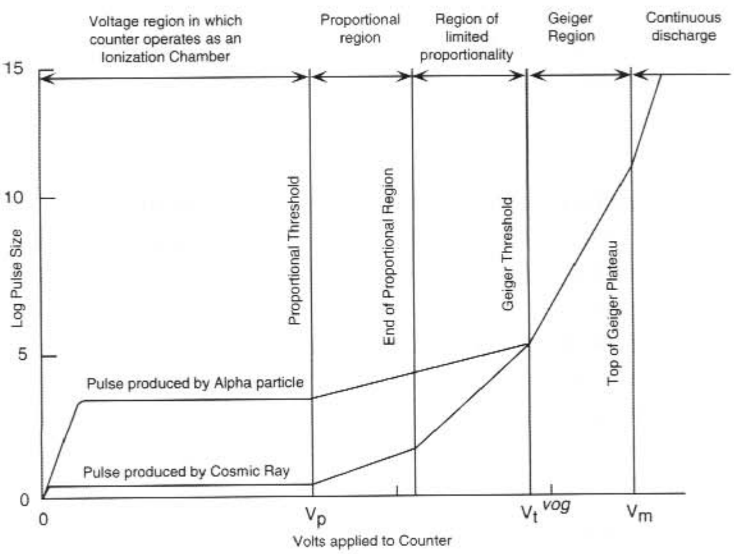


***Figure 5.** Operating regions of a gas-filled detector. The pulse size scale is logarithmic, with the middle of the Geiger region at about 9, i.e. the gas-gain is around 10^9. In this region a single electron released in the active volume gives a pulse of many volts.*

These investigators found what is now called the proportional region of gas-filled detectors, i.e. a range of operating voltages over which the output pulse size depends linearly upon the initial ionisation released by passage of the charged particle through the detector. Thus, alpha particles could be detected against a high background of beta particles or gamma rays. Figure 5 gives details of the various regions of detector operation. Figure 6 shows aspects of the operation of GM tubes.

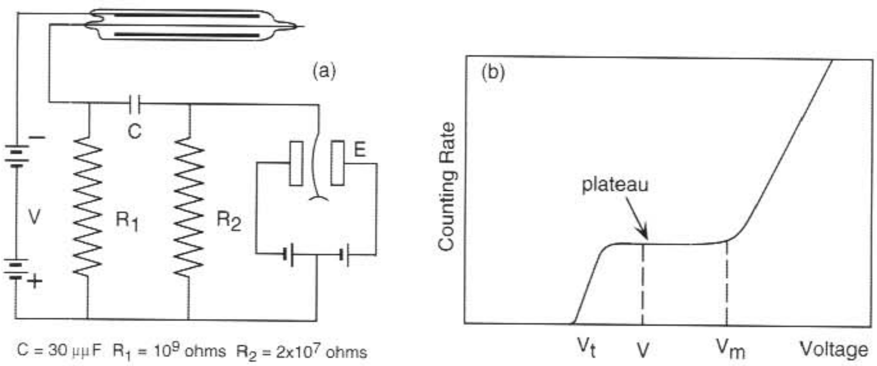


***Figure 6**. (a) A method for studying qualitatively the action of a Geiger-Müller counter, using a string electrometer as the detector. (b) Characteristic curve of a Geiger-Müller counter. Here, the counting rate rises rapidly when the operating voltage V_{og} exceeds V_t, the threshold of the Geiger region. On the plateau, the counting efficiency is close to 100%. Above V_m the counter produces many multiple pulses or a 'continuous' discharge.*

5.2.4 Development of gas-filled detectors and electronics

During the decade, 1930–1940, several important developments in gas filled detectors and counting techniques occurred, the latter made possible by the rapid advance in wireless technology (called radio in the US). For example, the triode thermionic valve was invented by Lee de Forest in America in 1907 and the tetrode by von Schottky in Germany in 1916, with improved radio receivers in mind. By the mid 1920's these valves (tubes) were in common use in domestic receivers and widely available to physicists who saw them as useful amplifiers and switches for very different applications.

With a better understanding of the nature of the electrical discharge process in gas filled detectors, various experimenters devised recipes for their successful construction. Desirable features included stable operation over lengthy periods with few extraneous or spurious discharges, or multiple pulses where residual effects in the counter tube lead to one or more parasitic pulses not due to ionising radiation. For cosmic ray research, where continuous operation for months or years is often required, it was considered best to use a glass counter envelope with glass to metal seals for the connections to the electrodes. The cathode usually consisted of a thin-walled cylinder of brass or copper and the anode a tungsten wire along the axis of the tube. The gas filling was usually argon plus some other gas, admitted after pumping to a good vacuum following an often elaborate cleaning process involving acid and numerous rinsings with distilled water. Successful counter construction was thus a lengthy process, usually carried out by a glass blower in the institution where the counters were to be used.

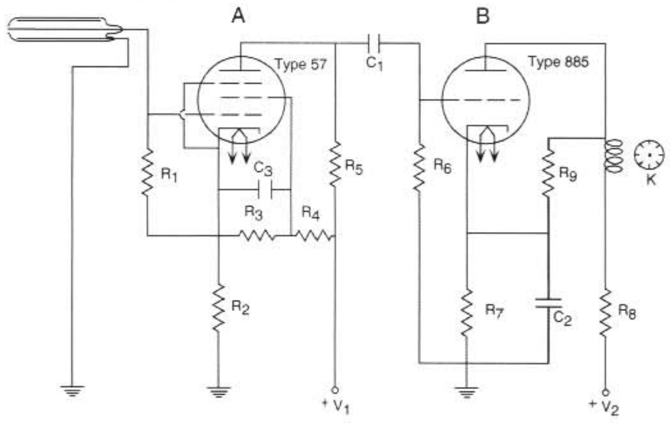
5.2.5 Self-quenching counters

Trost (1935) reported that good GM counters could be made reliably by using a filling of about 10% of ethyl alcohol vapour in argon at a total pressure of 10 cm Hg. Counters containing a small percentage of organic vapour were soon referred to as self-quenching counters because they gave fast pulses and could be used with a low value recovery resistor without going into continuous discharge. The discovery that organic vapours improve counter operation is possibly apocryphal – it was claimed in English physics laboratories that the glass blower in Trost's laboratory was an alcoholic who because of this habit was the best GM counter maker in Europe. On closely checking his construction techniques the unwitting secret was revealed!

Before the self-quenching gas filling was discovered, electronic methods were used successfully to turn off an otherwise slow counter before the discharge could develop fully and to achieve a fast recovery to a sensitive condition. With this external quenching of the discharge, it was possible to use high counting rates (up to 10^5 per minute) or use them in coincidence circuits with a relatively short resolving time (about 20 μ sec).

The concept of the coincidence circuit was first reported by Bothe and Kolhorster (1929) who used two grids of a radio valve such as a tetrode or pentode to control the anode current independently so that an output pulse would be produced only when both counters connected to these grids detected radiation at the same instant or within the resolving time of the circuit. This led to the ability to detect energetic ionising particles against a background radiation by their almost simultaneous penetration of the two counters. This concept was developed further by Rossi (1930) who extended the principle to cover more than two counters and to detect anti-coincidences which allowed events not accompanied by others to be recorded. This was achieved by using one radio valve for each counter and arranging it to switch off for each event – much as the present day AND gates in digital electronics.

Radio valves were also used in the 1930's to drive electro-mechanical digital pulse recorders to replace personally counting the events, as occurred earlier with electrometers (see Figure 7). These pulse recorders, or registers, were generally slow in their operation, so that counting was limited to about 10 events per second. This limitation encouraged the development of the scale-of-two electronic divider circuit whereby an output pulse occurs for every second input pulse (Wynn-Williams, 1932) (see Figure 8). These circuits may be cascaded to n stages, giving a division factor of 2^n. This was the first use of electronic circuits nowadays called binary counters.



$R_1 = 5 \times 10^6$ ohms $\quad R_2 = 10^6$ ohms $\quad R_3 = R_4 = R_6 = 0.5 \times 10^6$ ohms

$R_5 = 0.25 \times 10^6$ ohms $\quad R_7 = 10^4$ ohms $\quad R_8$ = current limiting resistance

$R_9 = 8 \times 10^4$ ohms $\quad C_1 = 50\ \mu\mu f$ $\quad C_2 = 0.2\ \mu f$

$C_3 = 0.1 \mu f$ $\quad V_1$ = counter threshold + 100v $\quad V_2$ = 250 volts

K = high-impedance electro-mechanical recorder

***Figure** 7. Section A assists the Geiger-Müller counter to quench the discharge. Section B shows a driving circuit for an electro-mechanical register.*

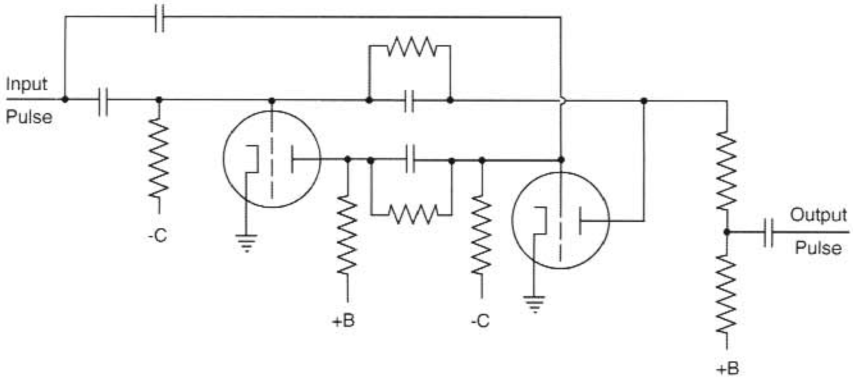
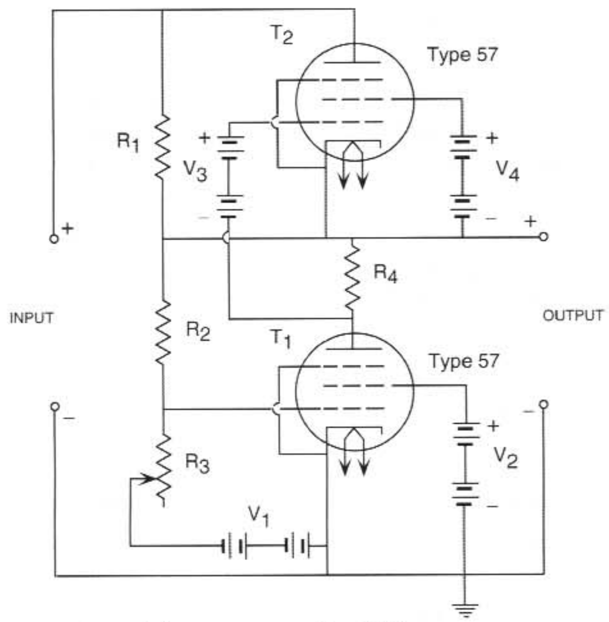


***Figure** 8. Showing the basic circuit of the divide-by-two scaler. A neon indicator lamp connected to the first valve glowed after one pulse was received by the binary pair. A second input pulse caused the lamp to turn off and a pulse to appear at the output. Circuits of this kind were cascaded to give scaling factors 2, 4, 8 etc.*

Physicists using GM counters in their research soon realised that even with a constant source of radiation, the counting rate observed would vary with operating conditions. One of the major causes of this variation was due to fluctuations in the potential difference applied across the counter, especially with mains operated high voltage DC power supplies. To deal with this problem, electronic voltage stabilising circuits were devised using the concept of negative feedback and a stable reference voltage source such as that provided by a dry-cell battery (see Figure 9), later replaced by high stability voltage regulator tubes.



$R_1 = 10^6$ ohms
$R_2 = 10^6$ ohms, wire wound
R_3 = variable, wire wound
$R_4 = 10^5$ ohms
V_1 = 90 volts
$V_2 = V_3 = V_4$ = 45 volts

Figure 9. *The above combination of two type 57 tubes permits excellent voltage stabilisation for current drains up to 1 milliampere. Drifts may be as low as 0.1 volt per hour in the output. Potentials from several hundred to several thousand volts can be stabilised with this circuit.*

5.2.6 Statistics of counting

It was recognised in the 1930's that if the events to be counted occur at random, as with radiation from radioactive substances and also presumably with charged cosmic ray particles, there will be statistical fluctuations associated with the data.

As an example, consider the case of an electromechanical register which is unable to respond to two pulses separated by a time interval less than τ seconds. If the average time interval between pulses arriving at the register is $\bar{t}$, which should obviously be large compared with τ, then to a good approximation the probability of finding a time interval less than τ is $\tau/\bar{t}$). Thus, if N particles are counted, the mean error in the count will be $N\tau/\bar{t}$, and the mean relative error will be $\tau/\bar{t}$. In the case of a register for which $\tau = 0.1$ second and a total of 60 counts is registered in 1 minute the average loss of counts will be $(60 \times 0.1)/1.0 = 6$, since $\bar{t}=1$ second. This fact was appreciated at the beginning of the Hobart cosmic ray research program, so binary scalers were introduced at an early stage to reduce losses due to register dead-time.

5.2.7 Sources of information

In the late 1930's and during the 1940's in Hobart, technical information was available from various sources. The Physics library (which was located in the Physics Department) had Physical Review, which in those days published technical information relating to experimental projects, and the Dictionary of Applied Physics in several volumes. Books useful during this period could be purchased through local or mainland bookstores. These included: 'Procedures in Experimental Physics' by John Strong, Prentice-Hall, 1942; 'Electron and Nuclear Physics' by J Barton Hoag (Second Edition), Van Nostrand, 1938; 'Electron and Nuclear Counters' by Serge A. Korff, Van Nostrand, 1946. With these books and reference to original papers it was not difficult to find out what was needed to commence cosmic ray research, in particular to produce GM counters plus the required electronics. To achieve these objectives it was necessary to learn glass blowing and electronics techniques largely by trial and error.

5.3 COUNTER CONSTRUCTION AT HOBART, 1945–46

Korff's book (mentioned above) became available in Australia soon after publication and was quickly acquired as a valuable reference on the theory of the discharge mechanism in, and practical information on, gas-filled counters. Of particular interest at the time was Korff's comment in the preface to his book that 'although counters have been known for about forty years, they are even today surrounded by an atmosphere of mystery, and their construction and operation are claimed by many competent scientists to involve magic. Various laboratories have developed special procedures for their manufacture and use, often without knowing why particular techniques appear to be successful'. Again, in the acknowledgements, Korff thanked Dr J.A. Fleming of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington "who gave important support to the study of counters at a time, during the early development period, when many persons doubted whether counters could ever be made into reliable and reproducible instruments of scientific measurement".

The above comments by Korff struck a resonant chord with this reviewer of the early efforts at Hobart to acquire the techniques of cosmic ray detection. In addition to tubes produced through self-taught glass blowing, some counter envelopes were contracted to the Claude Neon Signs workshop in Hobart. A pumping system with gas-filling manifold was assembled in a small laboratory dedicated to counter development at the new Sandy Bay site of the University. Advice and assistance was also obtained from the Physics Department at Melbourne University (at that time it was still called the Natural Philosophy or 'Nat Phil' Department and it was able to afford a professional glass blower).

It turned out that there was little to choose between the home-made and professionally constructed GM counter envelopes – neither reliably gave a really satisfactory performance when filled with the conventional gas mixture of 10% ethyl alcohol vapour plus 90% argon. Some tubes had usable plateau regions of about 100 volts length with a few percent increase in counting rate over this range, while others given similar treatment had little or no plateau and tended to go off into the discharge region prematurely. Even worse than this, some counters initially classified as satisfactory were later found to have a high background rate. This was often associated with bursts of multiple pulses clearly originating within the counter and not due to incident cosmic rays or gamma rays from the surroundings.

5.3.1 Commercial availability of counters, 1946

At about this time, information was received that GM counters were becoming available from overseas manufacturers. The wartime atomic weapons program had encouraged the development of instruments for radiation monitoring and these were soon declassified. In view of the problems with counter construction at Hobart it was decided, as a way of facilitating the proposed cosmic ray program, to purchase a small number from England. These were used in the first East-West asymmetry GM counter telescope set up at Hobart in 1947. However, these counters were not perfect as they displayed some of the faults of the home grown variety, though generally to a lesser extent. It was also found that the individual operating voltages of the counters were not as well matched within the batch received as could be achieved with the Hobart filling system. This meant that it was difficult to operate all the tubes at a single voltage – ideally they required individual adjustment, or careful selection from a large batch.

5.4 VISIT TO BIRMINGHAM, ENGLAND, 1947–48

In early 1946, Professor A.L. McAulay suggested that, partly because of our practical difficulties with GM counters and also to gain experience in modern overseas research laboratories, I should consider travelling to Birmingham and Manchester. He knew Professor M.L. Oliphant (Birmingham) and Professor P.M.S. Blackett (Manchester) personally and wrote to them asking whether they would agree to have me in their departments on a working visit during twelve months special leave from the University, which he thought he could arrange. In the event, I received leave of absence without pay, but Professor McAulay negotiated with Cadbury Fry Pascall of Claremont, Tasmania, on my behalf for an Overseas Fellowship, which enabled me to make the trip.

When I arrived at the University of Birmingham in early 1947, I found that Professor R.M. Chaudhri (on leave from the University of Aligarh, India) had devised a GM counter in which the anode wire in the active section could be changed without opening the counter or changing the filling. He was using this to investigate the effect of wire diameter on the plateau characteristics for a range of gas mixtures.

I was fortunate to be invited to join Professor Chaudhri in his research. Not only was this research of considerable interest for our Hobart cosmic ray work but also the other researchers at Birmingham were mostly doing design studies related either to a large cyclotron which was nearing completion, or to a proposed 1 GeV proton synchrotron which was only at the foundation stage (PhD students were literally using picks and shovels while checking the levels of the site for the magnet to the required accuracy!). Thus it seemed that the counter work was more likely to yield new results in the relatively short time I had available, than if I were to join a larger project. And so it turned out – the first paper on the results were submitted to The Proceedings of the Physical Society in June 1947 (Chaudhri and Fenton, 1948).

This early success in our investigation of the factors influencing the performance of GM counters led to the proposal by Professor Oliphant about mid 1947 that I should apply to the University of Tasmania for an extension of my leave to enable me to spend the minimum time required at Birmingham for a PhD project (eighteen months of the nominal two years research). The extra leave was duly approved and I enrolled retrospectively for the PhD. This decision also meant that I would spend most of my time at Birmingham, and visit rather than work at Manchester. The counter research for my PhD thesis may be grouped into three series of experiments:

(a) The first series, jointly with R.M. Chaudhri, in which the adjustable counter of Figure 10 was used as well as three others of similar construction but with fewer adjustable features.

(b) A second series, jointly with E.W. Fuller (a new PhD student), used the adjustable counter of Figure 10, together with electronics designed to study the spurious pulses and the electric charge per pulse. These experiments began in mid 1947 and concluded in mid 1948 (Fenton and Fuller, 1949).

(c) A third series, conducted after my return to Hobart in October 1948, with a new adjustable counter (Fenton, 1949).

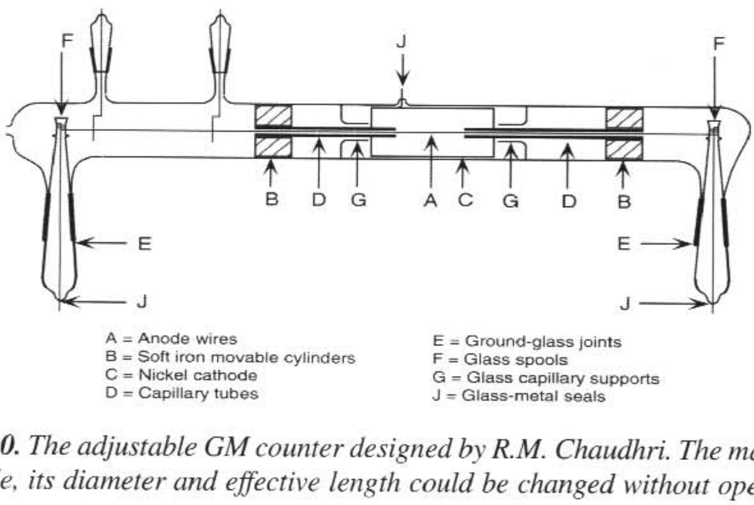


Figure 10. *The adjustable GM counter designed by R.M. Chaudhri. The material of the anode, its diameter and effective length could be changed without opening the counter.*

The first series of experiments with the adjustable counter of Figure 10 showed that the operating plateau characteristics depend strongly on the diameter of the anode wire but not on the anode material (e.g. copper, gold, tungsten). The claim by others that the discharge in the Geiger region spreads along the full length of the anode was confirmed. It was found that the counter became photosensitive when operated at a very high counting rate with a radioactive source, or by running for a short time just above the normal plateau region, usually called the continuous discharge region. This discovery explained some of the observations with counters at Hobart during 1946 mentioned earlier. The photosensitivity disappeared after a rest period or a lengthy period at background counting rate. It was clear that GM counters should be operated in darkness. The tests showed that the cathode section exposed to the high counting rate is responsible for these effects and neither the anode nor the gas is implicated.

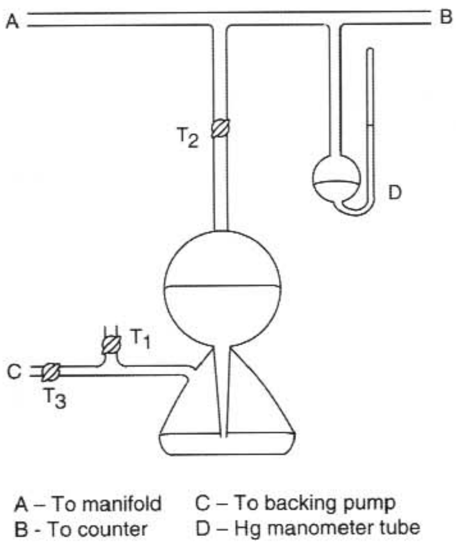


Figure 11. *The mercury plunger designed by A.G. Fenton for the second series of counter experiments. With this device the filling pressure could be varied, while keeping the same gas mixture.*

The second series of experiments, carried out with E.W. Fuller after Professor Chaudhri returned to India, were intended to extend the scope of the investigation to include gas pressure as a variable using the mercury plunger of Figure 11. Also, electronic circuits were constructed to measure the charge per pulse and to separate the spurious pulses from the random pulses due to cosmic rays or to a radioactive source. The adjustable counter of Figure 10 was used, this time fitted with a range of diameters of tungsten wire anodes. The results showed that the spurious pulses are strongly influenced by the gas pressure, anode diameter and the nature of the cathode surface, but the genuine pulse plateau is not affected by these factors. It was also found that the latter did not become approximately level (indicating close to 100% detection efficiency) until 100–200 volts above the beginning of the Geiger region. Two practical points emerged: Firstly, since the probability of a spurious pulse occurring after a genuine pulse decreases for larger anodes while it increases at higher filling pressures, there is an optimum anode diameter and filling pressure. Secondly, the spurious pulses may be eliminated from counting set-ups by imposing an artificial dead-time electronically (Elliot, 1949).

The third series of experiments, carried out at Hobart after my return from Birmingham in October 1948, was designed to follow up some of the findings from the earlier work, bearing in mind the needs of the cosmic ray research program at Hobart. For this purpose it seemed desirable that a set of counters should give reliable performance for a year or more without replacement. This required a life-time of at least 5×10^7 counts for the counter sizes then envisaged, whereas some reports in the literature indicated deterioration after as few as 10^7 counts. The counter used for this series (see Figure 12) had a movable anode wire with adjustable glass sleeves so that ageing effects could be attributed separately to the phenomena at the anode, cathode or in the gas filling. The mercury manometer enabled any gas pressure changes to be observed.

A 3 cm length near one end of the above counter was used for the age test. A small radium source was used to give a counting rate many times the normal background rate so that the ageing process could be studied over a period of a few months. The following results were obtained.

1. The high counting rate 'activated' the 3 cm cathode section so that the background rate after a total of about 10^7 counts, was high but decreasing immediately after the source was removed. After about 5×10^8 counts this effect disappeared and did not return before the end of the tests at 8.8×10^8 counts.

2. The counter was photosensitive between about 10^7 and 10^8 counts, but not thereafter up to the end of the experiment at 8.8×10^8 counts.

3. By 5×10^8 counts, the gas pressure had increased slightly, indicating a breakdown of the quenching agent into smaller molecules.

4. The pulse size at the fixed operating voltage had decreased. This was caused mainly by some change to the active section of the anode. It was inferred that a thin layer of products from the breakdown of the quenching gas had formed on the anode wire, thereby lowering the gas gain. The high voltage on the counter had to be increased by 100 volts to restore the pulse size to the original value.

Another counter discharge phenomenon studied during this period was the spreading of the discharge. It had already been suggested by other investigators that the discharge in a GM tube spreads along the whole length of the counter. With the adjustable counter it was found that the pulse size is proportional to the active length of anode employed – supporting the spreading hypothesis. Also, the time required for the pulse to reach maximum height depends on the anode length. By observing the pulses with a cathode ray oscilloscope, the spreading speed was established at 5×10^6 cm s^{-1} in a typical case, in agreement with other experiments and with a theory of the spreading process published by Wilkinson (1948). It appears that the discharge spreads along close to the anode wire in both directions from the original avalanche in steps of about 1 mm at a time, being propagated by short range photons produced by the successive electron avalanches in the high field region near the anode. It was discovered that a glow of faint blue light could be seen with dark-adapted eyes and could be recorded photographically by taking a long time exposure to integrate over many pulses.

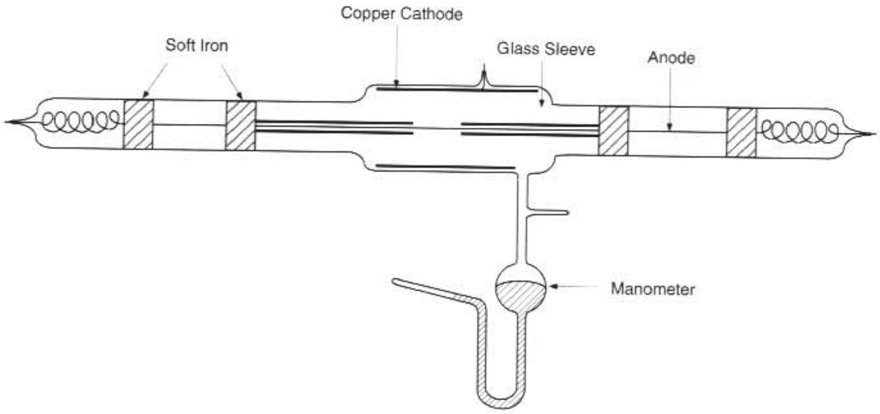


Figure 12. *The adjustable counter used during the life tests at Hobart.*

5.5 EXTERNAL CATHODE COUNTERS

Maze (1946) reported that glass counters of otherwise normal construction but with the cathode on the outside of the glass (a coating of colloidal graphite, or aquadag) give very good performance with long plateau regions. Counters of this type were investigated at Hobart in 1948 and 1949 with the result that external cathode counters were adopted for the cosmic ray program. For example, the new muon telescope for East-West asymmetry studies at Macquarie Island in 1950 used trays of sensitive area 20 cm x 20 cm made up from soda glass envelope counters of diameter 2.5 cm and effective length 20 cm with a 0.07 mm tungsten anode. The gas filling used was 9 cm Hg of argon plus 1 cm Hg of ethyl ether. The decision to use ether instead of ethyl alcohol was made because it was thought that at Macquarie Island the operating temperature might be sub-zero at times! These counters were operated at about 1100 volts and had a plateau length of 400 volts with an excellent slope of 0.02% per volt. The counting efficiency was measured to be 99% at 1100 volts. There are two disadvantages associated with external cathode GM counters but these are not a problem for cosmic ray research, where coincidence circuits are normally used: Due to the ^{40}K content of the soda glass (1.8% of potassium in the Australian glass) the background rate is several times that of an equivalent borosilicate (0.1% potassium) internal cathode counter. The other property of the Maze-type counters is that the pulse size decreases as the counting rate increases. This is explained in terms of the resistance of the glass wall (which is about 10^8 ohms in a typical counter) plus the build-up of electric charge on the inner surface, which acts as an inner cathode connected to the outer one by a capacitor and this resistance in parallel. The effective high voltage is lowered by the potential difference established across the wall resistance.

5.5.1 Counter trays of area 1 m^2

During the 1950's larger counter tray areas were desired for intensity variation studies, especially for the forthcoming International Geophysical Year (IGY), 1957–58. External cathode counters of 100 cm effective length and 4 cm diameter were constructed. These also performed very well, having long plateau regions with small slope. The counter trays were light-tight metal boxes which avoided photosensitivity problems as well as providing electrical shielding. Counters which gave a high background rate after filling usually settled down during operation after a day or two. Whereas the 20 cm x 20 cm tray counters could be connected in parallel, and still give adequate output pulses, this was not practicable with the 1 m^2 trays; consequently, each counter tube was connected to the control grid of a tetrode valve, used as a switch which turned off when the control grid reached -0.5 volts. The overall result was that a short output pulse appeared whenever a tray counter discharged, even though the individual counter pulses may be 100 microseconds or more in duration (details of the electronics will not be given here).

With the advent of transistors in the late 1950's it was decided to use quenching circuits on each counter instead of electronic switches in order to prolong the life of the counters. With a relatively simple circuit a reduction of the charge per pulse by about a factor of five was achieved, accompanied by a corresponding increase in counter lifetime.

5.5.2 Rejuvenation

Following the discovery in late 1948 and early 1949 with the Hobart adjustable counter that an aged counter has acquired a poorly conducting film on the anode, it was realised that this may be evaporated off the surface by heating the wire by passing an electric current through it for a few seconds to make it glow a dull red. The material removed may be seen as a puff of white smoke from the wire! This treatment usually restores the counter to a nearly normal operating plateau, with a slight shift to higher voltages due to the changed gas composition and pressure.

5.5.3 Life-time of counters in continuous operation

Since development of large external cathode GM counters for the IGY more than 6000 have been made for the Hobart cosmic ray program. Currently almost 800 are in operation. The oldest of these have been in continuous operation for 25 years! It has been found that the counters operate satisfactorily at least until the correct operating voltage has risen from the original 1100 volts to over 1400 volts, provided the glass-metal seals at the anode lead-in wires do not crack, thereby admitting air.

It was found in the mid 1960's by D.J. Cooke (1971) that this problem (cracked seals) could be circumvented or at least the deterioration delayed significantly by routinely coating the anode seals with epoxy resin (Araldite). If the seals remain intact, the counter may be repeatedly rejuvenated. More research into the cause of the cracking of the seals is desirable – the technique for preparing the seals and annealing them has been investigated by the glass blower, Mr M.G. Mason, without finding any problems on the construction side. It has been noted that the cracking is more likely to occur during operation rather than during storage, which points to some phenomenon associated with the presence of a high voltage across the counter. Unfortunately, the changes in muon telescope counting rate due to failure of a counter are a problem for a research program when long-term stable operation is desirable.

5.6 OTHER GAS-FILLED COUNTERS CONSTRUCTED AT HOBART

5.6.1 GM counters for balloon flights

When the Hobart cosmic ray group began a balloon launching program in the early 1960's many GM tubes of various sizes were constructed. Some were of the external cathode type but others had internal cathodes of nickel or copper. Special techniques were developed to construct thin walled aluminium tube counters. Hundreds of these counters were made. They performed well, withstanding the extremely low temperatures in the upper atmosphere.

5.6.2 Neutron counters

Neutron counters operating in the proportional region were constructed, starting in the 1960's for use in IGY-type neutron monitors. These were designed to be compatible with the original brass tube counters available from the US for the IGY program. This involved acquiring the techniques for generating, handling and purifying boron triflouride on the vacuum system. These counters were tested for satisfactory performance using a 24-channel pulse height analyser (PHA) constructed in 1960 by A.J. Tavendale (1962).

The Physics Department could not afford a commercially built PHA until about 1967 when a Nuclear Data 1024 channel PHA was acquired.

Many glass envelope neutron counters with nickel internal cathodes were made in the 1960's for the balloon program to study ^{14}C production in the atmosphere. Soda glass was used because borosilicate glass would have absorbed many of the neutrons. The counters were of good quality in spite of reports in the literature suggesting that boron trifluoride would attack glass (Fenton and Fenton, 1965).

5.6.3 Large proportional counters for cosmic ray muon telescopes

Attempts were made during the early 1950's to use large proportional counters (e.g. one to two metres in length by 10 cm diameter) as a way of avoiding the perceived problems of ageing and cracking in the GM counters. A multi-wire proportional counter of effective area 1 m^2 was constructed for use as a gas-flow counter at near atmospheric pressure, at a time long before such things were developed elsewhere! However, with the electronics available at the time, such a high gas gain was necessary to obtain a usable output, even with a multi-stage amplifier on each wire, that it was considered impractical compared with the external cathode GM tubes. The technology had to await the development of solid state electronics, including low-noise FET's, before large metal tube proportional counters became feasible. They were first used in large sizes in Canada in 1976 as gas-flow (purification plus recirculation) counters (Bercovitch and Agrawal, 1981) and later in Japan and India as sealed-off counters (Krishnaswamy et al., 1979).

The first large sealed-off proportional counters used by the Hobart group were made in the early 1980's. These were 2 m long copper cathode counters 10 cm diameter, for use in underground muon telescopes at Poatina, Tasmania. At about the same time over 400 Japanese proportional counters constructed of stainless steel tubes, 2.5 m length by 10 cm diameter were installed at Liawenee, Tasmania as part of a joint Hobart–Nagoya extensive air shower project. These counters were filled to 70 cm Hg pressure with a gas mixture 90% argon and 10% methane which is sold by supply companies as P10 gas. More recently (late 1980's) 2 m x 10 cm stainless steel tube proportional counters were constructed at Hobart for use at the Tunnel Hill cosmic ray underground observatory. These have a lower operating voltage than the usual counters of this type and size, due to the different gas filling mixture (argon, isobutane and hydrogen).

5.6.4 X-ray detectors

When our X-ray astronomy research began in 1967, jointly with the University of Adelaide, and sharing payload space with British Skylark rocket flights from Woomera, South Australia, the techniques of construction and filling of thin beryllium window proportional counters were developed. Later, other large multi-wire Xe filled thin window counters were developed for high altitude balloon flights. Leak detection methods and gas purification techniques were acquired to enable this program to proceed.

5.7 CONCLUSION

What began as a step towards the initiation of a cosmic ray research program at the University of Tasmania in 1946, developed into a PhD project for the study of the basic electrical discharge mechanisms operating in Geiger-Müller counters. It then became a facility in the Physics Department for the routine production of counter tubes for the cosmic ray program, as well as for research and development of other types of gas-filled radiation detectors. Many physics honours and PhD students as well as several post-doctoral researchers benefited from its support for their projects. Many of the detectors designed and constructed over the years were not available commercially and would have been costly and time-consuming to acquire by outside contract.

Unfortunately, due to recent cut-backs in University funding and the gradual reduction in student enrolments in physics, which have affected the staffing levels, the facilities and expertise built up over several decades are being lost to the University.

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6. THE AUSTRALIAN NEUTRON MONITOR NETWORK

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ABSTRACT

The neutron monitor was the new instrument in the study of the variations of the cosmic radiation in the early 1950's. Studies by John Simpson and co-workers, and by Adams and Braddick, had shown that the variability was greater than for mesons. The 'standard IGY monitor', copied from the Simpson instrument, was specified for world wide use during the International Geophysical Year (IGY).

The author commenced construction of Hobart's first neutron monitor in early 1955. The first monitor, consisting of only two 'Nancy Wood' counters, commenced operation on the 'rifle range' in May 1956. A four counter unit commenced operation at 'The Springs' on Mt Wellington, in July 1956. These small monitors provided excellent data from the very first – a number of major studies of Forbush decreases and the 11 year effect used data from those first months and Mt Wellington was one of three stations, world-wide, that recorded the small solar flare event of August, 1956.

Other monitors followed soon after. A 12-counter monitor was sent to Mawson in December 1956; a 6-counter monitor to Lae, New Guinea in June 1957 and another to Casey in 1960. The wide spread of latitudes and longitudes made the Hobart network one of the most useful in the international studies of cosmic ray variations from the beginning of the IGY (July, 1957).

Starting in the 1960's, the standard IGY monitor was replaced wherever possible by the Carmichael 'super neutron monitor'. Today, the Hobart network is one of the mainstays of the international study of time variations in the 1 to 10 GeV cosmic ray flux.

6.1 THE PRE-HISTORY

During my Honours year in 1954, Geoff Fenton made the suggestion that I consider enrolling for a PhD degree and that my first research task would be to build a neutron monitor for operation in Hobart.

In 1954 we knew next to nothing about neutron monitors. Adams and Braddick had experimented with a number of graphite moderated neutron counters in Manchester and had the good fortune to observe the solar flare of 1949 with it. The increase they saw was about 30 times that seen with the meson detectors of the day but it seems the implications were not recognised. Nothing more was ever heard of that neutron detector.

John Simpson and a succession of graduate students had also systematically investigated the neutron component of the cosmic radiation in the atmosphere, the emphasis being on the nuclear physics thereof.

Aircraft flights from high latitudes to the equator revealed a much greater latitude effect than seen with ionisation chambers and Trieman, in particular, recognised that the neutron component was more sensitive to low energy primaries. By 1951 the first routine time variations measurements were being made in Chicago and a monitor (as it was christened) soon followed at Climax, Colorado, where the altitude gave what were, in those days, quite unbelievable counting rates.

The data from these two neutron monitors soon indicated that the time variations in the neutron component were of greater amplitude than for muons. A major portion of my honours project involved the intercomparison of ionisation chamber, muon telescope, and neutron monitor data and this aspect was particularly clear to me. Further, the atmospheric corrections were simpler and more accurate. By 1954 it was clear that the neutron monitor was destined to play an important role in the study of the time variations and construction of a number of neutron monitors commenced worldwide.

6.2 THE HOBART MONITORS

The neutron counting rate increases rapidly with altitude, and conversely, the standard deviation of the counting rates decreases with altitude. So it was rather inevitable that the main Hobart monitor would be somewhere on the slopes of Mt Wellington. The real question was – where? The television stations were not yet on the summit, however there was a (dry) hotel at 'The Springs' at an altitude of some 700 m and there was good electrical power and road access to that point. In the 1950's the road was often closed by snow at 'The Springs' in winter and although the author was rather attracted to the idea of skiing up the 'Zig Zag' to a neutron monitor on the top of the mountain to check its operation each week, this was not deemed by more august personnel to be 'a good idea'. So it was decided that the monitor would be located some 50 m above 'The Springs', just 30 m from the main picnic hut on the main track to the summit. For safety, it was decided to build another small monitor to be located on the University campus.

Design and construction of the first monitor commenced in May 1955. The monitor itself was a faithful reproduction of the Chicago design, except that many cost cutting measures were taken. For example, Chicago used teflon insulators to support the main 3000 volt anode supply to the neutron counters. The neutron monitor pulses themselves were of the order of 1 millivolt and insulator leakage had to be avoided strenuously. Teflon insulators were extremely expensive and other solutions were sought. It was recognised that a variety of British war surplus coaxial cable used teflon between the inner conductor and the braid. The anode line insulators were therefore constructed from perspex for strength and easy machinability, with a teflon inset made from cannibalised coaxial cable. Simple, cheap and extremely successful, even in the 100% humidity of New Guinea.

While the monitor itself – the BF_3 counters; the paraffin; and the lead followed the Chicago design, the electronics were pure Hobart. The pulse counting circuits were the standard Hobart design, constructed using some of the myriad of 7C7 valves obtained from war surplus by the truck load. The author recalls personally wiring up about 10 of the long feedback amplifier strips that were used to amplify the small neutron pulses in all the monitors in the Hobart network. A PhD student had a simple choice then – learn to solder properly or spend years swearing at cruddy data.

However, the main contribution to the excellence of the electronics of the neutron monitors was made by the resident electronic engineer, Dudley Millwood. With a British background of radar electronics from World War II and excellent design and manufacturing skills, he produced a long line of reliable and stable electronic devices for both the meson and the neutron programme. Further, Dudley did not suffer fools gladly. To him, PhD students were, by definition – fools, and Australian PhD students particularly so. Nevertheless we learned a great deal from him and he gave us the designs that were the basis for the long term stability and reliability that became the hallmark of the data from the Australian network. Having a personal interest in things electronic, I received valuable training of a quality that I valued greatly in my later professional life.

The neutron monitors were built in the era when the data were recorded by photographing mechanical pulse counters and an aneroid barometer, each hour. Aneroid barometers with a scale large enough to record to fractions of a millibar were very expensive and once again the Australian propensity to improvise came to the fore. I was visiting Sydney and I visited a very famous 'war disposal' store. After an hour of searching, I bought the altimeter from a DC3 aircraft for five Pounds. That was the basis of the pressure correction of the Mt Wellington data until the first monitor was burnt down in the bush fires of 1967. The cameras used to photograph the data were 'home made' copies of a well known German camera.

The BF_3 counters were the critical path to the construction of the first monitor. The author spent some time trying to develop the apparatus needed to make and purify BF_3 gas to enable us to manufacture our own neutron counters – however it soon became clear how wise I had been in deciding to give up chemistry as a career. Wisely, Geoff Fenton ordered enriched BF_3 counters from the Nancy Wood Counter Company in Chicago. The lead time was almost a year – and but for that – but read on.

6.3 1956 – SWITCHING ON, AND THE MAWSON MONITOR.

For my generation of cosmic ray people, 23 February 1956 was the high point. The largest solar flare effect ever seen, before or since, occurred during our lunchtime and it got the 'hands on' treatment from Geoff Fenton and I, yielding fine time detail from the meson telescopes and my ionisation chamber that was unusual at that time. If the Hobart monitor had been operating, it would have seen a 25 fold increase. Alas, it wasn't. The Mt Wellington monitor was finished and installed in the Hobart laboratory, however the BF_3 counters were still in Chicago.

The BF_3 counters ultimately arrived in April 1956, on a Friday. They were installed that afternoon, the high voltage adjusted, and the first neutron records from Hobart were obtained over the following weekend. The 'hut' on Mt Wellington was finished in May and adorned with a sign on the door – DANGER – COSMIC RADIATION – KEEP OUT. Somehow, I don't think you would be well advised to use a sign like that these days.

The Mt Wellington monitor was installed in the 'Hut' in July, 1956. Another smaller monitor was operating at the University. And by then, construction had started on a 12-counter monitor to go to Mawson in December 1956 and a six-counter monitor to go to New Guinea in March, 1957. Yet another monitor – the 'airborne neutron monitor' – (see below) was also being constructed. That is, just a year after planning started, two monitors were operating and three more were well on the way to completion.

The Mawson monitor left Hobart as part of the annual Mawson relief voyage in December 1956. This was the most frantic phase of the installation of the whole neutron monitor network. Usually all the electronics, including the spares, were operated for a while in Hobart before being shipped out. Time did not allow that and, as a precaution, all the electronics wiring was photographed before being packed. As a result a wiring error in one of the 3000 volt supplies was detected prior to its arrival in Mawson. An urgent telegram therefore greeted the Mawson physicist, David Johns, on his arrival warning him to rectify the problem. As a consequence, turn on was extremely uneventful and Mawson was in operation in early 1957.

6.4 THE AIRBORNE NEUTRON MONITOR

John Simpson of Chigaco had a very useful arrangement with the US antarctic programme whereby a neutron monitor was installed on one of the relief ships. Over the years, they obtained a number of measurements of the dependence of counting rate on latitude at different longitudes. These showed that the minimum intensity was not observed at the magnetic equator in some regions of the world. Since the magnetic cutoff was an important quantity in many cosmic ray studies, these results implied that some of our cutoffs were wrong.

This was the era before numerically intensive computers. So the solution we would use today, to compute the cutoffs from the multipole expansion of the Earth's magnetic field, was not available. So the empirical approach was used – to make many measurements of the latitude dependence at different longitudes. To this end, Geoff Fenton convinced the Australian Air Force to fly a neutron monitor from the vicinity of Macquarie Island to Tokyo and return.

The aircraft to be used was a rather geriatric Lincoln Bomber. The Lincoln was early World War II vintage and it was neither large, fast, nor comfortable. The two-counter neutron monitor occupied the whole width of the fuselage. The flight was to be at 19 000 feet (5800 metres) – close to the reputed ceiling of the aircraft. The fuselage was unpressurised and unheated, so the operator was required to wear an oxygen mask for the whole trip.

Jack Storey from Auckland had recently joined the Hobart group and he was responsible for the whole airborne project. The flight to Japan in mid-1957 was relatively uneventful, however things started to go wrong in a rather spectacular manner on the return. Somewhere a long way north of New Guinea one engine failed and the aircraft descended to 17 000 feet. Then a second engine failed. For a while, it seemed possible that the neutron monitor would be jettisoned to keep the aeroplane airborne. However the aircraft managed to hold altitude at 12 000 feet and then limp into Momote, the northmost island of Papua. There it had to wait for a month for the engines to be replaced.

From memory, the Lincoln bomber was pensioned off as soon as the neutron monitor flight ended.

6.5 THE NEW GUINEA COSMIC RAY OBSERVATORY

It had been my ambition for many years to go to Antarctica. It was therefore my intention to take the 12-counter monitor to Mawson in 1957. Somehow that did not happen and David Johns took it there and I got the consolation prize, to take the six-counter neutron monitor and two 60 cm 'cubical' meson telescopes to Papua-New Guinea. Just where in New Guinea wasn't clear. I was told – find a good place.

It was ready to go in April 1957. It was packed into about 30 large boxes and about a hundred very small boxes. The small boxes were only about 500 x 250 x 100 mm in size, however they weighed 50 kg each. They were full of lead. Later they would cause me quite a bit of excitement.

Flying to New Guinea was an experience in itself. The aeroplanes used were rather tired DC4s left over from World War II. They flew at about 300 km hr^{-1} and it took over three hours to go from Melbourne to Sydney. Then we started north, landing every three hours or so at Brisbane, Townsville, Cairns, Port Morseby and finally arrived at Lae a day after leaving Sydney.

The air conditioners were primitive, they were noisy and uncomfortable. However many of the passengers didn't seem to notice this. At first they were too busy having a boisterous party and later they were in too great a state of intoxication to notice. I didn't realise it then, but that flight north was one of the great institutions in those days when New Guinea was a territory of Australia and the Australian population consisted, more or less in equal proportion, of planters, policemen, public servants and missionaries. The former three categories seemed to regard life in the tropics as a great game and parties on the 'big pella balus' (Pidgin for big bird) were a very important part of that game.

And so we landed in Lae. A rather short grass runway, a cluster of 'army huts' and several wrecked ships in the harbour were all I could see.

Arrangements had been made for the Australian Department of Civil Aviation to 'look after me' while I was in New Guinea. No one really knew what that meant, nor did they really care – it was typical of the very informal arrangements that were the norm in the Territory. These were still the days of 'the British Raj', and Europeans were referred to as Masta Dick, Tom or Harry. Since there were three Kens in the Civil Aviation establishment, another name was found for me. This was long before the establishment of a University in New Guinea and it had been explained to the New Guineans that I was from 'big fella school long Australia'. Somehow the idea of a 185 cm Masta, who towered over most of the Europeans and all of the New Guineans and who was still at school, caught the imagination of the locals. To all and sundry I was known as 'Lic Lic School Boi' (Little School Boy)

Civil Aviation also presented me with a driver and four 'bush kanakas' and told me where I could find my pile of boxes. Off we went and I used my very limited Pidgin English to tell the kanakas to do the obvious.

Thirty very big boxes and 100 very little ones. It takes no prizes to guess that they all went to the little boxes. The first one tried to pick one up and there was an immediate commotion. They all ran back about ten meters and stood shouting and jesticulating at my little boxes. They were very clearly of the view that there was something decidedly indecent about little boxes being so heavy. Not only indecent, but unhealthy too, as far as I could tell. It took a lot of coaxing before I had all of my boxes where I wanted them.

After several weeks the equipment was busily counting cosmic rays and there was little left for me to do other than to wait for it to break down. Which it didn't. By then we Tasmanians had learnt how to build reliable equipment and acute boredom set in.

Not for long, though. I talked to my friends in Civil Aviation and found that they had 'an arrangement' with the local airline that allowed them to fly anywhere in the Territory as 'supernumeraries' on the aeroplanes. As a supernumerary, you sat in the jump seat behind the pilots and occasionally did useful things such as telling the passengers to do up their seat belts. The passengers were primarily indentured labourers, so I would bellow out at the top of my voice – "Yu kissim seat belts quick time eh – maski buggerim up".

Up until that time, the data recording systems were the weakest link in the Hobart cosmic ray network. The recording cameras were rather temperamental and even skilled operators had the embarrassing experience of getting the film from the Mt Wellington observatory and finding that it had not wound on or that it was blank. We realised that a different method had to be found for New Guinea – and decided on a chart recorder running at about 10 cm per hour. The counting rates were scaled to yield a pen deflection every few millimeters. While chart recorders themselves were prone to occasional blockage of the pens, the fact that the operator would see that and rectify the problem within a day was a great improvement. Each week the chart would be mailed to Hobart; an arrangement that proved to be very satisfactory.

6.6 DATA PROCESSING

The neutron monitors were established at a time when there were only two electronic computing machines in the whole of Australia. All data processing was carried out on hand calculating machines. These were operated by the 'computing ladies' – who were the equivalent of the stored software in the modern PC.

At the time the neutron monitor network was being established, the computing ladies were already very skilled in correcting the meson data for both pressure and upper atmospheric temperature. These were linear corrections, each requiring a multiplication and addition, and were easy to streamline on a hand calculator.

Not so for the correction of neutron data. The absorption mean free path of the nucleonic component is short enough that an exponential correction was necessary. That meant looking up tables – a time consuming and error prone process.

This problem was circumvented by designing a special purpose slide rule, in which the counting rate scales were logarithmic, while the pressure was linear. The first model that was used for about six months consisted of scruffy hand made scales stuck onto the authors linear slide rule. Then Jack Storey designed a you-beaut circular slide rule, made from brass, with photographic scales attached to the body and the moving parts. It looked like a measuring device from the 19th Century.

The data from Mawson was sent to Hobart each day by telegram. They were all sent by morse code over a rather tenuous radio link through the auroral zone and therefore error detecting 'check sums' were included in the message. These were not the error correcting codes we use today – if the check sum did not validate the data, a request went back to Mawson (by morse code) for the data to be sent again. There were no telephones to Mawson and voice radio was rare, so all technical problems were dealt with the same way – through a laborious exchange of telegrams. These being expensive, we all became expert in saying a great deal with a few words.

6.7 THE SYDNEY NEUTRON MONITOR

In the early 1950's Harry Messel set about making the Physics Department at the University of Sydney into the Australian centre for cosmic ray and nuclear research. He recruited leading cosmic ray physicists and astronomers into the department. Among other activities, they planned to establish an eight counter neutron monitor as part of the Australian programme for the International Geophysical Year. Hobart welcomed this, since it would neatly bridge the cutoff rigidities between Lae and Mt Wellington.

From the beginning, Hobart had a strict policy of rapid circulation of data. Thus the Mt Wellington and Mawson data were soon being circulated world wide.

About the middle of 1957, I received a letter from the University of Sydney informing me that there must be something wrong with our monitors because the data we were circulating only showed a diurnal variation of about 0.5%. The Sydney monitor, I was informed, was seeing 10% diurnal variations. This was in the days before the diurnal variation was well understood, and furthermore, McCusker (while in Jamaica) and Sarabhai in India had recently observed 'giant' diurnal variations (between 10 and 20%) in the meson component. McCusker had moved to Sydney by 1957 and undoubtedly the concept of giant variations had moved there with him.

Some time later I visited the University of Sydney. We discussed the manner in which their high voltages and amplifier gains were stabilised and the nature of the counting rate versus high voltage curve. We discussed the optimum location of the operating voltage on the 'plateau' in that curve.

To this day I do not know what I said, but the Sydney monitor disappeared without trace soon after. This was a process I saw repeated many times – where many Universities found it to be impossible to achieve the required stability of amplification and high voltage in those days of fickle thermionic tubes and voltage references based upon the rather unstable characteristics of the neon discharge. The Hobart and Antarctic group achieved the required stability in every neutron monitor it built, largely, I believe, through the excellence of electronic design and manufacture that was provided by Dudley Millwood.

6.8 THE SCIENTIFIC RESULTS

This is not the place to review the scientific results from the Hobart/Antarctic Division neutron monitors in detail. However it can be asserted without fear of contradiction that the Australian neutron monitors have been -together with the Canadian, Chicago, and Bartol networks – the cornerstones of the world wide network.

Some examples are noteworthy:

(a) Mawson has been a major contributor to the study of a great many of the solar flare events since 1957. Its narrow asymptotic cone and its location on the celestial sphere have meant that it has repeatedly played a key role in the definition of the rapidly changing anisotropies soon after flare onset. This was particularly so in the analysis of the flare event of 4 May, 1960, that provided the experimental verification of the spiral nature of the solar system magnetic field,

(b) Starting with the initial discovery event of September 1958, Mt Wellington and Mawson, together, have allowed the anisotropies prior to the onset of Forbush decreases to be analysed in detail. Further, analysis of the September 1958 event led to the concept of using the Fourier transform of the asymptotic cones to analyse the diurnal variation,

(c) Based upon that concept, the Australian network, augmented by other monitors, allowed the worldwide characteristics of the diurnal variation to be systematised and the corotating nature of that variation established.

(d) These are the well known results. A characteristic of a creative research group is that there will be many other, less well known achievements. The author, with his rather myopic view of events, recalls the following –

(i) John Phillips' investigation of the directional atmospheric sensitivity of a neutron monitor by operating a small monitor at varying distances from a quarry wall. This provided experimental verification of an important theoretical prediction which was a key ingredient in the calculation of the asymptotic cones used for the analysis of both the solar and galactic radiation.

(ii) An abortive attempt by the author in 1956 to calculate the asymptotic directions for the Hobart monitors using a differential analyser in the Engineering Department of the University. This provided excellent tuition as how not to do it.

6.9 CONCLUSIONS

In the 1950's, Physics was a small department in the smallest independent university in Australia. It was housed in a disreputable collection of army huts left over from World War II. Yet it became a major player in the early days of exploration of the physics of the solar system. For two decades the spacecraft measurements, important though they were, needed interpretation in the light of earth based observations. The Australian neutron and muon networks were one of the leading sources of such data. The influence of the antarctic programme was vital, it provided the emphasis on high reliability and stability that was vital for such work, and provided access to geographic locations whose scientific value was not to be fully recognised until a decade later.

The cosmic ray group also played an extremely valuable role in education, in the wider sense of the word. The expeditioner physicists and the graduate students such as I, gained a great number of practical skills, that then translated very well into other areas of science and engineering. Personally, I believe that the practical experience I gained up until I left in 1959 and the 'can do' mentality that pervaded the whole programme, were major contributors to my later careers in solar system science, astronomy and research in support of the Australian mineral industry. I deem myself to have been incredibly lucky to have been associated with the programme.

6.10 ACKNOWLEDGEMENTS

The Hobart-Antarctic neutron monitor network was created through the foresight and leadership of Geoff Fenton and the senior officers of the Australian Antarctic Division. As noted herein key technical contributions were made by Dudley Millwood and the staff of the Physics Department workshop. Jack Storey and David Johns were instrumental, with the author, for establishing the measuring network under very trying and sometimes dangerous conditions. Mrs P. James, Mrs D. Chappel and Ms B. Harrop, the first of the 'data ladies', applied exponential correction to about 50 000 data points each year (by hand) and performed hundreds of multiple variate regressions – yet again by hand. As a result of the efforts of these people, and many more, the Australian neutron monitor network was in operation by the beginning of the International Geophysical Year, in July, 1957. It is a tribute to their work and that of their successors, that the network has been, and still is, a major contributor to mankinds' knowledge of the solar system influences upon the cosmic radiation.

7. UNDERGROUND STUDIES IN TASMANIA AND AT MAWSON

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ABSTRACT

Some features will be presented of experiences with the Cambridge telescope system, sidereal anisotropies and the Japanese connection, intercalibration of underground depths and the Mawson underground experiments.

7.1 INTRODUCTION

I would like first of all to express gratitude to the Antarctic Division and the University of Tasmania for generously enabling our Antarctic group to stay on in the Physics Department of the University, following the early years of the joint program at Hobart. Even in this brief mention of underground studies it is hoped that some of the benefits will be seen of our continuing close collaboration in research.

I propose to concentrate mainly on some of the experimental ideas and on the nature of the underground projects that were involved, rather than on detailed descriptions of the underground equipment.

7.2 THE CAMBRIDGE TUNNEL UNDERGROUND SYSTEM

Perhaps the most important idea of all was the idea of the Tunnel underground experiment itself. It occurred to Geoff Fenton at the Mexico Conference in 1955. It became his plan to place two geiger counter telescopes in the old railway tunnel at Cambridge, at a depth of about 18 metres underground. They were very large telescopes for their time, of the type that Nod Parsons had already designed and built and had operated with success at the surface at Mawson. In fact a core of exceptionally capable researchers – Geoff and Peter Fenton, Nod Parsons and the late Peter Burbury, even if not all around at the same time – would have had input to this far-sighted development.

The underground site was a most effective one. Besides being very conveniently placed and secure, if it had been much deeper than 18 metres underground the counting rate would have been rather low and, if much shallower, changes in the atmosphere would have had rather complicated effects on the counting rate variations. There were possibilities at that depth of very interesting responses both to solar and sidereal modulation – to do, for instance, with new phenomena and with studies of energy ranges and energy dependences of phenomena.

By the time of my return from Mawson in 1957 the two vertical semi-cubical telescopes had already been installed and Ray Taylor, then a post-graduate student, had commenced observations (Fenton et al., 1961). It was to transpire that these same telescopes were to contribute to an unequalled record of continuous observations at the Cambridge site, over a period of very nearly 40 years.

7.3 SIDEREAL ANISOTROPIES AND THE JAPANESE CONNECTION

It will be taken for granted in this talk that the use of the daily variation of the counting rate for studies of superimposed solar and sidereal anisotropies is understood and that solar and sidereal types of variation can be basically separated out by taking annual averages of the daily variation in solar and sidereal time respectively, but that variations in the solar response produce important spurious variations in sidereal time.

Although this part of the talk is about sidereal anisotropies, the solar response is particularly interesting at the moderate underground depths, notably in relation to ground level studies, and very effective work in this way has been carried out at Hobart and Mawson. I would like to add a word here especially for the valuable and enjoyable period of cooperative research in the 1970's and 80's initiated by Professor Martin Pomerantz and the late Professor Shakti Duggal of Bartol Research Foundation that culminated in discoveries centred on the Mawson underground and surface observations in 1982.

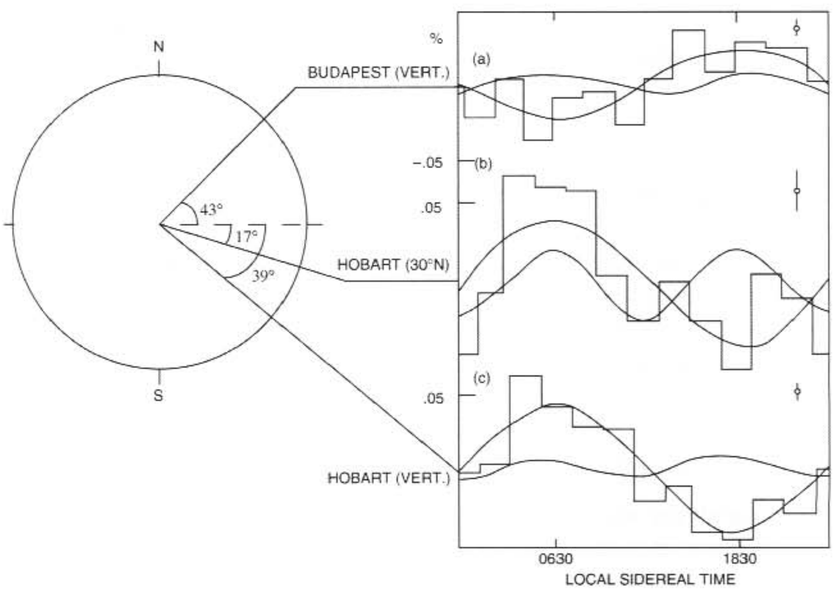

Figure 1*. The sidereal daily variation underground at three different geographic latitudes of viewing (adjusted for geomagnetic deflections):*

- *(a) Budapest (1959 + 1961) vertical;*
- *(b) Hobart (1961 + 1962) telescope inclined 30° north of zenith;*
- *(c) Hobart (1961 + 1962) vertical. The first and second harmonics of best fit to the histograms are shown. The error tails are the SEs of amplitude.*

Long before this, over a couple of years centred around 1960, substantial evidence for a sidereal anisotropy was obtained from vertical and inclined telescopes underground at Cambridge and a vertical telescope system at the same depth at Budapest (Jacklyn, 1966). I think most will understand this early figure (Figure 1) which shows evidence for a bi-directional anisotropy along an axis which produces a diurnal maximum at about 1800 hr in the Northern hemisphere and 0600 hr in the Southern hemisphere and an important semi-diurnal variation in phase with these, plus a uni-directional anisotropy with its maximum at about 0600 hr. A narrow angle telescope pointing into the Northern hemisphere from underground at Cambridge showed the bi-directional result could not have been caused spuriously through seasonal atmospheric changes in the solar daily variation.

The evidence for a bi-directional anisotropy was in accord with a Leverett Davis model for a pitch angle distribution of the intensity which favours particles with small pitch angles, providing for equal intensity maxima in opposite directions (Davis, 1954).

Soon afterwards Professor Sekido, director of The Cosmic Ray Research Laboratory (CRRL) Nagoya, was able to reproduce the Cambridge experiment from the Northern hemisphere, making use of his large narrow angle Cerenkov detecting telescope. He got essentially the same result as was obtained here and this was to have important consequences for the development of an underground detecting program in Japan. However, a few years later, Professor Nagashima at the same Cosmic Ray Laboratory in Nagoya produced a rigorous general theory of anisotropic response. In the course of it he had discovered a very serious spurious diurnal variation of solar modulation origin, connected with the orbital motion of the Earth (Nagashima and Ueno, 1971; Nagashima et al., 1985), that had the vital 1800 hr maximum in the Northern hemisphere and the 0600 hr maximum in the Southern hemisphere. If that component was removed from the observations, the Northern hemisphere diurnal variation would now be dominated by the uni-directional variation with its maximum at 0600 hr and so we would have 0600 hr maxima in both hemispheres, swallowing up the diurnal part of the bi-directional anisotropy which would then completely lose its impact.

The irony in all this is that if it hadn't been for the presence of the spurious component, not known at the critical time, purporting to be of bi-directional origin with a dominant 1800 hr maximum in the Northern hemisphere, the Japanese might well have been less inclined to go ahead with their very substantial underground program that came out of the early work. Eventually it was to confirm that a genuine phenomenon in the sidereal frame of reference was in fact being observed.

The bi-directional model was by no means invalidated by the spurious component, but for many years it was the semi-diurnal variation that was to hold things together. Any suggestion of a spurious contribution to it was removed by the results of experiments at Mawson using new narrow angle telescopes set at very high zenith angles so as to use the atmosphere as an equivalent of underground absorber.

As impressive results accumulated from the systems of multi-directional telescopes set at various depths in Japan, Nagashima, leading in these sidereal studies, was having great trouble trying to reconcile the Northern hemisphere observations with the Southern on the basis of a single overall model (Nagashima et al., 1991). Then, only about two years ago, it occurred to him that we could be looking at two quite different anisotropies, one from a galactic source located in the Northern hemisphere and virtually only detectable in that hemisphere and the other at lower energies in the Southern hemisphere and mainly only observable at Southern latitudes. His models derived not from the Leverett Davis ideas of pitch angle distributions but from the ideas of sources and sinks of the radiation, put forward by Sarabhai and Subramanian (Sarabhai and Subramanian, 1966).

A very small and seemingly insignificant result from seven years of observations of air showers at Liawenee (Fenton et al., 1990) under the COALA project, a cooperative program of Nagoya University, the University of Tasmania and the Antarctic Division, has tended to support the evident absence in the Southern hemisphere of the Northern hemisphere galactic anisotropy.

The anisotropy particularly relating to this part of the world is proposed to be of heliospheric origin, due to excess radiation entering along the tail of the heliomagnetic field (Nagashima et al., 1998) and the evidence for this has depended crucially on an analysis of the many years of observations at the Cambridge underground site. Findings such as this emphasise the great value to be gained from continuing long-term underground research in the Southern hemisphere as well as in the North.

7.4 INTERCALIBRATION OF UNDERGROUND SITES

With underground studies gaining momentum in the 1960's and 1970's it was noticed that reports of depths of some underground sites, in the sense of mass of material above the detecting systems, not literal depth, must be greatly in error, judging from inconsistencies in reported amplitudes of the solar daily variation. It was evident that accurate estimates of vertical depth were needed at all the underground sites, allowing weighted mean effective depths to be determined for each telescope which would take into account within its aperture the distribution of absorber and of telescope sensitivity.

At a symposium on high energy modulation held at Tokyo in August 1976 it was decided that intercalibration of underground depths should be undertaken, at least for the Japanese and Australian chain of sites. Measurements were to be taken at each place with a pair of specially designed comparator telescopes to be constructed in Japan. A similar technique was to be used in the USA for the calibration of three sites there. Dr Fujii of CRRL was to be in charge of construction of the comparators in Japan, with funds from our Antarctic Division, and for measurements in Japan. He would then bring the comparator system to Tasmania.

After the Cambridge and the very deep Poatina sites had been calibrated the comparator system was to be taken to Mawson which was to be used as a reference or master site. One of the advantages of the Mawson underground vault, at about the same depth as Cambridge, is that it is situated under uniform granitic rock and a relatively clear and flat surface. Therefore the depth can be calculated with good accuracy using the measured density of the material. This meant that the cosmic ray method of determining depth together with the performance of the comparator telescope itself could be accurately checked against the surveyed depth.

The measurements at the chain of stations (Figure 2), made possible with the collaboration of a number of people at each site, were carried out over a 6-month period from late 1978 to early 1979 (Fujii and Jacklyn, 1979). The run of calibrations ended up at Mawson, where a vertical depth of 40.5 ±0.05 mwe (metres of water equivalent) estimated from the cosmic ray observations compared with a surveyed depth of 41.2 mwe, confirmed the effectiveness of the calibrations and the high quality of performance of the beautifully constructed comparator telescopes.

Excellent agreement between estimated and surveyed depth was also obtained at the deep Poatina site, an observing period of one month being needed at that depth to achieve the statistical accuracy of a single day's measurements at stations such as Mawson. Significant discrepancies were seen at all the other sites, as a summary of results in Table 1 shows.

Generally, the project also resulted in greatly improved determinations of depths from the physical surveys.

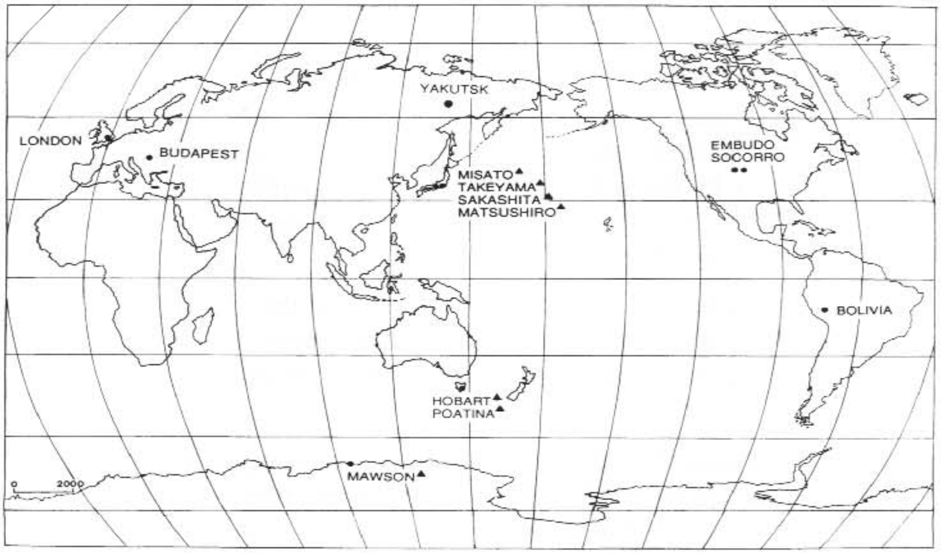

Figure 2. *Global distribution of cosmic ray sites located at moderate underground depths (40–200 mwe), circa 1980. The sites marked ▲ have been intercalibrated through the Japan/Australia project.*

Table 1. *Comparisons of underground vertical mass-depths, determined from physical surveys, with vertical depths and mean effective telescope depths estimated from cosmic ray measurements. Atmospheric depth is included in all estimates.*

Site	Surveyed depth m.w.e.	Estimated vertical depth m.w.e.	Effective Depth m.w.e.
Misato Japan	44.0	40.8 ±0.3	41
Mawson Antarcica	41.2	40.5 ±0.05	49.2 (N. tel.)
Hobart Tasmania	47.0	50.5 ±0.20	57
Takeyama Japan	65.0	79.0 ±1.7	79
Sakashita Japan	89.0	93.5 ±0.8	93
Matsushiro Japan	270.0	210.0 ±1.0	229
Poatina Tasmania	357.0	356.0 ±1.0	419

7.5 MAWSON UNDERGROUND EXPERIMENTS

Historically, experiments at Mawson at the equivalent of an underground depth of 40 mwe commenced in the original building in 1968 with a narrow angle telescope, designed and built by Attila Vrana, consisting of two units pointing in opposite directions, N and S, at a zenith angle of 76° so as to look through approximately 40 mwe of atmospheric absorber.

One of the significant results of the experiment was the finding of a latitude-dependent sidereal semi-diurnal variation, much too large to be due to the very small spurious effect predicted by the Nagashima theory of modulation (Jacklyn and Cooke 1971).

A high energy surface/underground installation came into being in 1972. Attila Vrana, electronics engineer in our Antarctic Section, was largely responsible for the design features and the construction of the telescopes and the recording systems. A vertical shaft had been excavated in the granitic rock to a depth of 40 mwe and two vaults, one for the cosmic ray telescopes, were further excavated at the base of the shaft. A building was erected at the surface to contain high zenith angle telescopes and the neutron monitor and to give access to the vertical shaft in one corner.

The excavation of the shaft in 1971 was a major achievement – for the miner sent down for the purpose, for many of the expeditioners and notably for the station leader, the late Lem Macey. Only simple excavating techniques could be used and it was very dusty work due to the lack of water for the jackhammers. At the other extreme, on two occasions blizzards blew away the tarpaulin that was covering the shaft and the whole thing filled up with snow! Amazingly, the excavations were completed on schedule and were ready for the building to be erected over the shaft in the 1971–72 summer. The title 'underground studies' has to be something of an understatement when it comes to covering such great efforts as this.

The idea of the new experiments was to make optimum use of the geographic and geomagnetic location of Mawson. To be brief, I will mention here only the main telescopes underground, having a high counting rate (330 000 pcles hr^{-1}) and set to look along the magnetic field at a zenith angle of 30°. Thus they scanned the same latitudes as the Cambridge vertical telescopes. In this respect the Mawson–Hobart combination was expected to be of value for comparisons of solar and sidereal times of maximum, for instance, that would help determine energy dependences of phenomena, with Mawson as a reference of response unaffected by the geomagnetic field. The ten-year sidereal diurnal result, 1983–1993, shown in Figure 3, indicates the agreement that existed between the very small sidereal diurnal vectors observed at Mawson and Hobart, with no significant evidence yet of a geomagnetic phase difference, suggesting high energies of sidereal response.

An operational step forward with important consequences took place at Mawson in 1982 with the commencement of replacement of all the Geiger counters with large proportional counters purchased in Japan. I am greatly indebted to Nagashima for his part in helping to bring this development about, involving arrangements with the manufacturers of the counters in Tokyo. This was also about the same time when Geoff and Peter Fenton and Max Mason were constructing proportional counters themselves to replace the Geigers at the Tasmanian sites. Their Hobart design considerably influenced the design of the counters in Japan.

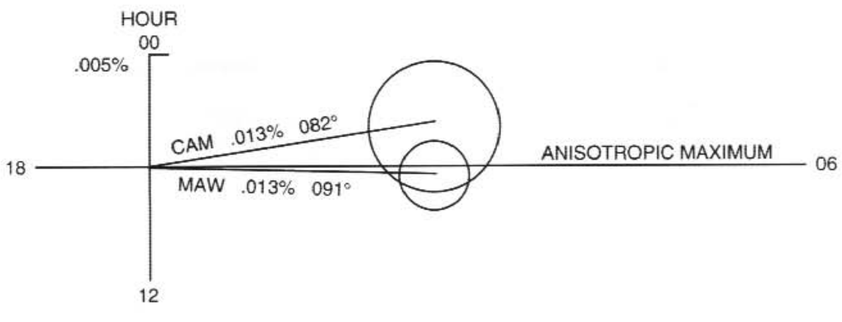

***Figure 3**. Ten year average, 1983–1993, of the corrected sidereal diurnal vectors at Mawson and Cambridge, shown on a harmonic dial, in relation to the direction of the maximum of the proposed southern hemisphere anisotropy. Statistical errors are obtained from the dispersion of vectors.*

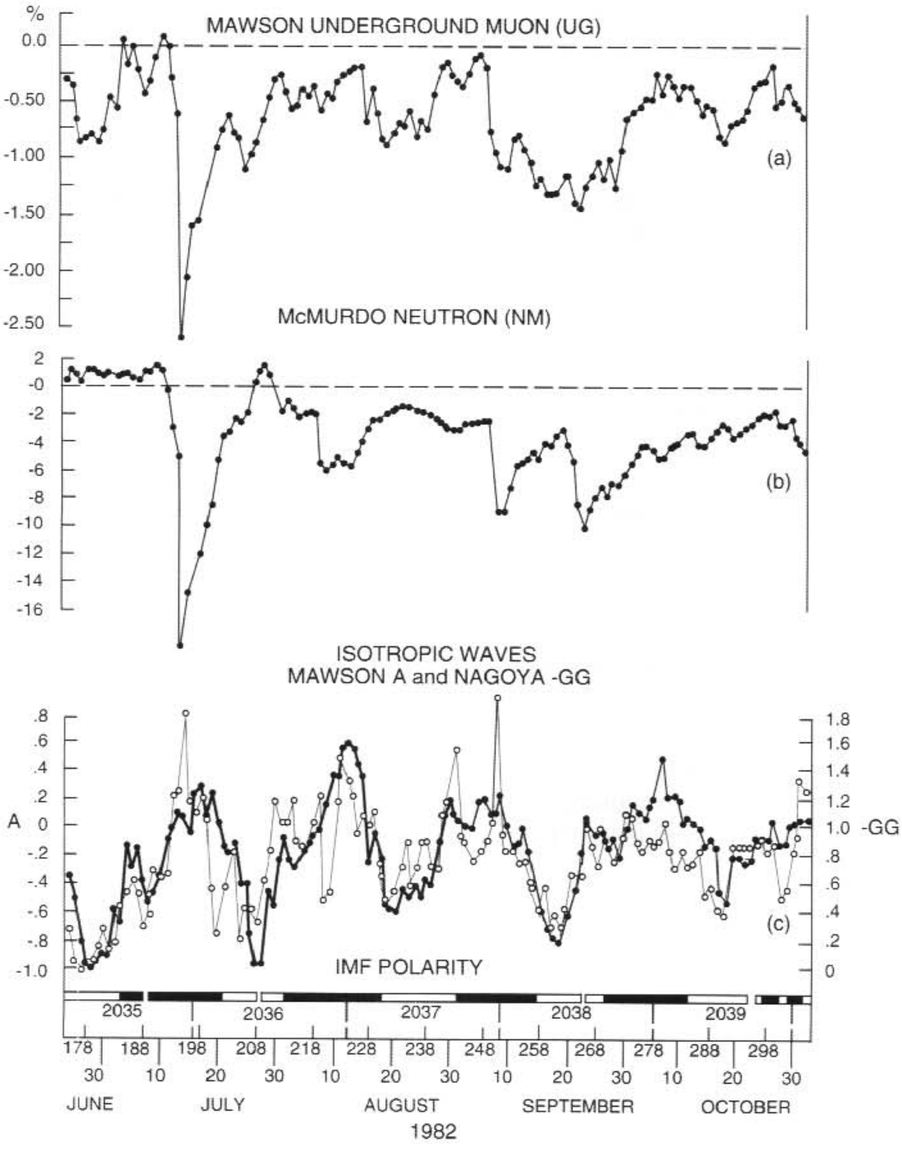

Figure 4. *Isotropic waves (c) of cosmic ray intensity detected through intensity differences:*
Mawson A (heavy line, filled circles) = underground muon (a) -0.14 surface neutron (b);
-GG Nagoya (light line, open circles) = inverse of GG (N-S, derived from surface muon telescopes);
Towards (unshaded) and Away (shaded) polarities of the mean solar magnetic field are shown above the date scale, along with the Bartels solar rotation numbers.

Geiger counters constructed at the Physics Department had been the mainstay of our detecting program for a great many years and for their type had been outstandingly effective. But they had useful operating lives of only about two years. It was the need for regular replacement of counters and constant monitoring of their performance that, if nothing else, required us to employ wintering-over cosmic ray expeditioners at the station. In another sense, though, this need was the means of introducing to us a succession of remarkably resourceful and stimulating companions in the pursuit of physics. Their names are listed in the Appendix. However, it was proportional counter detection that opened the way for complete automation of operations at the Mawson observatory, bringing about the new regime of high stability accomplished by Marc Duldig and his colleagues.

A highlight of the new era that was commencing was the discovery with the Mawson underground telescopes of an intriguing phenomenon of solar modulation at the time of a very large cosmic ray decrease in July 1982.

The variations became known as isotropic intensity waves (Figure 4) and their investigations were to be the last in the cooperative program of research that had involved Martin Pomerantz, Shakti Duggal, Marc and myself (Jacklyn et al., 1987). While it is thought that the intensity waves were connected with the motion past the Earth of the wavy neutral sheet separating the upper and lower regions of the heliomagnetosphere and co-rotating with the Sun, there have been no clear recurrences yet of the original event.

To conclude, it seems that there is a particularly interesting time ahead for cosmic ray underground studies in Tasmania and at Mawson, representing southern latitudes, not least for the vital inter-hemisphere differences that can now be observed with high counting rates of great stability at the moderate depths in both hemispheres.

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APPENDIX

The following list of cosmic ray expeditioners to Mawson, against their years of wintering over, relates to the whole period that followed the first two years of operations by Head Office researchers. From 1989 the expeditioners were employed for joint operations of cosmic ray and upper atmosphere physics equipment.

1957–D.H. Johns
1958–P.A. Trost
1959–R.E. Dunlop
1960–J.E. Humble
1961–I.L. K.McNaughton
1962–J. Phillips
1963–D.J. Cooke
1964–R.J. Francey
1965–A. Vrana
1966–D.G. Ellyard
1967–J.F. Reilly
1968–A. Vrana
1969–G.G. Cooper
1970–D.D. Parer
1971–R.A. Buckland
1972–D.D. Parer
A. Vrana

1973–A.D. Bennett
1974–W.R. Butler
1975–H.F. Nissink
1976–N.G. MacDonald
1977–K.R. Frearson
1978–R.E. Proudlock
1979–J.A. Cooper
1980–K.J. Campbell
1981–J.R. Peiniger
1982–J.A. Cooper
1983–P.J. Yates
1984–W.H. Williams
1985–J.A. Cooper
1986–P.J. Yates
1987–G. Harley
1988–F. Mino

1989–M. Dymond
1990–M. Campbell
1991–T. Oetterli
1992–D. Barrett
1993–M. Tate
1994–M. Manion
1995–S. Edwards
1996–A. Ng
1997–C. Boucher
1998–M. Harvey
1999–N. Mortimer
2000–K. Newbury

8 RECENT DEVELOPMENTS IN STUDIES OF THE HIGHEST ENERGY COSMIC RAYS

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ABSTRACT

Recent reports of observations of three cosmic rays with energies greater than 10^{20} eV have re-focused the attention of many to the central question of the origin of these extraordinary particles (Efimov et al., 1990; Bird et al., 1995a; Hayashida et al., 1994). Provided that they have low or zero charge, the paths of these energetic particles are little affected by the galactic magnetic field and the assumed extragalactic fields and so some sort of cosmic ray positional astronomy may be possible for the first time. Upper limits can be placed on the source distance based on the expected interactions of the particles with radiation fields, resulting in a belief that the sources are at distances less than 50 Mpc. Unfortunately, because of the directional uncertainties involved, no unambiguous point sources have yet been associated with the three particles in question.

8.1 INTRODUCTION

In recent years part of the focus of the Adelaide group has turned to the highest energy cosmic rays, those with energies above 10^{17} eV. After an association lasting more than a decade with the Utah Fly's Eye group, we have become formal collaborators in the next generation instrument, HiRes. We have also worked hard on proposals for the successor to HiRes, the Pierre Auger Project. The latter observatory, a \$100 M international collaboration, is currently in the funding stage and may begin construction in 1998 or 1999. Before expanding on these two projects, we provide a brief summary of the status of the field.

8.2 OBSERVATIONAL TECHNIQUES

At these high energies, the low cosmic ray flux precludes any direct measurement above the Earth's atmosphere. The integral flux of approximately 1 particle $km^{-2}\ yr^{-1}$ above 10^{19} eV requires large-area detectors that take advantage of extensive air showers (EAS) produced by interactions of the cosmic ray with the atmosphere. The EAS have large area footprints on the ground as a result of finite particle emission angles and Coulomb scattering of the shower electrons. A typical 10^{19} eV shower would contain 3×10^9 particles at sea level spread over an area of roughly two square kilometres.

Large arrays of particle detectors have been operated during the past 30 years to detect these most energetic EAS, starting with Volcano Ranch in New Mexico and followed by Haverah Park (UK), Sydney (Australia), Yakutsk (Russia) and Akeno

(Japan). The new array at Akeno, AGASA, represents the state of the art for this detection method, with detectors spread over an area of 100 km^2 to measure the various components of the EAS as they hit the ground. Apart from measuring the arrival direction of the EAS (and hence that of the primary cosmic ray), analysis from arrays estimate the energy of the primary and attempt to characterise the primary chemical composition in a coarse way, e.g. proton, CNO group, or iron group (Sokolsky et al., 1992).

A quite different technique was first proposed in Japan and the US in the late 1950's and was first successfully implemented in Utah in 1979 in the form of the Fly's Eye. Here, detectors composed of large mirrors and photomultipliers observe fluorescent light from atmospheric nitrogen induced by the passage of the EAS. It is possible to map out the entire development of the EAS and therefore achieve a calorimetric energy measurement and a somewhat more direct determination of the primary particle composition (Sokolsky et al., 1992). While the light source is weak (only five photons m^{-1} are emitted for every EAS electron), the light is emitted isotropically allowing a very large collecting area provided the showers are energetic enough. In fact the threshold energy for the Fly's Eye detector was 10^{17} eV with an acceptance above 10^{20} eV of 1000 km^2 sr. Unfortunately, this large area is effectively reduced by a factor of ten because of the requirement that the detector be run only on clear, moonless nights.

8.3 ENERGY SPECTRUM, COMPOSITION AND ANISOTROPY

There is very good agreement between experiments on the form of the energy spectrum at the highest energies. This is especially heartening, given the different detection and analysis techniques used. There is agreement on the features of the spectrum and the normalisation is in agreement to approximately 20% (Sokolsky et al., 1992). In summary, the differential spectrum above 10^{17} eV falls as a power law with index very close to -3.0, steepens at $10^{17.6}$ eV to an index of about -3.25 and then flattens to an index of about -2.7 above $10^{18.5}$ eV. This behaviour is best seen in the Fly's Eye spectrum for showers seen by two Fly's Eye installations in 'stereo' (Figure 1). The stereo data have superior energy resolution and show the features very clearly (Bird et al., 1993a).

There is a question about whether the spectrum cuts off at the highest energies. The Greisen-Zatsepin mechanism predicts a cut-off beyond about 6 x 10^{19} eV if the cosmic rays are protons from distant extragalactic sources because of interactions with photons of the 2.7 K cosmic microwave background (CMB). Unfortunately, the event statistics are too poor at this stage to be conclusive about the extent of this effect, especially given the handful of events recorded with energies in excess of 10^{20} eV (Bird et al., 1994).

Despite an expectation many years ago that a clear anisotropy might be seen in the very energetic cosmic rays, no such clear signal has been seen (Sokolsky et al., 1992). Of course, the galactic magnetic field of two or three mG can be blamed for this situation for galactic sources at moderate energies. If, however, the galaxy produces protons with energies above 10^{19} eV, it is generally believed that the current experiments should have seen a strong galactic plane excess (Lee and Clay, 1995). Thus, if protons make up the flux at the highest energies, it might be necessary to consider a large number of isotropically distributed extragalactic sources, or revise our ideas about the intergalactic magnetic field.

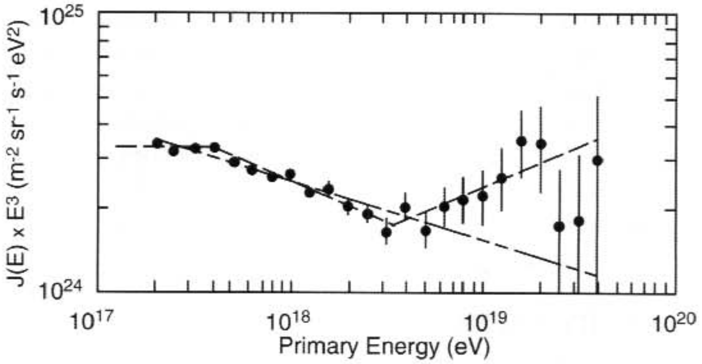

Figure 1. *The Fly's Eye experiment spectrum for showers seen by both sites. While this 'stereo' data-set is smaller than the 'mono' data-set, the energy resolution is better and structure in the spectrum is obvious.*

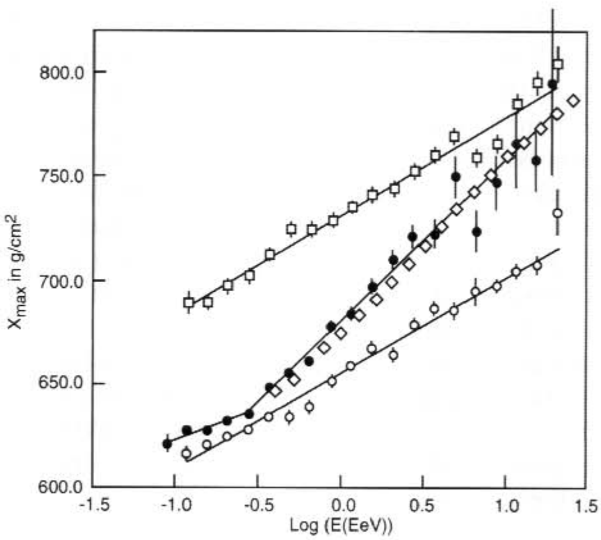

Figure 2. *Stereo Fly's Eye data on the behaviour of the depth of shower maximum with energy. The data points (solid circles) are compared with model predictions for iron (open circles, lower curve) and protons (open squares, upper curve). A composition which changes from iron-dominated to proton dominated is indicated by the open diamond symbols, and the middle curve.*

Recent Fly's Eye results on chemical composition contribute to the picture (Bird et al., 1993a). The Fly's Eye measures the depth in the atmosphere (X_{max}) at which the EAS reaches its maximum size. For a given primary energy this is a measure of the mass of the primary particle, with iron initiated showers developing about 100 g cm^{-2} shallower than proton showers. The measurements of X_{max} as a function of energy show a steeper slope than expected on the basis of a constant chemical composition at energies above 10^{17} eV (Figure 2). Comparing with shower development models, it appears that the data are consistent with a 'heavy' composition at 10^{17} eV that becomes lighter at higher energies, and perhaps purely protonic above 10^{19} eV. Of course, these predictions are model dependent (relying on theory and extrapolations of accelerator data), but a number of plausible models provide similar conclusions. The behaviour of the energy spectrum, anisotropy and composition is consistent with a model in which 'heavy' cosmic rays are produced in our galaxy with a steeply falling spectrum, which is overtaken with a flatter spectrum of protons from extragalactic sources at the highest energies (Bird et al., 1993a).

8.4 THREE VERY ENERGETIC EVENTS

As of the beginning of 1996, a total of eight events have been assigned energies above 10^{20} eV during thirty years of observations. These include three events reported in the last few years with energies well in excess of this threshold. One of them, seen with the Yakutsk array could have an energy as high as 2 x 10^{20} eV, but that EAS was highly inclined and muon-rich, and thus was unlike other events in the Yakutsk catalog (Efimov et al., 1990). As such the energy is uncertain.

The 'record' is held by the Fly's Eye with an event observed on October 15, 1991 with an energy of (3.2 ±0.9) x 10^{20} eV, the error derived from estimates of statistical and systematic errors (Bird et al., 1995a) (Figure 3). While the event was not seen in 'stereo', the view provided by a single Fly's Eye allowed a reasonable energy estimate and an error box of ±0.5° in RA and ±6° in declination. The particle arrived from the galactic anticentre direction, just north of the plane (l=163°, b=9.6°). A thorough investigation of reconstruction uncertainties was made. For example it was shown that if the reconstruction was forced to give a more 'normal' energy of 10^{20} eV, the shower would need to be initiated at an extreme depth in the atmosphere and the shower profile would then be unphysically narrow. The best estimate of the primary cosmic ray mass is around 20 amu, but because of intrinsic EAS development fluctuations and detector resolution, the primary could easily have been a proton, an iron nucleus or a gamma ray. (It would be extremely difficult to identify the composition of a single particle even with a perfect detector, using this necessarily indirect approach.)

The third extreme event has been reported by the AGASA experiment (Hayashida et al., 1994). It was detected on December 3, 1993 and has an energy estimate of (1.7–2.6) x 10^{20} eV and an arrival direction of l=131°, b=-41°. The event appeared normal in every way except for the extreme numbers of particles detected by the array of scintillators, with densities ranging from 0.3 m^{-2} at the edge of the shower to 24 000 m^{-2} closer to the shower core. No estimate of the mass of the primary particle was made.

A galactic plot showing the arrival directions of the Yakutsk and Fly's Eye events is shown in Figure 2 of a recent report by Sigl et al. (1994). Apart from the apparent coincidence in arrival directions of the two events (1% chance probability given the size of the error boxes and the exposure of the experiments) (Sommers 1993) there is nothing striking about the directions. An investigation of possible sources requires a discussion of galactic and extragalactic magnetic fields and interactions of the cosmic rays in intergalactic space. Two excellent summaries have recently been prepared Sigl et al. (1994); Elbert and Somers (1995).

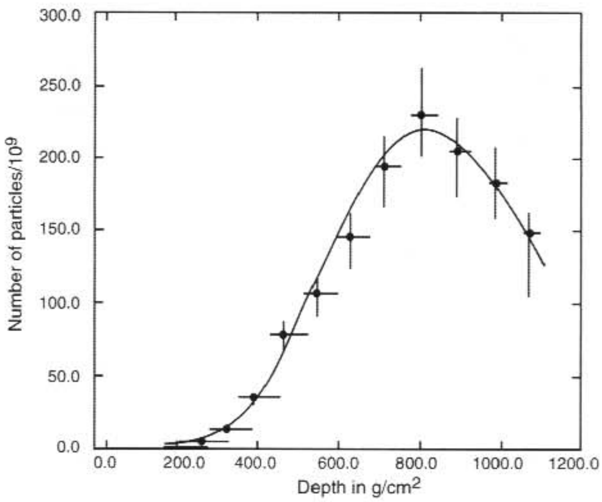

Figure 3. *The most energetic extensive air shower ever recorded. This shower development curve was observed by the Fly's Eye detector. The assigned energy is (3.2 ±0.9) x 10^{20} eV and the shower size peaks at a very impressive 2 x 10^{11} particles.*

Constraints on objects capable of accelerating particles to these energies seem to rule out galactic objects, although this is not at all certain (Hillas, 1984). If the particles are extragalactic, then it is likely that the sources are quite local, with distances less than 50 Mpc. This results from interaction mechanisms that limit the propagation distance for all the likely candidate particle types. These include interactions of nucleons with the 2.7 K CMB (pion photoproduction, mean free path about five Mpc, with the leading particle losing about 20% of its energy per interaction), photodisintegration of heavy nuclei by photons of the CMB (severe loss rate of about four nucleons/Mpc at 3 x 10^{20} eV) and pair production interactions for primary gamma-rays (with CMB and radio photons, together giving a mean free path of 7 Mpc) (Elbert and Somers, 1995). A primary neutrino would avoid all of these interactions, but would have a 10^{-5} probability of interacting in the Earth's atmosphere. (The EAS profile measured by the Fly's Eye looks very normal and does not require an exotic initiator.) The 50 Mpc source distance limit can be stretched if, for example, a source produces an extremely energetic proton (>10^{23} eV) at a larger distance (say 125 Mpc) (Sigl et al., 1994). However it is clear that for unexotic particles and processes the distance limit is quite severe.

Very little is known about the strength and orientation of extragalactic magnetic fields but it is likely that a 3 x 10^{20} eV proton would be deviated by less than 10° from its source direction (Sigl et al., 1994; Elbert and Somers, 1995). (The 10° maximum angle results from a 10^{-9} G field perpendicular to the particle's path and coherent over a scale of 100 Mpc.) Based on this assumption and assuming that the particle was indeed a proton, Elbert and Sommers (1995) searched for a source of the Fly's Eye cosmic ray. No obvious source (e.g. a nearby radio galaxy with radio lobe hotspots) was detected within the 10° search region. Sources like M87 and Cen A are 87° and 136° respectively away from the nominal source direction and may be plausible sources of heavier nuclei (especially the closer Cen A) which could be deviated in the magnetic fields, particularly if stronger than expected extragalactic fields exist.

More recently, Rachen (1995) has pointed out that the Fly's Eye event direction is close to the direction of a FR-II radio galaxy 3C134. This was not included in the survey of Elbert and Sommers because, being obscured by our galaxy, the redshift of 3C134 is unknown. However from the size of the radio structure it is estimated that the source distance could be between 30 and 300 Mpc. It is therefore a candidate source.

One viable but exotic possibility for the source of the highest energy particles is the decay of topological defects (e.g. cosmic strings) (Sigl et al., 1994). Such a decay would result in the production of GUT mass particles ($mc^2 \sim 10^{24}$ eV) which would decay to super-high energy hadrons, gamma-rays and neutrinos.

It is presently impossible to decide between the competing possibilities for the origins of these three events, especially as no outstanding candidate sources are visible in the nominal event directions. However we are fortunate that two large detectors are either operational (AGASA) or under construction (HiRes). In the next several years we can hope for a further handful of extreme events. On the horizon is the Auger Project, which may become operational at the turn of the next century and which promises up to 50 events a year above 10^{20} eV.

8.5 THE HIGH RESOLUTION FLY'S EYE (HIRES) PROJECT

Fly's Eye detectors observe the passage of cosmic ray extensive air showers through the atmosphere by means of the fluorescence light given off after the excitation of nitrogen molecules by relativistic electrons in the shower (Baltrusaitis, 1985). The original Fly's Eye was completed in 1981 with sixty seven 1.5 m diameter mirrors and a 2π steradian solid angle (i.e. full sky) coverage. A second Fly's Eye was added in 1986 with thirty-six mirrors at a distance of 3.4 km from the original Fly's Eye in order to view certain showers stereoscopically giving better shower reconstruction. The HiRes detectors build on the experience gained in the original experiment. The stereo concept has been retained and improved with the fully funded Stage 1 of

HiRes involving the construction of two sites 13 km apart at the Dugway Proving Grounds in the western desert of Utah. The sites will contain over seventy 2 m diameter mirrors, arranged so as to optimise the acceptance for the highest energy (and most distant) events. The focal plane of each mirror contains 256 hexagonal photomultipliers, each with a view of a 1° diameter section of the sky. The estimated reconstructable aperture for this arrangement at an energy of 3 x 10^{19} eV is over 5000 km^2 sr. The detectors operate on clear, moonless nights and typically have a duty cycle of 10–12%.

The electronics for each mirror is modularised and each mirror is controlled by its own microprocessor. Flash ADC electronics is being implemented, allowing digitisation of each of the photomultiplier signals and consequently a more flexible and powerful analysis than was possible with the original Fly's Eye detectors or the HiRes prototypes. However measured, the light signal and light arrival time enable the track of a shower to be reconstructed in space, since the shower front effectively travels at the speed of light. These data thus yield the shower arrival direction, spatial position and the light emission as a function of atmospheric penetration. The latter gives rather directly (a) the relativistic charged particle component as a function of penetration which gives in turn (almost calorimetrically) the cosmic ray primary energy and (b) information on the mass composition of the primary particle.

Apart from more modern and sophisticated electronics, the large gains in HiRes aperture and quality over the original Fly's Eye are due to larger mirrors and smaller photomultiplier aperture. In HiRes, the tube pixel size is a 1° diameter hexagon, compared with a 5.5° diameter hexagon with the Fly's Eye. This results in gains in signal to noise (the noise here being fluctuations in the mean night sky background) and pixel granularity in geometrical reconstruction and shower longitudinal profile determination. For showers seen by both Stage 1 HiRes stations at 10^{19} eV, the expected resolution in depth of shower maximum X_{max} is 15 g cm^{-2} and the statistical energy resolution is expected to be of the order of 7%.

The full complement of 14 prototype HiRes mirror units has been in operation since March 1993 at the Five Mile Hill site. Great progress has been made in the fine tuning of the optics, electronics and system issues. Predictions of earlier modelling in the areas of aperture and reconstruction ability are being tested with the aid of high power pulsed YAG lasers which can be used to simulate air showers at distances of up to 20 km. Initial results in both areas are better than expected (Bird et al., 1993b–f). Since late 1994, four instrumented mirrors have operated at the second HiRes site at Camel's Back Mountain.

Geometrical reconstruction of air showers uses data on tube signal amplitudes and trigger times. The first step is to define the shower detector plane, a plane defined by the shower axis (a line in space) and the detector (a point). This is reconstructed easily using the locus of firing phototubes projected on the celestial sphere, although sophisticated routines are used to locate this plane to much better accuracy than the tube width (1°). The beauty of the stereo technique is that the simple intersection of the shower detector planes determined at each site yields the shower axis.

At Adelaide we have shown that the reconstruction can be improved upon by also using the tube firing times in a global fit. The success of the technique relies on synchronisation of the central clocks at the two sites to the order of 100 ns. We have employed the Global Positioning System (GPS), an array of US satellites designed for navigation and timing. We found a source of inexpensive GPS receivers that we interfaced with fast oscillators to produce clocks that have an absolute accuracy of 1 ms and a relative accuracy of around 10 ns (Bird et al., 1995b). This impressive relative timing ability is possible since the clocks have a view of the same set of GPS satellites at the same time.

Our group at Adelaide is also centrally involved in atmospheric studies at the Dugway site, specifically investigating the effect of varying aerosol concentrations on the transmission of light from distant air showers. A portable and steerable high power laser has been developed at Adelaide. The laser shots are viewed by the HiRes detectors, allowing us to study details of the laser light scattered from the beam, including the angular distribution and variability.

The 14 prototype mirrors have been positioned to overlook the densely instrumented ground array, CASA-MIA. This array of 1089 surface scintillator detectors spread over an area of 250 000 m^2 is supplemented by 2500 m^2 of buried muon detectors. Events seen by HiRes in conjunction with these detectors (threshold energy a rather low 5×10^{16} eV) are currently being analysed, with an expectation of providing unique data on the mass composition of cosmic rays at this energy. We look forward to the completion of the detector and the beginning of work at energies above 10^{19} eV, where we expect to collect approximately 300 events per year.

8.6 THE PIERRE AUGER PROJECT

Our group is a founding member of the Auger collaboration. The project is currently in a R&D phase after a six-month design study in 1995 produced a 250-page design document, (Auger Collaboration, 1995). Construction of the $100 M observatories (one in the north and one in the south) is expected to commence in 1998 and will continue for four years. When fully operational, the Auger Project will collect more than 5000 cosmic rays per year with energies above 10^{19} eV, with good measurements of their energy and arrival direction. In addition, estimates of the mass composition of the primary particles will be available.

The Auger Project will take over from HiRes and the Japanese AGASA array in the first few years of the next decade. An international collaboration has formed to design and construct two detectors, one in each hemisphere. The project is led by J.W. Cronin (University of Chicago, Nobel Prize 1980) and the design document calls for each site to consist of a ground array of 3000 km^2 area, with three large fluorescence detectors (of the HiRes-type) at positions within each array. A ground array will consist of over 1600 detectors, each with an area of 10 m^2, arranged on a hexagonal grid with a typical spacing of 1.5 km.

Such a 'Hybrid' detector (array plus fluorescence detectors) has two key advantages. During the time when both types of detector are operating (up to 15%), there will be an opportunity to check each technique's method for assigning arrival directions, energy and mass composition. This will allow the ground array to operate with confidence for the remainder of the time. In addition, those showers viewed during the fluorescence detector operation will be extremely well measured. Design studies performed in Adelaide have shown that the Hybrid detector combination will provide an arrival direction resolution of around 0.25°, and energy resolution of better than 8% at 10^{19} eV. A great opportunity will also exist for mass composition studies based on a variety of measurements.

At Adelaide we have made a major contribution to the design of the observatories. Being collaborators on another major experiment in the field, HiRes, we have been influential in convincing the Auger collaboration to include Fly's Eye-type detectors in the observatories and have been heavily involved in the detailed design of those detector elements. We have also had leading roles in determining the reconstruction quality of events observed simultaneously by the ground array and fluorescent light detectors, in understanding the optical transmission of the atmosphere (important for the fluorescence detectors) and in understanding the sensitivity of the detectors to the mass of the primary cosmic rays. Geoff Kelly of Telstra took a leading role in the design of a novel communications system to transfer data and house-keeping information from the isolated ground array detectors.

Our contributions also included putting forward Woomera as a candidate southern hemisphere site. After reaching the interview stage of the Major National Research Facilities scheme, we did not attract funding support and following an enthusiastic response from Argentina the collaboration chose that country as the site. The northern site was recently chosen to be in Millard County, Utah, about 150 km south of the HiRes site. Despite not getting a site in Australia, we are still very committed to the project.

With HiRes coming on line within the next two years and the Auger Project perhaps four more years down the track, we will soon have a wealth of data on the highest energy particles in nature. Instead of just a handful of events above 10^{20} eV, Auger will provide at least 50 such events per year, with HiRes producing hundreds of high quality events per year in the decade of energy below 10^{20} eV. We can look forward to doing positional astronomy with many of these particles and uncovering some of the mystery surrounding how such particles are accelerated to these enormous energies.

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9. COSMIC RAYS IN THE $10^{12} - 10^{15}$ eV ENERGY RANGE

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ABSTRACT

Some of the reasons for interest in this energy range are outlined, including the possibility of obtaining information about the motion of the solar system with respect to the nearby interstellar medium (ISM) from studies of the sidereal anisotropy. Important information relating to the origin and propagation of cosmic rays has been obtained through studies at the low end of the range of the chemical composition of the charged primaries, as well as through studies of the neutral primaries (assumed to be γ-rays) which give evidence for the existence of localised regions in which acceleration is taking place. Methods of studying cosmic rays in the energy range are discussed, including direct measurements at high altitudes and in space and indirect observations involving extensive air showers and underground muons. Some details are given of the particles and photons produced in air showers and of the simulations used to interpret the observations. In general, the references cited do not extend beyond 1996.

9.1 INTRODUCTION

There are several important reasons why the study of cosmic rays in the 10^{12}–10^{15} eV energy range is of interest. Some of these are referred to below. In this range, we have a reasonable opportunity of determining the details of the sidereal anisotropy of the charged particles in cosmic rays because the flux of particles, though low, is sufficiently high for adequate statistical accuracy to be attainable with moderate detecting areas in times that are not inordinately long. The total flux of charged particles of energy exceeding 10^{12} eV/nucleon is somewhere in the range 250–300 $m^{-2}\ sr^{-1}\ hr^{-1}$. The integral spectrum is approximately $N(\geq E) \propto E^{-1.7}$, which means that in each successively higher decade of energy the flux falls by a factor of ~50, giving a flux of ~5 $m^{-2}\ sr^{-1}\ hr^{-1}$ in the range 10^{13}–10^{14} eV and ~0.1$m^{-2}\ sr^{-1}\ hr^{-1}$ in the range of 10^{14}–10^{15} eV.

An important feature of this energy range is that the gyroradius of a 10^{12} eV proton in a 2–3 μG (0.2–0.3 nT) field, believed typical of the local galactic spiral arm (e.g. Valée, 1991; Beck et al., 1996) and of the outer parts of the heliosphere (e.g. Burlaga et al., 1991) is 75–100 AU (4–5 x 10^{-4} pc). Even at the orbit of Earth, where the interplanetary field is an order of magnitude greater, the gyroradius is still ~10 AU. Thus deflections within the solar system are expected to be insufficient to destroy an anisotropy of arrival directions of 10^{12} eV charged particles from the Galaxy and certainly at the 10^{15} eV end of our energy range the heliospheric deflections are insignificant.

Such an anisotropy of the charged particles arriving from the Galaxy is to be expected if the solar system is moving relative to the nearby interstellar medium (ISM). For, it is reasonable to assume, as have Fatemi et al. (1995), that, irrespective of where they originate, charged particles will be sufficiently scattered by magnetic irregularities in the ISM that they will become isotropic in regions whose dimensions are of the order 10 gyroradii. Thus a bulk motion of the nearby ISM (out to a parsec or so) relative to the solar system should produce an observable sidereal anisotropy through the Compton-Getting effect in the energy range we are considering. If V is the velocity of the observer with respect to the frame of reference in which the cosmic ray gas is isotropic a Compton-Getting effect of fractional amplitude $\delta I/I = (2+\alpha\gamma)V/c$ will result (e.g. Forman, 1970), where γ is the index of the differential energy spectrum (~2.7 in the present case) and where $\alpha = (T+2\ Mc^2)/(T+Mc^2)$, T being the kinetic energy of the particle. Thus for the particles with which we are dealing, $\alpha \sim 1$, and the small observed sidereal anisotropy of ~0.06% (Fenton et al., 1995), if due to the Compton-Getting effect, would correspond to a bulk motion of the nearby ISM of velocity $V \sim 38$ km s^{-1} with respect to the solar system.

The cosmic ray anisotropy represents one of the very few means we have of investigating the bulk motion of the ISM in our vicinity but, because the anisotropy is so small, large numbers of particles (preferably $\geq 10^8$) must be observed from a range of directions in order to obtain details of the anisotropy with acceptable statistical significance. So far, the only such measurements which have been made have depended upon underground muon detectors or surface-based air shower detectors which rely on the rotation of the Earth to provide the range of directions. I will be emphasising the need later in this paper for establishing detecting areas appreciably larger than any we now have but the achievement of which is not beyond the bounds of human capability.

It is near the 10^{12} eV end of this energy range that evidence has been obtained for the existence of localised sources or localised regions in which acceleration of particles to high energies is taking place and, thus, for making progress towards solving one of the great puzzles of our field of study, namely, that of how and where do cosmic rays originate. This evidence has come from the observation of effects due to neutral primaries, assumed to be γ-rays, where, at $\sim 10^{12}$ eV, the fluxes are sufficiently high to be observable against the charged particle background.

Particularly at the low end of this energy range, it is possible to obtain information on the chemical composition of the heavy primaries, information also expected to be of importance in answering questions concerned with the problem of the origin of cosmic rays, especially when used in comparison with the composition data available at lower energies.

There is the possibility that, in the future, further contributions may be made in basic particle physics. For instance, there are questions of whether prompt muon production occurs and of whether quark-gluon plasmas may be produced in high energy interactions. However, the current Fermilab centre-of-mass energy of 1.8×10^{12} eV for head-on collisions of protons and antiprotons corresponds to a laboratory energy of ~10^{15} eV, which suggests that any undiscovered particle physics is likely to be occurring at still higher energies where cosmic ray particles are even more rare.

Methods of observing cosmic rays in the 10^{12}–10^{15} eV energy range must take into account the fact that the interaction mean free path for protons in the terrestrial atmosphere is ~80 g cm^{-2} at 10^{12} eV decreasing to ~60 g cm^{-2} at 10^{15} eV (e.g. Forti et al., 1990). For the heavy primaries the interaction mean free path varies as $A^{-2/3}$, where A is the mass number, so that for ^{56}Fe it is ~5 g cm^{-2} at 10^{12} eV/nucleon and ~4 g cm^{-2} at 10^{15} eV/nucleon. The interaction mean free path for γ-rays is ~38 g cm^{-2} in the 10^{12}–10^{15} eV energy range.

A brief reference to primary electrons will be made at the end of Section 9.3 on the composition of the primary cosmic rays.

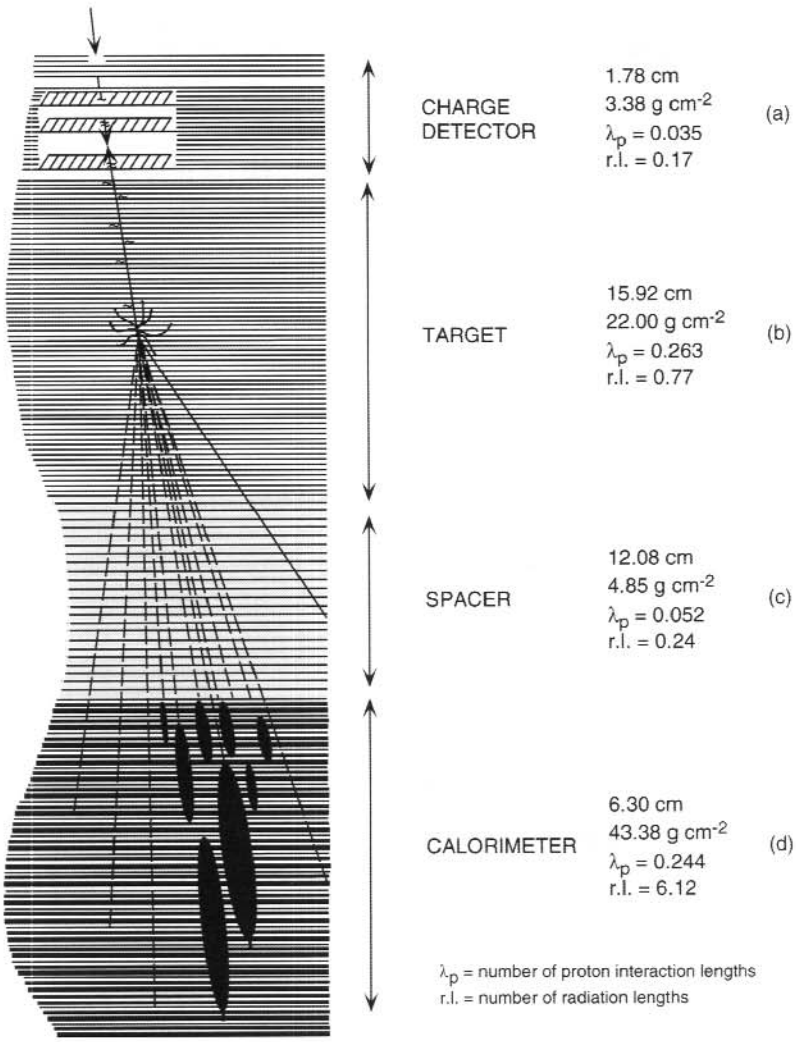
9.2 DIRECT METHODS OF OBSERVATION

The first direct observations aimed at obtaining spectral information above 10^{12} eV were made by Grigorov et al. (1971) using calorimeter instruments on the PROTON satellites and were reported at the Hobart International Cosmic Ray Conference. This work has been continued by the Moscow State University using an improved calorimeter instrument known as SOKOL aboard COSMOS satellites (Vernov et al., 1981) and has provided composition as well as spectral information (e.g. Ivanenko et al., 1993). There have been two additional series of experiments in recent times also aimed at obtaining composition and spectral data in this energy range, particularly of the heavy primaries, one being the balloon observations of the JACEE collaboration (Japanese American Cooperative Emulsion Experiment) and the other being the University of Chicago Space Shuttle experiment. These latter two will now be discussed in turn.

9.2.1 JACEE

Because of the short interaction mean free path and the low flux of heavy primaries, it is necessary to make observations above an atmospheric depth of ~5 g cm^{-2} for as long a time as possible. From 1979 to the end of 1994 there have been 14 balloon flights, with more planned, using stacks of emulsion and plastic detectors, as illustrated schematically in Figure 1 (Burnett et al., 1986). Several of these were 30–40 hour flights from Palestine, Texas, but there have been at least two from Alice Springs to South America lasting 5–7 days.

Since there has been some emphasis at this Conference on cosmic ray observations in Antarctica, it is interesting to note that the JACEE Collaboration has most recently launched several summer flights from the McMurdo base, taking advantage of the slow circumpolar circulation in late December and January. Although the low geomagnetic cut-off in high latitudes results in a higher background in the emulsions, especially near solar minimum, there are many distinct advantages of flying in Antarctica, a fact which we too have realised but of which we have only rarely been able to take advantage. The continuous sunlight in mid summer greatly reduces the altitude changes which occur due to the sunset-sunrise effects experienced in mid



Chambers assembled in 40 cm x 50 cm precision machined light-tight boxes. Either a flipper mechanism keeps them inverted except at float altitude or a plate shifter mechanism moves the upper emulsion layers out of alignment except at float altitude.

a. Thick (200–400 μm) and thin (50–100 μm) nuclear emulsions, CR-39 and Lexan solid state track detectors. $\Delta Z = (0.1\text{–}2)e$ for $Z = 1\text{–}26$.

b. ~50 thin emulsion plates interleaved with low-Z acrylic material, for maximum probability of nuclear interaction and minimum probability of photon interaction (pair production).

c. Paper honeycomb to permit divergence of closely collimated γ-rays created in target. Thin emulsion plates ~5 μm apart to assist in tracing events.

d. 1 μm and 2.5 μm lead sheets interleaved with X-ray films and thin emulsion plates. The X-ray films (25 μm emulsion on both sides of 175 μm polyester base) are for naked-eye scanning and for energy estimation by photometry. The emulsion plates (50–400 μm nuclear emulsion on both sides of 500 or 800 μm acrylic plates) are for observation of individual heavy charged fragments, hadrons and cascade electrons and for determination of energies of electromagnetic cascades.

Figure 1. *Schematic diagram of the Japanese American Cooperative Emulsion Experiment (JACEE) (based on Burnett et al., 1986).*

latitudes and, hence, long duration flights with minimum ballast are possible. In the most recent JACEE flights, virtually no ballast was required except to test the ballast system. Due to the Antarctic Treaty, balloons can overfly any part of Antarctica without fear of being shot down, a feature which has historically distinguished the Antarctic from the Arctic. The high altitude winds follow the lines of latitude, so that a balloon circles the continent and, in due course, comes back nearly over the launch site, typically after 200–300 hours, appreciably longer than the trans-Pacific times. Normally the payload is cut down within 100 km of McMurdo, within helicopter recovery range but sometimes Twin-Otter aircraft are used when the payload has come down further afield. One payload is at the bottom of the Ross Sea due to a mechanical failure of the termination mechanism.

I will discuss the results obtained in these experiments after I have referred to the other direct observations I wish to mention in this energy range, namely those made by the University of Chicago Cosmic Ray Nuclei detector (CRN).

9.2.2 CRN Experiment

Flown in the NASA Space Shuttle 'Challenger' in 1985 and commonly known as the Chicago 'Egg' this instrument had an area of 4 m^2. A detailed description of the equipment, illustrated in Figure 2, is given by L'Heureux et al. (1990).

A major problem in designing a large area detector for use in space is that of achieving a low enough total mass. As it was, the Egg weighed 2700 kg, but a calorimeter type instrument of comparable performance would probably have had ten times the mass. The low mass was achieved by using transition radiation detectors for the energy determination rather than the large mass of absorber needed in a calorimeter. Since transition radiation is not as well known as, for instance, Cerenkov radiation, I will now refer to some of its basic properties.

Transition radiation is electromagnetic radiation emitted by a fast charged particle when it crosses the interface between two media with different dielectric properties, such as may be achieved with a stack of mylar films with air spaces between them, and is due to the abrupt changes of electric polarisation as the fast particle crosses the interfaces. We can also think of the radiation as arising when the charged particle and its oppositely charged image in the adjoining medium coalesce at the interface, producing annihilation photons.

Ginzburg and Frank (1946, for reference to this work, see Ginzburg and Tsytovich, 1979) were the first to propose the existence of such radiation and it was first observed in the optical range by Goldsmith and Jelley (1959) using 5 MeV protons impinging on aluminium, silver or gold targets. Inman and Muray (1966) were the first to observe the effect using relativistic particles, electrons up to 662 keV, again in the optical range. Early reports on this topic were presented by Yuan (1971a and b) at the Hobart ICRC and a general discussion of the theory is given by Jackson (1975). Other important contributions have been made by Cherry (1978), Ginzburg and Tsytovich (1979) and Swordy et al. (1990).

One of the essential features of transition radiation for present purposes is that the total energy radiated is approximately proportional to the Lorentz factor ($\gamma = E/Mc^2$)

of the particle. Hence a detector designed to respond to transition radiation will produce a pulse whose amplitude increases with the energy of the particle, unlike detectors which depend on the dE/dx energy loss (such as proportional counters or scintillators) or on the Cerenkov light output, for which the pulses due to relativistic particles are virtually independent of energy. Another important feature is that, for high values of γ (e.g. ~1000), most of the photons produced are in the 2–20 keV energy range, readily detectable in thin-window proportional counters containing xenon.

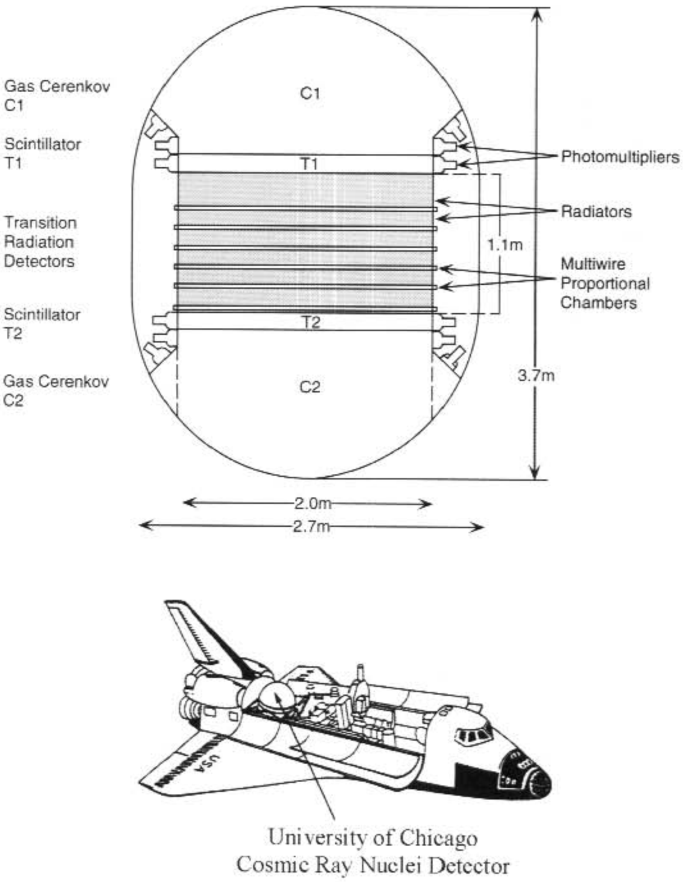


Figure 2. *Schematic of the CRN Experiment and its placement in the NASA Space Shuttle (from L'Heureux et al., 1990).*

The radiators used for the CRN detector were made from the polyolefin fibre batting of the type used, for instance, in cold weather jackets. This material provided the very large number of interfaces needed for a sufficiently high yield of transition photons, given the very low number produced at each interface ($\propto Z^2/137$). The transition radiation was detected by the multiwire proportional chambers (MWPC), shown in Figure 2, in which the gas filling consisted of a mixture of 25% Xe, 60% He and 15% CH_4 at a pressure of one atmosphere. This combination resulted in a high efficiency of detection of the transition X-ray photons, with only a small contribution to the pulse size from the ionisation energy loss (dE/dx) of the charged particle.

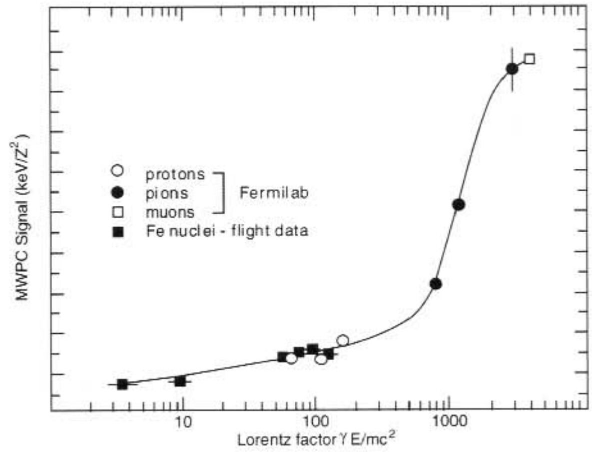


Figure 3. *The CRN Transition Radiation Detector (MWPC) Signal vs Lorentz Factor for Fermilab Particles and Fe Flight Data (from L'Heureux et al., 1990).*

Figure 3 shows the strong dependence of the MWPC signal on the Lorentz factor for the CRN detector, particularly for large values of γ, and Figure 4 shows the MWPC signal vs the Cerenkov signal for oxygen nuclei observed during the flight, indicating that the energy of the transition radiation increases with γ whereas the Cerenkov signal saturates, as expected. These Figures are from L'Heureux et al. (1990).

The Egg has been flown once, in the July–August 1985 Challenger flight, the last before its ill-fated flight in January 1986. It was this disaster, more than any other single factor, which was responsible for the demise of our MIRRABOOKA X-ray astronomy project using a SPARTAN satellite. The 1985 flight was one which passed over Hobart and, as a result of activating its Onboard Manouvering System (OMS) engines, the Shuttle released exhaust gases (H_2O, H_2 and CO_2) into the upper atmosphere, the objective being to help several groups, including the local radioastronomers and auroral physicists, to investigate whether the removal of free electrons from the atmosphere by attachment to the H_2O molecules would lead to an increase in the transparency of the ionosphere to low frequency galactic radio waves and also whether the recombination radiation expected at 630 nm would lead to an enhanced airglow. Because of the local interest, I will give very brief details of these experiments.

The OMS burn over Tasmania began at 0300 hours local time on 5 August 1985 and lasted for 16 seconds, the amount of fuel burnt being 245 kg. Unfortunately, solid cloud cover over all of Tasmania prevented observation of the airglow. However, the critical frequency of the ionosphere, f_0F_2, as measured by the Hobart ionosonde, dropped from 1.99 MHz to 1.8 MHz within three minutes of the burn and then slowly decreased to less than 1.3 MHz during the next 100 minutes. Galactic radioemission was observed at 1.7 MHz during this time by the low frequency radioastronomy array at Hobart with an angular resolution of 25°, the first such observation ever made. The nearest similar measurements had been made by a lunar orbiting spacecraft at 1.3 MHz but with an angular resolution of 130°. The details of this Hobart work are given by Ellis et al. (1987) and of Northern Hemisphere experiments during the same Shuttle mission over the New England region of the US by Mendillo et al. (1987).

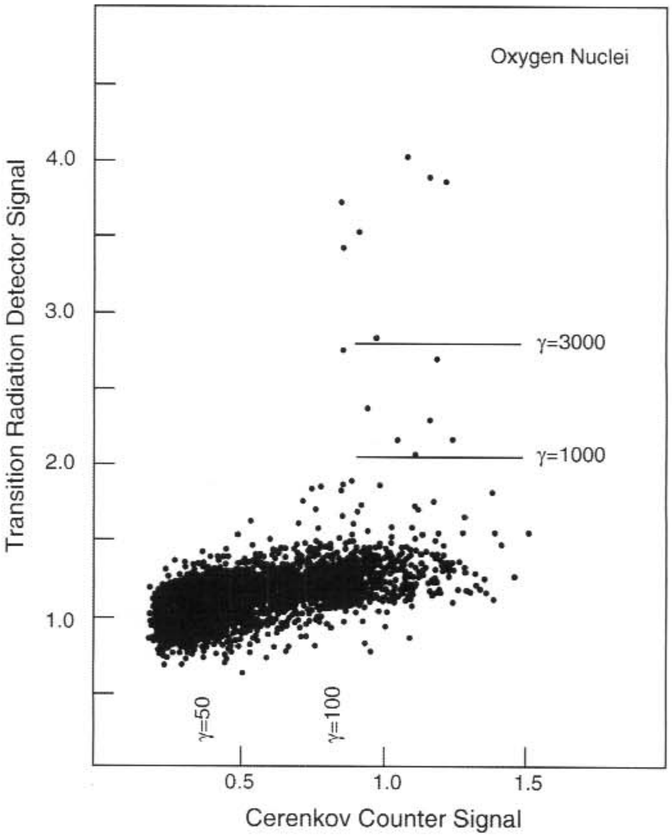


Figure 4. *The CRN transition radiation detector signal vs Cerenkov counter signal for oxygen nuclei during the shuttle flight (from L'Heureux et al., 1990).*

The higher than usual latitude involved because of these experiments was not ideal for the CRN observations because the high voltages to all detectors were automatically turned off when the Shuttle encountered the South Atlantic anomaly. The duration of the flight was only eight days and, because of the multidisciplinary nature of the mission, the detectors could not always be pointed at space. Thus, the total time for cosmic ray data taking was only 78 hours during which about 40 million events above 5×10^{10} eV/nucleon were observed. Sufficient of these were in the 10^{12} eV/nucleon range to yield some composition information near that energy.

The flight established the feasibility of the techniques, especially of the transition radiation detectors, and what is now required is a flight of a year, or preferably several years, which could be achieved with the Space Station, though I have heard no mention of this possibility. There does, however, appear to be a proposal for a calorimeter project known as ACCESS (the Advanced Calorimeter for Composition of Elements on the Space Station). While this would be a very welcome development, such a project would only be capable of yielding data on the anisotropy of cosmic rays as a function of composition if the calorimeter detectors provided the direction and time of arrival of each particle in the manner in which the CRN detectors do.

It is to be hoped that at some time in the future it will be possible to determine the isotopic composition of the primaries at energies higher than the current achievable limit of $\sim 10^8$ eV/nucleon. Such information should be of value in considering problems concerned with the origin and propagation of cosmic rays, especially in the ultrarelativistic range where radioactive nuclides would be expected to be of importance because of the time dilatation effect, e.g. on ^{26}A1. In addition to measuring the charge, determination of the isotopic composition would require the simultaneous measurement of γ and E, each to considerable accuracy, using a combination of transition radiation detectors and a calorimeter. For instance, to resolve the isotopes at around A=20 would require both γ and E to be measured with an error of ~1%.

9.3 DIRECT MEASUREMENTS OF COMPOSITION AND SPECTRA

An excellent review of the results of observations made by the JACEE, CRN and SOKOL groups in the 10^{12}–10^{15} eV/nucleon range up to 1993 has been given by Swordy (1993) as a rapporteur paper at the Calgary ICRC. The situation does not appear to have been significantly modified by subsequent data. Some of the main features are illustrated in Figures 5 and 6, taken from Swordy's paper, showing the proton and helium data (Figure 5) and the carbon-nitrogen-oxygen, neon-sulphur and iron data (Figure 6). In both cases the differential fluxes are multiplied by $E^{2.75}$ to permit small differences between the spectra to be seen more easily. These figures indicate that agreement in the absolute fluxes, within statistical errors, has been obtained in the different experiments. The following are among the features which appear to be of importance and which require explanations by a satisfactory theory of the origin of cosmic rays:

a. The helium/proton ratio appears to increase with increasing energy;

b. There is a suggestion of a cut-off in the proton spectrum around 10^{14} eV, approximately where the effectiveness of supernova shock acceleration is thought likely to decline (Axford, 1981);

c. The spectra of the heavy elements are flatter at energies above ~10^{12} eV/nucleon, the differential spectral index being ~2.5, i.e., the spectra are significantly less steep than at lower energies. Thus the cosmic rays are becoming richer in the heavy elements as the energy rises.

Swordy has produced Table 1 giving an estimate of the composition of the primary cosmic ray nuclei at 10^{14} eV/particle (Swordy, 1993), from which it will be seen that helium contributes 36% of the particles at this total energy and that the CNO group makes almost the same contribution as the protons. This is a matter of great importance for the air showers in the energy range we are considering.

Table 1. *An estimate of the composition of arriving nuclei at 10^{14} eV/particle*

	p	He	CNO	Ne-S	Fe group
A	1	4	14	24	56
E (GeV/n)	10^5	2.5×10^4	7.14×10^3	4.17×10^3	1.79×10^3
Flux estimate (GeV/n)	1.3×10^4	2×10^3	1.2×10^2	30	7
Flux calc (GeV/particle)	1.3×10^4	2.26×10^4	1.22×10^4	7.81×10^3	8.02×10^3
Relative Abundance (%)	20	36	19	12	13

Regarding primary electrons above 10^{12} eV, most of the information we have has come from a series of balloon flights of emulsion chambers conducted since 1976 by the Japan-US Galactic Electron Collaboration (Nishimura et al., 1990). A tiny flux has been observed up to ~3×10^{12} eV with a steeply falling integral spectrum $N(\geq E) \propto E^{-2.3}$. There appears to be no information so far on the proportion of positrons in this energy range. It is to be expected that the flux of electrons and positrons in the high energy range would be much smaller than that of protons because of synchrotron radiation losses in the galactic magnetic field. It is, of course, this radiation which accounts for much of radioastronomy.

9.4 INDIRECT METHODS OF OBSERVATION OF 10^{12}–10^{15} eV COSMIC RAYS – AIR SHOWERS

Most of the intensity and spectral information we have in this energy range at the present time has come from observations at the surface of the Earth (or underground) of the products of the interactions of the primary cosmic ray particles and photons in the Earth's atmosphere. As noted, the interaction mean free paths in the atmosphere are between 60 and 80 g cm^{-2} for protons (and less for heavy primaries) and ~38 g cm^{-2} for photons (i.e., a radiation length, e.g. Weekes, 1988), which means that, even at the highest altitude on the surface of the Earth (~8.8 km), ~99% of the vertically incident primaries have interacted in the ~320 g cm^{-2} of atmosphere above, producing showers of particles and photons.

Elementary particles of all known types (and possibly some currently unknown) emerge from the first interactions, dominant among them being pions, kaons and nucleons (i.e., hadrons) for incident primary protons and heavy nuclei, while electron-positron pairs are dominant for incident primary photons (though some photopion production also occurs, e.g. Reid, 1990). The neutral pions and kaons quickly give rise to electromagnetic cascades while the charged pions and kaons either interact with further atmospheric nuclei (with energy dependent mean free paths ranging from ~85 to 135 g cm^{-2}, Forti et al., 1990) or decay to muons and neutrinos. The greater the altitude of the first interaction of the primary particle the greater is the probability that the pions and kaons produced will decay rather than interact in the low density atmosphere. Hence, on a per nucleon basis, heavy nuclei would be expected to produce more muons and neutrinos than would protons or light nuclei (of the same energy per nucleon). In addition to the energetic particles, electromagnetic radiation over most of the spectrum, including the optical and radio range, is produced in the atmosphere by the charged particles in the cascade.

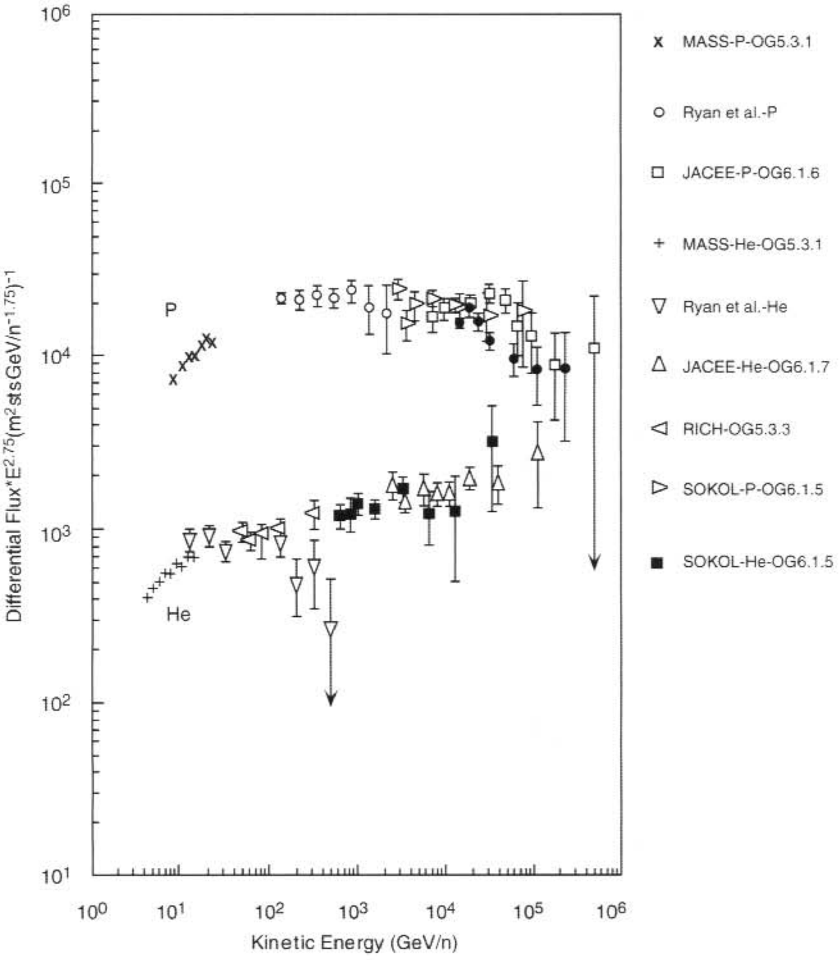


Figure 5. *Energy spectra of primary cosmic ray protons and helium nuclei (from Swordy, 1993).*

High energy interactions are only partially inelastic and a high energy primary cosmic ray nucleon is believed to retain about half its kinetic energy after collision with an air nucleus, the other half going into the production of secondary particles. The primary therefore continues on to cause many more collisions and, because of its high forward momentum, it is deflected very little from its original direction, thus defining the axis or core of the shower. A heavy primary is very likely to fragment in its first collision with an air nucleus and, because the paths of the fragments are likely to diverge slightly from one another, and, because of the high altitude of this first collision, there is an expectation that heavy primaries may produce showers which have multiple cores at ground level. At each subsequent collision by the continuing nucleon(s), secondary hadrons are produced, which means that the core of the shower is characterised by nuclear active particles which, in turn, lead to the production of more γ-rays, electrons and positrons. Muon production becomes less likely as the core progresses deeper into the atmosphere.

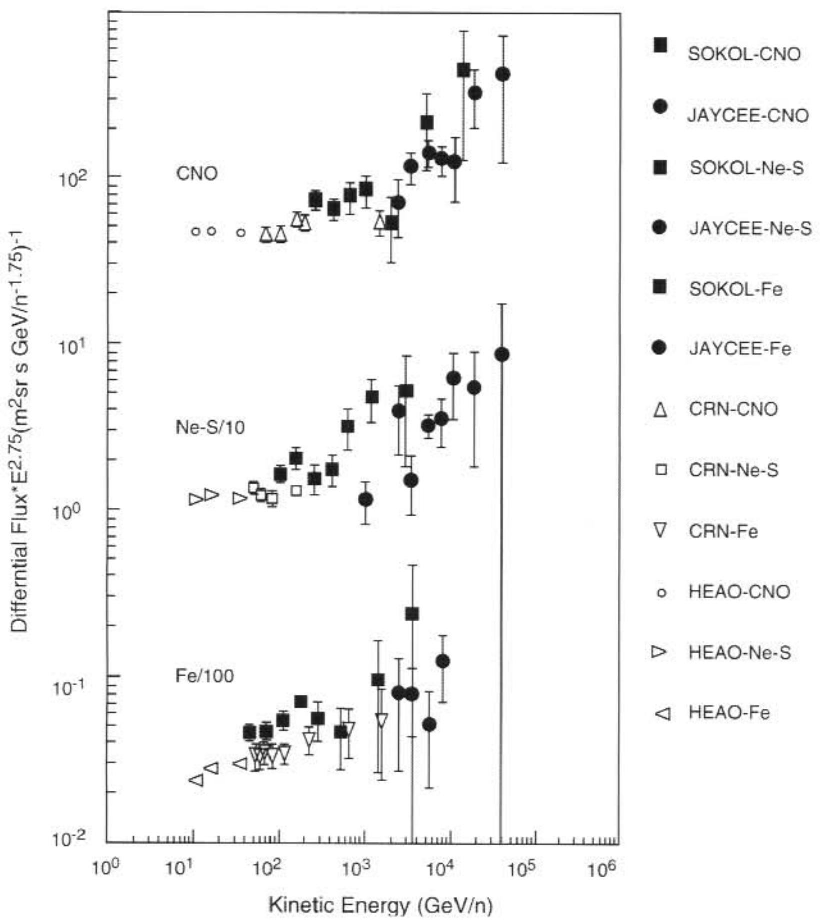


Figure 6. *Energy Spectra of Primary Cosmic Ray CNO, Ne-S and Fe Nuclei (from Swordy, 1993).*

There is considerable uncertainty about the magnitude of the inelasticity (e.g. Yuda, 1991) but, for present purposes, we can take it as 0.5 which implies that a vertically incident 10^{15} eV proton may reach sea level with an energy of ~6×10^{10} eV, after ~14 collisions with atmospheric nuclei. However, a 10^{12} eV primary proton would be unlikely to reach sea level, with most of its nucleonic core and accompanying electromagnetic cascade being absorbed at a higher altitude.

Thus, depending upon the energy of the primary in the 10^{12}–10^{15} eV range, the surface of the Earth may be struck by the core of the air shower, by the surviving electrons, positrons and γ-rays in the electromagnetic cascade, by the muons and neutrinos originating from the nucleonic processes, by the optical photons (if the sky is sufficiently cloud free) and by radio waves. We now refer in a little more detail to those components which have proved useful in studying extensive air showers.

9.4.1 Optical photons

The charged particles in the cascades initiated by the primary cosmic rays produce Cerenkov photons when their speed exceeds the speed of light in the atmosphere. Most of the details of this process were originally worked out by Jelley and early progress in the field has been reviewed by Jelley and Porter (1963) and by Jelley (1967). Near sea level the threshold for Cerenkov light production by electrons is ~21 MeV and by muons ~4.4 GeV. At an atmospheric depth of ~70 g cm^{-2} the thresholds are ~80 MeV for electrons and 16.5 GeV for muons. Near sea level ~30 photons in the wavelength range 350–550 nm are produced per metre of path and at ~70 g cm^{-2} ~2 photons per metre are produced by each particle above the Cerenkov threshold. To obtain an idea of the intensity of the Cerenkov light produced in a shower it is of interest to have an estimate of the number of photons each particle creates over a path length of, say, 10 km in the upper atmosphere. It is not easy to make this estimate for electrons and positrons (which form the majority of the charged particles in a shower and therefore contribute most of the light) because a 10 km journey corresponds to many radiation lengths, with many individual electrons and positrons disappearing and others being created in the cascade over such a distance. But a muon, created at an energy above 16.5 GeV at ~70 g cm^{-2} would produce ~60,000 optical photons if it travelled vertically down into the atmosphere for 10 km to ~330 g cm^{-2} (a journey which it would be likely to survive, since 75% of muons created at ~70 g cm^{-2} with an energy of ≥10 GeV reach sea level and, in fact, penetrate at least a further 40 hg cm^{-2} of rock).

Because of the low refractive index of air, Cerenkov photons travel almost parallel to the particles which produce them and they reach the ground within a few nanoseconds of the particle, spread over an area of diameter ~150 m. They are observable on clear dark nights as a pulse of light of a few nanoseconds duration. In the case of an air shower of primary energy 10^{12} eV, the flux of optical photons is ~50 m^{-2} within 100 m of the shower axis (e.g. Weekes, 1988). The flux of photons is closely proportional to the total primary energy, except that Monte Carlo calculations by, for instance, Baillon et al. (1993) show that a proton requires more energy by an average factor of 1.2 to produce the same density of optical photons as a γ-ray for the experimental conditions applying to their THEMISTOCLE array.

In addition to the Cerenkov radiation, fluorescence photons are produced in the optical range as a result of the charged particles exciting the atmospheric N_2 and N_2^+ molecular band systems. These are mainly in the wavelength range ~320–420 nm, with each minimum ionising particle producing ~5 photons per metre at an atmospheric depth of ~70 g cm^{-2} and ~4 per metre near sea level (Baltrusaitis et al., 1985). Thus, about 50 000 photons are produced by a particle in travelling the 10 km from the 70 g cm^{-2} level to 330 g cm^{-2}, but, since these photons are radiated isotropically from their points of production, their density at ground level is much less per particle than is that of the Cerenkov radiation near the shower axis. The nitrogen fluorescence light is used by the Fly's Eye and HiRes detectors for giant air showers of $\geq 10^{18}$ eV.

9.4.2 *Electrons, positrons and γ-rays*

Most of the energetic electromagnetic cascade is initiated by events at the core of the shower, with only a small proportion being due to other processes, such as electrons from muon knock-on events. If the primary is a γ-ray, the cascade arises from the first encounter with a nucleus at which an electron pair is produced, while, if the primary is a proton or nucleus, the cascade arises from the γ-rays from the decay of neutral pions and kaons, which then continue on to produce electron pairs. Irrespective of the nature of the primary, the electrons and positrons so created, in turn, produce more γ-rays through bremsstrahlung, and so the cascade develops. The electrons and positrons suffer multiple Coulomb scattering which causes a lateral spread of the particles away from the core of the shower and is largely responsible for the showers being referred to as extensive.

The theory of the lateral spread of the energetic electromagnetic component (as well as many other aspects of extensive air showers) has been reviewed by several authors, in particular Greisen (1956 and 1960) and Galbraith (1958), and the distribution of the electrons, as observed by the arrays used to the present time agrees reasonably well with the theory of a pure electromagnetic cascade. A commonly used lateral distribution function is the Nishimura, Kamata, Greisen (NKG) function, based on the theory of Nishimura and Kamata (1950, 1951 and 1952), as modified empirically by Greisen (1956). This function is frequently used to make an estimate, for instance, of the location of the axis of a shower observed by an array of detectors, based on the numbers of electrons sampled by each of the detectors in the array.

A convenient approximate form of the NKG function, also given by Greisen (1960) is:

$$\rho(N_e, r) \cong \left(\frac{aN_e}{r}\right)e^{-r/b}$$

where N_e is the total number of electrons in the shower, r is the perpendicular distance from the shower axis, a is a normalisation constant and b has a typical value of 74 m near sea level, close to the Molière characteristic length at sea level of 79 m (for reference to Molière's original 1942 paper, see for instance Greisen (1956) or Galbraith (1958)). It is of interest to note that, to the extent that it is a correct representation, this expression implies that the geometrical spread of electrons is independent of the total number of electrons in the shower, and hence, of the primary energy, E, given that $N_e \cong 10^{-10}E$ at sea level (e.g. Galbraith 1958, p. 115). Although use of the NKG function continues to be widespread, the evidence in recent years indicates that a steeper function is more appropriate. The situation has been reviewed briefly by Erlykin (1990).

According to the above approximate expressions, half of the electrons fall within a radius of ~50 m of the core for a vertically incident shower near sea level, while 85% are within ~140 m of the core. In the case of a 10^{15} eV primary, the number, N_e, of electrons and positrons at sea level would be ~10^5, so that the average density would be ~6 m^{-2} within ~50 m of the core and it would be ~0.6 m^{-2} between ~50 and ~140 m of the core. If any electrons and positrons reach sea level for a 10^{12} eV shower, these expressions would predict ~100 as the total number, with a density of 6×10^{-3} m^{-2} within 50 m of the core, rendering such a shower very difficult to detect at sea level via the electrons.

These densities rise appreciably with altitude, reaching a peak of ~10 times the sea level density at an atmospheric depth of ~500 g cm^{-2} (~5.5 km altitude). Therefore, although some particles in the cascade produced by primaries in the energy range 10^{12}–10^{15} eV are certain to reach sea level, an air shower array which relies on sampling the electrons or positrons in the cascade will record a higher rate of showers at a high altitude than it will record at sea level. For example, in an early experiment, Hilberry (1941) drove a vehicle from Chicago (altitude 91 m) to Mt Evans (4320 m) carrying a small air shower array and found that the shower rate increased by a factor of about 16, obeying an exponential absorption law with an absorption length of ~140 g cm^{-2}. Corresponding to this there is a barometric coefficient for an electron positron sampling array in the lower atmosphere of ~10%/cm Hg (-0.75%/g cm^{-2}). (We note that the absorption length and barometric coefficient are very similar to those for the nucleonic component as observed with a neutron monitor.)

Few measurements have been made of the proportion of γ-rays in showers, but Monte Carlo simulations by Trzupek et al. (1991) give a ratio of $N_\gamma/N_e = 5.5$ for 10^{14} eV primary protons, where N_γ and N_e, are, respectively, the numbers of γ-rays and of electrons and positrons ≥3 MeV at ground level. Using their GRAND array at the University of Notre Dame, these authors made observations in which γ-rays striking a steel plate (thickness 2.87 radiation lengths) produced electrons and positrons which were detected below the plate. Designating by N_g, the number of γ-rays which produced a detector response below the steel, their observed value of the ratio N_g/N_e, was 0.46 ± 0.09, compared with the value predicted from the simulation of their array response of 0.47 for 10^{14} eV primary protons. This excellent agreement suggests that the ratio of γ-rays to electrons and positrons of about five at sea level is realistic and that, therefore, about 85% of the energetic electromagnetic component of a shower at sea level consists of γ-rays. Because of the high proportion of γ-rays in showers, it has become customary to place a thin sheet of lead (~1 radiation length) above the detectors in shower arrays to increase the efficiency of detection through the electrons and/or positrons they create in the lead.

9.4.3 *Muons*

9.4.3.1 Lateral distribution and proportion in shower

Since most of the energetic muons (i.e., those of energy above ~10^{10} eV) are created at altitudes above ~15 km, small angles between the paths of the muons and the axis of the shower will result in some of them reaching the ground well away from the axis. In fact, many muons are observed hundreds of metres from the shower axis, with half the muons at sea level being at distances exceeding 320 m from the axis. The density of muons $\geq 10^9$ eV at sea level, as given by Greisen (1960), is

$$\rho\left(N_\mu, r\right) = 18\left(\frac{N_e}{10^6}\right)^{0.75} r^{-0.75}\left(1+\frac{r}{320}\right)^{-2.5} m^{-2},$$

with the distance given in metres.

Although, near the axis, muons constitute only about 2% of the charged particles at sea level (most being electrons and positrons, depending, of course, on the energy of the primary), at greater distances from the axis the proportion of muons rises to several tens of percent, with the result that, in the shower as a whole, about 10% of the particles are muons (e.g. Galbraith 1958, pp 73–74). For a shower of 10^6 charged particles at sea level (corresponding to a primary energy between 10^{15} and 10^{16} eV), about 17% are muons (Greisen, 1960).

The muons close to the axis have a harder energy spectrum than those at a great distance, with the spectrum at ~475 m being similar to that of the background muons (Bennett and Greisen, 1961). The average energy of the muons in a shower is higher than the average energy of the electrons and the muons carry much more total energy at sea level than does the electron component. For the example of a shower of 10^6 charged particles at sea level, Greisen (1960) gives the total energy of the muons as 9×10^{14} eV compared with 1.6×10^{14} eV for the energetic electromagnetic component. These figures would imply that the average energy of the muons is ~5×10^9 eV and of the electrons ~1.6×10^8 eV.

The energy spectrum of the muons as a function of distance from the shower axis, as well as the lateral distribution itself, are dependent upon the details of the initial interactions between the primaries and the atmospheric nuclei. It has long been accepted that it must be inferred from the muon observations that pions and kaons may receive high values of transverse momentum from these interactions. Greisen (1960), for instance, suggested that the lateral distribution of muons is consistent with values of p_T ~0.5 GeV/c at production. (The vector sum of the values of p_T of the particles emerging from an interaction must, of course, be zero; although it is not customary to be specific, it is the RMS value of p_T to which authors refer.)

9.4.3.2 Jets and muon bundles

There has been evidence from early cosmic ray observations, as well as more recently from accelerator experiments, that, in the centre-of-mass (CM) system, the pions and other secondary particles emerge in jets from the interaction region. For example, Rossi (1952, p. 401 and pp. 515–517) discusses an event observed by Lord et al., 1950) in a nuclear emulsion exposed by balloon at an atmospheric depth of ~19 g cm^{-2} in which early evidence was obtained not only that multiple production of pions in a single nucleon-nucleon collision occurred but also that the production was in two cones or jets. In one of these jets, seven minimum ionising particles were emitted in a very narrow cone of half-angle 0.003 radian and, in the other, eight minimum ionising particles were in a cone of half-angle 0.13 radian. This observation strongly suggested that, in the CM system, there were two oppositely directed cones or jets of particles, assumed to be mainly pions. An accurate determination of the energy of the primary proton in this event was impossible, with estimates ranging from 3×10^{12} to 3×10^{13} eV. In the terrestrial or laboratory system, such an event in the atmosphere at an altitude of 10 km, for a vertically incident primary, would translate into a group of muons near the core of the shower out to a distance of ~30 m, corresponding to the narrow cone, and an outer group out to a distance of ~1300 m for the wider cone. The muons in the inner group would have much higher energies than those in the outer group if, in the CM system, the two groups had the same energy spectra.

The production of pions and kaons in jets, as observed with cosmic rays and proton-antiproton collisions in accelerator experiments, appears to be accounted for by what is customarily called the Standard Theory, involving quark-quark interactions. It is my understanding that this theory predicts that, although the jets can emerge from the interaction region at any angle in the CM system with respect to the directions of motion of the colliding nucleons, there is a preference for the jets to be aligned with the directions of motion. In the laboratory or terrestrial system, this translates into a strong preference in favour of the forward and backward jets inferred, for instance, from the observations by Lord et al. (1950) just mentioned. The fact that the jets in the accelerator experiments tend to be at right angles to the beam directions is because the particle detectors which provide the evidence for the jets must be outside the vacuum region and cannot be placed in the beams.

From early in the study of muons there have been reports of 'bundles' of muons. Possibly the first such report was from a group at Sâo Paulo (Wataghin et al., 1940) who, in observations made at an altitude of 800 m with counter telescopes separated by 30 cm, observed pairs of particles capable of penetrating 16 cm of lead. They assumed that the particles responsible were muons (mesotrons) and 'the results..... lead us to think that the observed particles are associated with the penetrating cores of the extensive air showers discovered by Auger and his coworkers'. Subsequent experiments by this group (de Souza Santos et al., 1941) showed that showers containing at least two penetrating particles could be observed underground at a depth equivalent to 60 hg cm^{-2}.

Barrett et al. (1952), using a hodoscoped array of counters deep underground (594 m or 1574 hg cm^{-2}, corresponding to a minimum muon energy of ~3×10^{11} eV), observed a small number of events in which two or three penetrating particles traversed the array in parallel straight lines, the linear dimensions of the array being ~1 m. There was a 'remarkable correlation' with extensive air showers detected at the surface of the ground above the underground array and these showers were, on average, much larger than those associated with single muons underground.

The authors suggested that it was reasonable to assume that the multiple muons were close to the shower axis.

Another early report of bundles of muons came from Higashi et al. (1957) who used a cloud chamber of sensitive volume 80 x 70 x 40 cm^3 located under 15 m of rock and who found, in 218.5 hours of observing time, four events in which there were four, five, seven and nine parallel muon tracks. In all such observations, the density of muons in the bundles greatly exceeded the average density of muons in the remainder of the shower and the frequency of occurrence of bundles appeared to be greater than could reasonably be expected by the chance association of unrelated muons.

At the present time, a great deal of effort is being devoted to making detailed observations of muon bundles. For instance, the giant MACRO (Monopole, Astrophysics, Cosmic Ray Observatory) array underground at the Gran Sasso Laboratory in central Italy, where the minimum absorber thickness is ~3150 hg cm^{-2}, is very suitable for studying the spatial distribution of energetic muons ($\geq 6 \times 10^{11}$ eV) as a function of distance from the core of the shower (the so-called decoherence curve). The MACRO array of streamer tube chambers, liquid scintillator tanks and track-etch detectors, described by Bellotti et al. (1990) and by Ahlen et al. (1992), is constructed in modules each 12 m long x 12 m wide x 9 m high. The complete array has six adjacent modules and gives a spatial resolution of 1.1 cm, corresponding to an angular resolution of 0.2° for muons crossing ten horizontal planes. It is thus possible to obtain detailed data on bundles of muons in which the separations are up to ~70 m. Transition radiation detectors have been added over some of the array which will provide muon energy data in addition (Spinelli et al., 1995).

In parallel with these experiments, a great deal of effort is being devoted to understanding the origin of the muon bundles and, in particular, whether it can be accounted for in terms of the Standard Theory of nuclear interactions. For example, Monte Carlo simulations of bundles of muons detectable by the MACRO array have been presented in a preliminary report by Battistoni et al. (1995a). Based on the shower code produced by Forti et al. (1990) known as HEMAS (Hadronic, Electromagnetic and Muonic components in Air Showers, which, in turn, appears to be based on the Standard Theory of particle interactions), these simulations indicate that clusters of muons occur within the bundles and that the bundles generally have a central cluster close to the shower axis containing most of the muons in the event. The simulations, in which the primary energy was $\geq 2 \times 10^{15}$ eV/nucleus, also indicate that bundles produced by heavy nuclei contain a larger number of clusters than occur in bundles produced by protons. A brief discussion of muon bundles is given by Gaisser (1990, p. 207).

A comparison of the MACRO observations with these simulations (e.g. Battistoni et al., 1995b) results in a qualitative agreement with predictions assuming a 'light' composition model at primary energies ~10^{15} eV/nucleus, meaning only a limited increase of $\langle A \rangle$ with increasing energy.

9.4.3.3 Background muons at the surface and underground

The flux of muons at sea level at latitudes greater than about 50° which penetrate 167 g cm^{-2} (~15 cm) of lead is given by Wolfendale (1963, p. 129) as 127 m^{-2} s^{-1}. In the present context, we refer to these as the background muons and most of them arise from showers in which the energetic electromagnetic component and the nucleonic component have been absorbed at higher altitudes. The electromagnetic and nucleonic components of the showers which do reach ground level are absorbed at even shallow depths underground, but many of the muons are able to penetrate to appreciable depths.

Most of the energy loss suffered by muons is due to the excitation and ionisation of the atoms near which they pass (at the rate of ~2 MeV/g cm^{-2} at ~10^{10} eV and rising slowly with increasing energy). After penetrating the atmosphere, a muon created at 10^{10} eV can penetrate ~40 hg cm^{-2} of rock and one created at 10^{11} eV can penetrate ~360 hg cm^{-2}. At ground level, the energy spectrum of the background muons $\geq 10^{10}$ eV follows a power law approximately, with an exponent of about -1.6 for the integral spectrum. This means that, if the energy at ground level required to penetrate to a given depth is E_1, about 90% of the muons which reach that depth from the vertical direction have an energy at ground level between E_1 and $4E_1$, and the average energy at ground level of all the muons reaching that depth is ~$2.7E_1$. The average energy of the muons at the underground depth is ~$1.7E_1$. Although these figures are sensitive to the exponent of the power law, the muons observed at any given depth underground are, effectively, in a narrow energy range.

A question to be addressed is: what is the energy range of the primaries which lead to the muons observed at a given depth underground? Several attempts have been made to answer this question. One of these was by Dorman (1957) who suggested that the minimum proton energy would be 10 times the energy required by a muon to reach the given depth. A little later, A.G. Fenton (1963) applied the statistical model of Fermi (1950) to the problem of estimating the average energy of the protons responsible for the production of the muons observed at the first of the Hobart group's underground observatories at a vertical depth of 40 hg cm^{-2}. Currently, the most widely used response functions for underground observatories are those due to Murakami et al. (1979), which are based on the data then available from accelerator experiments and Feynman scaling (Feynman, 1969). The same authors (Murakami et al., 1981) have published tables giving the median rigidities of the primaries responsible for the muons observed at a number of underground sites. The median rigidity is defined as that value above and below which equal fluxes of muons observable at the site are produced. For instance, the value they calculate for our underground telescopes at Poatina (depth 365 hg cm^{-2}) is 1385 GV (essentially equivalent to 1.385 x 10^{12} eV for protons).

There is some evidence from surface observations of muons that the response functions due to Murakami et al. may not be entirely satisfactory. For example, Cramp (1996), in her analysis of the 29 September 1989 GLE (in which solar energetic particles of energies exceeding 15 GeV were present, leading to an enhancement observed by muon telescopes, some even at shallow underground depths, as well as by low latitude neutron monitors), encountered difficulties in modelling the event over the whole energy range and concluded that there is some doubt as to the accuracy of the muon response functions below rigidities of ~10 GV.

In my opinion, it would be appropriate to revisit this problem in the light of the information from the collider experiments and the Standard Theory of high energy nuclear interactions. It is clear that the minimum energy proton which can create a muon of energy E_1 is very nearly E_1, but this would be a rare occurrence, requiring, as it does in a nucleon-nucleon collision, that the two resultant nucleons move in the backward direction in the CM system while a single pion (or kaon) is created which moves in the forward direction. This pion must then decay to a muon which also moves in the forward direction. But, in the cases in which we are interested in which the proton energy is appreciably above the threshold for pion production in the laboratory system (293 MeV for collision with a nucleon at rest), multiple production of pions becomes more probable. Given that the evidence also points to the pions and kaons being predominantly produced in forward and backward moving jets in the CM system, resulting in showers reaching the ground with muons of much higher energy near the core than at the periphery, it is clear that primaries over an appreciable range of energies will be responsible for the muons which are able to penetrate to a given depth.

Some JACEE interaction events at $>10^{12}$ eV/nucleon have been observed (Wilczynski et al., 1995) in which azimuthal asymmetries among the secondary particles are not accounted for by known processes included in their Monte Carlo simulations. The authors suggest that these events may be a signature of some new phenomenon, such as the production of particles heavier than the bottom quark or the formation of disoriented chiral condensates.

9.4.4 EAS Simulations

There is voluminous literature on extensive air showers, with the proceedings of each successive ICRC (International Cosmic Ray Conference) containing large numbers of new contributions, which it is certainly not the purpose of this paper to attempt to review. One of the topics to which a great deal of attention is being directed is that of whether it is possible to determine the nature of the primary cosmic ray from observations made on the ground of the measurable features of each shower. In principle, it should be possible to determine, for each particle in a shower, its type, its position on the ground and its time of arrival. It is conceivable that ultimately it may also be considered worthwhile determining the energy of each particle in a shower. The question is whether or not all this information would make it possible to determine the type and energy of the primary responsible for each shower.

The current situation seems to be that a consensus has not yet been reached about unambiguously determining the nature of the primary from the shower parameters which are currently measured. In order to determine the energy and nature of a primary it is necessary to compare parameters measured for each shower with quantities predicted by some accepted model. Although there have been many

Monte Carlo simulations relating to this problem (and we have referred to a few of these), the two front-runners at the present time seem to be the four-dimensional Monte Carlo simulations known as MOCCA and CORSIKA. MOCCA (MOnte Carlo CAscades) is due to Hillas (1983) and has been progressively updated with its recent status described by Hillas (1995). This program uses a thinning technique, which avoids following all the particles in a shower, in order to make calculations up to 10^{20} eV in a reasonable time. Hillas point out that, whereas the complete simulation (i.e., without thinning) of a 10^{12} eV shower takes about 6 minutes of his computer time, a 10^{18} eV shower would take about nine years and a 10^{20} eV shower centuries (even though the cosmic ray particles themselves make the trip through the atmosphere in ~100 μs!).

CORSIKA is a program developed specifically to perform simulations for the KASCADE experiment at Karlsruhe (a 200 m x 200 m array for a detailed study of showers above 10^{14} eV, described by Schieler et al., 1995). Developed in the early 1990's, with a recent version given by Knapp et al. (1995), CORSIKA does not employ thinning techniques and, partly as a consequence, is currently restricted to energies below ~10^{16} eV.

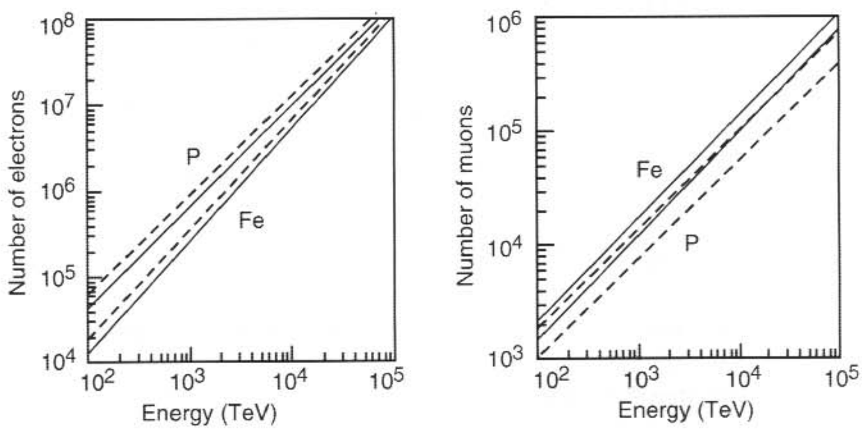


***Figure** 7. Average values of N_e and N_μ vs primary energy for protons and iron nuclei calculated using the MOCCA (dashed lines) and CORSIKA programs (solid lines). The electrons have energies >3 MeV, the muons >700 MeV (from the CASA-MIA group, Borione et al., 1995).*

The MOCCA and CORSIKA programs have been used by the CASA-MIA group to calculate the expected numbers of electrons and muons (N_e and N_μ) as a function of energy and mass of the primaries which would produce showers meeting the detector response and trigger requirements of their array. The energy range was 10^{14} to 3 x 10^{16} eV for protons and several heavy nuclei up to Fe. The results are shown for protons and Fe in Figure 7, taken from the paper by the CASA-MIA group (Borione et al., 1995). The programs agree with one another to the extent that they give very similar slopes, but MOCCA predicts 15-20% more electrons than

CORSIKA while CORSIKA predicts 20–30% more muons at 10^{14} eV, rising to 40–100% more at 10^{17} eV. The authors attribute these differences to differences in the hadronic interaction used in the two programs, resulting in CORSIKA showers developing higher in the atmosphere leading to more muons and fewer electrons at ground level than MOCCA predicts.

It is evident that the event reconstructions based on the numbers of electrons and muons observed by the detectors in the array will lead to different energy and mass values for the primary of each shower, depending upon which Monte Carlo program is used. Until some criteria can be established for favouring one program over the other, or for developing an improved program, confidence in the results obtainable from shower observations regarding the composition of the primaries will remain limited. Likewise, the question of whether the knee in the energy spectrum at about the upper end of the energy range we are considering is due to a change in composition, a change in the interaction physics or a change in the primary spectrum, will remain without a clear answer.

9.5 CONCLUDING REMARKS

It had been intended to include in this paper a review of the evidence for the existence of localised regions in which particles are being accelerated to energies $\geq 10^{12}$ eV, evidence which has come from several arrays in many parts of the world observing the short bursts of Cerenkov light produced in air showers, presumably initiated by γ-rays. However, since it has not been possible to do this, readers are referred to recent reviews by other authors, such as that by Bhat (1997). Similarly, the chemical composition and other features of the charged primaries have been reviewed by Watson (1997).

With regard to making progress in obtaining details of the sidereal anisotropy, referred to briefly in Section 9.1 and Section 9.2.2, it is clear that much larger detecting areas are needed than have been available up to the present time. Our own measurements (Fenton et al., 1995) have been made with underground muon telescopes of total area 4 m^2 at a depth of 365 hg cm^{-2} over a period of 8 years. As noted in Section 9.1, the result was an anisotropy of 0.06%, the maximum being from the direction 4.0 hrs RA and, as noted in Section 9.4.3.3, the current estimate is that the median energy of the primary protons responsible for this effect is a little over 10^{12} eV. If due to a Compton Getting effect, this anisotropy would correspond to a velocity of ~38 km s^{-1} of the solar system with respect to the nearby interstellar medium. The fact that this velocity is close to the speed of Earth in its orbit about the Sun (30 km s^{-1}) means that a seasonal modulation may be present. We plan to investigate this, particularly as we now have a few more years of data, with a total of ~4 x 10^8 muons, with the result that the statistics may now be sufficient to warrant a seasonal analysis. It is, nevertheless, desirable that other detectors, at similar or greater depths, and with larger areas be used to investigate the sidereal anisotropy. Ideally, one should have such a counting rate that the sidereal effect could be seen in each rotation of Earth, in the manner in which radioastronomers have large enough arrays to see the emission from the Milky Way each day.

There is also a need to have large area air shower arrays responding to primaries

$\geq 10^{13}$ eV. It is pleasing that the Tibet Air Shower array, at an altitude of 4300 m (606 g cm^{-2}) and with a threshold of $\sim 10^{13}$ eV, has been enlarged and now has an event rate of ~250 Hz (e.g. Amenomori et al., 1997). This means that in a full year of operation $\sim 2.5 \times 10^9$ events could be recorded. I am not aware of any analysis as yet of the Tibet data to search for the sidereal anisotropy.

I also entertain the hope that the two very large Auger arrays, each of 3000 km^2 in Argentina and Utah at ~1200 m altitude, principally to study the very highest energy cosmic rays (e.g. Boratov et al., 1997), can be planned to respond to lower energy primaries, perhaps down to 10^{15} or 10^{16} eV. The rate of primaries of energy $\geq 10^{15}$ eV over each array would be expected to be $>5 \times 10^{10}$ per year. It would seem to be well worth giving serious consideration to including whatever modifications are required to the detector arrays to achieve such a large counting rate. After all, the additional cost would probably be small and would be far less than that of establishing arrays elsewhere specifically designed to achieve such counting rates independently.

Another large area project proposed is the network of Pion Eye Observatories (Catalano et al., 1997) which would have a total area of 3000 km^2 in 10 separate arrays around the globe and is estimated to have a rate of 4×10^8 events per year $\geq 5 \times 10^{15}$ eV.

I also hope that a CRN type experiment will be flown in space, for example on the Space Station. Even if no larger than the Chicago 'Egg', the number of events observed in a year could be $\sim 10^9$ above 5×10^{10} eV/nucleon and the advantage of such an observation would be that the anisotropy could be studied as a function of composition. It is worth noting that this type of cosmic ray measurement is one of the few which can be made in a near-Earth low latitude orbit (such as that of the Space Station), because the Earth's magnetic field does not allow much lower energy particles to be observed. However, in interpreting any seasonal effect in near-Earth orbit, the spacecraft speed of ~7 km s^{-1} would need to be taken into account together with the orbital speed of Earth of ~30 km s^{-1}.

In considering the importance of determining the anisotropy as a function of composition, it is of interest to recall a suggestion made several years ago by Rasmussen and Peters in an unpublished late paper (OG6-7b) at the 14th International Cosmic Ray Conference, Munich, 1975, to the effect that ~15% of the cosmic rays are due to a local and presently active source which produces the α-particle type nuclei from ^4He to ^{56}Ni (which decays to ^{56}Fe), the remainder of the cosmic rays being from older distant sources. According to this suggestion, these older cosmic rays originally had the same composition as the young ones, but a steady state has been reached between their production and destruction in collisions with the interstellar gas. The protons are mainly spallation products, according to this model, and would be expected to be more nearly isotropic than the young nuclei from the nearer source. Only by employing detection methods which are composition sensitive can we hope to determine whether there is a composition dependent anisotropy.

Finally, I should note that, at our deep underground site, we have recorded events due to multiple muons (two or more) (Fenton et al., 1995) and have searched for an anisotropy, motivated by the expectation (as mentioned in Section 9.4) that more muons are produced by heavy primaries than by protons of the same energy per nucleon because of the higher altitude of their first interaction in the atmosphere. Our analysis has not revealed a sidereal diurnal variation significantly different from zero, although it also showed that the probability was vanishingly small of the observed variation being compatible with that observed for the single muons. Whether the improved statistics now available will change this situation remains to be seen.

For further discussion of some of the reasons investigations of the anisotropy are important from an astrophysical point of view, see Fenton (1975).

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10. HELIOSPHERIC MODULATION: THEORY AND UNDERGROUND OBSERVATIONS

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ABSTRACT

The modulation of cosmic rays in the energy range 10^{10}–10^{12} eV is caused by solar activity. Long term modulations resulting from the solar sunspot cycle (11 years) and the solar magnetic cycle (22 years) are now apparent. The heliospheric wavy neutral sheet is also recognised as an important part of the modulation process. Observations of cosmic ray anisotropies allow us to determine parameters of the modulation such as the particle mean free paths and density gradients and their temporal and energy dependencies. A review of the status of long term modulation research through underground observations is presented.

10.1 THE HELIOSPHERE

The heliosphere is created by the solar wind plasma travelling radially from the rotating Sun and carrying the magnetic field frozen in it. This gives rise to the so-called interplanetary magnetic field or IMF. At the helioequator the effects of solar rotation and radial outflow result in a field that has an Archimedean spiral structure. The tightness of this spiral varies with the changing solar wind speed but, on average, forms an angle of 45° to the Sun-Earth line at the Earth's orbit. The outflowing plasma, carrying the magnetic field, does not allow the field lines from the northern and southern hemisphere of the Sun to connect but rather stretches the field outward along the helioequator. This idealised picture is shown in Figure 1. In this image the rotation is assumed to be aligned with the magnetic field axis. This is not generally the case and in the near field regions higher moments of the field mean a simple dipole does not give a particularly good representation of the field. When the angle of the magnetic axis to the rotation axis of the Sun is included and more complex field structures are present then the neutral sheet becomes wavy as can be seen in the artist's impression of Figure 2.

The structure defined so far represents the inner heliosphere. If we consider the heliosphere on larger scales our conclusions become, necessarily, more speculative. A good working model was presented by Venkatesan and Badruddin (1990) and is reproduced in Figure 3. The existence of a bow shock is conjecture at present but is likely to arise from the motion of the solar system through the interstellar medium. The boundary of the heliosphere is defined by the transition of the solar wind from supersonic to subsonic flow. The shock front distance from the Sun is not yet known but within this boundary the field is ordered by the Archimedean spiral as described above. Outside the shock the field is likely to be disordered with turbulent plasma flow (Venkatesan and Badruddin, 1990).

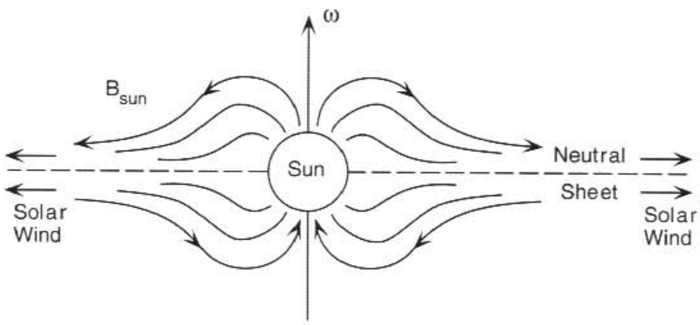

Figure 1. *Idealised picture of the formation of the heliospheric neutral sheet.*

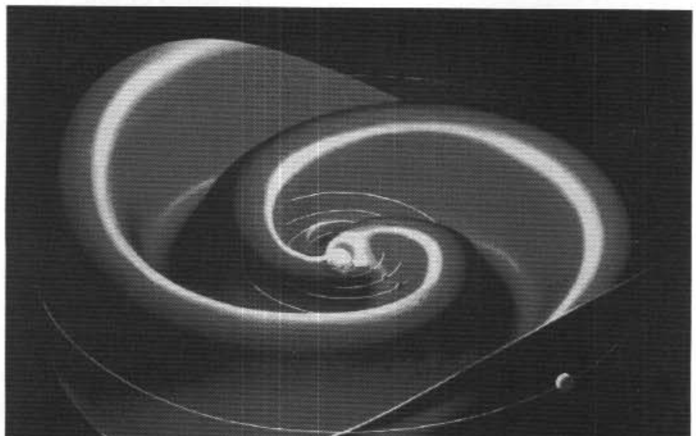

Figure 2. *Artist's impression of the structure of the heliospheric neutral sheet.* *Artist: Werner Heil (1977). Commissioning Scientist: John M. Wilcox.*

It is important to note that the heliosphere is not a static environment. The solar activity cycle, usually represented by the smoothed monthly sunspot numbers, has an average period of ~11 years. The solar activity climbs from its minimum activity relatively rapidly to its maximum activity over three or four years. It remains near peak activity for about one year before declining more slowly back to quiet conditions. At minimum activity the heliospheric neutral sheet is relatively flat but it becomes more wavy, extending to higher and higher heliolatitudes, as solar activity increases. Near solar maximum the field becomes highly complex and the neutral sheet may extend almost to the poles for short periods. At solar maximum the solar field reverses polarity. This process takes from a few months up to a year or slightly longer to complete. Thus there is also a natural ~22 year cycle to solar phenomena. The orientation of the heliomagnetic field is referred to as its polarity and is positive, denoted by A>0, when the field is outward from the Sun's northern hemisphere (e.g. during the 1970's and 1990's).

The cosmic ray flux is believed to be galactic in origin and to reach the heliosphere isotropically. It is the effect of the heliosphere on this cosmic ray flux (modulation) that gives rise to observed anisotropies and gradients.

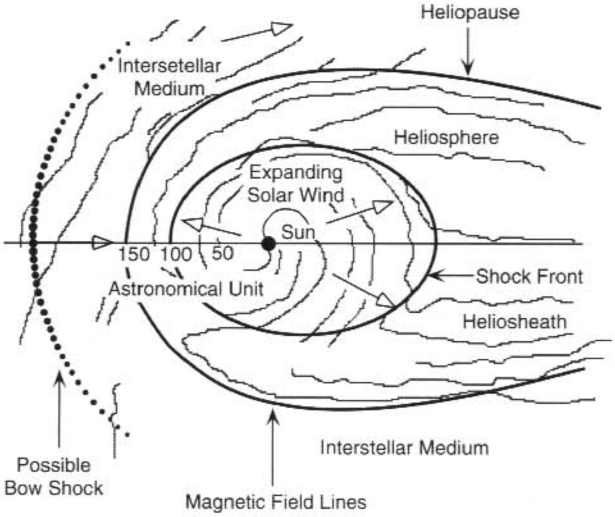

Figure 3. *A Schematic view of the heliosphere and its interaction with the interstellar medium. (Venkatesan and Badruddin, 1990).*

10.2 MODELLING COSMIC RAY MODULATION

Following pioneering work by Parker (1965) and Gleeson and Axford (1967), Forman and Gleeson (1975) formalised the theoretical framework which describes the passage of cosmic rays from the heliospheric boundary into the inner regions of heliosphere. This model showed that a solar diurnal anisotropy should be expected and that various gradients in the cosmic ray density should be present. The early model development included a number of assumptions. Subsequent models developed by Jokipii and Kota in the USA and Potgeiter and Moraal in South Africa have progressively reduce the number or severity of these assumptions. Furthermore, these later models have been able to take advantage of improved computer power, becoming more complex and extending to more dimensions. The most recent models are beginning to include more realistic representations of the IMF. A varying and wavy neutral sheet and better estimates of the polar IMF (resulting from the Ulysses spacecraft measurements) are the latest additions to the models. There is still, however, some way to go before the development of a fully realistic three-dimensional time varying IMF with solar generated shocks propagating outward. Such a model is beyond our computational abilities at present and would require a greater coverage of in situ measurements of the IMF away from the heliomagnetic equator.

10.2.1 Components of the Modulation

It is assumed in all models that the cosmic ray density outside the heliosphere is approximately isotropic. Cosmic rays cross the heliospheric boundary due to random motions. They continue to propagate inward along the IMF field lines and are scattered at small scale irregularities. This process is known as diffusion and is independent of the solar field polarity but will depend on solar activity because of the stronger field and greater number of field irregularities near solar maximum.

As we have already seem the IMF is curved in a spiral pattern and the field also weakens as it expands outward through the heliosphere. This field gradient and curvature lead to cross field forces on the cosmic rays. The resulting particle movements are known as drifts and depend on the solar field polarity.

Finally, the expanding IMF tends to convect particles outward. Convection is also polarity independent but depends on the level of solar activity because the solar wind and field strength are higher at solar maximum. The three modulation components combine to produce observable effects on the cosmic rays in the heliosphere.

10.2.2 Effects of the modulation

A radial gradient in the cosmic ray density around the helioequator will be present with increasing density toward the heliospheric boundary. This gradient is affected by all three components of the modulation and thus should exhibit both 11 and 22 year periodic variations.

A latitudinal gradient will depend on the polarity of the IMF and thus exhibits 22-year periodicities. This gradient, which is known as the bi-directional latitude gradient, is either maximum or minimum at the neutral sheet. A second uni-directional gradient which crosses the sheet has been claimed to be present by some observers but is difficult to reconcile with the symmetric models presently used. It is possible that such a vertical gradient would be expected from a more accurate model of the IMF and the heliosphere.

The models also predict particle streaming in the helioequatorial plane and perpendicular to it. The solar diurnal anisotropy should be observed in the plane whilst the North-South anisotropy should be observed perpendicular to it. Some other parameters which describe the behaviour of cosmic rays in the heliosphere are also influenced by solar activity and the IMF polarity. These include the mean free path parallel and perpendicular to the IMF. These anisotropies and modulation parameters are discussed in more detail below.

10.3 PREDICTIONS OF COSMIC RAY MODULATION MODELS

10.3.1 Cosmic ray transport

All modern cosmic ray modulation models predicted the transport of cosmic rays into the heliosphere from the isotropic distribution in nearby interstellar regions as shown in Figure 4. In the positive polarity state (A>0) cosmic rays enter over the poles and exit along the equator and the neutral sheet has little effect. In the negative polarity state (A<0) the cosmic rays propagate in along the helioequator and out via the poles. A neutral sheet extending to high heliolatitudes significantly affects the inward flow making it difficult to predict the expected gradients.

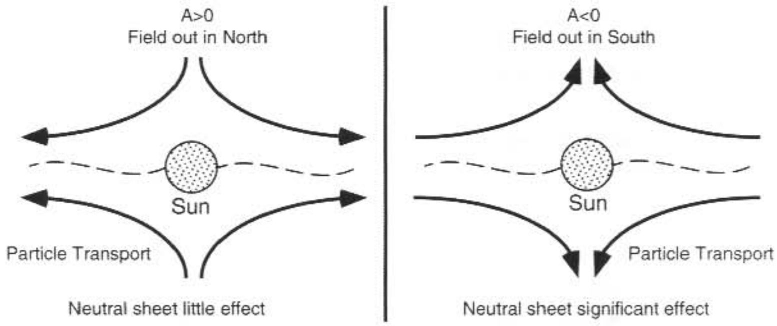

Figure 4. *Global cosmic ray transport predicted by modern modulation models.*

10.3.2 Cosmic ray density gradients

Current modulation models predict that the radial density gradient of cosmic rays, $\mathbf{G_r}$, should be smaller at solar minimum than at solar maximum. The solar wind and IMF generated by the active Sun is more efficient at blocking the diffusion of cosmic rays into the inner heliosphere. This results in steeper cosmic ray density gradients in the inner heliosphere. Furthermore, due to the different particle transport modes described above for the two polarity states of the IMF, $\mathbf{G_r}$ should be larger during the A<0 polarity state. This is a direct result of the neutral sheet effects.

A bi-directional latitudinal gradient G_z, is also predicted. This gradient is symmetrical about the neutral sheet and reverses its sense with each IMF polarity reversal. Most modelling of this gradient has not fully taken into account the neutral sheet effects and has assumed a flat sheet. The gradient should produce a minimum density at the neutral sheet in A>0 polarity states and a maximum at the neutral sheet for A<0 polarity. Kota and Jokipii (1983) have considered the effect of a wavy neutral sheet on the density and found that the minimum will be offset slightly from the sheet. This is shown in Figure 5 which is from their paper.

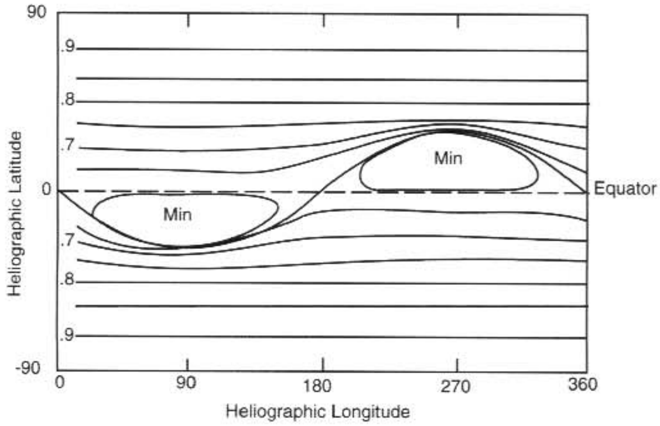

Figure 5. *The predicted latitudinal distribution of cosmic rays in the A>0 polarity state. From Kota and Jokipii (1983).*

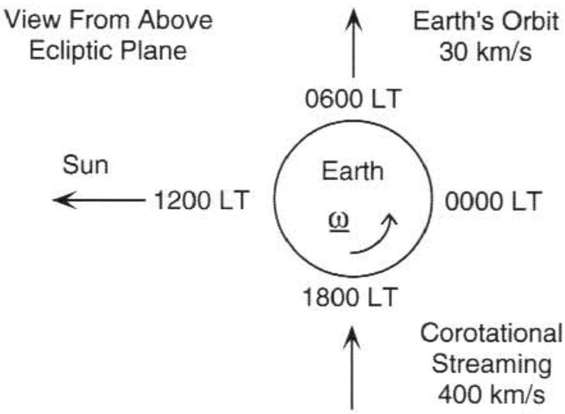

Figure 6. *The solar diurnal anisotropy resulting from corotational streaming of particles past the Earth. Local solar times are shown and the view is from above the ecliptic plane.*

10.3.3 The solar diurnal anisotropy

In their original description of the cosmic ray transport formalism Forman and Gleeson (1975) showed that the cosmic ray particles would corotate with the IMF. As the IMF rotation at the Earth is of the order of 400 km s^{-1} the particles would overtake the Earth travelling in its orbit at only 30 km s^{-1}. Thus an anisotropy would be expected to arrive from the local solar time direction of 18 hours. Figure 6 shows the geometry of the solar diurnal anisotropy when viewed from above the ecliptic plane.

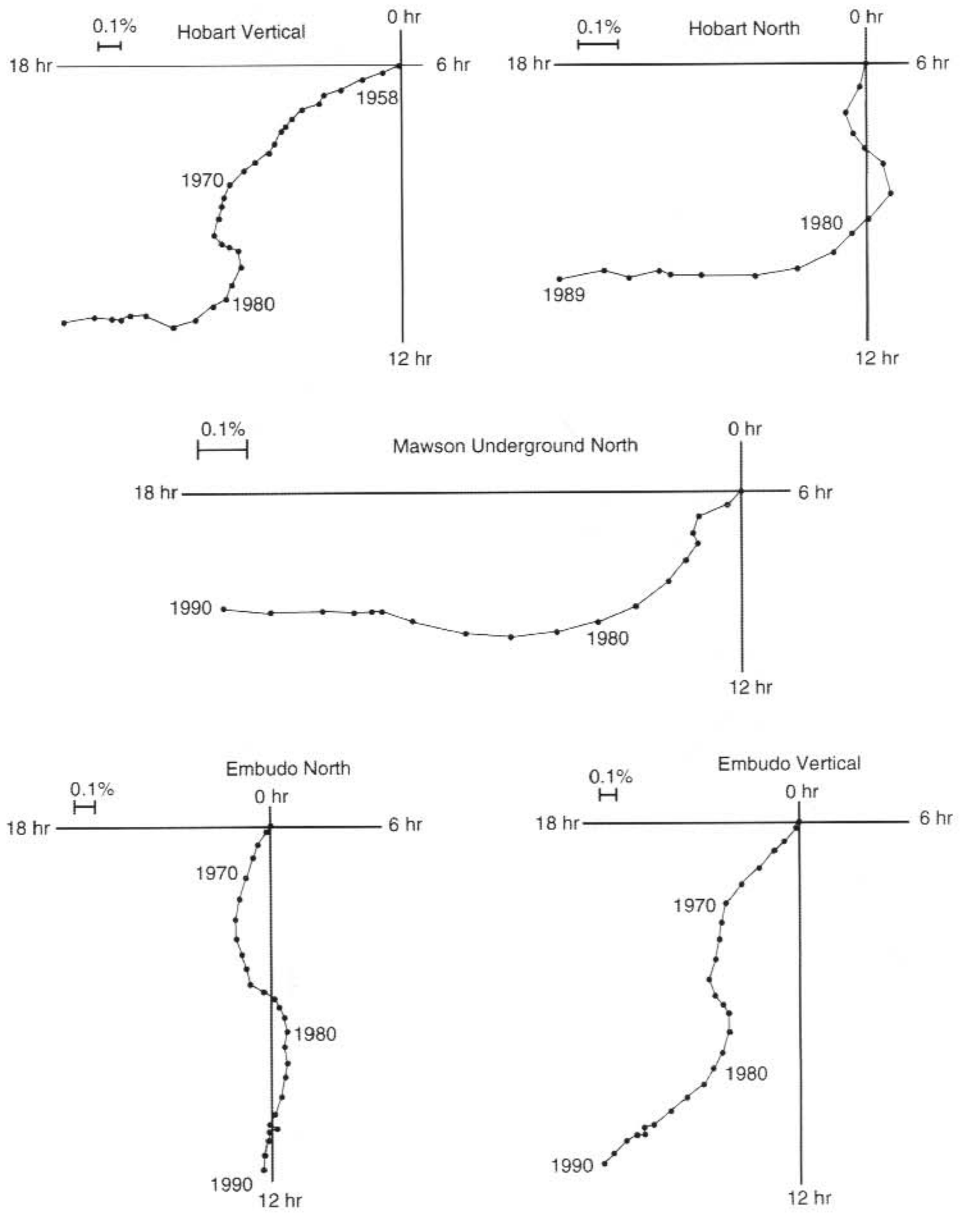

Figure 7. *Underground observations of the solar diurnal variation uncorrected for geomagnetic bending. The change of phase after each IMF reversal is clearly seen. The years of reversal are shown. It should be noted that the Mawson underground north telescope is unaffected by geomagnetic bending and shows the phases expected. Top left: Hobart vertical; Top right: Hobart north; Centre: Mawson north; Bottom left: Embudo north; and Bottom right: Embudo vertical.*

Forman and Gleeson (1975) neglected drift terms in their analysis but showed that the anisotropy should have an amplitude of 0.6%. Levy (1976) and Erdös and Kota (1979) included drifts in their later models and were able to show that the amplitude of the anisotropy should be given by:

$$0.6 \times \frac{1-\alpha}{1+\alpha}\ \%$$

where $\alpha = \frac{\kappa_\perp}{\kappa_\parallel}$
is the ratio of the perpendicular to parallel mean free path of the particles.

The apparent arrival direction of the anisotropy is also affected by drifts during the positive polarity state and the phase of maximum response shifts from 18 hours local solar time in the A<0 state to 15 hours in the A>0 state. Figure 7 shows observations of the solar diurnal anisotropy from a number of observatories. These observations are not corrected for geomagnetic effects but the change of phase is evident following each IMF reversal. The Mawson underground observations are unaffected by geomagnetic bending and show the expected phase variation quite dramatically.

An extended analysis of neutron monitor and muon telescope data yielded clear evidence of variations of the upper limiting rigidity and the spectrum of the solar diurnal anisotropy (Hall, 1995; Hall et al., 1997). These variations are shown in Figure 8. Clearly the amplitude of the anisotropy shows an 11 year solar cycle variation. The upper limiting rigidity also shows some evidence for an 11 year periodicity with a tendency for large values around solar maximum. The four very large values are likely to be unreliable as the χ^2 contours of the fit indicated a large range of possible solutions. It was also noteworthy that there was strong tendency for the spectrum to depend on the IMF polarity.

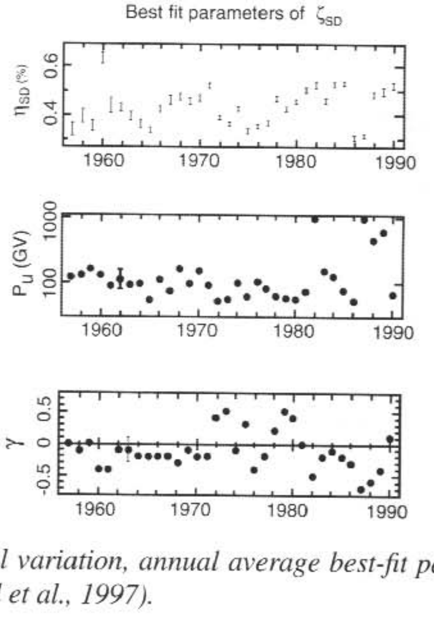

Figure 8. *Solar diurnal variation, annual average best-fit parameters. Typical 1σ errors are shown. (Hall et al., 1997).*

10.4 DERIVATION OF MODULATION PARAMETERS

10.4.1 Further development of modulation theory

In a landmark paper Bieber and Chen (1991) further developed the theory of cosmic ray modulation. They showed that

$$\overline{\lambda_{\|}G_r} = \frac{\frac{A_{SD}}{\delta A_1^1} G(P)\cos\left(\chi + t_{SD} + \delta t_1^1\right) + \eta_{ODV}\sin\chi + \eta_c\cos\chi}{\cos\chi}$$

where A_{SD} and t_{SD} are the annual average amplitude and phase of the solar diurnal anisotropy corrected to free space conditions by removing geomagnetic bending effects; χ is the angle of the IMF at the Earth (on average ~45°); η_{ODV} is the orbital Doppler effect; and δA and δt are coupling coefficients. Bieber and Chen (1991) also demonstrated that

$$G_{|Z|} = \frac{\text{sgn}(I)}{\rho}\left(\alpha\overline{\lambda_{\|}G_r}\sin\chi - \frac{A_{SD}}{\delta A_1^1} G(P)\sin\left(\chi + t_{SD} + \delta t_1^1\right) + \eta_{ODV}\cos\chi - \eta_c\cos\chi\right)$$

where

$$\alpha = \kappa_{\perp}/\kappa_{\|} = \lambda_{\perp}/\lambda_{\|}$$

$$\text{sgn}(I) = \begin{cases} +1, & A > 0 \text{ IMF polarity state} \\ -1, & A < 0 \text{ IMF polarity state} \end{cases}$$

All the parameters of these equations are known or available from observation except α. To separate the components $\lambda_{\|}$ and $\mathbf{G_r}$ we need an independent determination of one of them.

10.4.2 The North-South anisotropy

It is possible to derive the radial gradient, $\mathbf{G_r}$, from observations of the North-South anisotropy. This anisotropy is shown schematically in Figure 9. The anisotropy arises from a $\mathbf{BxG_r}$ flow of the cosmic ray flux. When the Earth is in one IMF sector the cosmic rays will gyrate in a clockwise sense. This is the configuration shown in the top half of Figure 9. The increasing density away from the Sun results in a smaller flux of particles arriving from the north than from the south. This is because the source of some of the particles arriving to the north is closer to the Sun than the corresponding southern arrivals from a denser cosmic ray region. When the Earth is in the opposite IMF sector the situation is reversed. This can be seen in the lower half of Figure 9 where the excess flux now arrives in the north.

There are two complicating factors to consider with this anisotropy. Firstly, the Earth's rotational axis is not aligned with the heliomagnetic equator and so observations from Earth which use north-south differences actually observe the north-south asymmetry which is related to the north-south anisotropy as shown in Figure 10. The other vector component shown in Figure 10 is a sidereal diurnal variation. This can be differentiated from any true sidereal anisotropy by its dependence on the IMF sector structure.

Secondly, the Earth's orbit is also inclined to the heliographic equator as shown in Figure 11 and this modifies very slightly the corrections to be applied for viewing direction. It should also be noted that this latter variation could result in seasonal changes related to any vertical density gradients that may be present.

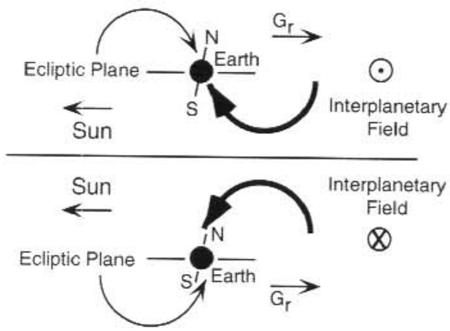

Figure 9. Schematic representation of origin of the North-South anisotropy and its dependence on the IMF direction.

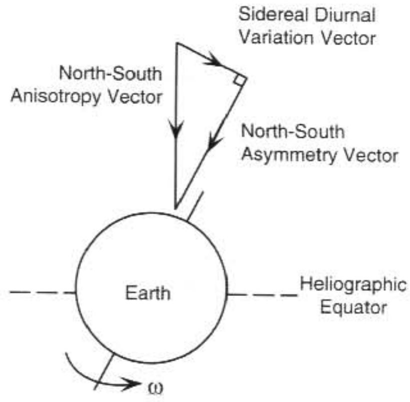

Figure 10. Geometric components of the the North-South anisotropy.

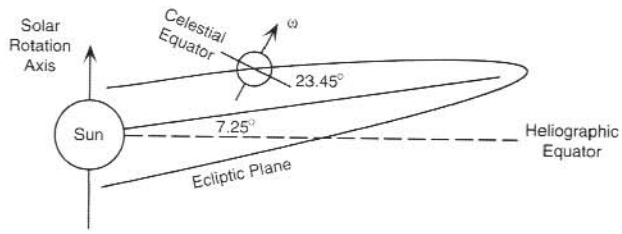

***Figure 11.** Orientation of the Earth's rotation axis to the heliographic equator.*

Thus there are a number of ways of observing the North-South anisotropy. One can take differences between northern and southern viewing telescopes from a single location taking into account the expected response. One can use the difference between northern and southern polar neutron monitors whose cones of view are appropriate (Chen and Bieber, 1993). Alternatively one can look at the sector dependent sidereal diurnal anisotropy, using differences between the response in toward and away sectors. The most recent studies have used the latter method to derive the radial gradient (Hall, 1995; Hall et al., 1994a, 1995a).

At various rigidities the gradient is related to the average annual difference in the North-South anisotropy for toward and away sectors by

$$G_r(P) \approx -\frac{\xi_{NS}^{T-A}(P)}{\rho \sin \chi}$$

where

ξ represents the anisotropy amplitude and ρ the particle gyroradius at rigidity P.

10.4.3 Sector dependent sidereal diurnal anisotropy observations

A number of recent studies have been published by local researchers deriving the radial gradient from observations of the sector dependent sidereal diurnal variation (Hall, 1995; Hall et al., 1994a, 1994b, 1995a, 1995b). Some of the results from these studies are shown in Figure 12. The four traces are harmonic dials from the Deep River neutron monitor, Mawson surface vertical muon telescope, Mawson underground north muon telescope and the Hobart underground muon telescope. All annual vectors are averages of toward minus away responses corrected for the spurious sidereal variation by the method of Nagashima et al. (1985). The error circles shown represent the error on each vector as determined by the scatter of daily vectors within the year. The studies included almost 200 detector years of observation from twelve telescope systems at eight locations across the globe.

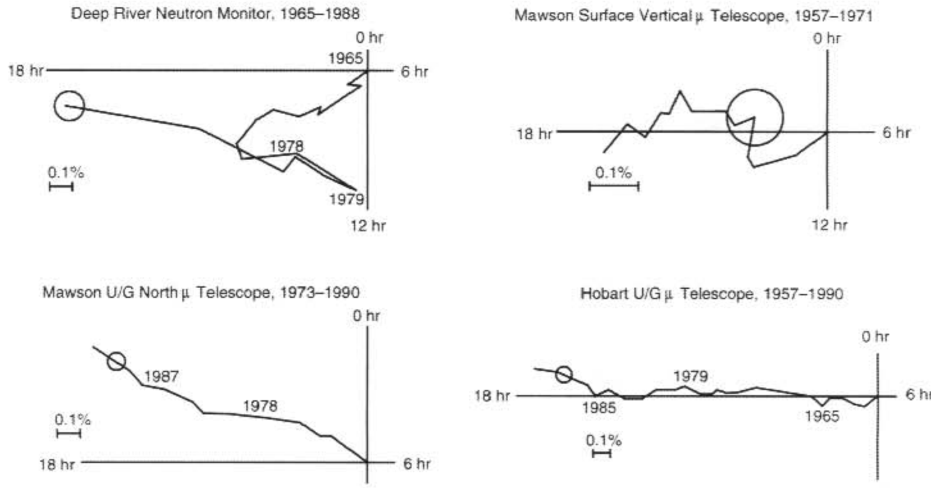

Figure 12. *Observed annual average toward-away sidereal diurnal vectors from a sample of stations. (Hall, 1995; Hall et al., 1994a, 1994b, 1995a, 1995b).*

10.4.4 Separation of $\mathbf{G_r}$ *and* $\lambda_{||}$

Using the formalism of Bieber and Chen (1991) and the observed solar diurnal anisotropy described above we obtain, $\overline{\lambda_{||}G_r}$, the average annual value of the combined modulation parameters. By employing the observations of the sector dependent sidereal diurnal anisotropy described above we can separate these parameters using the independent value of $\mathbf{G_r}$ at a range of rigidities. In Figures 13 and 14 we see the results of this analysis for the lowest and highest rigidities studied, 17 and 185 GV respectively. In these figures a value of α of 0.01 has been assumed but it was found that the picture did not change significantly with much greater values. This value was chosen for comparison with previous results (Bieber and Chen, 1991; Chen and Bieber, 1993).

The results from this and other studies indicate that the radial gradient has a small 11 year periodicity with higher values around solar maximum. There is no evidence for polarity dependence. (Chen and Bieber, 1993; Hall, 1995; Hall et al., 1994a, 1994b, 1996). The mean free path would appear to have an 11 year variation and a polarity dependence at all rigidities, being larger in the A<0 state. (Hall, 1995; Hall et al., 1994b, 1996, 1997).

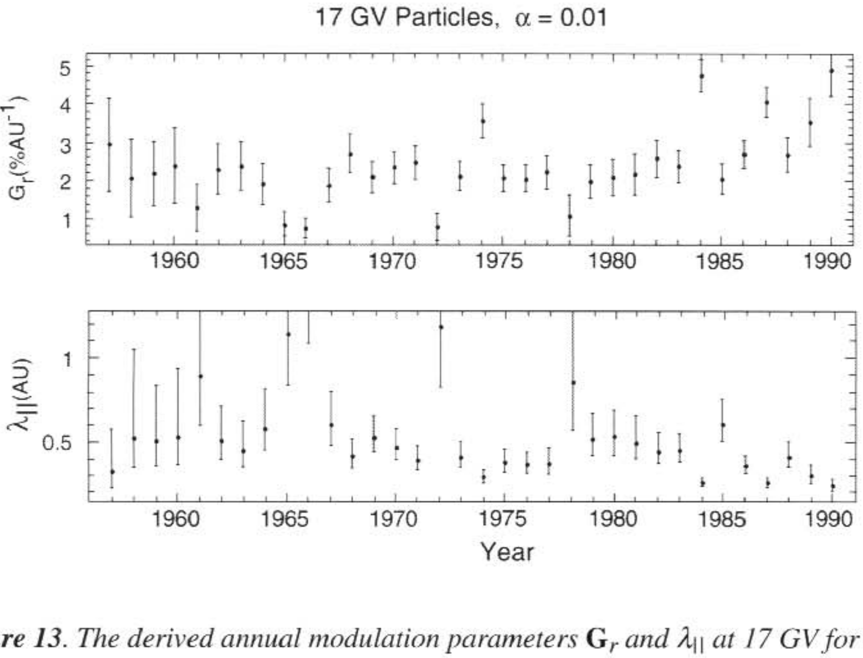

***Figure 13**. The derived annual modulation parameters* $\mathbf{G}_r$ *and* $\lambda_{||}$ *at 17 GV for the ratio of perpendicular to parallel diffusion,* $\alpha = 0.01$*. (Hall, 1995; Hall et al., 1995b, 1996).*

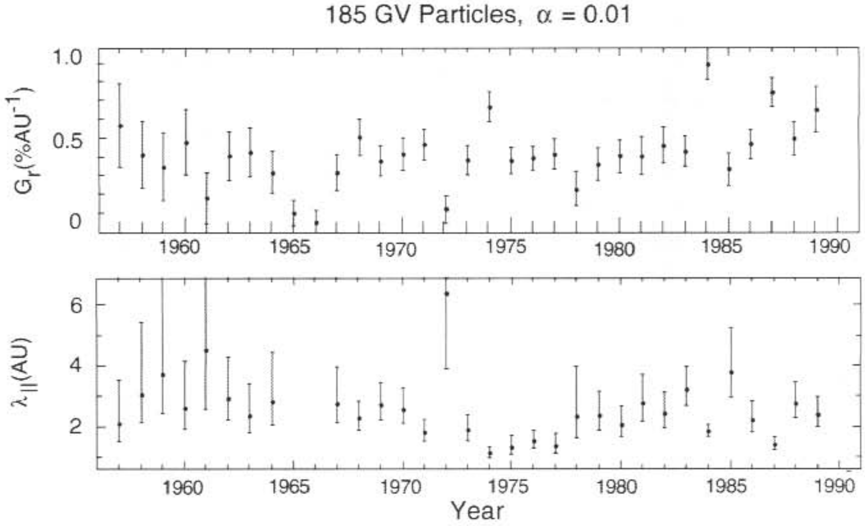

Figure 14. *The derived annual modulation parameters* $\mathbf{G_r}$ *and* $\lambda_{||}$ *at 185 GV for the ratio of perpendicular to parallel diffusion,* $\alpha = 0.01$. *(Hall, 1995; Hall et al., 1995b, 1996).*

10.4.5 The symmetric latitudinal density gradient, $G_{|Z|}$

We have seen above that the symmetric latitudinal gradient, $G_{|Z|}$, can also be determined from the observations. In Figure 15 the results of such an analysis are shown (Hall, 1995; Hall et al., 1994b, 1996, 1997). There is a clear polarity dependence with the sense of the gradient reversing from maximum at the neutral sheet (negative values) in the negative polarity state to minimum at the neutral sheet in the positive state (Hall et al., 1997). This agrees with the results of Bieber and Chen (1991), Chen and Bieber (1993) and others.

It is also clear that the polarity dependent changes still exist up to quite high rigidities represented by the Embudo and Hobart observations in the lower two panels.

These results have assumed an invariant spectrum of the solar diurnal anisotropy with $\gamma = 0$ and a fixed upper limiting rigidity of the modulation of 100 GV. Although these approximations are known to be invalid, the results are not sensitive to the known range of variation in these parameters. It does mean that caution must be applied to assumptions about the maximum rigidity at which $G_{|Z|}$ exhibits polarity dependent behaviour. A value of $\alpha = 0.01$ has also been assumed in this work. It has since become apparent that α may be 0.1. The results do not change at this value but begin to appear somewhat different when values of α significantly greater than 0.1 are employed.

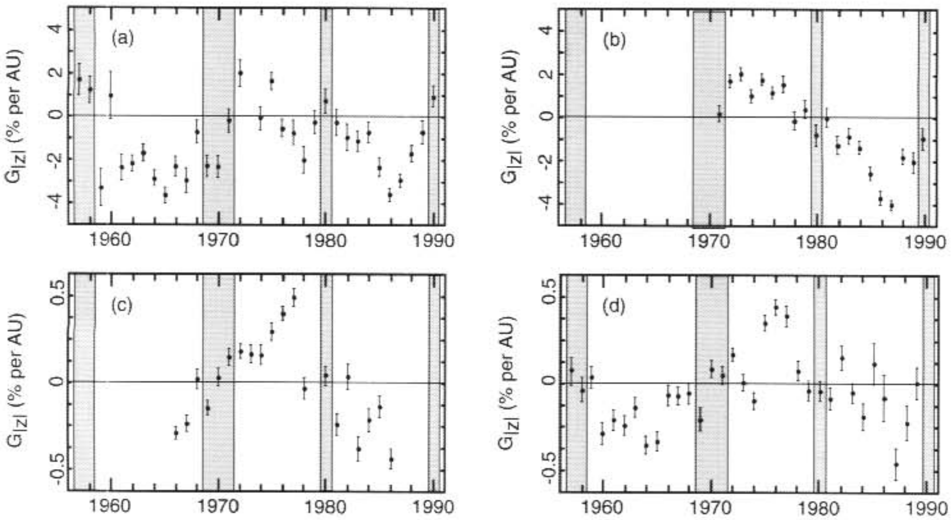

Figure 15. *Modulation parameter, $G_{|Z|}$, calculated from the solar diurnal variation recorded by:*

(a) Mawson neutron monitor (median rigidity ~17 GV) 1957–1990,

(b) Mt Wellington neutron monitor (median rigidity ~17 GV) 1965–1988,

(c) Embudo underground muon telescope (median rigidity ~135 GV) 1966–1985 and

(d) Hobart underground muon telescope (median rigidity ~185 GV) 1957–1989. (From Hall et al., 1997).

10.4.6 Derived limits for α.

Hall (1995) studied the possible limits on α that could be derived from his observational studies. He found that the values of α were polarity dependent. In the A<0 state he found that the maximum allowed value of α near 1 AU was probably rigidity dependent and that most instruments indicated $0.3 < \alpha < 0.4$. Conversely, in the A>0 state he found a strong rigidity dependence on the maximum allowable value of α ranging from 0.17 at 17 GV up to 0.91 at 195 GV. Bieber and Chen (1991) and Chen and Bieber (1993) found a similar polarity dependence and derived a maximum value of α of 0.16 for particles up to 17 GV.

In contrast to these results the work of Palmer (1982) implies a value of α between 0.02 and 0.08. Ip et al. (1978) estimated $\alpha = 0.26 \pm 0.08$ for particles above 0.3 GV and more recently Ahluwalia and Sabbah (1993) estimated that α must be less than 0.09.

There is clearly still much work to be done to resolve the controversy regarding the value of α and its variation.

10.5 SUMMARY

Although the structure of the heliosphere is not yet fully known and the location of the termination shock is still only a best estimate, modulation models have been fairly successful in explaining cosmic ray observations. The global features are now understood but a number of details remain to be explained.

The observed average rigidity spectrum of the solar diurnal anisotropy agrees well with modulation model predictions. This spectrum may depend slightly on the solar polarity state. The upper limiting rigidity has an 11 year periodicity.

The radial gradient shows 11 year solar activity cycle variations in agreement with theory. It is larger at times of solar maximum but shows no sign of polarity dependence. The bi-directional latitudinal gradient has a maximum at the neutral sheet during the $A<0$ polarity state and reverses in the $A>0$ state to a minimum at the neutral sheet. This is also in broad agreement with theory. This gradient appears to have its maximum values at times of solar minimum.

The parallel mean free path appears to have a polarity dependence which is not expected from current models. The evidence suggests a larger value in the negative polarity state. There is also an 11 year periodicity resulting in larger mean free paths at solar minimum as would be expected from the models.

The relationship between the perpendicular and parallel mean free paths is less clear. Contrary claims have appeared in the literature but it seems most likely that the ratio of these parameters is polarity dependent. There is no theoretical reason why this should be so. The ratio exhibits rigidity dependence in the positive polarity state and may do so in the negative state. The value of the ratio is still disputed and requires further study.

It is noteworthy that the predictions of modulation models have been found to be applicable up to rigidities an order of magnitude beyond those for which the models were developed. It should also be noted that the improved knowledge of the polar heliomagnetic field arising from the Ulysses spacecraft measurements will mean further development and refinement to the models. There is still the prospect of model improvements by inclusion of a realistic neutral sheet and fully dynamic three dimensional representations of the field. The future is full of promise.

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11. THE STATUS OF GROUND LEVEL ENHANCEMENT MODELLING

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ABSTRACT

Cosmic Ray Ground Level Enhancements are increases in the count rate of ground-based instruments due to solar-accelerated particles. The particle rigidity spectra and arrival distributions can be deduced by analysis of data from a world-wide network of detectors. The development of models of the ground level response is briefly reviewed culminating with the most recent work done by the University of Tasmania and the Australian Antarctic Division.

The particle spectra and pitch angle distributions derived from the model provide information about particle acceleration processes and the propagation characteristics of the interplanetary medium. The derived spectral forms have been found to be largely consistent with theoretically determined shock acceleration spectra. The form of the fitted pitch angle distributions allow rigidity dependence and bi-directional flow to be investigated. Several interesting results are presented, including backscattering of particles from beyond the Earth and the effect of an unusual interplanetary magnetic field configuration when a magnetic-cloud like structure had just passed the Earth.

11.1 INTRODUCTION

Enhancements in ground level cosmic ray intensity occasionally arise due to detection of solar accelerated particles. There have been 53 such events since reliable records began in the 1940's. The largest of these occurred on 23 February 1956 when intensities ~45 times the pre-event background were observed. Although the long-term average occurrence rate is only about one per year, there was an unprecedented series of 13 ground level enhancements (GLE's) within two years during the last solar maximum period.

Solar acceleration mechanisms are not well understood. GLE's have traditionally been linked with visible solar flares, however it seems increasingly likely that the particle acceleration process is associated with coronal mass ejections (CME's) rather than flares. CME's may occur without a visible solar flare, however solar particle events of sufficient energy to be recorded at Earth are usually accompanied by flare activity.

Charged particles propagating away from the Sun follow the interplanetary magnetic field. The field has an Archimedean spiral form. Under nominal conditions, the field line intersecting Earth has a footpoint ~60° W on the solar disk (see Figure 1). Solar accelerated particles must gain access to this field line if they are to be observed at Earth. Thus it is unusual to observe particles associated with activity east of central meridian.

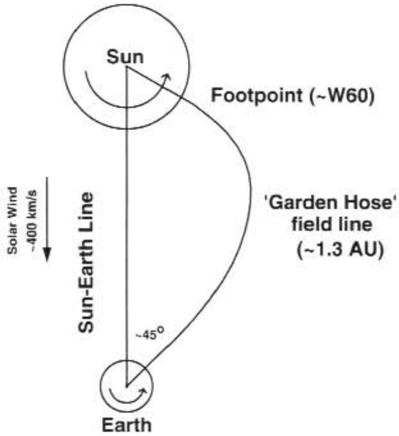

Figure 1. Schematic representation of the 'garden hose' field line from the Sun to the Earth (from Duldig, 1994).

11.2 MODELLING

11.2.1 Geomagnetic effects

Particles approaching Earth encounter the geomagnetic field. Given an accurate mathematical model of the field, particle trajectories can be traced to locations on the surface of the Earth. It is more practical to begin calculations at the site of each ground level detector and trace the path of particles moving away from the detector. Particles of the same rigidity (momentum per unit charge) but opposite charge will follow the same path through the field as particles arriving from the Sun. Rigidity-dependent 'viewing directions' can thus be determined for each instrument. These are commonly called asymptotic directions of approach (McCracken et al., 1962, 1968) and represent the directions from which particles must enter the geomagnetic field in order to be detected by the particular instrument. In many cases it is sufficient to consider only those particles arriving with vertical incidence at the detector. This has been shown to be unsatisfactory when modelling extremely anisotropic events (Cramp et al., 1995). The region of space above the monitor can be divided into nine regions of equal galactic cosmic ray contribution. Asymptotic directions determined for particle arrival at the centre of each of these regions then give a better representation of the 'viewing directions' of the monitor.

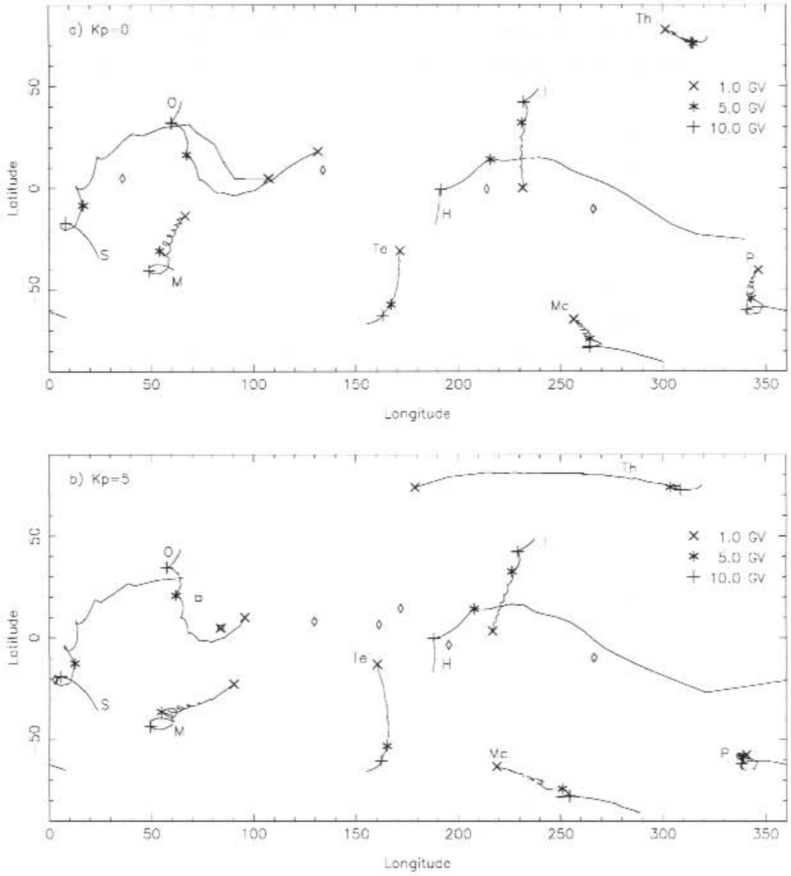

Figure 2. *Viewing directions at 1805 UT on 22 October 1989 under a) quiet (Kp=0) and b) disturbed (Kp=5) geomagnetic conditions. Sanae S and □; Mawson M; Oulu O; Terre Adelie Te; Hobart H and ◊; Inuvik I; McMurdo Mc; Thule Th; South Pole P. The viewing directions at 1, 5 and 10 GV are indicated by ×, ∗ and + respectively.*

Some calculated trajectories do not escape from the field. These are said to be re-entrant and indicate that the site is not accessible along the trajectory for particles of that rigidity. For a particular arrival direction at the monitor there is a limiting rigidity (geomagnetic cut-off) below which particles can not gain access. Above this rigidity there may be a penumbral region in which particles of some rigidities cannot gain access (Cooke et al., 1991). Geomagnetic cut-off rigidities range between zero at the poles and ~14 GV at the magnetic equator.

The internal geomagnetic field can be well modelled by a series of spherical harmonic functions known as the International Geomagnetic Reference Field (IGRF) (IAGA Division 1, Working group 1, 1992). The geomagnetic field is distorted by current systems resulting from the flow of the solar wind. These cause compression of the field on the sunward side and an extended tail on the anti-sunward side. This distortion must be taken into account when modelling the viewing directions of neutron monitors. Tsyganenko (1987, 1989) developed models of the external geomagnetic field for different degrees of distortion indicated by the Kp geomagnetic index (Menvielle and Berthelier, 1991). Flückiger and Kobel (1990) combined these models with the IGRF and developed software to determine particle trajectories through the field. Thus we can determine viewing directions for all neutron monitors appropriate to the level of geomagnetic disturbance at the time of interest.

Figure 2 shows a comparison of the rigidity dependent viewing directions of several stations under geomagnetically quiet (Kp = 0) and moderately disturbed (Kp = 5) conditions. The differences are most pronounced at polar stations, but are also evident at mid-latitudes. The viewing directions of such stations span a wider range of longitudes under the disturbed conditions. The distorted field also leads to lower geomagnetic cut-off rigidities at some stations.

11.2.2 Neutron monitor response

The response of a neutron monitor to particles arriving at the top of the atmosphere can be described by the following equation.

$$N = \sum_{P_{min}}^{P_{max}} Q(P)J(P)S(P)G(\alpha)\Delta P \qquad (1)$$

where

N is the count rate
Q is 1 for accessible arrival directions, 0 otherwise
P is rigidity
P_{min} is the cutoff rigidity
P_{max} is the highest rigidity present
J is the particle rigidity spectrum
S is the yield function
G is the particle pitch angle distribution and
α is the pitch angle.

Q is defined by the viewing direction calculations described in the previous section. The yield function (S) depends on rigidity and accounts for attenuation due to particle interactions with atmospheric nuclei. Such interactions result in an atmospheric cut-off rigidity of ~1 GV. This value is used as P_{min} for stations with geomagnetic cut-off below 1 GV. For galactic cosmic rays, J is the modulated galactic cosmic ray spectrum (Badhwar and O'Neill, 1995) and the pitch angle distribution (G) is isotropic. For solar particles, J and G are unknown and must be represented by functional forms appropriate to the physical processes involved in particle acceleration and propagation. These functions need to be of parametric form so that the spectrum and pitch angle distribution can be adjusted to reproduce the conditions of any given event.

Equation 1 can be used to calculate predicted neutron monitor increases for any given solar particle spectrum and pitch angle distribution. When modelling a particular event, a test spectrum and pitch angle distribution must be used to compute responses. The calculated responses are then compared with the observed increases and the spectrum and pitch angle distribution adjusted to provide better agreement. This iterative process must continue until the spectrum and pitch angle distribution are refined sufficiently that the predicted increases agree satisfactorily with the observations. In general, the spectrum may be described by one or two parameters. The pitch angle distribution may require many more parameters depending on the complexity of its shape, however most simple distributions can be described by one or two parameters for the shape and another two parameters for the axis of symmetry. Hence, the model requires adjustment of at least four parameters to successfully determine the particle rigidity spectrum, the pitch angle distribution and its axis of symmetry. If this process is to be done 'by hand', there is very little scope for introducing further complexities into the model as the task of adjusting parameters becomes impractical. Introduction of a least squares procedure has made the determination of the best fit parameters much easier. More complex functional forms may be introduced into the model allowing investigation of unusual propagation characteristics. The nature of least squares fitting is such that one must be careful that the derived solution is indeed the best-fit and not simply a local minimum in parameter space. It is advisable to choose several widely varying sets of initial parameters and ensure that each converges to the same final solution.

Recent improvements of the model have allowed bi-directional flow and rigidity dependence to be incorporated into the pitch angle distribution functions. A deficit cone associated with a disturbed region in the interplanetary medium has also been modelled. This is discussed in Section 11.3.3.

11.3 INTERPRETATION OF RESULTS

The form of the particle rigidity spectrum is related to the acceleration process. Power law and exponential forms are often used to model solar particle spectra but are sometimes inadequate. Modification of the power law to allow steepening with increasing rigidity is often necessary to satisfactorily reproduce observed increases (Cramp, 1996). Ellison and Ramaty (1985) derived theoretical shock acceleration spectra which are very similar to the modified power law forms. This is consistent with acceleration related to coronal mass ejections as these are associated with coronal and interplanetary shocks.

The particle pitch angle distribution results from the combined effects of adiabatic focusing and diffusion as the particles propagate through the interplanetary medium. Thus the modelled distribution provides information about the propagation characteristics of the medium. Rigidity dependence in the shape of the distributions may be related to rigidity dependent scattering conditions or access to the interplanetary magnetic field (IMF) line to Earth. Bi-directional particle flow may indicate the presence of looped magnetic field structures or preferential scattering of particles back towards Earth by a structure beyond 1 AU.

The following sections outline some interesting results which illustrate the modelling technique discussed above. In all cases five minute neutron monitor data were used in the models. Quoted modelling times are the start of the five minute interval.

11.3.1 29 September 1989

The GLE which occurred on 29 September 1989 was the largest recorded since 1956 with an increase in excess of 400% at the Calgary neutron monitor. Neutron monitor increases were observed even at equatorial locations such as Darwin, indicating the presence of particles of at least 14 GV. Swinson and Shea (1990) reported an increase at the Embudo underground muon telescope which has a threshold rigidity of ~19 GV. Data from underground muon telescopes at Mawson and Hobart (threshold ~30 GV) showed no evidence of the event. These observations are consistent with a maximum upper rigidity of ~25 GV for particles in this event. It is very unusual for solar accelerated particles of such high rigidity to be present in significant numbers.

Figure 3 shows the response at several neutron monitors. It is interesting to note the different intensity-time profiles evident in this figure. In particular, several stations recorded two peaks in intensity while others observed a single peak at one of the two peak times. Modelling has been undertaken at the time of the two peaks and also at one time later in the event.

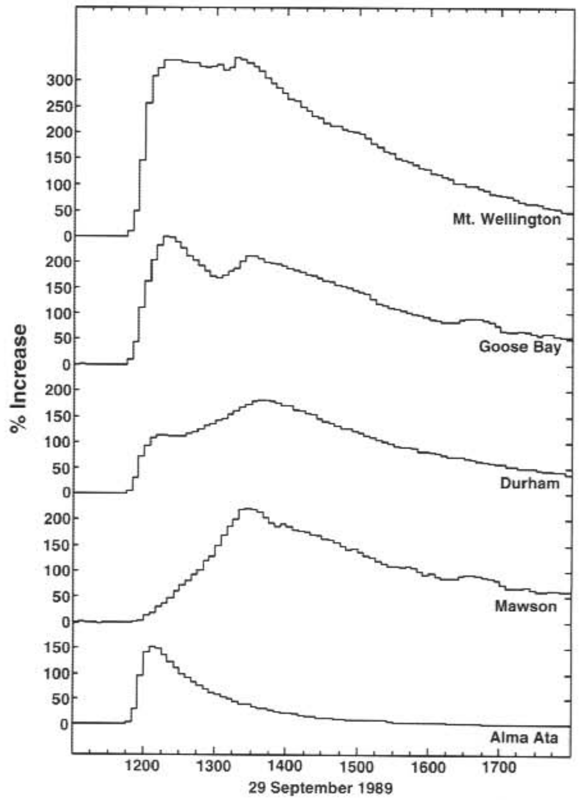

Figure 3. *Cosmic ray increases at Mt Wellington, Goose Bay, Durham, Mawson and Alma-Ata neutron monitors between 1100 and 1800 UT on 29 September 1989.*

The derived pitch angle distributions are shown in Figure 4. A rigidity dependent distribution was modelled for 1215 UT (left-hand plot). This indicates that the low rigidity particles had a more anisotropic distribution. It had been expected that any rigidity dependence in modelled pitch angle distributions would be due to low rigidity particles being more affected by scattering in the interplanetary medium. This was found to be true for some GLE's (Cramp, 1996), however the rigidity dependence was in the opposite sense early in this event. In this case, the rigidity dependence may be related to particle access to the field line connected to Earth, rather than scattering in the interplanetary medium. Higher rigidity particles have larger gyroradii and hence may gain access to field lines further from the acceleration site. This may lead to a population of high rigidity particles propagating with large pitch angles. No significant rigidity dependence was found in pitch angle distributions modelled later in the event.

The modelled pitch angle distribution at 1325 UT (the time of the second peak in neutron monitor data) shows some evidence of enhancement at 180° pitch angle. This may be due to preferential scattering of particles from a region beyond the Earth. The fitted pitch angle distribution at 1600 UT shows that scattering had become more uniform by this time resulting in a smaller anisotropy superimposed on an isotropic background.

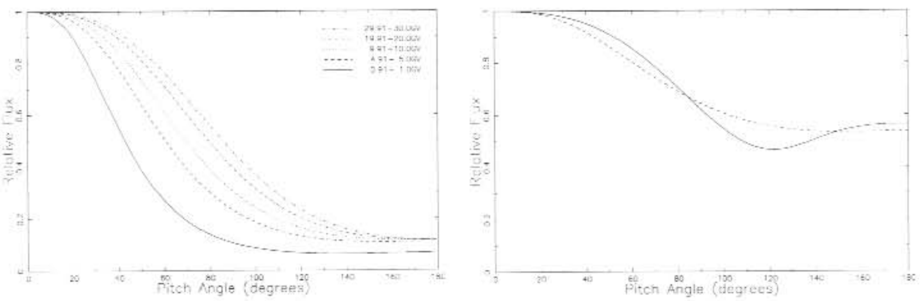

Figure 4. *Rigidity dependent pitch angle distribution derived for 1215 UT on 29 September 1989 (left). Rigidity independent pitch angle distributions derived for 1325 UT (solid line) and 1600 UT (dashed line) during the same GLE (right).*

Two peaks in the neutron monitor data during this event can be explained by the enhancement of particle intensity around 180° pitch angle. This has been interpreted as back-scattering of particles from beyond the Earth. Stations which viewed towards the local IMF line recorded a single peak early in the event, while those viewing away from the Sun (e.g. Mawson) recorded a slow rise in intensity and a later maximum. Stations viewing a wide range of directions (e.g. mid-latitude stations) both near the local IMF direction and >90° away from it recorded two distinct peaks in intensity.

11.3.2 22 October 1989

The GLE of 22 October 1989 was the second in a sequence of three events and occurred during the recovery phase of a Forbush decrease. The cosmic ray profile was unusual and varied significantly between stations. Six neutron monitor stations observed a very narrow (<20 minute) spike preceding the main event. In the case of McMurdo, the intensity of the spike was nearly five times the maximum intensity of the main GLE. Figure 5 shows the cosmic ray profiles of the stations which observed the spike. The peak of the main event did not occur at the same time at all stations. Most reached their maximum within the half hour from 1830 UT to 1900 UT, with some exhibiting two distinct maxima. Data from some stations which did not observed the spike are shown in Figure 6. The timescale is the same as for Figure 5.

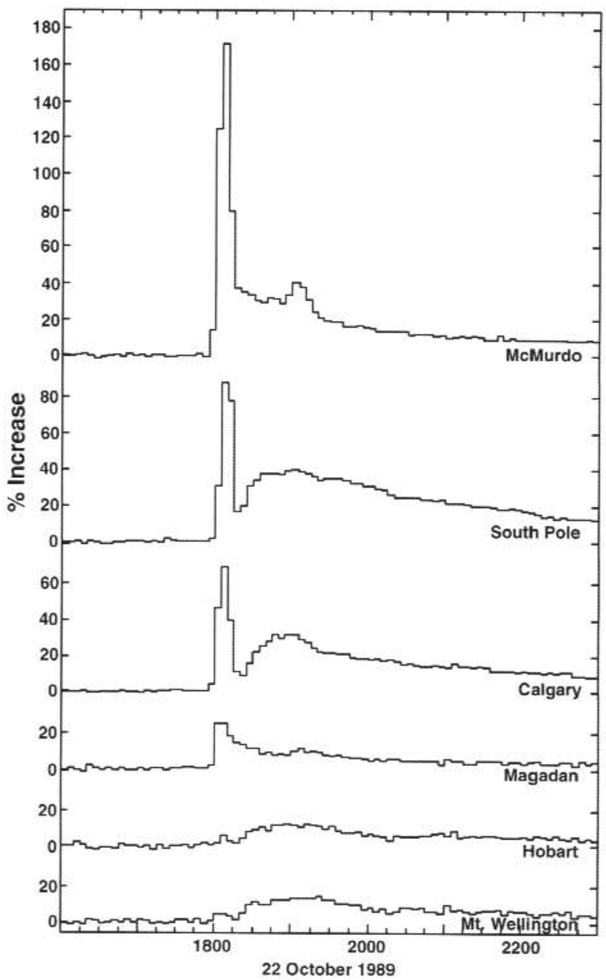

Figure 5. *Cosmic ray increases at McMurdo, South Pole, Calgary, Magadan, Hobart and Mt Wellington neutron monitors between 1600 and 2300 UT on 22 October 1989.*

The modelled pitch angle distributions for eight times during the GLE are shown in Figure 7. It is clear that the initial particle distribution was extremely anisotropic. Later in the event there were significant contributions from pitch angles greater than 90°. Bi-directional flow was evident between 1830 and 1850 UT. At these times the flow of particles from the Sun was still quite anisotropic. The cause of the bi-directional flow is probably back-scattering from a region of disturbed plasma located beyond the Earth.

Such a region was observed to pass the Earth ~2 days prior to the GLE. The timing of the passage of this structure indicates that it probably extended from 1.8 to 3 AU at the time of this GLE. This location is consistent with the time delay between the spike and the first observation of back-scattered particles.

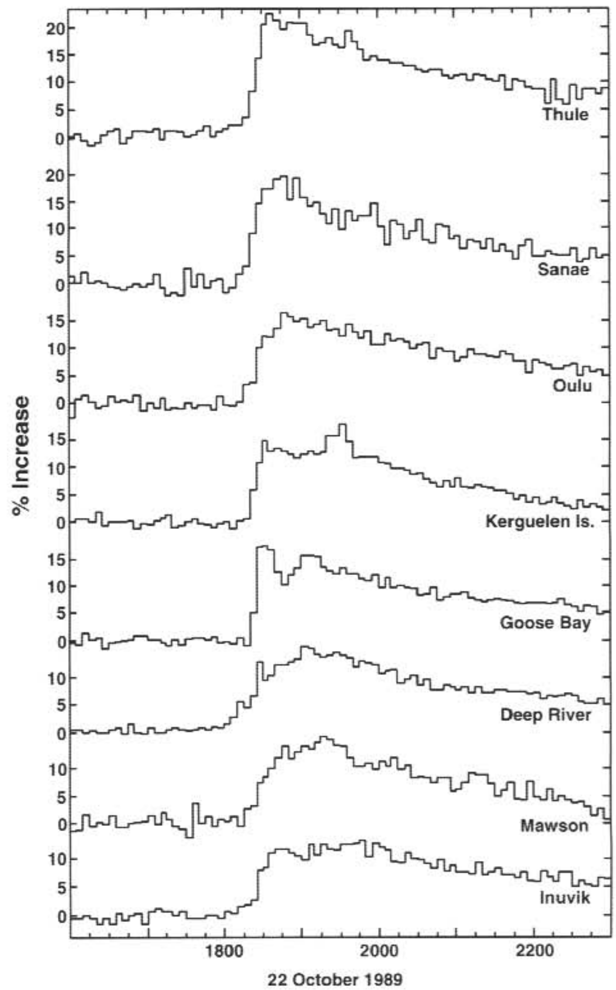

Figure 6. *Cosmic ray increases at Thule, Sanae, Oulu, Kerguelen Island, Goose Bay, Deep River, Mawson and Inuvik neutron monitors between 1600 and 2300 UT on 22 October 1989.*

The particle rigidity spectrum was modelled as a modified power law which allowed the spectral slope to increase at higher rigidities. This form is comparable with shock acceleration spectra determined by Ellison and Ramaty (1985). The spectrum softened during the main event, however, there is some indication that the spectrum of the initial spike was softer than at the start of the main event.

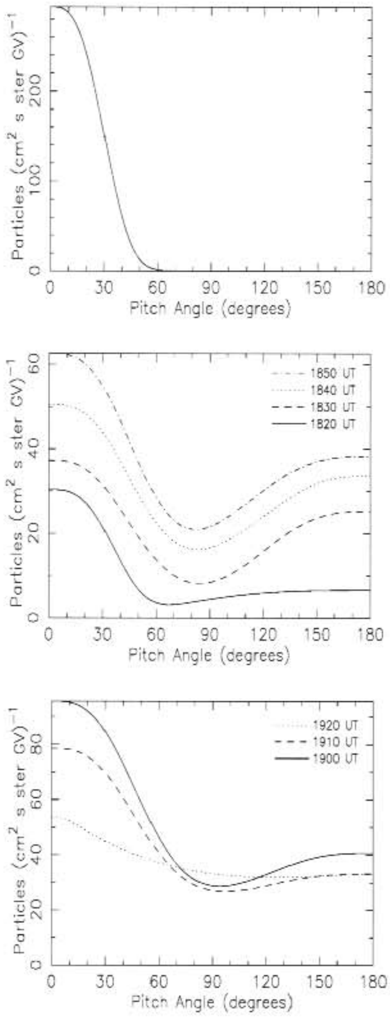

Figure 7. *Derived particle pitch angle distributions for 1805 UT (top), 1820, 1830, 1840 and 1850 UT (middle) and 1900, 1910 and 1920 UT (bottom), 22 October 1989. The plots are scaled so that the flux in the forward steradian is equal to that derived in the model at 1 GV. The shape of the pitch angle distributions was assumed to be independent of rigidity.*

Several scenarios have been considered to explain the unusual time profile of this event (Cramp et al., 1996). The most logical of these appears to be an initial anisotropic particle injection followed by an extended period of shock acceleration. The highly anisotropic pitch angle distributions indicate that the particles propagated through a region where adiabatic focusing dominated over diffusion. A significant contribution was also made by particles back-scattered from beyond the Earth. A high field-strength, turbulent plasma region is thought to be responsible for the scattering.

11.3.3 7–8 December 1982

A GLE began around 2350 UT on 7 December 1982. Responses at neutron monitors peaked at various times between 0000 UT and 0030 UT. It can be seen from the data plotted in Figure 8 that some stations (e.g. Kerguelen Island and Alert) recorded a very rapid increase with a narrow peak while other stations (e.g. Deep River and Goose Bay) recorded similarly fast onsets but slower decays. A third group of stations (e.g. Apatity, Oulu and Inuvik) displayed a slower rise to maximum intensity, peaking 15–30 minutes after those with the rapid onset.

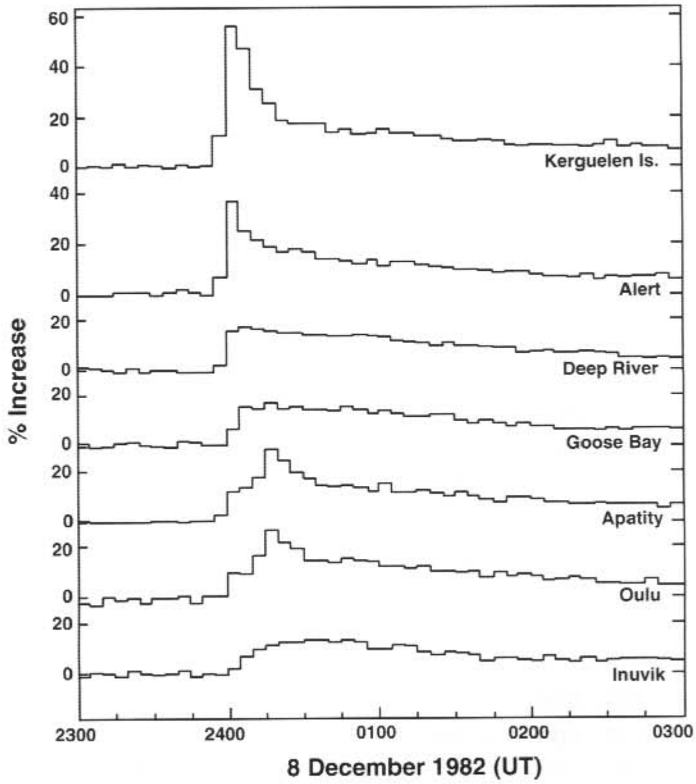

Figure 8. *Cosmic ray increases at Kerguelen Island, Alert, Deep River, Goose Bay, Apatity, Oulu and Inuvik neutron monitors between 2300 UT, 7 December 1982 and 0300 UT, 8 December 1982.*

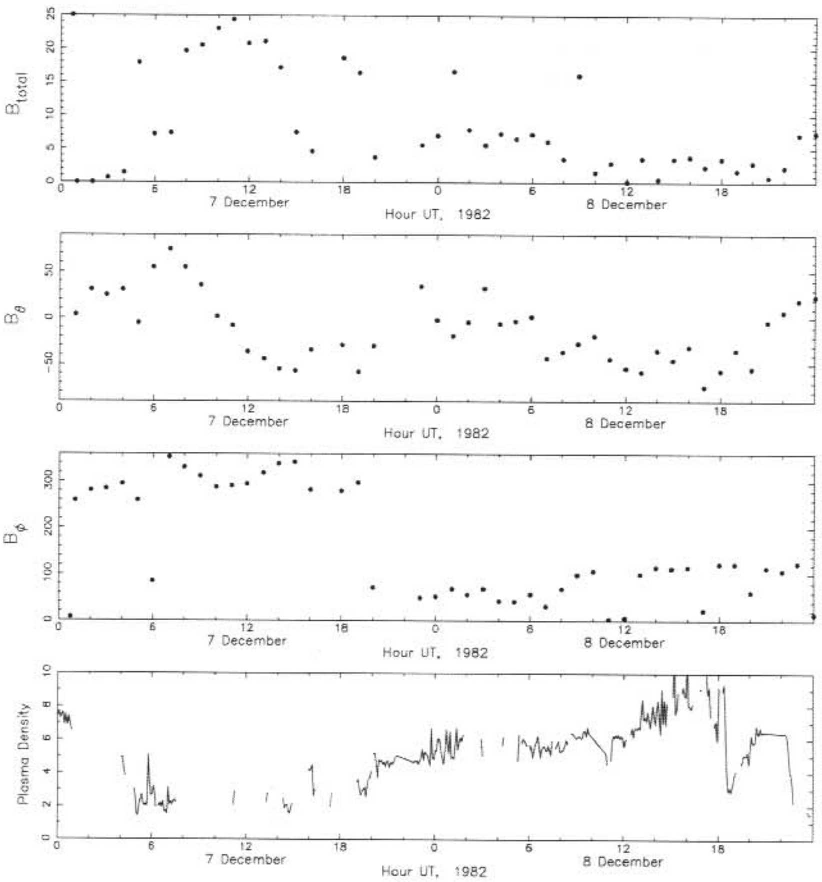

Figure 9. *Interplanetary magnetic field magnitude (top panel), latitude (second panel), longitude (third panel) in GSE coordinates and plasma density (bottom panel) for 7 and 8 December 1982.*

A moderate geomagnetic storm (Kp = 6+) occurred during 7 December, but the Kp index had reduced to 4 by the time the GLE began. The IMF direction measured at IMP8 was ~110° west of the Sun-Earth line. This means that the field was either looped back towards the Sun or kinked from its nominal position and locally approaching from ~70° east of the Sun-Earth line. The hourly average IMF magnitude, latitude and longitude in GSE coordinates and five minute average measurements of the plasma density for 7 and 8 December 1982 are plotted in Figure 9. This shows a smooth rotation of the field latitude between ~0500 and 2300 UT on 7 December. At the same time, the field strength was high (~20 nT) and the plasma density was low. High field strength accompanied by a rotation in the field direction and low plasma temperatures indicate the presence of a magnetic cloud (Burlaga, 1991). Plasma temperature data are not available for this time but the sudden depression of plasma density suggests a discontinuous plasma regime which could be a magnetic cloud. The geomagnetic disturbance which occurred during 7 December also indicates the presence of a disturbed plasma region moving past Earth. The propagation of this feature from the Sun was probably the cause of the unusual field direction observed at the time of the GLE. Such a structure will affect particle propagation towards Earth. This is particularly important early in the event when it was still very close to Earth.

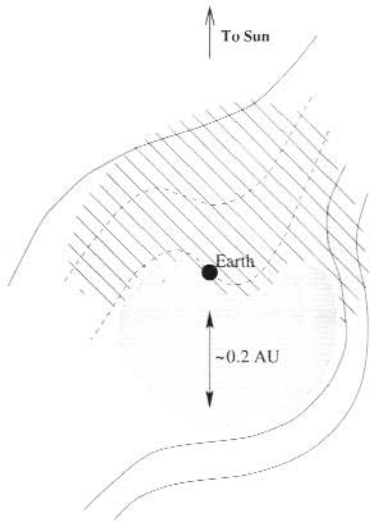

Figure 10. *Possible field configuration at the time of the 7–8 December 1982 GLE. The shaded region is a discontinuous plasma structure and the hatching represents a turbulent magnetic field region behind this feature. Possible field lines have been drawn with dashed lines to produce the observed field direction ~110° west of the Sun-Earth line.*

Figure 10 shows a possible IMF configuration which could have produced the observed field direction at Earth. The shaded area represents a discontinuous plasma region. The radial dimension of this feature has been estimated from the solar wind speed and the length of time it took to pass Earth. The timing also indicates that it was ~0.01 AU beyond Earth at the start of the GLE. The hatching represents a region of turbulent magnetic fields behind the propagating plasma. Some possible field lines have been drawn in this region (dashed lines). These would produce the observed field direction which persisted for some time at Earth. The likely shape of the plasma structure is unclear, but the measured interplanetary magnetic field direction at Earth is consistent with a situation such as that shown in the figure.

The standard GLE model applied to responses at 0000 UT substantially over-estimated increases at Apatity, Oulu, Durham and Tsumeb, while the response at stations such as Deep River, Kiel, Leeds, Moscow and South Pole was under-estimated. The rigidity dependent viewing directions of some of these stations are shown in Figure 11 along with the measured interplanetary magnetic field direction (solid circle) and the best fit particle arrival direction (diamond). Different line styles have been used for those stations whose response was over- or under-estimated by the model (see figure caption for details). Note that the response at one station must be fixed in order for absolute fluxes to be determined. The viewing direction of this station is also indicated in Figure 11. The measured IMF direction was chosen as the initial particle arrival direction for the least squares routine. It can be seen that the fitted particle arrival direction moved to the north and east to minimise the predicted response at Apatity and Oulu. This resulted in low calculated responses for many other stations. The derived pitch angle distribution was also much narrower than expected considering the turbulent magnetic fields surrounding Earth.

It appears that if the particle arrival direction is to be aligned with the measured IMF direction, there must be a deficit cone in the region of space viewed by Apatity and Oulu. This has been modelled by suppressing the response in an ellipse of variable size and orientation. The centre, eccentricity, orientation and length of one axis of the ellipse were variable parameters in the modified model. A sixth parameter was the factor by which contributions from inside the ellipse were attenuated.

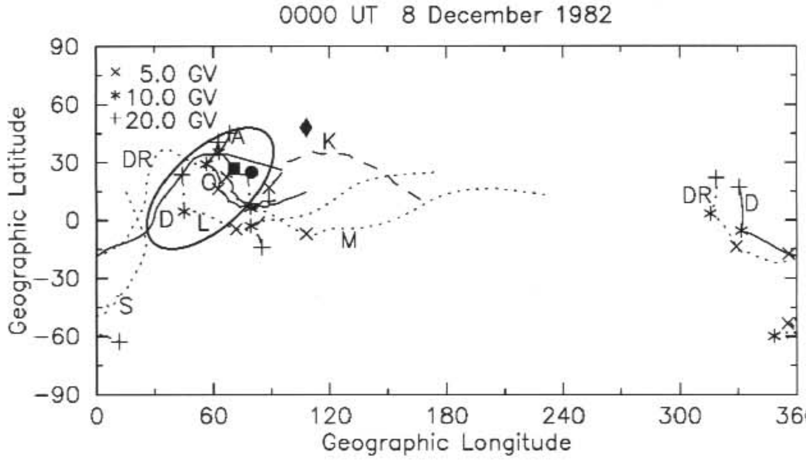

Figure 11. *Viewing directions for Apatity (A), Deep River (DR), Durham (D), Kerguelen Island (K), Leeds (L), Moscow (M), Oulu (O) and South Pole (S) for 0000 UT on 8 December 1982, rigidities from 20 GV to the station cutoff. Viewing directions at 20, 10 and 5 GV are indicated. Stations whose response was over-estimated by the standard model are shown with solid lines, those which were under-estimated are shown with dotted lines and the normalisation station is shown with a dashed line. The measured IMF direction is marked with a solid circle and the fitted particle arrival direction with a diamond. The best fit deficit ellipse in the modified model is shown along with the apparent particle arrival direction derived from this model (square).*

The best fit ellipse is shown in Figure 11 along with the new apparent particle arrival direction (square). The multiplicative factor derived for inside the ellipse was 3.0×10^{-2}. The apparent particle arrival direction was within 10° of the measured IMF direction. Many of the previously poorly modelled responses were significantly improved by this model. Specifically, the calculated response at Apatity reduced substantially, while at Durham, Oulu and Tsumeb, smaller improvements were made. The calculated responses at Deep River, Kiel, Leeds and Moscow were all much closer to the observed values and the response calculated for South Pole increased a little.The presence of the modelled deficit cone is probably associated with the plasma structure situated ~0.01 AU beyond Earth early in the event. The local IMF line suggested in Figure 10 passed very close to this region before reaching Earth. Particles gyrating around this field line with sufficiently large gyroradii may be deflected away from Earth due to discontinuities in the magnetic field. This could produce a deficit region on the anti-sunward side of the local IMF line. A larger portion of the modelled ellipse was located on the anti-sunward side of the particle arrival direction.

The model described above is much simpler than the physical reality. Clearly the size and shape of the deficit region will depend on rigidity since it is, in part, the gyroradius of the particles which determines whether they pass close enough to the plasma feature to be deflected away from Earth. It is probable that the deficit region would be smaller at low rigidities since these particles have smaller gyroradii and are therefore more likely to follow the field line to Earth. Another major simplification is that the attenuation factor applied inside the ellipse was constant over the whole region. This produces a 'well' with sharp edges which will not occur in reality. Further elaboration of the model is not practicable given the extra parameters required and the small number of stations viewing the relevant region of space.

It may be expected that the effects of the plasma feature would still be evident later in the event. The standard model gave satisfactory results for 0015, 0020 and 0050 UT indicating that there was no significant deficit cone at these times. The structure would have only moved a further ~0.002 AU away from Earth between 0000 and 0015 UT. The strength of the field through which the particles were moving as they approached Earth was ~7–8 nT. The gyroradii of 1-3 GV particles in such a field is comparable to the distance through which the structure would have moved, so it is likely that fewer of these particles would be deflected away from Earth than at 0000 UT. Higher rigidity particles would still be affected, but to a lesser extent than before. The spectrum fitted for 0015 UT steepened significantly with increasing rigidity. It is possible that this is a compensation for a deficit cone at high rigidities. It should also be noted that significant scattering would occur in the turbulent region surrounding Earth so the deficit cone may be expected to fill rapidly.

11.4 CONCLUSIONS

The ground level response to solar particle events can be successfully modelled using functional representations of particle pitch angle distributions and rigidity spectra, combined with calculated asymptotic viewing directions. The Tsyganenko (1989) representation of the geomagnetic field and software developed by Kobel (1989) allow the determination of viewing directions for appropriate levels of geomagnetic disturbance. A least squares method for finding the best fit parameters removes the trial and error of adjustment 'by hand', but steps must be taken to avoid finding local minima in parameter space.

Rigidity dependence and bi-directional flow in the pitch angle distributions can be modelled. These features provide information about the propagation characteristics of the interplanetary medium as well as the structure of the local interplanetary magnetic field. Particle rigidity spectra have been found to be consistent with shock acceleration. This is in agreement with the idea that coronal mass ejections (which drive coronal shock waves) are important in the acceleration of solar energetic particles.

11.5 ACKNOWLEDGMENTS

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12. NEW IDEAS CONCERNING SOLAR-TERRESTRIAL RELATIONS

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ABSTRACT

This paper reviews the various observations which support the idea that coronal mass ejections rather than flares play the dominant role in solar-terrestrial relations. A brief history of early observations which suggested a primary role for flares is also provided. Particular emphasis is placed on the origin of solar energetic particles.

12.1 INTRODUCTION

Solar-Terrestrial Physics has undergone a change as it has become widely recognised that the long-held belief in a central role for solar flares is not tenable. Rather than flares it is coronal mass ejections (CMEs) which play the central role. CMEs and the interplanetary shocks which they drive are responsible for large, non-recurrent geomagnetic storms, for major energetic particle enhancements and for short-term decreases in the cosmic ray intensity. Flares are only responsible for ionospheric disturbances and some generally less energetic particle events. CMEs are observed in white light and were first imaged with space-borne coronagraphs in the early 1970's (Tousey, 1973; Gosling et al., 1974). Although various aspects of the 'new paradigm' have been proposed since the early 1980's, a heated debate began in 1993 after Gosling published a paper in the Journal of Geophysics Research entitled 'The Solar Flare Myth' (Gosling, 1993) (see also Kahler, 1992). This paper has led to a 'flares versus CMEs' controversy in the solar-terrestrial community (e.g. Hudson et al., 1995; EOS, 1995).

In the simplest terms the old understanding was that a flare generated a shock which caused a geomagnetic storm when it impacted the Earth's magnetosphere. (For a detailed description of the early ideas see pages 576–580 in Kundu, 1965). The shock was detected when it was close to the Sun by virtue of the meter wavelength radio emission (type II burst) it generated. The shock appeared to be generated ahead of a plasma cloud (also called the piston or driver gas) indicated by the presence of type IV radio emission. Energetic particles either came from flares or possibly were accelerated by the shock since a good correlation between particle events and type

II bursts was found (Svestka and Fritzova-Svestkova, 1974). However, since type II bursts typically last 5–10 minutes (Kundu, 1965) impulsive particle injection was implied. For the largest events, flares, interplanetary shocks, energetic particles, and type II/type IV bursts all occur. Initially the incorporation of CMEs into the picture required no modification since CMEs were thought to be the plasma clouds emitted by flares. But various inconsistencies became apparent. This paper summarises these inconsistencies and considers the relationships between CMEs and a) interplanetary shocks, b) flares and c) type II bursts. Energetic particle observations are also reviewed with an emphasis on those observations that link particle acceleration with CMEs/interplanetary shocks rather than flares.

12.2 CMEs AND INTERPLANETARY DISTURBANCES

Sabine (1852) was first to note that geomagnetic activity tracks the solar cycle. The first 'flare' ever observed, in white light, was followed about 18 hours later by a geomagnetic storm (Carrington, 1860). Later, Newton (1943) found a significant correlation between large flares and subsequent geomagnetic storms. Gold (1955) was the first to suggest that the sudden commencements of geomagnetic storms were caused by the impact of shocks driven by plasma clouds ejected from the Sun. The idea of plasma clouds had been suggested earlier by Lindeman (1919) and Chapman and Ferraro (1929). The existence of such clouds and the partial exclusion of cosmic rays from the interior of the clouds was invoked to explain the sudden decreases in cosmic rays (Forbush, 1938) associated with geomagnetic storms. Morrison (1956) proposed that magnetic fields in plasma clouds were turbulent whereas others (e.g. Cocconi et al., 1958) suggested they were smooth. There were also conflicting ideas about whether the plasma clouds were closed, plasmoid-like structures disconnected from the Sun (Piddington, 1958) or whether they remained connected back to the Sun leading to magnetic tongues (Cocconi et al., 1958). Note that Parker's theory of the solar wind was not developed until 1958. Parker (1961) introduced the idea of a 'blast wave' created by a widespread elevation in the solar wind flow speed. This could cause a cosmic ray decrease via a shell of turbulent field behind the shock. This of course was a different proposal to that of Gold (1955) whose suggestion involved the concept of a driven shock.

By the early 1970's, less than 10 years after the first spacecraft observations of interplanetary shocks (Sonnett et al., 1964), a fairly reasonable idea had been formed of the geometry of shocks and plasma clouds (Hundhausen, 1972). Hundhausen (1972) used the term 'flare ejecta' for the plasma cloud and the term 'ejecta' is often used instead of plasma cloud or driver gas. Subsequently, Barnden (1973) suggested that Hundhausen's two-component model of ejecta plus swept up, compressed ambient field with shock, could explain the observed two-step structure seen in many Forbush decreases.

CMEs were first observed in the early 1970's. From studies of the events observed by Skylab (Gosling et al., 1974) it was obvious that these ejections were capable of producing the high speed flows required to produce interplanetary shocks because a number of the events had outward speeds above 1000 km s^{-1}. Since these were associated with flares, it was assumed that the CME was caused by the flare.

Second generation coronagraphs were flown in the 1980's. During cycle 21 the Solwind coronagraph (Howard et al., 1985) observed many CMEs and showed, without doubt, that CMEs are the drivers of interplanetary shocks (Sheeley et al., 1985; Cane et al., 1987). The Solar Maximum Mission (SMM) coronagraph (MacQueen, 1980) observed over 1000 CMEs (Burkepile and St. Cyr, 1993) during two solar maxima and also during solar minimum.

Although there is a clear association between flares, shocks and CMEs, several observations suggest that flares are not responsible for CMEs and shocks. Thus, whereas most major interplanetary shocks are preceded by a flare and meter wavelength type II and type IV bursts (Hundhausen, 1972; Cane, 1985), not all shocks can be associated with a flare, and most flares cannot be associated with an interplanetary shock (Hundhausen, 1972). Furthermore it is unlikely that the high speed flow following shocks and lasting for a day or so can come from a flare which lasts typically a few hours.

12.3 CMEs AND FLARES

Detailed studies of the relationship between flares and CMEs have been undertaken using the SMM coronagraph observations. There are five basic results from these studies which should dispel any belief that flares can cause CMEs:

1. Statistics: Only a minority of CMEs (<40%) are associated with flares with the most common association being with eruptive prominences (Munro et al., 1979; Webb and Hundhausen, 1987).

2. Spatial Sizes: The characteristic angular sizes of CMEs are about a factor of 3–10 greater than those of flares and active regions (Hundhausen, 1988; Kahler et al., 1989; Harrison et al., 1990). From the SMM data base (Burkepile and St Cyr, 1993) the average angular width of all CMEs was 48°. In addition it should be noted that interplanetary shocks are even larger than their associated ejecta (Borrini et al., 1982; Cane, 1985).

3. Timing: CME onsets tend to occur before flares (Wagner, 1982; Harrison, 1994 and references therein).

4. Energies: The estimated energies of interplanetary shocks can be a factor of 10 larger than the energies of big flares (Hundhausen, 1972).

5. Locations: Flares can occur anywhere under a CME and are not centered underneath as was originally believed and anticipated if they cause CMEs (Harrison, 1994 and references therein).

12.4 CMEs AND CORONAL SHOCKS

Type II radiation is plasma emission and using a density model of the corona the emission frequency can be related to a coronal height. The bursts typically occur in the frequency range 100–20 MHz (i.e. wavelengths in the range 3–15 meters) (Kundu, 1965). Thus meter wavelength type II bursts originate within about 3 solar radii of the Sun. The frequency drift rates can be used to determine a speed of the responsible agent and it was this calculation that led to the realisation of the presence of shocks. In the following text the term 'coronal' shock is used when discussing the agent responsible for meter wavelength type II bursts.

Since it was assumed that coronal shocks were the progenitors of interplanetary shocks it was thought that type II bursts would be well associated with CMEs and their source locations would be in front of CMEs where shocks should form. This was not found to be the case. The relevant observations are (see Cane, 1984 for the specific references):

1. Type II bursts have been reported in the absence of CMEs.
2. Radio imaging of type II bursts suggests that they are located behind CMEs.
3. The close coupling between coronal type II bursts and flares is not found for CMEs.
4. The distributions of the durations of flares associated with type II bursts and those associated with CMEs are dissimilar.
5. Some type II bursts have very high starting frequencies indicating heights below the heights where CMEs form.
6. Shock speeds deduced from type II drift rates and CME speeds are inconsistent.

Thus it has been suggested that coronal type II bursts are not directly related to CMEs and that there are two types of shocks. The shocks producing type II bursts would be blast waves related to the flare (Wagner and MacQueen, 1983; Cane and Reames, 1988; Gopalswamy and Kundu, 1995). However various arguments can be proposed which explain the observations in the context of a single shock model. For example, since the fastest CMEs are generally associated with type II bursts this could account for the many slower CMEs seen without accompanying type II bursts. Also, since CMEs are difficult to observe when they originate far from the solar limbs, such selectivity could account for type II bursts without associated CMEs (cf. Sawyer, 1985). Another possibility (e.g. Robinson and Stewart, 1985) is that some type II bursts originate from blast waves and some from CME-driven shocks. This seems unlikely given that there are no radio characteristics that distinguish the two groups. Robinson et al. (1986) reported that type II bursts associated with CMEs have low starting frequencies but Cane and Reames (1988) showed that starting frequencies are related to the impulsiveness of the associated flare and low starting frequencies are characteristic of gradual solar events which are well associated with CMEs.

There is no doubt that radio emission at very long wavelengths (frequencies less than 1 MHz) does originate at interplanetary shocks. This emission, which must be observed from space, originates at heights extending from about 10 solar radii all the way to the Earth where the radio emission coincides with the arrival of the shock. To avoid confusion with coronal type II bursts these radio events (first well observed from ISEE-3 in the late 1970's) were called IP type II events (Cane, 1985). Cane et al. (1987) found an excellent correlation between IP type II events and large, fast CMEs. In an analysis of the drift rates of IP type II events it was found that there was difficulty relating emissions at frequencies below 1 MHz with those at higher frequencies; the velocity curves were incompatible. Thus Cane (1983) suggested a two shock model wherein the higher frequency emission came from a flare initiated blast wave and the low frequency emission originated in an interplanetary shock driven by a CME. However if the CME-driven shock only commences above about 10 solar radii, as it might if the radio emission below 1 MHz signifies the creation of the interplanetary shock, then this shock clearly cannot produce the highest energy prompt particles, which commence before CMEs reach 5 solar radii (Kahler, 1994).

12.5 ENERGETIC PARTICLES

Most particle events are preceded by a flare which is why energetic particles were assumed to come directly from flares. However if flares are the sources of energetic particles one has to explain why large energetic particle events last for days and can be observed on field lines which connect to the Sun more than 100 degrees away from the flare. Until the 1980's it was held that processes in the corona were responsible. The long durations could be accounted for by storage and the huge traversals across the disk could be accounted for by a process called 'coronal diffusion' whose details were not identified. It is relevant to describe briefly the pre-1980's scenario for particle acceleration. It was thought that there were two acceleration phases. The first (impulsive phase) was directly related to flares and generated electrons up to an energy of a few 100 keV. These electrons also generated microwaves and hard X-rays. The second phase consisted of the shock acceleration of protons and high energy electrons. The timing relationship was based on the occurrence of type II (shock generated) radio bursts several minutes after type III (electron stream generated) radio bursts. It was believed that the second phase required the first. It was also known that interplanetary shocks accelerate particles (Rao et al., 1967) but it was believed that the maximum energy achievable was about 10 MeV and that the whole effect was only seen locally as the shock passed. It was thought that the particles 'from the flare' provided an energetic 'seed' population on which the shock operated.

The following observations show this picture is not correct:

1. Kahler et al. (1978) found a correlation between CME speed and >4 MeV proton intensity. They also noted that the sizes of CMEs are comparable to the heliolongitude range over which particle events did not show delays to onset – the so-called 'fast-propagation region' in which coronal diffusion was inferred to occur rapidly (Reinhard and Wibberenz, 1974).

2. Gosling et al. (1981) showed that a particle enhancement associated with an interplanetary shock had a spectrum which continued smoothly to thermal energies suggesting that these particles were drawn from the solar wind rather than accelerated flare particles. It is important to note, however, that this particle event was not detectable above 10 MeV.

3. Domingo et al. (1979), Kahler et al. (1986) and Cane et al. (1986a) discussed energetic proton events which were not associated with flares, only erupting prominences and interplanetary shocks.

4. Cliver et al. (1983) discussed a number of energetic proton events in which the impulsive phase was weak.

5. Mason et al. (1984) showed that the abundances of events did not vary as a function of the longitude of the event. This puts severe restraints on the 'coronal' diffusion process, since different ions diffuse at different rates, but is reasonable if the particles are accelerated over a range of heliolongitudes at a large shock.

6. Cane et al. (1986b) found that interplanetary particle events could be divided into two classes. The large events were associated with the type of flare events associated with CMEs and interplanetary shocks. They could originate anywhere on the disk. The other particle events were associated with impulsive flares (without CMEs) and were only observed following flares in regions that were magnetically well connected to the observer suggesting a much smaller source region.

7. Cane et al. (1988) showed that the intensity-time profiles of events were very well organised by the longitude of the event and could be explained in terms of the large-scale structure of interplanetary shocks. The delays to maximum intensity of eastern events were a natural consequence of continued acceleration and improving connection to the stronger parts of the shock. The organisation by observer location was substantiated by observations of the same event from separated spacecraft.

8. Reames (1988) obtained a bi-modal distribution in the Fe/O abundances of all energetic particle events, substantiating the existence of two particle populations.

It is now firmly established that solar energetic particles observed in the interplanetary medium are of two basic populations (Cane et al., 1986b; Lin, 1987; Reames, 1993, 1995). One population has its origins in flaring regions and the events are Fe-rich, He^3-rich, electron-rich, last for hours at most, have small cone sizes ($<30°$) and are NOT associated with CMEs. The associated electromagnetic flare emissions e.g. H_{α}, are impulsive. In contrast, the so-called 'gradual' events are proton-rich, last for days, often spread over more than 180° in longitude and are well associated with CMEs. The flares associated with these events are generally, but not always, gradual. On the other hand these particle events certainly have more gradual intensity time profiles than do the impulsive particle events. Another indication for the presence of two particle populations is the inconsistency between the numbers of particles interacting at the Sun to produce gamma rays with those observed in space (Cliver et al., 1989).

12.6 CURRENT PROBLEMS

The relationship between flares and CMEs is not established. The most likely scenario is that flares occur under favourable conditions as a by-product of the process causing the mass ejection. Although everyone agrees the ultimate energy source for CMEs is magnetic, the details have yet to be determined.

The debate as to whether 'plasma clouds'/ejecta are open or closed is still not totally resolved. There is evidence for the existence of magnetic tongues (e.g. Richardson and Cane, 1996) but the existence of plasmoids cannot be ruled out.

Recently, Cliver (1996) has cautioned researchers that the picture of two classes of particle events is overly simplistic. For example, the impulsive events isolated by Cane et al. (1986b) were much more energetic than typical He^3-rich events and many were associated with CMEs. Cliver (1996) suggests calling these events 'mixed-impulsive'. Cane and Reames (1990) suggested that in addition to 'flare-particles', protons accelerated at coronal shocks accompany many of the more energetic impulsive events. Also Van Hollebeke et al. (1990) suggested that the high energy He^3, Fe-rich interplanetary particles seen in the impulsive June 3, 1982 flare resulted from a second-phase shock acceleration of flare particles.

Another modification to the 'two class' picture is the existence of particle events with essentially no associated flare emissions (such as hard X-rays and radio bursts), which are associated with interplanetary shocks caused by less energetic CMEs. These so-called 'disappearing filament' events (Cane et al., 1986a; Kahler et al., 1986; Sanahuja et al., 1991) have steep energy spectra and typically do not extend above about 10 MeV. They consist of an intensity enhancement commencing about a day before shock passage and peaking at the shock. Of course there is a continuum of events and the more energetic ones, of which that of December 5, 1981 (Kahler et al., 1986) is the prime example, extend to higher energies and are indistinguishable from flare-associated particle events in the interplanetary medium. It has been suggested that for the less energetic events there is essentially no acceleration at or close to the Sun and that the relatively low maximum energy is a reflection of the limited extent to which shocks can accelerate particles beyond about 0.3 AU (Kallenrode, 1996). Unfortunately with few observations from widely spaced detectors it is not possible to say whether a component of particles accelerated close to the Sun has been missed because of bad connection or because it was not accelerated. There is one event observed by multiple spacecraft where it would appear that the latter is the case (Cane, 1995).

Multispacecraft observations support the fact that in large events particles are seen rather promptly from widespread regions (up to 300° in longitude) (Cliver et al., 1995; Cane, 1996). The wide spread acceleration is difficult to reconcile in terms of the latitudinal extents of CMEs and the longitudinal extents of interplanetary shocks at 1 AU. It is possible that shocks rapidly decrease in longitudinal extent as they move away from the Sun (Cane, 1996). Alternatively the widespread acceleration of particles in the early stages of major events may be related to the presence of 'global CMEs' revealed by the new LASCO coronagraph on the SOHO spacecraft (Brueckner, 1996). Another possible scenario is that the earliest particles are accelerated at a shock which is not that driven by a CME, i.e. that there are two shocks.

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13. ^{14}C VARIATIONS IN THE ATMOSPHERE: A SOUTHERN PERSPECTIVE

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ABSTRACT

^{14}C is a cosmogenic isotope produced mainly in the atmosphere, which becomes stored chronologically in suitable ice cores and tree rings. New measurements of trace gas concentrations and isotopes in Antarctic ice cores and of ^{14}C in Tasmanian tree rings are summarised. The results from both palaeo-resources have the potential to clarify historic ^{14}C production rates by cosmic rays over much of the Holocene (the last 10 000 plus years).

The main focus of our recent work has been on ice cores from high snow accumulation sites on Law Dome. A vital step in reconstructing trace gas histories from the air trapped in the ice cores involves measurements of ^{14}C in the entrapped CO_2 resulting from 1960's nuclear testing in the atmosphere. High time resolution histories of atmospheric trace gases and stable isotopes can then be inferred and used to identify global biogeochemical carbon exchanges. A consequence is that ^{14}C variations of biogeochemical origin can be predicted and subtracted from ^{14}C records (usually from tree rings), to provide cosmic ray induced production rate changes. ^{14}C inventories of the Earth's carbon reservoirs over recent centuries are presented for constant and assumed cosmogenic ^{14}C production rates.

The Antarctic ice offers other opportunities to independently determine cosmogenic isotope production rates. These involve comparisons of $\Delta^{14}C$ determinations in ice and air bubbles from both high and low accumulation rate, and high and low altitude sites. Direct cosmic ray in situ production of ^{14}C in the upper layers of the firn will be much more pronounced in high altitude and/or slowly advecting low accumulation sites and, by inter-site comparison, may be distinguished from ^{14}C arriving from the atmosphere. Complementing these measurements with ^{10}Be (produced at the top of the atmosphere mainly by spallation of nitrogen and oxygen and deposited at the surface after attachment to aerosols) and possibly ^{36}Cl (produced mainly by spallation of argon and deposited via aerosols, but measured relative to

^{35}Cl with large natural variation) may strengthen the identification of the cosmic ray induced influences.

13.1 INTRODUCTION

Significant new palaeo-environment records from the South Pacific region have recently been developed (ATRIC workshop, 1996, reviewed by Jones, 1996). Two of these, millennia-long tree ring chronologies using Tasmanian Huon pine, and millennia-long atmospheric trace gas records obtained from ice cores drilled at Law Dome, East Antarctica, are discussed here as having particular potential to contribute to knowledge about past cosmic ray variations. In both cases, the ability to accurately date over millennia, material carrying information relevant to the time of formation, is vital.

Though we emphasise links to cosmic ray research, the unifying theme through this paper is the global carbon cycle. In particular, we are concerned with calibrating models of the global carbon budget which can be used to project future atmospheric loadings of the trace gases capable of modifying the Earth's climate (see for example, Climate Change 1995 (1996)). Calibration of these models relies on accurate histories of the trace gas levels in the atmosphere; here we will focus on carbon dioxide. From ice cores it is possible to extract air from bubbles and measure the trace gas composition, for example the CO_2 mixing ratio and the isotopic ratios $\delta^{13}C$ and $\Delta^{14}C$. The isotopes carry the 'signature' of particular exchange mechanisms between the atmosphere and other reservoirs. The challenge in utilising air trapped in ice-cores is to quantitatively describe, and/or minimise, various modifications to trace gas composition which occur during the trapping processes.

The tree rings do not retain atmospheric CO_2 mixing ratios, but the carbon in tree rings can be analysed for the two isotope ratios. A tree-ring $\Delta^{14}C$ record is established throughout the Holocene, however the variations reflect both ^{14}C production rate variations as well as exchange between the Earth's reservoirs. From the carbon budgeting point-of-view, the separation of these two influences provides a valuable new constraint, that is the pre-bomb and pre-industrial atmospheric ^{14}C variations due to 'natural' reservoir exchanges. An example of a preliminary attempt at using this constraint is given by Beer et al. (1994), who use ^{10}Be as an independent indicator of solar variability and cosmic ray induced ^{14}C production. While independent cosmic ray variability is required to exploit the $\Delta^{14}C$ history for carbon budgeting purposes, independent information on climate variability is also relevant in that many of the carbon exchange mechanisms exhibit a sensitivity to climate.

The Tasmanian tree rings and Law Dome ice cores are now discussed from these perspectives, that is clarifying the global carbon budget with emphasis on the links to cosmic ray variability.

13.2 TASMANIAN TREE-RINGS

Starting in 1981, a series of expeditions were mounted to the western Tasmanian rainforests with the objectives of determining three types of past environment information from tree rings (Francey et al., 1984). Long lived endemic conifers, in particular the Huon pine (Lagarostrobus franklinii, C.J. Quinn), were targeted.

1. An objective of reconstructing atmospheric CO_2 concentrations using the stable carbon isotope ratio, $^{13}C/^{12}C$, in tree ring cellulose proved difficult. The work demonstrated that atmospheric-composition-dependent physiological responses influenced the fractionation of carbon isotopes during photosynthesis, competing with the atmospheric record (Francey and Farquhar, 1982).

2. The second objective of determining past physical climate from ring widths is progressing well. A Tasmanian temperature reconstruction from sub-alpine Huon pine from a site on Mount Read now extends to 1260 BC. The Mount Read stand, at 950 m altitude, is one of only a few documented occurrences of the species above 500 metres (Peterson, 1990). The reconstruction is based on an unusually large number of independent samples, for example from 800 BC to AD 1991 sample depth is greater than 15 independent ring-width sequences or 'series', and sample depth increases to around 45 series or more from 1300 AD. The extension prior to AD 900 (c.f. Cook et al., 1991, 1992) was made possible by a recent collection of wood from exposed stumps and buried stem remnants and is reported separately by Cook et al. (1996a). The average segment length in the tree ring chronology of 613 years is also unusual, with many individual ring series (logs or cores) well in excess of 1000 years. Cook et al. (1991, 1992) reported an unusual direct temperature sensitivity of the tree rings from the Huon pine stand on Mount Read. A further discussion of the factors influencing the temperature reconstruction is given by Cook et al. (1996b). In the present context, and apart from information on climate variability, the Mount Read chronology provides a well-dated (to single year accuracy) collection of atmosphere-derived radiocarbon over most of the last 3000 years.

3. Of even more interest here is a potentially much longer tree ring chronology using (mostly) Huon pine from a low altitude site on the margins of the Stanley River. In these trees the climate response is more complex (Buckley et al., in preparation) but still sufficient to ensure good 'cross-dating' between different samples, even if climate reconstructions are less reliable. Chronology (dating accurate to one year) is established back to 273 BC, including living trees up to 2000 years old. In addition, over 350 well-preserved sub-fossil logs have been sampled from the river banks and flood-plain sediments, only about half of which have been dated. They range in age from >38 ka to modern, with good coverage (and cross-dating) emerging for the periods 9 to 3.5 ka and from 2.5 ka to the present. However, the major gap appears between ca. 3.5 ka and 2.5 ka BP (calendar year), which future analyses and/or collections (perhaps at neighbouring sites) are expected to fill in. A primary objective with this chronology is the calibration of the radiocarbon calendar throughout the Holocene, using both live and sub-fossil southern hemisphere material (Barbetti et al., 1992, 1996; Francey et al., 1984).

Radiocarbon calibration is reasonably well-established for the Holocene, using northern hemisphere trees. The differences between tree-ring ages and ^{14}C ages have been determined for the last 11 400 calendar years by high-precision ^{14}C measurements on 10- or 20-ring samples, independently dated by dendrochronology

(Stuiver et al., 1993). The European and North American chronologies exhibit statistically significant oscillatory behaviour in $\Delta^{14}C$ over close to ten millennia (at periods of 45, 88, 145, 210 and 510 years, Stuiver and Braziunas, 1993), with solar variability suggested as a probable influence. There is some interest in confirming the curve using southern hemisphere material. Even though atmospheric mixing suggests a sufficiently homogeneous atmosphere for global comparisons, small regional differences are possible, and the significantly longer segment lengths of the Tasmanian trees offer significant advantages in confirming chronologies based on cross matching smaller segments in the northern chronologies. The longer segment lengths are particularly valuable for spectral analyses. In this last context, the close similarity in reported spectral behaviour in the northern hemisphere tree-ring $\Delta^{14}C$ record and oscillatory patterns in the Mount Read ring-width record is intriguing (Cook et al., 1996a), suggesting a solar-variability climate link despite the apparent absence of a sufficiently energetic transfer process to bring this about.

Some of the older Stanley river logs, in particular a 'floating chronology' around 9.5–9.9 Ka are currently the focus of extra international attention as a possible improved link between the almost 10 000 year German oak chronology with a floating 1920 year German pine chronology beyond that date (Kromer and Becker, 1993). The link would come from matching periods of steep ^{14}C changes in the different chronologies about that time.

We speculate here that a subset of the sub-fossil Stanley River logs may provide a special opportunity for cosmic ray studies. These are logs, with mean ages spanning several millennia, which have apparently rested in an exposed horizontal position over much of the intervening period. Lal et al. (1985) have proposed that radial differences in ^{10}Be in rings from low latitude, horizontal trees will reflect in situ cosmic ray production due to high energy particles. Compared to ^{10}Be measurements in ice cores, the tree ring in situ produced variations would provide a more direct indication of cosmic ray behaviour, without influences related to the atmospheric transport of ^{10}Be. Although similar differences might also occur for $\Delta^{14}C$, the large contribution of ^{14}C derived from the atmosphere makes detection difficult.

13.3 LAW DOME ICE CORES

At CSIRO, most progress to date has occurred in clarifying the global carbon budget over recent centuries using high precision measurement of CO_2, $\delta^{13}C$ of CO_2 and other trace gases in air from the firn and ice bubbles from Law Dome, East Antarctica. The Law Dome ice cores provide trace gas histories with significantly improved time resolution compared to previous studies and Antarctic cores in general appear to avoid chemical modification of some trace gases, in particular CO_2, observed in northern hemisphere cores (Anklin et al., 1995). The time resolution is an important consideration for trace gas budgeting studies and also for any attempts to infer cosmic ray behaviour from radiocarbon measurements on air trapped in ice. In the process of trapping atmospheric trace gases in ice, mixing of air from different years occurs due to diffusion in the overlying compressing snow (firn), typically between 70 and 100 m deep. Furthermore, different trace species diffuse in the firn at different rates. Also, bubbles in a sample of ice close-off at different times.

The firn diffusion effects are relatively constant from site to site and result in a typical decadal smoothing of atmospheric signals, however the bubble close-off effect (and second order advection effects) are heavily dependent on the snow accumulation rate, with extra smoothing ranging from 1–2 years at high-accumulation rate sites, to many hundreds of years at low-accumulation sites, for example in the Vostok core (Raynaud et al., 1993). The firn diffusion also implies that the mean age of trapped air is much younger than the age of surrounding ice.

The Law Dome cores used here, DE08, DE08-2 and DSS, are from high-accumulation rate sites, with the DE08 cores being the highest accumulation cores yet to provide reliable reconstructions of atmospheric CO_2 concentrations. The DE08 cores combine the rare combination of very heavy accumulation, up to 1100 kg m^{-2} y^{-1} (about 1.2 m yr^{-1} ice equivalent), with the virtual absence of summer surface melt. A full description of the sites, drilling and analyses on the cores is given by Etheridge et al. (1996) and references quoted therein, who present a 1000 year history of atmospheric CO_2 from the 3 cores. For the most recently drilled core, DE08-2 in 1993, the high accumulation means that the entrapped CO_2, for the first time, overlaps direct modern records. In addition, air pumped from different depths in the firn and analysed for a wide range of trace species, has provided detailed information on the trace gas modification by diffusive processes. The results were used to calibrate a model of firn diffusion and bubble trapping (Trudinger et al., 1997), which predicted smoothing of CO_2 signals trapped in the ice with a characteristic timescale of 10–15 years. A critical test of the diffusion part of the model involved comparison of CO_2 and CH_4 stable isotope signals with measurements on the unique Cape Grim Air Archive (containing baseline marine air in high pressure steel containers collected since 1978 and described in Langenfelds et al., 1996). More recently, Levchenko et al. (1996, 1997) have directly determined the spread of ages of CO_2 trapped in the ice, by Accelerator Mass Spectrometer (AMS) measurements of bomb-produced $^{14}CO_2$ extracted from the firn and ice bubbles at DE08. The very sharp increase in atmospheric ^{14}C in the early 1960's due to atmospheric testing of nuclear weapons has just become trapped in the ice and provides a unique opportunity for measuring this key parameter. The mean age of CO_2 trapped at the bottom of the firn is 8.9 ±0.5 years (compared to the age of the surrounding firn/ice of 40 years) with an age spread in the ice of 12.5 ±1.5 years. The DE08 cores provide measurements over 150 years, prior to which the DSS core is employed. DSS is from a lower accumulation site (600 kg m^{-2} y^{-1}) and is expected to have proportionately larger age spread (15–20 years, soon to be precisely determined by AMS measurement on DSS trapped air).

The trace gas measurements on the air extracted from the Law Dome cores also represent generally higher precision than previously reported. The developments and methodologies leading to improved precision are described in Francey et al. (1996). The majority of samples analysed for CO_2 concentration have also been analysed for the stable carbon isotope ratio ($^{13}C/^{12}C$ expressed as $\delta^{13}C$) of CO_2 (Francey et al., 1999).

With the new high precision, high time resolution CO_2 and $\delta^{13}C$ records there is an opportunity to re-calibrate a box-diffusion model of the exchangeable carbon budget on Earth. Using a model described by Enting and Lassey (1993), we have re-calibrated using the conventional ^{14}C 'bomb-spike' plus the new ice core records. The model includes the following reservoirs:

1. troposphere (containing 480 GtC pre-industrially, with close to zero $\Delta^{14}C$)
2. stratosphere (containing 120 GtC pre-industrially, with $\Delta^{14}C$ of -105%)
3. ocean mixed layer (680 GtC with $\Delta^{14}C$ -40‰, pre-industrially)
4. deep ocean, containing 37 000 GtC, at $\Delta^{14}C$~-150%,
5. short-lived terrestrial biota (140 GtC with 6 year exchange time with the long-lived biota and 1.83 year exchange time to the atmosphere, thus close to $\Delta^{14}C$ equilibrium with the troposphere), and
6. long-lived terrestrial biota (1400 GtC with residence time of 60 years, and initial $\Delta^{14}C$~-8‰).

The model has permitted new predictions of the atmospheric ^{14}C variations over recent centuries which are attributable to reservoir exchanges on Earth. In the context of this paper, accurate prediction of the 'reservoir' contribution to atmospheric ^{14}C variations over past millennia (as determined in tree rings), permits the variation due to cosmic ray induced production to be determined. While that comparison is not yet completed, interesting features emerge from the inter-reservoir ^{14}C fluxes on Earth, triggered by human activity. These are illustrated in Figures 1–4.

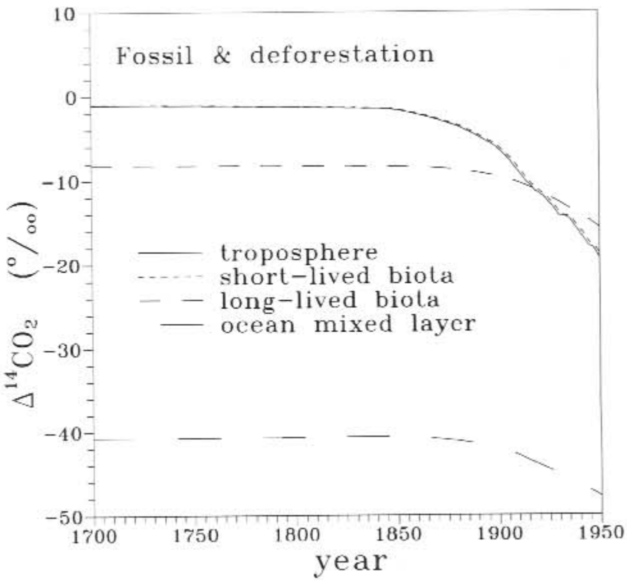

Figure 1. *Model (Enting and Lassey, 1993) predictions of $\Delta^{14}C$ in various global reservoirs from 1700 to 1950 (just prior to atmospheric nuclear testing). The declining proportion of ^{14}C in all reservoirs is predominantly the result of fossil fuel emissions.*

In Figure 1, where production of ^{14}C by cosmic rays is assumed constant, the influence of releasing ^{14}C-free fossil fuel carbon, plus carbon from deforestation, and their redistribution among the other reservoirs, can be clearly seen in the declining $^{14}C/^{12}C$ ratios in all reservoirs. The decline is predominantly (95%) due to the fossil fuel input. If, however, we use the model output to show the ^{14}C inventories in each reservoir, quite a different picture of terrestrial ^{14}C fluxes between reservoirs emerges, a picture more appropriate to separating cosmogenic ^{14}C production from terrestrial reservoir exchanges.

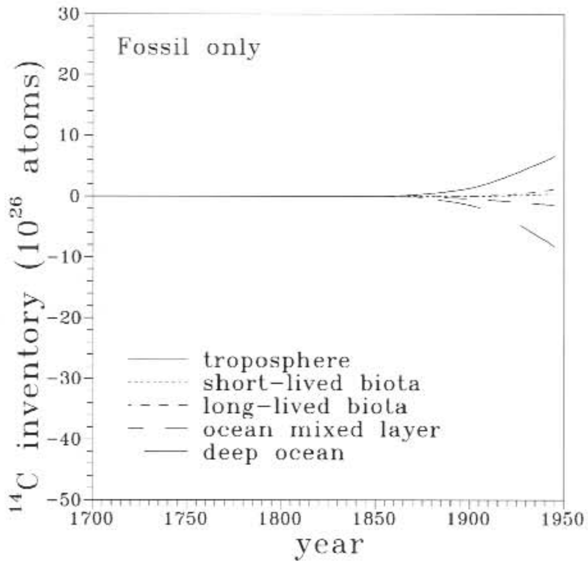

Figure 2. *Model output showing the changes in ^{14}C inventories of global carbon reservoirs for the fossil fuel source only. Constant cosmogenic production of ^{14}C is assumed. Note the increasing ^{14}C in the atmosphere and a decrease in the deep oceans.*

In Figure 2, the model is run, again with constant cosmogenic ^{14}C production, for a fossil fuel input only. Surprisingly, the troposphere then shows an increase in ^{14}C, despite decreasing $\Delta^{14}C$. The decreasing $^{14}C/^{12}C$ ratio results from increasing fossil fuel ^{12}C which exceeds an increase in ^{14}C. We attribute the increase in ^{14}C in the troposphere to an exchange from the oceans, which is reflected in the declining deep ocean inventory, and this occurs because gross carbon fluxes between oceans and atmosphere respond to the increased partial pressure difference. The increased exchange results in a different isotopic equilibrium between the ^{14}C production at the top of the atmosphere and the ^{14}C depleted deep oceans. The short lived reservoirs merely act as conduits for the ^{14}C re-equilibration fluxes.

Figure 3 represents another constant cosmogenic input test run, with no fossil fuel carbon release, rather only a release from deforestation (see the appendix by R.A. Houghton in Enting and Lassey, 1993).

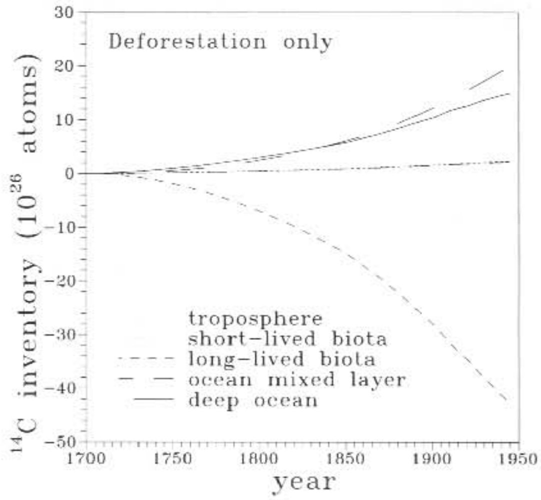

Figure 3. *Model output showing the changes in ^{14}C inventories of global carbon reservoirs for a deforestation source only. Constant cosmogenic production of ^{14}C is assumed. Note the much larger ^{14}C changes compared to Figure 2 and the transfer of long-lived terrestrial biotic carbon to the deep oceans.*

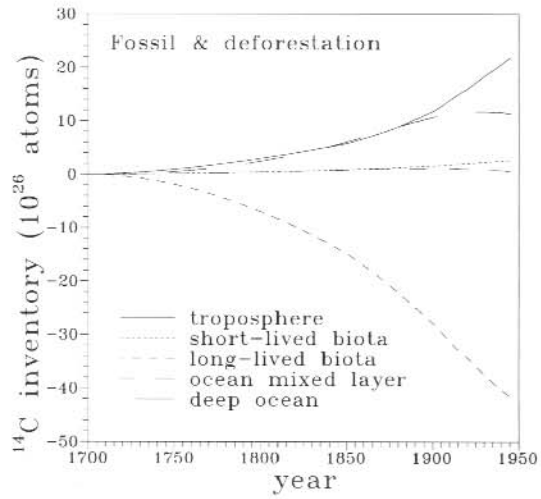

Figure 4. *Model output showing the changes in ^{14}C inventories of global carbon reservoirs for both fossil fuel and deforestation sources (a combination of Figures 2 and 3).*

Here the ^{14}C inter-reservoir fluxes are much larger, with a large decline in ^{14}C of the long-lived biota reservoir (consistent with a decline in the total carbon reservoir), which is transferred into the atmosphere and deep ocean. Figure 4 combines these two release scenarios, showing the domination of the deforestation on terrestrial ^{14}C fluxes, with only second order effects due to fossil fuel. Note that after 1960 the massive bomb injection of ^{14}C into the stratosphere dominates the short-lived reservoirs.

Before using the model to explore the influence of variable cosmogenic ^{14}C production on the terrestrial carbon reservoirs, the information available from measurement of cosmogenic nuclei in the ice and tree rings is reviewed.

13.4 COSMOGENIC NUCLEI

The reconstruction of past cosmogenic isotope production rates can address fundamental questions, such as galactic cosmic rays flux, solar activity and geomagnetic histories, or be applied to such things as the reconstruction of ice accumulation rates from cosmogenic nuclei measurements in ice cores, or, as discussed above, the constraint of global carbon budgets using ^{14}C as a tracer. The causes of cosmogenic isotope production rate variations, manifestations of the cosmic ray flux and/or spectrum variations at the top of the atmosphere, are reviewed in a number of publications (for example, Lal, 1992). Cosmogenic nuclei content measured in various archives (tree-rings, ice cores, stalagmites etc.) cannot always be directly referred to the isotope production rates because, prior to being stored, the isotopes go through quite a complex atmospheric transport processes (^{10}Be, ^{36}Cl) or are included in biogeochemical cycling (^{14}C). Climate induced variations of the transport and biogeochemical cycling mechanisms compete with production rate induced variations in the archives and the separation of the two causes can be very difficult.

The variety of ice and firn cores drilled by Australian Antarctic Expeditions at the sites with different snow accumulation rates at Law Dome, East Antarctica (Etheridge, 1990) provide opportunities to investigate further the determination of cosmogenic isotope production rates. The cores are well dated, mainly by annual layer counting, so the past accumulation rates and site altitudes are known. Recent advances in AMS radiocarbon measuring technique and in its application to ice core studies (Van De Wal et al., 1994, Wilson, 1995 and Levchenko et al., 1997) and progress in understanding the ice accumulation and air trapping (Trudinger et al., 1997, Levchenko et al., 1996) permit high precision $\Delta^{14}C$ measurements in both ice and air bubbles and a quantitative comparison of data from different ice cores.

Radiocarbon in measurable quantities is not only trapped from the atmosphere into the air bubbles in accumulating ice but is also produced in situ in the nuclear spallation of mainly oxygen nuclei (in the ice H_2O) by secondary cosmic rays in the upper layers of accumulating firn (Lal et al., 1987). The in situ produced ^{14}C thus resides predominantly in the ice lattice (from which some fraction may diffuse into the bubbles). The distinction between in situ and atmosphere-derived ^{14}C is important, not only because atmospheric transport and exchange processes are not involved in one case, but also because different energy cosmic rays are involved in the two processes. The Law Dome ice core in situ radiocarbon will reflect the galactic cosmic ray flux. Production rate variations at the top of the atmosphere due to major solar flares (Lingenfelter and Ramaty, 1970) and variations due to redistribution in the atmosphere (biogeochemical cycling) will not be recorded and secondary cosmic rays from solar flare protons are of insufficient energy to reach the ice surface in significant quantities. Because the geomagnetic latitude of Law Dome is high enough, changes in the Earth's geomagnetic dipole field will also not affect the in situ production rate, certainly over recent millennia.

By comparing the radiocarbon measurements in a high accumulation ice core with measurements in a low accumulation and/or higher altitude core where in situ production is more pronounced, we expect to determine separately the in situ production (directly influenced by the high energy cosmic ray component) and the entrapped air $\Delta^{14}C$ (a mixture of in situ produced and atmospheric radiocarbon). Uncertainty concerning the degree to which in situ ^{14}C is detected can be elucidated using different extraction techniques, for example melting or sublimation, which detects all ^{14}C (Wilson, 1995) compared to dry crushing (detecting only ^{14}C from the bubbles). Alternatively, the input of tree-ring radiocarbon measurements (Stuiver and Braziunas, 1993) into a firn diffusion and trapping model (Trudinger et al., 1997) can be used to calculate the atmospheric radiocarbon amount, for comparison with measurements on the ice core ice and air, where the difference is the in situ production.

The in situ radiocarbon is produced over a characteristic depth-range in the ice of a few metres (absorption mean free path is 150 g cm^{-2}), so that the recorded time resolution of the galactic cosmic ray production will be smoothed over a time determined by the snow accumulation rate. At the very high accumulation cores at Law Dome of around 1 m water equivalent per year, the time resolution will be around 5 years; at lower accumulation sites the age resolution will be less. Coincidentally, the age resolution is about half of that of CO_2 stored in the ice bubbles in these cores (which is determined by the diffusion in the firn and the rate of close off of bubbles at the bottom of the firn layer). This makes the implied production rates appropriate for interpreting $\Delta^{14}C$ variations measured on CO_2 extracted from the ice bubbles (both the atmospheric history and in situ production history have similar smoothing), but this is a limitation to be kept in mind when using the production rates in other contexts (for example the 11-year cycle will not be well resolved). Possible other advantages in only using ice core measurements to compare production rate and the combined production rate and biogeochemical cycling changes (rather than using tree rings for the latter), may emerge from avoiding changes in regional biogeochemical influences on atmospheric $\Delta^{14}C$ and improved signal-to-noise from using uniform laboratory techniques.

The same ice may yield additional clues. Complementing the radiocarbon measurements with the measurements of ^{10}Be in the same cores could significantly strengthen the identification of cosmic ray induced production rate variations. Cosmogenic isotope ^{10}Be is produced continuously in spallation of nitrogen and oxygen nuclei of atmospheric gases by cosmic rays. After production, ^{10}Be becomes attached to aerosols. 75% of the production occurs in the stratosphere (Lal and Peters, 1967) and ^{10}Be is removed after a mean residence time of 1 to 2 years (the removal of tropospheric ^{10}Be is of order 1–2 months). The application of ^{10}Be as a tool to reconstruct solar variability and cosmic ray flux in the past has been discussed several times (Raisbeck and Yiou, 1980, Beer et al., 1990), and several attempts have been made (Kocharov et al., 1990, 1992). On the other hand, ^{10}Be concentration measured in ice was suggested as an indicator of ice accumulation rate variations (Yiou et al., 1985). However, Beer et al. (1992) emphasised that variations of ^{10}Be concentration in ice can also be due to variations in atmospheric transport of aerosols, the major mechanism delivering ^{10}Be to ice sheets. The remoteness of Law Dome from significant dust-borne sources of ^{10}Be is clearly a potential advantage. As the in situ produced radiocarbon is free from the terrestrial sources and atmospheric transport related influence, the coupled study of in situ radiocarbon production rate and ^{10}Be deposition flux can possibly shed light on the causes of discrepancies observed between ^{10}Be and tree ring measured ^{14}C variations over recent millennium (Beer et al., 1994) and beyond (Beer et al., 1984).

Another cosmogenic radioisotope, ^{36}Cl, which is produced mainly in the atmosphere in spallation of argon nuclei by cosmic rays (Lal and Peters, 1967) is also transported to the ice sheet via aerosols, but experiences significantly larger variability than ^{10}Be, presumably due to significant alternate sources of Cl and ^{36}Cl, for example from oceans, volcanic sources and/or ^{36}Cl resulting from neutron capture by Cl in the troposphere. Recently another tracer, namely nitrate concentration in polar ice, has been suggested as a proxy for the solar proton events (Dreschhoff and Zeller, 1994). Amalgamating nitrate studies with cosmogenic isotope investigations (Konstantinov et al., 1992), especially done in the same core, offers further opportunities to obtain information of the solar activity and cosmic ray fluxes in the past.

13.5 DISCUSSION

Given the uncertainties in the exact cause of ^{10}Be variations measured in ice cores (and the variation of the ^{10}Be between ice cores, Beer et al., 1994), we illustrate the potential impact of a variable ^{14}C production rate on the terrestrial ^{14}C reservoirs in Figure 5.

In Figure 5, the ^{10}Be record of Beer et al. (1994) is used to provide a proxy ^{14}C production rate. The predicted history of atmospheric $\Delta^{14}C$, with fossil and deforestation inputs, is compared to the $\Delta^{14}C$ measured in tree rings (Stuiver and Braziunas, 1993). Also shown is the model output for the constant production rate case. The most significant implication of Figure 5, also observed by Beer et al., follows from the difference in $\Delta^{14}C$ between the constant and varying ^{14}C production rates throughout the 20th century. This is because carbon cycle models presently in wide use, have often been calibrated against the $\Delta^{14}C$ change over the early part of this century, assuming the change is entirely due to dilution resulting from fossil fuel releases.

Because of the apparent differences in ^{10}Be records from different ice cores, the discrepancies between predicted and measured $\Delta^{14}C$ changes prior to 1800 are considered more likely due to the complexity of influences on the deposition of ^{10}Be than carbon cycle influences. This question will be directly addressed by ^{10}Be and in situ ^{14}C measurements on the Law Dome cores and possibly by measurements on selected Stanley River logs which permit detection of in situ produced ^{10}Be.

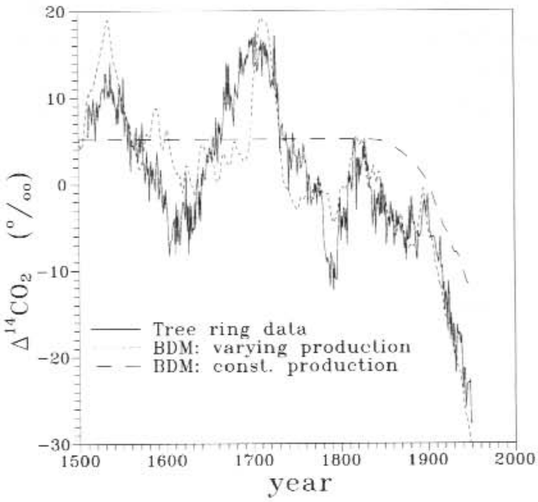

Figure 5. *The influence on tropospheric $\Delta^{14}C$ of a changing cosmogenic ^{14}C production rate (short dashes). Here preliminary measurements of ^{10}Be in ice cores (Beer et al., 1994) are used as a proxy for cosmogenic production, with other inputs as for Figure 4. The predicted $\Delta^{14}C$ are compared to $\Delta^{14}C$ measured in tree rings (solid line, Stuiver et al., 1993). For comparison, the constant production rate case is included (long dashes).*

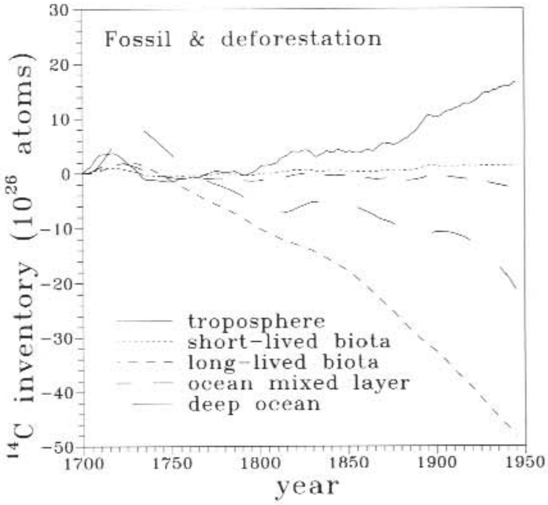

Figure 6. *Model output showing the changes in ^{14}C inventories of global carbon reservoirs for fossil and deforestation sources and varying cosmogenic production of ^{14}C. ^{10}Be in ice cores (Beer et al., 1994) are used as a proxy for cosmogenic production of ^{14}C.*

In terms of the reservoir inventories, the cosmogenic ^{14}C variations are superimposed on all terrestrial reservoirs as shown in Figure 6. This is likely to become important information when interpreting improved ocean and terrestrial inventories of ^{14}C emerge from many current international and national measurement programs on oceans and terrestrial ecosystems.

13.6 ACKNOWLEDGMENTS

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14. FUTURE OF HELIOSPHERIC MODULATION OBSERVATIONS

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ABSTRACT

The major source of data for understanding the long term interaction of galactic cosmic rays with the heliosphere has come from surface and underground cosmic ray measurements. Space based observations at energies below 1 GeV are likely to play a significant role for many decades. The need for the world-wide network of standardised neutron monitors is as pressing as ever although a new generation of detectors of greater efficiency should be developed and deployed. Similarly, the need for surface and underground muon telescopes continues. In the southern hemisphere such telescopes are only operating at Mawson and in Tasmania whilst the northern hemisphere systems are effectively only to be found in Japan. The world-wide coverage at these higher energies is the absolute minimum necessary for high quality research and it is imperative that these instruments continue to operate for at least a few solar cycles.

A discussion of the remaining questions in modulation research is presented together with a summary of the observational requirements to address these questions.

14.1 UNDERSTANDING THE HELIOSPHERIC FIELD

The Pioneer 10 and 11 and Voyager 1 and 2 spacecraft are continuing to extend our measurements of the interplanetary magnetic field (IMF) and low energy particle density out beyond the orbits of the planets. Sometime in the next few decades these spacecraft are likely to encounter the termination shock and we will then have a much better picture of the region of space dominated by the solar wind flow and the heliomagnetic field.

In the meantime the Ulysses spacecraft has already collected our first direct measurements of the particle and field domain away from the ecliptic up to high heliomagnetic latitudes. This spacecraft is about to start its second orbit; this time around solar maximum. We will obtain our first direct measurement of the variation of the three-dimensional heliospheric structure with solar activity. There is even the possibility of continued Ulysses data collection after the next solar maximum and heliospheric polarity reversal.

These combined measurements will enable truly representative models of the field to be incorporated into galactic cosmic ray modulation models for the first time.

This will lead to better understanding of the high energy processes involved. New predictions that can be tested against observations are also likely.

14.2 WHERE TO OBSERVE FROM?

It is certain that no space or lunar based experiments are likely in the >5 GeV range for many decades and so we are restricted to Earth based observations. Ground based observations will therefore remain our only source of information on high energy interactions in the heliosphere. It is essential for proper interpretation of these observations that good latitude and longitude coverage is maintained.

If significant advances are to be made it will not simply be a matter of extending the length of the time series of data available, although that is important, but also to improve the statistics of the observations. New neutron monitor designs, possibly based around ^{3}He technology, with lower unit cost should enable higher count rate systems to be installed. Muon telescope systems of larger area will also be needed to give higher count rates and thus better statistics. It would also be valuable to employ narrower angle muon systems to study both anisotropies and transient phenomena in more detail.

14.3 LIMITATIONS OF THE DATA SETS AND MODELS

The present data set extends back to the 1940's but data of sufficient quality for derivation of modulation parameters is only available for less than two solar magnetic cycles. With such a small number of cycles it is impossible to decide which variations in these parameters are common to all cycles and which may be applicable to only the last 50 years. We know that solar modulation must undergo much greater variability than we have observed because of the solar sunspot cycle records and the observed episodes like the Maunder minimum. A complete understanding of the possible modulation of galactic cosmic rays may take centuries but a good model of the modulation should be developed on much shorter timescales so that useful predictions can be achieved for a range of possible solar conditions in the future.

Today we do not have sufficient statistical accuracy of our datasets to unequivocally decide the spectral exponents or the upper limiting rigidities of the North-South anisotropy or the Solar Diurnal anisotropy. We are even less certain about the parameters describing the Solar Semi-Diurnal anisotropy and the Sidereal anisotropy. We are unable to explain the apparent 22 year phase variation in the North-South anisotropy although this may be related to an unresolved galactic anisotropy.

We have no single satisfactory explanation for trains of enhanced Solar Diurnal variations. There have been half a dozen models proposed and each gives a very good explanation for some of the trains but no model applies in all cases. There appears to be no substantial differences in the trains themselves but it is possible that there are several causes which lead to the same manifestation.

The mechanism producing Isotropic Intensity Waves, particularly their sudden appearance and slow decay, remains a mystery.

Table 1. Predictions and observations of solar modulation parameters, from Hall et al. (1996).

Quantity	Model predictions	Observations	P (GV)	Notes
G_r	IMF polarity dependence		≤10	Predicted by Potgieter and Moraal (1985) and others
	IMF polarity dependence		≤10	Predicted Jokipii and Kota (1990) Moraal(1989),
		1–4% AU^{-1}	spacecraft	Venkatesan and Badruddin (1990)
		1–3% AU^{-1}	10	Bieber and Pomerantz (1986) – 11 year variation
		3.0 ± 1.1% AU^{-1}	10	Yasue (1980)–negligible temporal variation
		1.8 ± 0.7% AU^{-1}	20	
		0.5 ± 0.2% AU^{-1}	150	
		0.9% AU^{-1}	20	Kudo and Wada (1977) – definite cyclic
		0.4% AU^{-1}	80	variation of about 11 years
		0.3% AU^{-1}	150	
		1.0% AU^{-1}	10	Hall et al. (1994a) – definite cyclic
		0.32% AU^{-1}	100	variation of about 11 years
G_θ	Bi-directional		≤10	Predicted Jokipii (1989) and others
	and reverses	Supports	spacecraft	McKibben et al. (1979) and others
	direction at	Supports	10	Antonucci et al. (1985)
	IMF polarity	2% AU^{-1}	17	Bieber and Chen (1991) – assumed
	reversal	0.5% AU^{-1}	67	$\alpha = 0.01$
		Supports	130	Swinson et al. (1986)
		< 0.5% AU^{-1}	165–195	Hall et al. (1993, 1994b)
		0.03% AU^{-1}	300	Ahluwalia and Sabbah (1993)
		Contradicts	spacecraft	McKibben (1989) and others
		Contradicts	130	Swinson et al. (1991)
$\lambda_{\|}$		0.08–0.3 AU	≤ 4	Palmer (1982)
		> 0.5 AU	17	Chen and Bieber (1993), Hall et al. (1995) – polarity dependent
			50–195	Hall et al. (1995) rigidity dependent at all rigidities examined
		0.2 AU	10	Yasue (1980)
		1.0 AU	100	
$\alpha = \lambda_{\perp}/\lambda_{\|}$		0.02–0.083	≤ 4	Palmer (1982)
		0.26 ± 0.08	spacecraft	Ip et al. (1978)
		0.16	17	Bieber and Chen (1991)
		0.09	≤300	Ahluwalia (1993)

We now understand the gross features of classical (or rapid onset) Forbush Decreases but we do not yet understand the details. The clear anisotropies present at quite high energies are still to be understood. We do not have satisfactory explanations for slow Forbush Decreases or their 27 day recurrences. Fast solar wind streams may play a role in these events but the question remains open at present.

The heliospheric models predict that there should be a polarity dependence to the radial density gradient but no evidence for such a variation has been found and it would seem that we can be fairly confident that the data preclude such a variation. Most other model predictions seem to agree reasonably with observation but better polar fields need to be incorporated into the models to remove assumptions that we know to be somewhat restrictive.

The present status of model predictions and observations is summarised in Table 1 which is a reproduction from Hall et al. (1996).

14.4 NEW ANISOTROPY MODELS

Nagashima et al. (1995a, 1995b) have proposed a new model to explain the sidereal daily variation. In this model the sidereal daily variation is explained in terms of a narrow region of excess flux (half angle 68°) arriving from a direction (~6 hours right ascension and -24° declination) near the expected heliomagnetic tail (6 hours right ascension and -29.2° declination) and a separate loss cone anisotropy from a direction of 0 hours right ascension and -20° declination. This new model also predicts that there is no Compton-Getting effect in sidereal time.

The evidence for this model is mounting. It explains a number of problems associated with the earlier model which proposes a simple unidirectional flow of cosmic rays past and through the solar system with a possible bi-directional flow superposed, probably related to the local spiral arm magnetic field orientation.

The new model causes the observed daily variation in sidereal time to produce an excess flux and a deficit flux separated by 6 hours with a form that is not well fit by 2 or 3 harmonic sinusoids of primary period 1 sidereal day. This in turn implies that the standard harmonic analysis technique, which has been the mainstay of the field for several decades, is difficult to interpret correctly and may give a quite misleading picture of the true structures present.

It is quite clear that new automated analysis techniques will have to be developed to study such anisotropies. It may also indicate that the well-known solar anisotropies should be re-examined for possible shapes that are better described in other forms. This could be particularly valuable when looking at enhanced diurnal variation trains. Such trains during the recovery phase of Forbush decreases are quite likely to be associated with anisotropies that have complex spatial structures.

14.5 PRE-FORBUSH DECREASE SIGNATURES?

Nagashima et al. (1992, 1993, 1994) and Sakakibara et al. (1993, 1995) have proposed that some Forbush Decreases include a narrow loss-cone region near the shock front that is scanned by neutron monitors each day. This deficit is recorded in the neutron monitor record as a dip one or two days before the arrival of the shock at the Earth and the subsequent Forbush Decrease. It is yet to be demonstrated how often such precursor signals are present and if their signature is sufficiently characteristic to use the observations predictively. If this proves to be possible then it will have implications for magnetic storm warnings for the satellite and power industries.

14.6 CLOSURE OF OBSERVATORIES

Deep River, arguably the baseline neutron monitor against which all others were compared, closed in 1995 even though there was an international outcry. Other neutron monitor observatories have also been closed with one or two new ones opening in the last decade. The world-wide neutron monitor network is still functional but its effectiveness is coming under threat. It is imperative that further observatory closures be opposed from all quarters. The interpretation of many phenomena require global coverage and large gaps in the network could make it impossible to study such phenomena in any meaningful way.

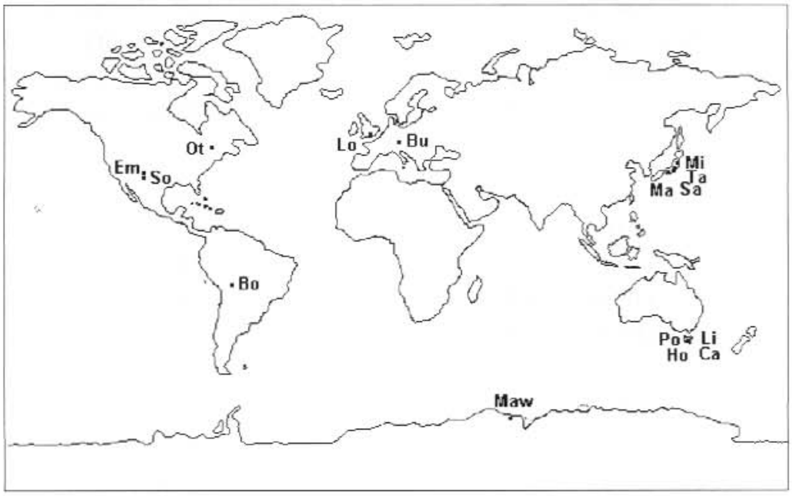

Figure 1. *Underground cosmic ray observatories operating in the last few decades. In the energy range 500–1500 GeV the currently operating stations are Matsushiro (Ma) and Poatina (Po). In the energy range 15–500 GeV the currently operating stations are Liapootah (Li), Cambridge (Ca), Hobart (Ho), Mawson (Maw), Takeyama (Ta) and Sakashita (Sa). The remaining stations, all in the lower energy range have closed; They are Ottawa (Ot), Embudo (Em), Socorro (So), Bolivia (Bo), London (Lo), Budapest (Bu) and Misato (Mi).*

Surface and underground muon telescope observations are in an even more precarious state. Misato, Embudo and Soccoro underground stations have all recently closed. The status of former Soviet Union stations is bleak with only a few surviving and some producing sporadic and limited data often of poor quality. Figure 1 shows most of the underground and surface muon telescopes which have operated over the last two decades. Not shown in the figure are the Nagoya multi-directional surface telescope and the former Soviet Union systems. The only remaining systems are those in Japan, Australia and at Mawson, Antarctica. Further closures will greatly compromise the data acquisition coverage. There is also a problem of diversity of groups collecting data with all data now being obtained by two Japanese groups (in close collaboration) and two Australian groups (also in close collaboration). The Japanese and Australian groups are also working closely together, particularly through the Japanese experiments in Australia. This convergence tends to restrict the interpretation of data more than is desirable.

14.7 THE TASMANIAN SITUATION

The last University staff member in the cosmic ray field, John Humble, retires at the end of 2000. There is little likelihood of funding to operate the full range of stations and rationalisation will have to occur. It is imperative that the neutron monitors at Darwin, Brisbane, Hobart and Mawson continue to operate. How this can be achieved is not clear. The Mawson monitor will be taken over by the Australian Antarctic Division and should continue to operate well into the future. The Darwin and Brisbane monitors could be handed over to a mainland Australian university if one can be found that is willing to operate them. The University of Tasmania, Hobart campus and Mt Wellington monitors will need to operate through another mechanism. It is possible that the Australian Antarctic Division could take on this role.

Surface muon observations on the University of Tasmania Hobart campus are undertaken with two experiments. The first is an old Geiger counter vertical telescope system. This system can probably continue operation whilst the observatory building remains available. The second is a multi-directional scintillator telescope operated by Nagoya University. This modern instrument is crucial to bi-hemisphere studies of anisotropies and transients and will continue to operate whilst Japanese funds are available. This instrument also requires the observatory building to be held for cosmic ray purposes.

The muon telescopes at Cambridge tunnel need to continue operation. They are at moderate underground depths and view further north than the Mawson system at similar depth. There is also some viewing direction overlap with Mawson which is valuable for consistency checks of observations.

Liapootah is a Japanese operated and funded underground observatory with Tasmanian group support. It is at a depth between that of Cambridge and Poatina and is the only such southern hemisphere observatory. It will continue to operate for the lifetime of its Japanese funding. It is expected to continue operation at least until the next solar minimum, around 2005. It would be extremely valuable to extend these observations for several solar cycles, especially throughout a full magnetic cycle.

The deep underground station at Poatina is the only one of its kind in the southern hemisphere. It does have a very low count rate and this needs to be increased but the system costs almost nothing to operate and should be kept running.

14.8 THE ANTARCTIC SITUATION

Most neutron monitors in Antarctica will continue to operate except the Russian experiments which are collecting data on a sporadic basis due to funding problems. As an example, the Vostok base is operating on a summer only basis at present.

The only surface or underground muon telescopes at polar latitudes in either hemisphere are at Mawson. The future of this system is secure for the present. If Marc Duldig should leave the Australian Antarctic Division then the resources will be diverted and the cosmic ray program will cease with the closure of the observatory at Mawson.

14.9 SOUTHERN HEMISPHERE COSMIC RAY OBSERVATIONS – THE FUTURE

Australia operates or hosts the only muon observatories in the southern hemisphere. The need for bi-hemisphere observations is undisputed and without them the field of research itself is threatened. Australian observatories also cover the largest geomagnetic cutoff range of any part of the world-wide neutron monitor network as well as a significant proportion of the latitude and longitude coverage. The question remains – what must we do to ensure future southern hemisphere observations.

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15. FUTURE TRENDS IN GROUND LEVEL ENHANCEMENT MODELLING

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ABSTRACT

Significant improvements have been made in the modelling of Cosmic Ray Ground Level Enhancements with the incorporation of realistic geomagnetic field models and least squares determination of parameters. A major contribution to future research could be made by applying the current modelling techniques to as many historical data sets as possible. Such a study would allow comparison of the features of different events and could lead to a greater understanding of the acceleration and propagation mechanisms involved. Extension of the analysis to future events may also reveal solar cycle trends which can only be identified from a study spanning several cycles. Modelling of future events will only be possible with the continuation of the world-wide neutron monitor network. Surface muon telescopes are also important during the most energetic events. The modelling process should also be expanded to incorporate a wider range of particle energies. This may require some refining of the yield functions which couple the ground level response to the primary particle population.

15.1 INTRODUCTION

The process of modelling cosmic ray ground level enhancements (GLEs) has been described previously (Cramp, this volume, Chapter 11). Current modelling techniques incorporate realistic geomagnetic field models which account for distortion at times of geomagnetic disturbance (Tsyganenko, 1987, 1989). These models enable the accurate determination of viewing directions for ground level instruments (Flückiger and Kobel, 1990).

A least squares procedure is used to determine the best-fit parameters in the GLE model. This has facilitated the introduction of more complex functional forms to describe the pitch angle distributions and particle rigidity spectra. These functions should represent the physical processes involved in particle acceleration and propagation. The best-fit solutions provide information about these processes for the individual event being modelled.

This paper discusses possible future trends in the modelling of GLEs. The three main areas covered are: studies of historical datasets; studies of future events (including the necessity to maintain the world-wide neutron monitor network); and extension of studies to a wider rigidity range.

15.2 HISTORICAL DATASETS

There have been 53 GLEs since reliable data records began in the 1940's. Figure 1 shows the number of events per year (histogram) and the smoothed monthly sunspot number for the period 1940–1995. Of particular interest is the unprecedented series of 13 GLEs which occurred within two years near the time of the last solar maximum.

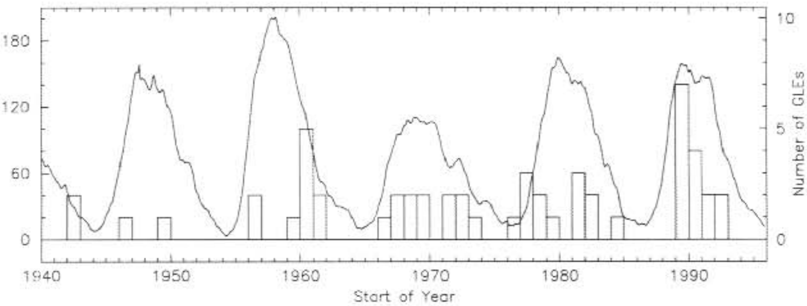

Figure 1. *Monthly smoothed sunspot numbers and number of GLEs (histogram) for the period 1940 to 1995.*

Many of these events have been studied in detail (e.g. Cramp, 1996). Good quality, short time-interval neutron monitor data should exist for all events of the 21st and 22nd solar cycles following the introduction of super neutron monitors at most stations after the International Year of the Quiet Sun in 1965. The GLE database should be expanded to include as many of these events as possible.

While detailed study of individual events is interesting and worthwhile, it is important not to study them in isolation. Modelled features should be compared with those of other events to find similarities and differences. It may then be possible to relate similar and different features to other properties of the solar emission or the interplanetary medium.

An example of similar features shown by two events was revealed in a study of historical datasets by Shea et al. (1995). The GLE of 22 October 1989 had a highly anisotropic initial phase followed by a world-wide event (Cramp et al., 1997). This was thought to be very unusual. Shea et al. (1995) found remarkable similarities between this event and that of 15 November 1960. Figure 2 shows data from Mawson for the 1960 event and McMurdo for the 1989 event. Also shown in this figure is data from South Pole and Calgary neutron monitors during the 19 October 1989 GLE. This event also showed a small anisotropic increase prior to the main event. Decay products of solar neutrons have been suggested as the cause of this feature (Shea et al., 1991), however the observation of a later spike at many of the same stations may lead to an alternative explanation (Cramp, 1996). A systematic study of historical datasets may uncover further sets of events with common features.

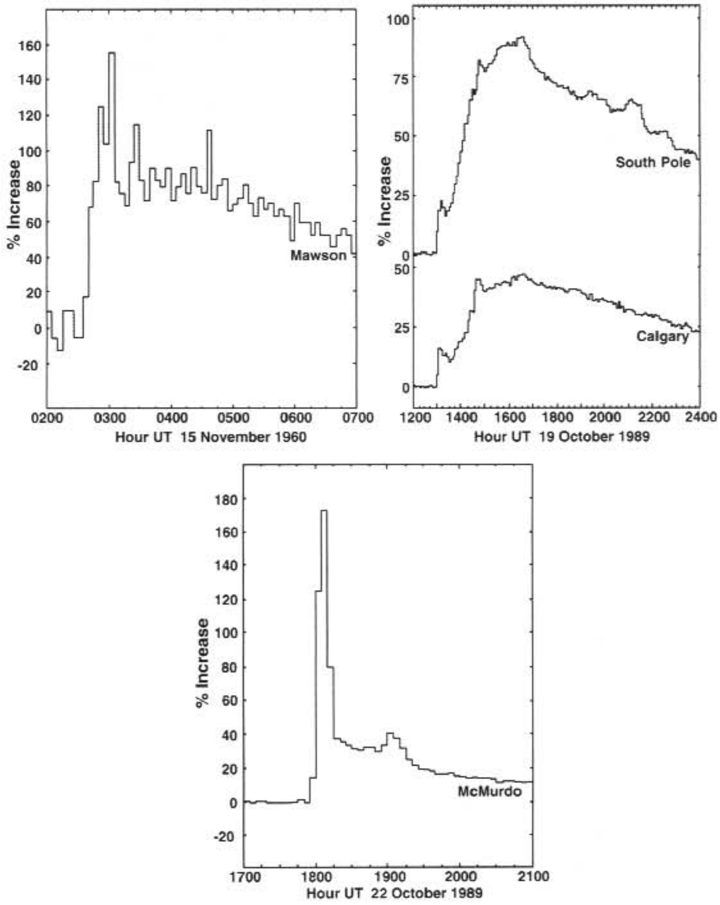

Figure 2. *Neutron monitor count rate increases at Mawson on 15 November 1960, South Pole and Calgary on 19 October 1989 and McMurdo on 22 October 1989.*

15.3 FUTURE EVENTS

A sample of 53 events, many with insufficient data for detailed study, is not a large enough set to draw statistically significant conclusions. It is important to keep collecting data so that the number of GLEs for which we have high quality data is increased. A longer time span is also required to identify any solar cycle trends in the modelled features.

The modelling process requires good spatial and cut-off rigidity coverage which can only be achieved by a substantial world-wide network. The rigidity dependent viewing directions of some selected stations are shown in Figure 3. This plot shows viewing directions of all the polar neutron monitors currently in operation. Those in the southern hemisphere are fairly evenly spaced in longitude and provide sufficient coverage for most events. Closure of one of these stations would result in a significant gap in the available viewing directions. High latitudes in the northern hemisphere are less well covered. There are many neutron monitors which view mid-latitude regions, however those operated by the University of Tasmania (Hobart, Brisbane and Darwin) view a longitude range which is only partially covered by other stations. This set of stations is also valuable for spectral determination as the cut-off rigidities range from 1.8 GV at Hobart to ~13 GV at Darwin.

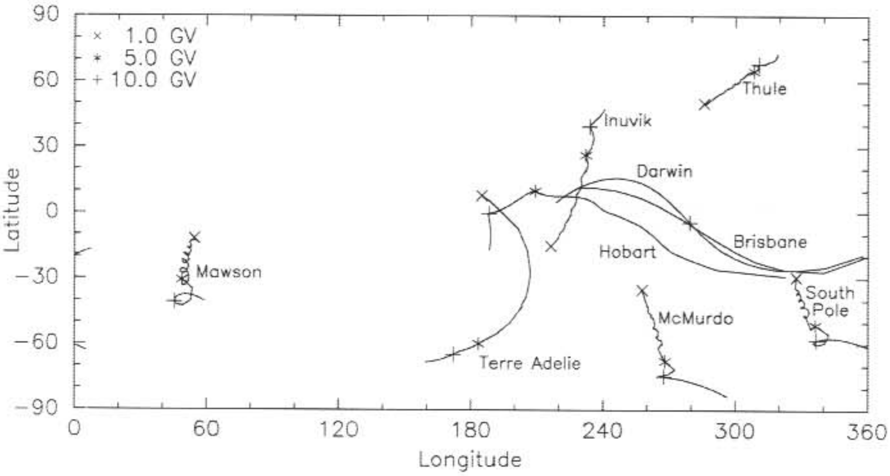

Figure 3. *Rigidity dependent viewing directions of selected neutron monitor stations under quiet geomagnetic conditions. Viewing directions from 20 GV down to the cut-off (geomagnetic or atmospheric) are plotted and those at 10, 5 and 1 GV are indicated (where these rigidities are above the cut-off).*

15.4 WIDER RIGIDITY RANGE

The threshold rigidity for particles to penetrate the Earth's atmosphere is ~1 GV. Using data from ground level neutron monitors at different cut-off rigidities spectral information can be obtained up to ~14 GV (the cut-off at the geomagnetic equator). Expansion of the modelling to a wider rigidity range requires data from a different type of detector. Solar accelerated particles rarely exceed rigidities of ~20 GV, however, during the 29 September, 1989 GLE there was evidence of particles with rigidities up to ~25 GV. Increases were observed in the count rate of surface and shallow underground muon detectors. The surface muon data have been used with limited success in modelling this event (Cramp, 1996). Further work is needed to satisfactorily normalize the yield functions of the muon and neutron detectors so that they are directly comparable.

An obvious next step is to extend the modelling process to lower rigidities. This means moving outside the Earth's atmosphere to satellite instruments. Once again, the normalisation between different types of detector is a problem but if this could be overcome, spectral information could be obtained over an energy range from a few MeV to tens of GeV.

Many GLEs produce significant responses only at high latitude sites on Earth due to insufficient numbers of high energy particles. While the world-wide neutron monitor network may provide reasonable spatial coverage for these events, there is little spectral information to be obtained. Satisfactory incorporation of satellite particle data into models of these events may greatly increase the number of GLEs which can be modelled.

15.5 CONCLUSION

It is important to model as many GLEs as possible and to draw comparisons between them. Explanations for any similarities and differences should be sought from other solar or interplanetary data. The number of events which have been modelled in detail is not sufficient to draw any significant conclusions. A study of historical datasets may reveal events with similar features. Events for which there are sufficient data should be modelled with the upgraded technique. It is also necessary to continue operating instruments to observe future events. Data spanning several solar cycles are needed to identify any solar cycle dependent trends in the modelled parameters. A good selection of ground level instruments must be maintained to obtain data for future events. It is important that these instruments provide good spatial coverage and span a range of cut-off rigidities.

The energy range over which spectral parameters can be obtained should be increased by the incorporation of data from different types of observing instruments. A study including surface muon data has revealed the need to normalize the yield functions of the neutron and muon detectors so that they are directly comparable. Incorporation of data from satellite based particle detectors would increase the energy range. This may also allow modelling of events which produced increases only at high latitude sites on Earth as the satellite data would provide further information on the spectrum.

15.6 ACKNOWLEDGMENTS

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