COMMONWEALTH OF AUSTRALIA
DEPARTMENT OF EXTERNAL AFFAIRS

AUSTRALIAN NATIONAL ANTARCTIC RESEARCH EXPEDITIONS

# ANARE REPORTS

## SERIES A

## VOLUME IV

# GLACIOLOGY

## Solar Halos in Antarctica

by

J. R. BLAKE

(59)

ISSUED BY THE ANTARCTIC DIVISION,
DEPARTMENT OF EXTERNAL AFFAIRS, MELBOURNE,
JUNE 1961

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## SUMMARY.

Solar halo displays originating in low altitude ice-crystals over the ice-cap inland from the Australian National Antarctic Research Expeditions' station, Mawson, are described. Various forms of the upper contact arc to the 22°-halo are discussed in more detail with special reference to an unusual circumscribed ellipse and to the very rare double upper contact arcs. Other rare halos are reported, together with a very extensive and unusual display. A general analysis of observed halo components is given and some comparison made with the data obtained from Maudheim in 1950-52. An appendix of results is included, containing also descriptions of the more extensive displays.

# SOLAR HALOS IN ANTARCTICA

by

## J. R. BLAKE

[*Manuscript received October 15, 1959*]

## I. INTRODUCTION.

During the Southern Seismic Traverse from the Australian National Antarctic Research Expeditions' station, Mawson (67° 36.3′ S, 62° 52.9′ E) to latitude 70° 50′ S, between September 30, 1958, and January 17, 1959, the phenomenon of solar halos was frequently seen. The displays varied from the very simple to the very complex systems, frequently being extremely brilliant, and occurred during either the formation of low, apparently stationary, suspensions of " ice-needles ", denser, drifting ice-crystal " clouds ", or ice-fog. All halos were " low " halos, i.e., occurring near ground level, and not, as is usually the case in middle and low latitudes, occurring in high cirriform clouds. It should be noted, however, that the elevation of the ice-cap during the period for which records were kept, was between 6500 ft. and 9000 ft. above M.S.L.

Owing to the fact that " low ", or even extensive or brilliant " high ", halos were rarely, if ever, seen at Mawson during 1958, the first appearances of the halos were somewhat of a novelty, and, apart from the obvious fact that they were produced in connection with the ice-crystals, little else was known of the different halo forms and their origins. For this and other reasons, the records kept during the Seismic Traverse are somewhat incomplete, especially those of less intense or not-unusual displays. As displays usually occurred while the seismic trains were travelling, very few angular measurements were obtained, although on a few occasions, astrocompass readings were taken, or more approximate methods used. No equipment was carried for studying ice-crystal types, but surface air temperatures and general meteorological data are known; however, attempts at measuring the upper air temperature inversion with improvised apparatus were not successful.

* Antarctic Division, Department of External Affairs, Melbourne (Now with Commonwealth X-Ray and Radium Laboratory, Melbourne).

## II. ICE CRYSTALS.

Several workers have studied temperature dependency of ice-crystal formation at water-saturation for temperatures between 0° C and —40° C (Liljequist, 1956, and Mason, 1957, both contain reviews of this work, giving many additional references). Briefly, ice-crystals are of hexagonal base, with perpendicular principal axis, and occur in three main basic types. Those with little development along the principal axis are termed " plates ", while those developed along this axis are termed " short " or " elongated columns ", depending on the degree of development.

Simple plates occur between 0° C and —5° C, then short and twin prisms down to about —10°C., when the structure reverts fairly sharply to plate form, but of complicated structure, with a maximum of dendritic growth at about —15° C. At about —20° C to —25° C column formation takes over again, crystal size decreasing and frequency of irregularities increasing as temperature decreases.

A fourth type of ice-crystal, about which very little is known, is the pyramidal ice-crystal.

Ice-crystals tend to float in the atmosphere so that their air resistance when falling is a maximum. Hence:—

(*a*) plates will oscillate through the horizontal, the principal axis thus oscillating about the vertical;

(*b*) short columns will have no preferred orientation;

(*c*) elongated columns will oscillate with horizontal principal axis.

## III. HALO TYPES.

The form of the halo results from reflections and/or refractions at one or more faces of the crystals, the intensity being dependent on density, distribution, orientation, and size of the crystals, and on the height of the sun (or moon). Some forms change with the sun's elevation, some reaching intensity maxima, others not being formed at all, at certain elevations.

Figure 1 summarises the three main halo groups, and the types of ice-crystal in which the components of each group originate are given below. (Figure 1 is taken from Liljequist, 1956, pp. 32-33.)

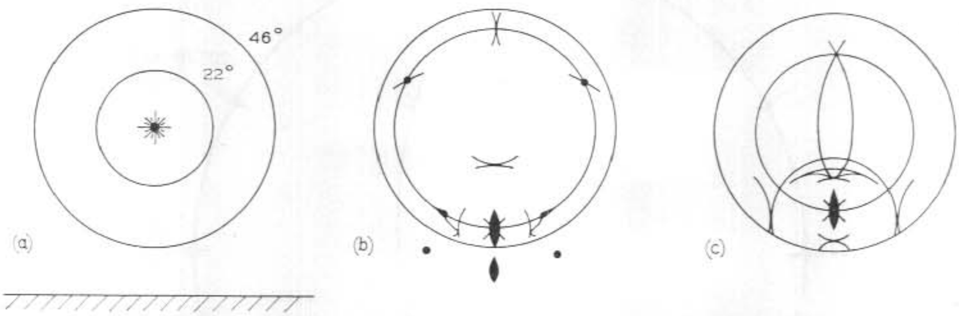


FIG. 1.—Halo Components produced in (*a*) Ring Group, (*b*) Plate Group, (*c*) Column Group (Liljequist, 1956).

(*a*) *The Ring Group of Halos.*—This group originates in short columns, single or in aggregates, and compound bullets (i.e., bullet-like columns, with the thin ends attached to a central core) with or without plates attached to the columns.

(*b*) *The Plate Group of Halos.*—These halos originate in plates, and table-crystals or capped columns (columns with comparatively large plates attached to one end).

(*c*) *The Column Group of Halos.*—This group originates in elongated columns.

A description of the more common halos, and others relevant to this article, are given below, together with some indication of their origin. Comprehensive summaries have been given by Hasting (1920);

Humphreys (1940) ; Liljequist (1956) ; Putnins (1934) ; Wegener (1926) ; and Woollard (1936, 1937, 1941). Most of the halo-components are identifiable on Figure 2.

(i) 22°-*Halo.*—This halo is the most common and widely known of all, being frequently seen in high cloud. It is produced by refraction through 60° prisms, in short columns, the principal axes of which have no preferred orientation. The red inner border, or focal line, lies at approximately 22° from the sun, being produced by ice-crystals in the

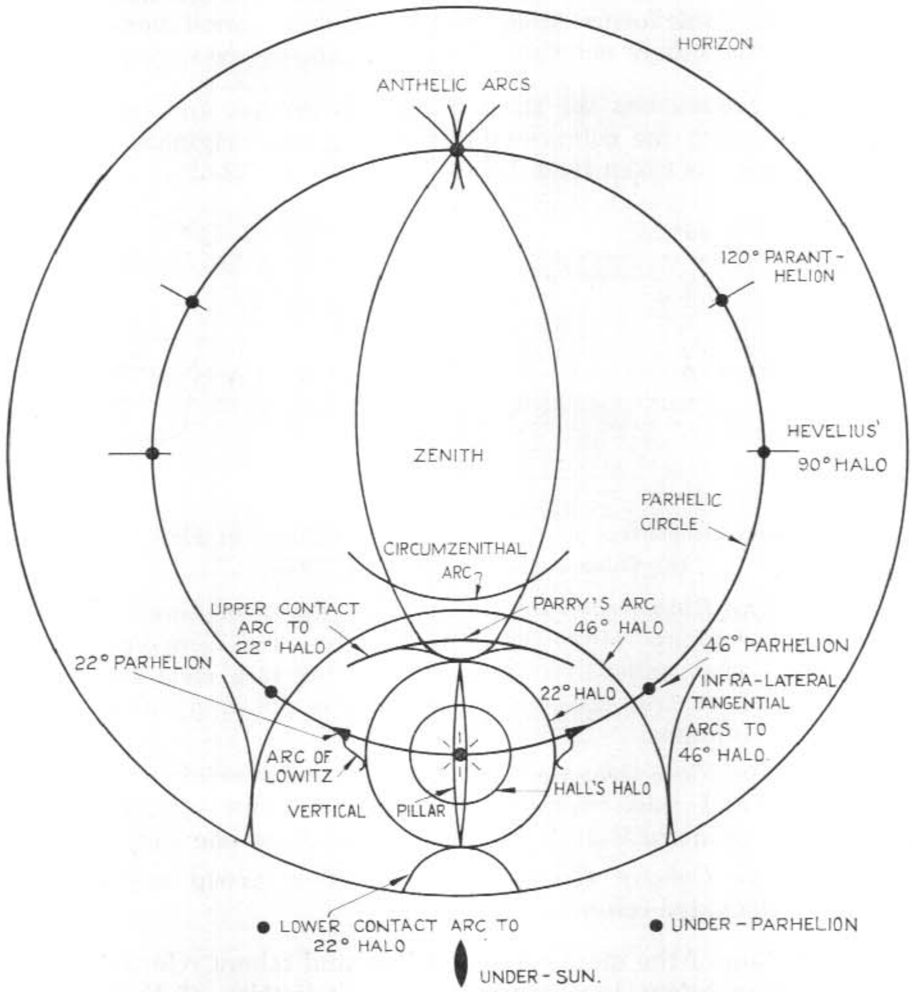


FIG. 2.—Some possible Solar Halos, drawn on the Celestial Sphere.

position of minimum deviation in the principal section of the 60° prisms, the rest of the ring being produced by other ray paths or orientations (See Humphreys, 1940).

Portions of this halo are produced under different conditions. Plates and table-crystals, oscillating with the principal axes near-vertical, produce parts of the 22°-halo near the parhelia (i.e., in the sun's horizontal), by refraction through the 60° prisms. The limits of the arcs above and below the parhelic circle are a measure of the oscillation of the ice-crystals.

Similarly, elongated columns oscillating with principal axes near-horizontal, produce portions of the 22°-halo near the sun's vertical, by refraction through 60° prisms.

(ii) 46°-*Halo*.—Although this halo is usually rarer and fainter than its 22° counterpart, its colours are purer and more distinct. It originates in a similar manner to the 22°-halo, the refraction being in the 90° prisms formed by base-surfaces and prism faces (See Humphreys, 1940).

This halo is also produced by refraction in the 90° prisms of horizontal elongated columns, the orientation of the principal axes in the horizontal plane being non-preferred.

Portions of the 46°-halo in the solar vertical are produced in a similar manner to the 22°-halo near the parhelia, with refraction in the 90° prisms. The bright circumzenithal arc may tend to mask this, however.

(iii) 22°-*Parhelia*.—This brilliant halo consists of a pair of mock suns on either side of the sun, situated on the parhelic circle. From the coloured parhelia proper, white tails extend away from the sun. With the sun on the horizon, the parhelia coincide with the 22°-halo; as the sun's altitude increases, the parhelia recede from it along the parhelic circle, decreasing in intensity, and the tails also shortening.

This halo is produced by refraction in 60° prisms of plates and table-crystals having vertical principal axes, and orientated so as to give minimum deviation. The white tails are produced by ray paths other than those of minimum deviation (See Wegener, 1926).

If the rays are reflected from the lower base of the crystal, *under parhelia* are produced, below the horizon, being images of the parhelia (Wegener, 1926). Similarly, an *under sun* is produced by reflection against the upper and lower bases of the crystals, usually being extended vertically due to crystal oscillation (Liljequist, 1956, mentions these halos, giving further references). Neither of these latter two halos was observed during the Southern Traverse.

(iv) 46°-*Parhelia*.—This very rare halo is produced in a similar manner to the 22°-halo, the refraction occurring in the 90° angles. Again, with the sun on the horizon, these parhelia coincide with the 46°-halo, receding from it with increasing solar altitude, but remaining on the parhelic circle (See Humphreys, 1940).

(v) *Parhelic Circle*.—This halo consists of a white ring, parallel to the horizon, and at the same altitude as the sun. It is produced by reflections, both external and internal, from vertical prism faces and vertical base surfaces and hence originates in plates and table-crystals, having vertical principal axes, and in elongated columns, having horizontal principal axes. It may exist in part or complete, sometimes occurring only within the 22°-halo, sometimes only outside it. Frequently the part inside the 22°-halo is of markedly less intensity than the part outside it (see Wegener, 1926).

(vi) *Vertical Pillar*.—Again, both plate and table-crystals, and elongated columns cause this halo which results from reflections from the base surfaces of the former and the prism faces of the latter, both types of which are oscillating. In the latter case there is also a considerable contribution from reflections from prism faces with non-preferred orientation of the principal axes in the horizontal plane.

The pillar may extend up to the 22°-halo and down to the horizon, and even down to the under-sun (see Wegener, 1926; Liljequest, 1956).

(vii) *Upper and Lower Tangential Arcs to the* 22°-*Halo* (*Circumscribed Halo*).—These arcs are also produced in elongated columns having horizontal principal axes of non-preferred orientation, the focal line being produced by minimum deviation in 60° prisms.

The shape of this halo varies with solar altitude. Below 29.2° two arcs occur, one above and the other below the sun, being tangential to the 22°-halo in the solar vertical. Above 29.2° the two arcs join, forming a halo circumscribed about the 22°-ring, initially somewhat crescent-shaped, but becoming more elliptical with increasing solar altitude, coinciding with the 22°-ring when the sun is in the zenith.

The theory is developed by Wegener (1926), and the various forms given by Humphreys (1940).

(viii) *Arcs of Lowitz*.—This rare halo is produced in a similar manner to the parhelia, except that the principal axes are oscillating through the vertical, those oscillating in the solar vertical being of particular interest.

The halo appears as short arcs extending from and mainly below the parhelia, and towards the 22°-halo. If the crystal tilt in the solar vertical reaches the value of the solar altitude, the arcs meet the 22°-halo tangentially, and for greater tilts are produced below the points of tangency. With the sun on the horizon, the points of tangency coincide with the parhelia.

The arcs are further discussed by Humphreys (1940), who also gives further references to forms of crystal tilting other than in the solar vertical.

Another form of lateral tangential arc to the 22°-halo, produced by plates oscillating through the mean position with vertical principal axes, the method of production being similar to that for the under-parhelia, is described by Liljequist (1956). These arcs pass through the under-parhelia instead of the parhelia.

Neither of these arcs was seen during the Southern Traverse.

(ix) *Parry's Arc.*—This halo is also rare, being produced by refraction in 60° prisms of horizontal elongated columns having two prism-faces horizontal. This orientation only occurs under very favourable conditions, such as very low turbulence (Wegener, 1926), as the air resistance of the falling crystal is then at a maximum. Besson has suggested an alternative requiring four elongated columns united to form a cross, and floating with both bars horizontal (Liljequist, 1956).

The arc is usually seen as a faint white line, appearing in conjunction with the circumscribed halo, which requires a non-preferred orientation of secondary axes. The observations discussed in this article, however, are of very intensely coloured arcs.

The theory is developed by Wegener (1926).

(x) *Arcs of Putnins.*—Putnins has discussed the arcs produced by different ray-paths in crystals orientated as required for Parry's Arc, and also in crystals orientated with two prism faces vertical (Putnins, 1934).

These arcs are tangential to the 22°-halo, or very nearly so, for certain solar altitudes and may in some cases closely resemble the circumscribed halo. It is suggested in this report that some forms of these arcs give rise to the very rare double upper contact arcs of the 22°-halo.

(xi) *Circumzenithal Arc.*—Refraction in 90° prisms of plates and capped columns, having vertical principal axes, results in this halo, the colours of which are very pure. Between solar altitudes of 15° and 25°

it is very nearly tangential to the 46°-halo, forming a partial arc around the zenith. The theory of this halo is given by Wegener (1926).

On very rare occasions, it may join a second arc, forming a complete coloured circle around the zenith. This second arc is very weak and is known as *Kern's Arc* (Humphreys, 1940). It was not seen on the Southern Traverse, although the circumzenithal arc itself was quite common.

A true upper contact arc to the 46°-halo (the arc of Galle) has been suggested as due to a predominance of ice-crystals with a 90° refracting edge horizontal, the crystals being otherwise randomly disposed (Saville, 1944).

(xii) *Infra-Lateral Tangential Arcs to the 46°-Halo.*—Although these arcs were never seen on the Southern Traverse, they are apparently not very rare. They are produced by refraction in 90° prisms of elongated columns, having horizontal principal axes, and are analogous to the circumzenithal arc. The theory is given by Wegener (1926).

(xiii) 120°-*Paranthelia.*—These mock suns result from two internal reflections in ice-crystals with vertical principal axes, across angles of either 60° or 120°, resulting in light concentrations on the parhelic circle and at 120° azimuth from the sun. Oscillation of the crystals results in short arcs being produced through the paranthelia (Humphreys, 1940, and Hastings, 1920).

As pointed out by Liljequist (1956), plates are more likely to produce the 120°-paranthelia at low solar altitudes, whereas table-crystals are probably the origin at higher altitudes.

(xiv) *Anthelic Arcs.*—There appear to be several different forms of anthelic arcs. Wegener (1926) considers the anthelic halo to be a reflection of the circumscribed halo in the base surfaces of elongated columns, having horizontal principal axes. The halo consists of two arcs running from the upper part of the 22°-halo and intersecting in the anthelic point (which corresponds to a reflection of the points of intersection of the circumscribed halo with the parhelic circle and hence is not produced for solar altitudes below 14.1°). For high solar altitudes the arcs meet again at the lower limit of the 22°-halo forming a closed curve. Frequently the only part seen is that near the anthelic point.

Hastings (1920) considers the halo to be due to rays entering one prism face, being reflected from the vertical base of the elongated column and finally emerging through the prism face opposite the entrance face. This results in two intersecting arcs being produced at the anthelion, where they resemble Wegener's arcs, except that they occur only near the anthelion. Occasionally both types may appear together (Bavendick, 1920).

A third type of anthelic arc is suggested by Liljequist (1956) as resulting from plates. These arcs are tangential in the anthelion, instead of intersecting.

(xv) *Halos Produced in Pyramidal Ice-Crystals.*—Many halos of unusual radii have been ascribed to pyramidal ice-crystals. These include Hall's Halo, of radius about 9°, and Hevelius' 90°-Halo and mock suns. Humphreys (1940) explains this latter halo by two internal reflections in bipyramidal ice-crystals, the sides of which are inclined at 24° 51′ to the longitudinal axis. If visible, the red would be on the side away from the sun, in contrast to most other coloured halos. This crystal type also explains other halos of rare radii.

(xvi) *Other Halos.*—Under certain conditions, other types of halo are produced. These include anti-solar halos at 46° and 82°, oblique heliac arcs and slanting arcs, circumhorizontal arc (analogous to the circumzenithal arc but below the 46°-halo), lateral and supra-lateral tangential arcs to the 46°-halo, an under-Parry's Arc and a mock sun and horizontal ring of Hall's Halo. Also, the fog-bow or Bouger's Halo is sometimes seen with ice-crystal halos. Some of these are mentioned later in this article; for further reference see Humphreys (1940), Wegener (1926), Liljequist (1956), Hastings (1920).

## IV. 22°-HALO SYSTEM.

On almost all halo occasions the 22°-halo was present, in most cases having the 22°-parhelia on or close to it, and frequently with some form of upper and/or lower contact arc also in evidence.

The upper contact arc could take one of several forms, although, on the few occasions on which the lower contact arc was seen, it was always of the same form, being more diffuse and less definite in colour and general outline than its upper analogue. When the coloured upper contact arc was convex towards the sun, it was usually brilliant at the point of contact and was frequently associated with an intense, coloured arc of the form known as Parry's Arc.

On several occasions, a complete "circumscribed" ellipse was seen, sometimes together with an additional upper or lower contact arc. However, there are some appreciable discrepancies from the generally accepted theory of the circumscribed halo. On all observed occasions (of which there are four in the records), the halo had an approximately identical shape, despite the fact that the solar altitude ranged from 19° to nearly 40°. The shape was approximately elliptical (in fact it is described in the original observations as "halo and ellipse"), the major axis being along the parhelic circle, and the ellipse and 22°-halo merging smoothly into one curve, at approximately one-third of the parhelic circle—solar vertical arc-distance above and below the parhelic circle (i.e., at approximately 30° above and below the parhelic circle, taking the sun as centre). This is illustrated in Figure 3.

According to the theory of the circumscribed halo (Wegener, 1926), the upper and lower contact arcs of the 22°-halo do not join to form a complete circumscribed halo until the solar altitude reaches 29.2°. At this altitude the azimuth of the point of intersection of the circumscribed halo with the parhelic circle would theoretically be 41.7° (solar distance 36.2°). This is an extra two-thirds of the radius of the 22°-halo, and, although only one angular measurement was obtained, it can safely be stated from memory that the displacement of the point of intersection from the 22°-halo was never as great as this. On the single occasion when a measurement was obtained, at a solar altitude of 39.4°, the azimuth of the point of intersection was 34° (solar distance 26.1°), as compared to the relevant theoretical value at 40° (solar distance 30.7°), which is not

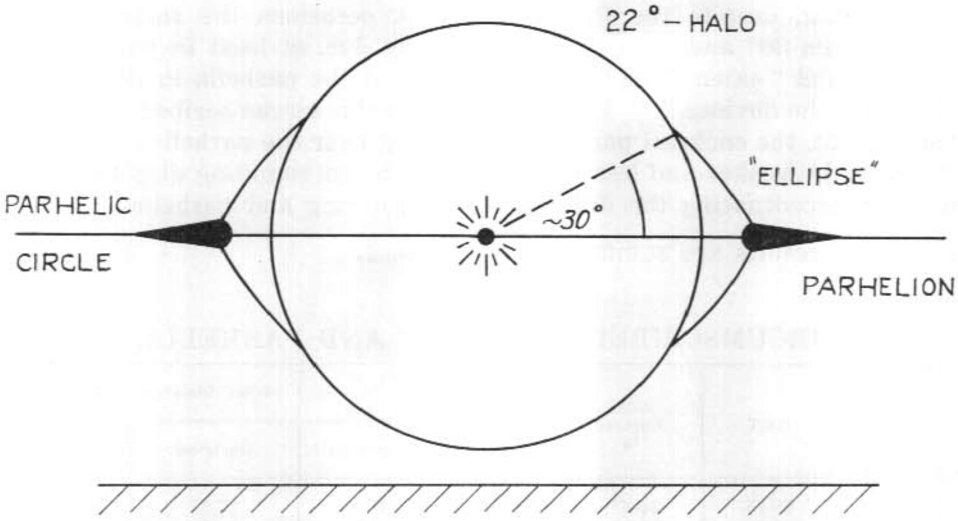


FIG. 3.—22°-Halo and "Ellipse".

good agreement even allowing for the accuracy of the astrocompass used to make the measurement.

On three of the four observations, an additional contact arc of the 22°-halo was observed, two being on the lower side, convex towards the sun, the other being on the upper side and concave towards the sun.

Also on these three occasions, the parhelia were observed to occur at the intersection of the circumscribed "ellipse" with the parhelic circle. On the fourth occasion (solar altitude $h_S = 19.0°$) no parhelia were visible although the region of the "ellipse" in the vicinity of the parhelic circle was considerably brighter than elsewhere on either this halo or the 22°-ring

According to the theory of Wegener (1926), the solar distance of the parhelia increases from 21.8° at $h_S = 0°$, to 24.8° at $h_S = 30°$, and 27.6° at $h_S = 40°$. As has already been indicated, the single measurement obtained on the circumscribed "ellipse" and parhelia at solar altitude $h_S = 39.4°$ is not in good agreement with the theory of the circumscribed halo; however, the theoretical solar distance of the parhelia at this altitude is 27.3° (c.f. 26.1° from the measured azimuth of 34°), which is reasonable agreement, considering the instrument.

It should be remarked that on all other occasions when parhelia were recorded (21 occasions), other than the three mentioned above, they were not noted as being appreciably different in solar distance from the 22°-ring, despite the fact that on six occasions the solar altitude was between 30° and 40°. This is probably due, at least in part, to the intensity and " extent " of the 22°-ring and of the parhelia in this region " masking the obvious ".* In contrast, when this circumscribed " ellipse " was present, the enclosed part of the 22°-ring near the parhelic circle, was considerably weaker and less marked, than the surrounding display, hence probably accentuating the difference between ring and parhelia.

These results are summarised in Table 1.

TABLE 1.

CIRCUMSCRIBED " ELLIPSE " AND PARHELIA.

| Date. | GMT | Solar Altitude $h_s$ | Solar Distance of Intersection of Parhelic Circle and c/s Halo. | | Solar Distance of Parhelia. | |
|---|---|---|---|---|---|---|
| | | | Observed " Ellipse " | Theoretical† | Observed. | Theoretical† |
| 1.xii.58 | 0915 | 30.4° | 26.1° | 30.7° | 26.1° | 27.3° |
| 4.xii.58 | 1200 | 29.1° | .... | 36.2° | on " ellipse " | 24.7° |
| 9.xii.58 | 0600 | 39.7° | .... | 30.5° | on " ellipse " | 27.3° |
| 22.xii.58 | 1430 | 19.0° | .... | 44.5° | not visible | 23.0° |

† Wegener (1926).

Hence we see that, if the theoretical solar distances of the parhelia are accepted as the correct ones (and the theory of Wegener for the parhelia has been well verified by observations—see Wegener, 1926), then the circumscribed " ellipse " of these observations is certainly not the circumscribed halo of Wegener's theory. This is supported by the fact that the shape of the halo remained virtually constant for widely differing solar altitudes.

It should be pointed out, however, that the complete circumscribed halo of Wegener, although not common, has been observed. See, for instance, Neuberger (1934) and the observations of Barkow on the Filchner Expedition, 1911-12, discussed by Sander (1951).

To the author's knowledge this " ellipse " has not previously been described, although it is possible it has been confused with Wegener's circumscribed halo which is, however, of considerably different shape. The various forms of this halo for different solar altitudes are given by Humphreys (1940).‡

* A similar case of " masking the obvious " has possibly occurred in connection with the records of the circumzenithal arc, also very intense and extensive at its contact point. This will be discussed later.

‡ It has recently been suggested by Professor S. W. Visser in a private communication (September, 1960) that the theory of the Arcs of Lowitz must be completed by considering total reflection at the base surfaces of the floating plate-ice crystals. He suggests that if the lower portion of this " ellipse " is considered to be the Arc of Lowitz, then the upper portion could be due to such a reflection at these horizontal faces.

This extension of the theory of the Arcs of Lowitz by Professor Visser is to be published shortly in " Die Haloerscheinungen." Handbuch der Geophysik, Band VIII.

Let us now return to the upper and lower contact arcs of the 22°-halo as distinct from the complete circumscribed halo. As has already been mentioned, these were observed to take one of several forms. The most common form was the single, U-shaped arc, sometimes with the ends of the U turning down towards the parhelic circle. This form has also been reported by many other expeditions and observers (e.g., Liljequist, 1956; Arctowski, 1902; Putnins, 1934), and is explained theoretically by Wegener (1926) as being the form taken by the upper part of the circumscribed halo, for low solar altitudes.

On several occasions this halo was accompanied by Parry's Arc, taking the form of a coloured arc concave to the sun with its apex in the solar vertical, and merging smoothly with the turned down ends of the U. On these occasions, both Parry's Arc and the contact arc were intensely bright, although the contact arc, especially at its point of tangency, was usually slightly brighter. This appears to be somewhat unusual as Parry's Arc is normally rather faint and white, and is seen only on rare occasions (e.g., during the two years' stay at Maudheim, Liljequist observed this halo only three times, all appearances being faint and uncoloured. Several other polar expeditions have not reported it at all—e.g., see Arctowski, 1902; Sander, 1951, 1953). As noticed by Liljequist, Parry's Arc often appears to be an upper bound of the luminous white "veil" of the contact arc.

On the display of November 29, 1958, at 1345 GMT ($h_S = 19.7°$), a few estimates were made of the positions of various points on the upper contact arc and on Parry's Arc. These are summarised in Table 2, together with the theoretical values (Wegener, 1926).

TABLE 2.

UPPER CONTACT ARC AND PARRY'S ARC.

| Point of Measurement on Halo. | Estimated Position. | Angle. | |
|---|---|---|---|
| | | "Observed" | Theoretical |
| Solar distance of apex of Parry's Arc (in Sun's vertical) | c. ¼-⅓ of radius of 22°-halo above point of tangency | 26°-28° | 29° |
| Azimuth of intersection of contact arc and parhelic ring | Extremities of contact arc almost reached 46°-ring at parhelic circle and if produced would have done so | 49.0° | 48.3° |
| Approx. azimuth of mergence of Parry's arc with contact arc. | Vertically above ⅔ radius of 22°-halo | c.15°-16° | 25°-30°*<br>18°-20°† |

* Assuming Wegener's Theory for the circumscribed halo.
† Assuming Putnins' Theory for arc I-V (see later).

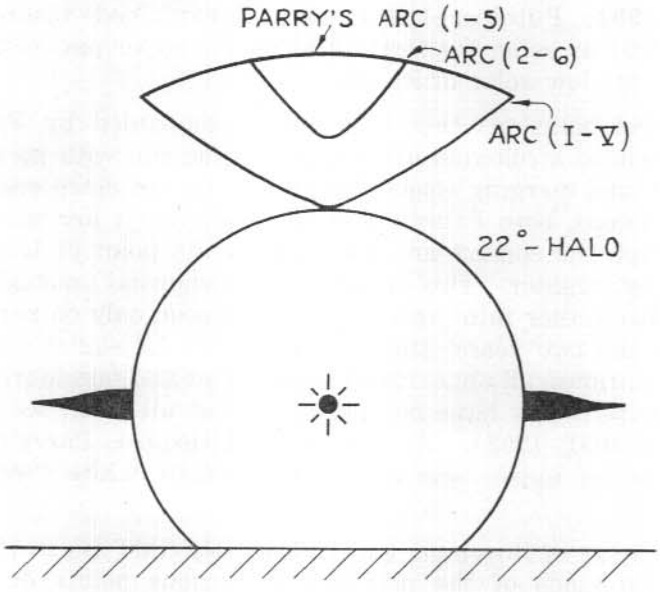


FIG. 4.—Double Upper Contact Arcs and Parry's Arc.

Thus, in the first two cases, theory and observation are in reasonable agreement, considering the accuracy of the measurements. The last case will be discussed later.

Another form taken by the upper contact arc was that of "double arcs" convex to the sun, the lower one being in contact with the 22°-halo. These appeared to be hyperbolic or elliptical in shape, but not circular, and all three cases on record are for solar altitudes below 15°. On two of these occasions a few measurements or estimates were noted, and on one of these occasions (a very complex display occurring at 2400 GMT on December 2-3, 1958, $h_S = 13.0°$, which is discussed later) Parry's Arc was also visible. On this latter occasion it was noticed that neither of the two arcs merged smoothly with Parry's Arc, but rather appeared to intersect it, both arcs terminating at their points of intersection. The three arcs, together with the 22°-halo, are shown in Figure 4, and the measurements relating to Parry's Arc are given in Table 3.

TABLE 3.

PARRY'S ARC FOR $h_S = 13.0°$.

| Point of Measurement on Halo. | How Measured. | Angle. | |
|---|---|---|---|
| | | "Observed" | Theoretical. |
| Solar distance of apex of Parry's Arc (in Sun's vertical) | Angular distance from 22°-halo measured with astrocompass (13°) | 35° | 32.7° |
| Azimuth of point of intersection or mergence of lower of two contact arcs with Parry's arc | Vertically above 22°-parhelia | 23°* | 30°-35°† |

* Assuming Wegener's Theory for parhelia, with $h_S = 13.0°$.

† Using Wegener's Theory for the circumscribed halo (i.e. single upper contact arc); the two curves become almost tangential, but do not quite touch.

The first measurement agrees, within the instrumental accuracy, with the theory; the second measurement is discussed below.

Putnins (1934) has discussed Parry's Arc and also those arcs which should be produced by different ray paths through crystals with horizontal principal axes. Cases with two prism faces horizontal and also vertical are considered, the former being the orientation required for Parry's Arc (Wegener, 1926), the ray path being 1 - 5 (i.e., entrance: face 1, emergent: face 5) in Fig. 5 (*a*), and the latter orientation being considered as a result of the experiments of Besson (see Putnins, 1934). Putnins also considers the relative intensities of the various arcs which result and gives tables and plots of the arcs for various solar altitudes from —30° to +90°.

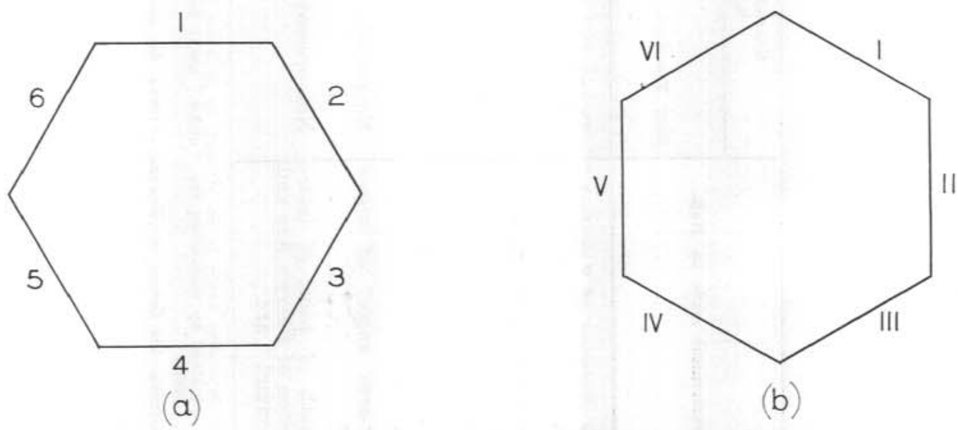


FIG. 5.—Crystal orientations discussed by Putnins (1934).

TABLE 4.

## ARCS OF PUTNINS.

| Measurement made on Halo. | November 28, 1958, 1600-1730. $h_s$ = 09.2°—04.3° | | | December 2-3, 1958, 2400. $h_s$ = 13.0° | | | Dec. 22, 1958 1800. $h_s$ = 06.0° |
|---|---|---|---|---|---|---|---|
| | How Measured. | Angle | | How Measured | Angle | | |
| | | "Observed" | Theoretical | | "Observed" | Theoretical | Theoretical |
| Solar distance of "contact" arc | Tangential to 22°-halo | 22° | 22.6°-23.7° | Tangential to 22°-halo | 22° | 22.2° | 23.3° |
| Solar distance of upper arc | c. $\frac{1}{8}$ radius halo above point of tangency | c.26°-27° | 26.8°-24.7° | Astrocompass measurement from 22°-halo of 4° | 26° | 29° | 25.0° |
| Inter-arm angle* of "contact" arc | Estimated | c.100° | c.120° | Estimated | c.130° | c.125° | c.120° |
| Inter-arm angle* of upper arc | No record | .... | c.70° | Estimated | c.80° | c.80° | c.70° |
| Azimuth of point of intersection of Parry's Arc and "contact" arc | Not present | .... | .... | Vertically above 22°-parhelia | 23°† | 23° | .... |

* The inter-arm angle is an attempt to estimate the apparent angle between the main arms of the arc. The so-called "theoretical" values were obtained by measuring the "mean" angle between the arms of the plotted theoretical curves. The comparison is necessarily very approximate.

† Assuming the theory of Wegener (1926) for parhelia.

With both crystal orientations present, for solar altitudes from 0° to somewhat less than 15°, a " double upper contact arc " could be produced by ray paths 2 - 6 and I - V (Fig. 5), the upper arc being of somewhat weaker intensity than the lower one. The three recorded occasions are compared with this theory in Table 4; no measurements were made during the display of December 22, 1958, but the theoretical figures are given as a matter of interest.

If we compare the observed point of intersection or mergence of the lower of the two arcs with Parry's Arc, on the occasion of $h_s = 13.0°$, with the theoretical values obtained from Wegener's circumscribed halo theory (Table 3), and from the theory of Putnins' Arc I - V (Table 4), we see that, although Putnins' theory agrees with the observations, Wegener's arc does not fit so well. Firstly, the " contact " arc was observed to cut Parry's Arc, as required by Putnins' theory, whereas Wegener's theory requires no intersection but rather that the two arcs become " parallel " and so close together as to appear to have merged into one. Secondly, the azimuth of this " point of mergence " is appreciably different from the observed point of intersection, the azimuth of the latter agreeing with that required by Putnins' theory.

The comparison in Table 4, while not agreeing with any great accuracy, indicates that the theory of Putnins is a very likely explanation of the " double contact arcs ", and suggests the advisability of more detailed and accurate measurements and, in particular, of ice-crystal sampling during displays.

These " double contact arcs " are apparently an extremely rare phenomenon. Visser and Alkemade (1956) have reported an appearance of this phenomenon over Brunswick, Germany, on November 8, 1944, and suggest an alternative explanation. The lower arc is assumed to be the " normal " contact arc of the 22°-halo, while the upper arc is explained as the contact arc of the rare $24\frac{1}{2}$°-halo (this halo not being visible during the display), being produced by refraction through an angle of 64° 46′ in pyramidal ice-crystals (c.f. Humphreys, 1940, who requires a refracting angle of 65° 09′ in pyramidal ice-crystals to produce a halo of radius 24° 34′).

Their calculation results in an arc with an inter-arm angle of 108° instead of the observed estimate of 75° which they explain as an error in estimation. However, it appears unlikely that an angle of considerably greater than 90° would be estimated as considerably less than 90°. If the observations are compared with the theory of Putnins (arcs 2 - 6 and I - V, for $h_s = 03.0°$), we obtain an inter-arm angle of approximately

75° and a separation of 1.1° between the two arcs in the solar vertical, as compared with the estimated 2°. Thus it appears that Putnins' theory also explains this appearance of the " double contact arcs " of the 22°-halo.

As regards cases of single " contact " arcs, the focal line of arcs produced by horizontal columns with non-preferred orientation of a secondary axis (Wegener's theory) can be very similar to that of arcs produced by horizontal columns *with* a preferred orientation of a secondary axis (Putnins' theory and Parry's Arc) for certain solar altitudes; however, Liljequist (1956) points out a criterion: the " white veil " is exclusively a feature of Wegener's circumscribed halo and is not present with the arcs of Putnins. Unfortunately, no records were made of this white veil in our own notes, as its significance was not realized at the time.

It should be pointed out here that the data for the upper contact arc given in Table 2 appears at first sight contradictory. Although the general shape of the arc and the would-be azimuth of intersection with the parhelic ring agree with Wegener's theory of the circumscribed halo, the point of mergence of this halo with Parry's Arc appears to agree more closely with the theory of Putnins' Arc I - V. However, at this solar altitude ($h_S = 19.7°$) the separation of Parry's Arc and the contact arc is far less than that in the case of Table 4 ($h_S = 13.0°$), and hence the two arcs meet at a very acute angle. This results in two considerable errors: firstly, the difficulty in the field of estimating the exact " point of mergence ", and secondly, the difficulty of determining from the theoretically plotted graph the exact point on which the original estimate was made. It is suspected that these errors have here accumulated to produce this apparent anomaly. It should also be noted that Putnins' Arc I - V would intersect Parry's Arc (as is the case in Table 4), rather than merge smoothly into it, as was observed. There can be little doubt that, on this occasion, it was Wegener's circumscribed halo which was present.

We now consider the final form in which an " upper contact arc " of the 22°-halo was observed—the inverted U or arc smoothly concave to the sun. This form was not as common or as brilliant as the other forms, but it has been recorded on three occasions, all of which have a solar altitude of greater than 25°.

After considering the known forms of contact arc for a possible explanation, we must immediately eliminate both the arcs of Putnins and Wegener's circumscribed halo, as the forms in which these occur for solar altitudes 28° - 32° could not be called both smoothly concave and tangential, or nearly so, to the 22°-halo. Compare, however, the solar distances of Parry's Arc in the sun's vertical on these occasions (Table 5).

TABLE 5.

PARRY'S ARC IN THE SOLAR VERTICAL.

| Date and GMT. | Solar Altitude $h_s$ | Solar Distance of Parry's Arc in Sun's Vertical. |
|---|---|---|
| 28.xi.58; 1200 | 28.3° | 25.3° |
| 4.xii.58; 1200 | 29.1° | 25.0° |
| 27.xii.58; 1200 | 31.6° | 24.3° |

Hence it is possible that, owing to the breadth and diffuseness of the 22°-halo in the solar vertical, these appearances of an inverted contact arc were really Parry's Arc close to the 22°-halo. These forms of Parry's Arc were, however, much less intense than their low solar altitude counterparts, although still not "weak". This appears to be more in line with other observations of Parry's Arc, although it is also usually seen together with the circumscribed halo.

Apart from the apparent intensity anomaly, the observations on Parry's Arc give in Tables 2 and 3 appear to be in good agreement with Wegener's theory.

In addition to the upper "contact" arcs of the 22°-halo, on three occasions there are records of lower "contact" arcs. As no detailed measurements are available these may be explained by either Wegener's circumscribed halo theory or Putnins' theory for arc II - IV (Fig. 5*b*). Two appearances were in association with the circumscribed "ellipse" described above, and the third appearance was in conjunction with the inverted upper contact arc of December 27, 1958 (Table 5) suggested above as being Parry's Arc.

Also, on one occasion, the point where the lower edge of the 22°-halo just reached the horizon has been recorded as exceptionally brilliant, resembling a mock sun. On another occasion (h = 19.0°) the area on the horizon between the arms of the 22°-halo has been noted as being extremely bright.

## V. OTHER HALOS.

A few words will here be said concerning halos other than those discussed above. Their frequency of occurrence in the records is given in Table 7.

Hall's halo (radius c. 9°) was observed only once. This halo is rare and is apparently produced in pyramidal ice-crystals. It was observed at a solar altitude in the vicinity of 05.8° and was very faint and diffuse. Its radius is recorded as being approximately half that of the 22°-halo, but any colour was completely masked by the combined effect of the sun's brightness and the halo's faintness. Only the upper half of the ring was visible, and it is also worth noting that only the upper half of the vertical sun-pillar was visible, although this half extended up to the 22°-halo. The parhelic circle was likewise very weak on this occasion and only extended to perhaps 10° - 12° from the sun. Other than on this occasion, halos of abnormal radii were not seen at all.

The display of November 29, 1958, at 1345 GMT ($h_s = 19.7°$) is also of interest. On this occasion the rare 46°-parhelia were noted. Theoretically (Humphreys, 1940) these should have been displaced some 5° of azimuth from the 46°-halo itself; however, there is no note to this effect in the records.

Also present on that occasion was a fairly bright coloured arc, apparently circular and passing through or close to the zenith, concave to the sun. The curvature of the arc appeared to be the same as that of the 22°-halo, and the colours, although not exceptionally bright, were very pure and distinct, with red as usual towards the sun. This arc does not appear to have been previously reported; it is possibly produced in pyramidal ice-crystals, the presence of which is suggested by the appearance of Hevelius' 90°-halo during this display.

The rare Hevelius' halo or 90°-mock-suns were noted on five occasions as white light-concentrations on the parhelic circle, on one occasion having faint white arcs extending down to the horizon. This halo is explained by Humphreys (1940) as being due to two internal reflections in bipyramidal ice-crystals, red being on the opposite side to the sun; colour was never discernible in our observations, however. It is interesting to note that on each of the appearances of this halo, the exceptionally brilliant Parry's Arc and upper contact arc of the 22°-halo were also visible.

On one occasion, additional mock-suns were seen at approximately 10° further from the sun than the 90°-mock-suns, their general appearance otherwise resembling the latter, which were also present. These were possibly portions of the 82°-anti-solar halo discussed by Humphreys (1940). On two occasions mock-suns were noted at approximately 120° from the sun on the parhelic circle. In the absence of measurements these are assumed to have been the 120°-paranthelia, although there are other possibilities (see Humphries, 1940).

The 180°-anthelion was usually seen as a light concentration on the parhelic circle, sometimes with a faint diffuse white pillar through it. This pillar was never resolvable into separate arcs, either tangential or intersecting, as suggested by the theories of Hastings (1920) and Wegener (1926) and observed by, for instance, Liljequist (1956), or occurring in the more extensive displays of Bavendick (1920), Woolard (1920) and Sieger (1934) the first of which describes a display during which both types of anthelic arc were present at once. The one possible exception is described below.

TABLE 6.

ANTHELIA.

| Date GMT. | $h_s$ | Ice Crystal (Halo Type). | Description of Anthelion. |
|---|---|---|---|
| | | $h_s > 14.1°$ | |
| 29.xi.58 1345 | 19.7° | Elongated column & pyramids (Parry's Arc & Hevelius' Halo) | Pillar, not quite reaching horizon |
| 9.xii.58 1300 | 25.0° | Elongated column & pyramids (Parry's Arc & Hevelius' Halo) | No record |
| 11.xii.58 1340-1500 | 22.0°-15.9° | Elongated column & pyramids (Parry's Arc & Hevelius' Halo) | Bright spot only |
| 14.xii.58 1200 | 30.6° | Plates (120°-parant., no contact arcs) | Bright spot only |
| 22.xii.58 1430 | 19.0° | Plates? & pyramids (120°-parant. & Hevelius' Halo but no 22°-parhelia) | Bright spot only |
| | | $h_s < 14.1°$ | |
| 21.xi.58 2100 | 01.3° | Probably plates & short columns only (no contact arcs) | Faint spot only |
| 28.xi.58 1600-1730 | 09.2°-04.3° | Elong. columns (Putnins' Arcs) | Pillar, extending to horizon |
| 2-3.xii.58 2400 | 13.0° | Elong. columns (Putnins' & Parry's Arcs) | Y-shaped pillar to horizon (see below) |
| 27.xii.58 1800 | 05.8° | Elong. columns & pyramids (Parry's Arc & Hevelius Halo) | No record |

The nine occasions on which the anthelion was seen are summarized in Table 6. The theories of Wegener and Hastings both require the presence of columns, but the former arcs are not produced for solar altitudes below 14.1°. The observations given in Table 6 have thus been grouped according to whether the solar altitude is above or below 14.1°, and some attempt has been made to ascertain the type of ice-crystals present by considering the various forms of halo components visible in the display. In addition to the crystal types listed, plates and short columns must be included in all cases. The halo components given in brackets are those which were visible at the time and are produced by the listed ice-crystals.

Thus on three occasions a pillar occurred extending from the horizon, or near it, through the anthelion to somewhat above it, instead of the intersecting arcs required by the two columnar-ice-crystal theories. On one of these occasions the top of the pillar forked to form a Y-shape, but this occurred during the complex display of December 2-3, and may have been the result of another halo meeting the anthelic pillar. The display is described later.

Although elongated columns were apparently present on each of these three occasions, so were plates, and as the anthelic pillar does not agree in shape with either column theory, it is reasonable to assume that they may have been produced in the plates, as suggested by Liljequist (1956). On several of the other occasions, apparently no elongated columns were present and hence these, too, were presumably produced in the plate crystals.

The 46°-halo occurred on approximately one of every two appearances of the 22°-halo, and was usually quite bright and coloured. It was frequently associated with the circumzenithal arc, also, usually very bright and coloured; however, on every occasion this has been recorded as an " upper contact arc " of the 46°-halo, the solar altitudes ranging from 04.3° to 25.0°. The theory of Wegener (1926) for the circumzenithal arc indicates, however, that the angular separation from the 46°-halo, in the sun's vertical, would be from 08° to zero for these solar altitudes. It is reasonable to suppose that small angular separations would not be detected due to the intensity and extent of this region, but it is difficult to see how a separation of 8° (which is more than one-third of the radius of the 22°-halo) could remain undetected. This suggests the possibility that on at least some occasions some form of true contact arc to the 46°-halo was present. This arc was first suggested by Galle (Melmore, 1944), its existence apparently depending on a predominance of ice-crystals with a horizontal 90° refracting edge (Saville, 1944).

The relative frequencies of the parhelic circle and, more especially, of the vertical sun pillar given in Table 7 are probably somewhat unreliable, as it is suspected that on many occasions these halos were present, at least in part, but no record was made. This applies to the sun-pillar in particular as, although usually quite bright, its proximity to the sun and to the spectacular 22°-halo " contact arc system " caused it to be overlooked in the hastily written notes.

In the display of November 28, 1958, with a solar altitude between 09.2° and 04.3°, the only portion of the parhelic circle visible was in the vicinity of the anthelic pillar. On nine occasions the complete parhelic circle was recorded, the solar altitude ranging from 01.3° to 30.8°. Otherwise the general appearance of the parhelic circle was similar to that described by Liljequist (1956)—it may exist either inside the 22°-halo only, outside the 22°-halo only, or on both sides; in the last case, the portion inside the 22°-halo was frequently much less intense than the portion outside.

One display is worthy of special mention, not because of its intensity but because of its extremely unusual form. This was the display of 2400 GMT on December 2-3, 1958, with a solar altitude of 13.0°, during which 14 individual halo-components were present. The display is depicted in Fig. 6, and has already been referred to several times for some of its unusual characteristics. On this occasion the " double upper contact arcs " of the 22°-halo (Arcs of Putnins) and Parry's Arc occurred together. In addition to these and the other components shown in Fig. 6, the four arcs designated 1, 2, 3, 4 and an anthelic pillar, all white in colour, were also present. These curves, although not bright, were certainly not faint, and were quite distinct.

Curve 1 appeared to be approximately circular, passed through the sun and intersected both 22°- and 46°-halos at about one-third of the parhelic circle—solar vertical arc distance above the parhelic circle, crossing the solar vertical in the region of the zenith. Curve 2 was approximately concentric to curve 1, starting at the 22°-parhelia, and cutting the 46°-halo about midway between its intersection with curve 1 and the parhelic circle. It was not visible inside the 22°-halo, although elsewhere its intensity and colour were similar to that of curve 1.

Extending from the anthelion itself was another curve (curve 3), apparently elliptical in shape, which was tangential to curve 1 in the solar vertical and also of similar intensity. Branching from the top of the anthelic pillar, portion of another curve (curve 4) was visible, being approximately " parallel " to curve 3, but very much fainter and more

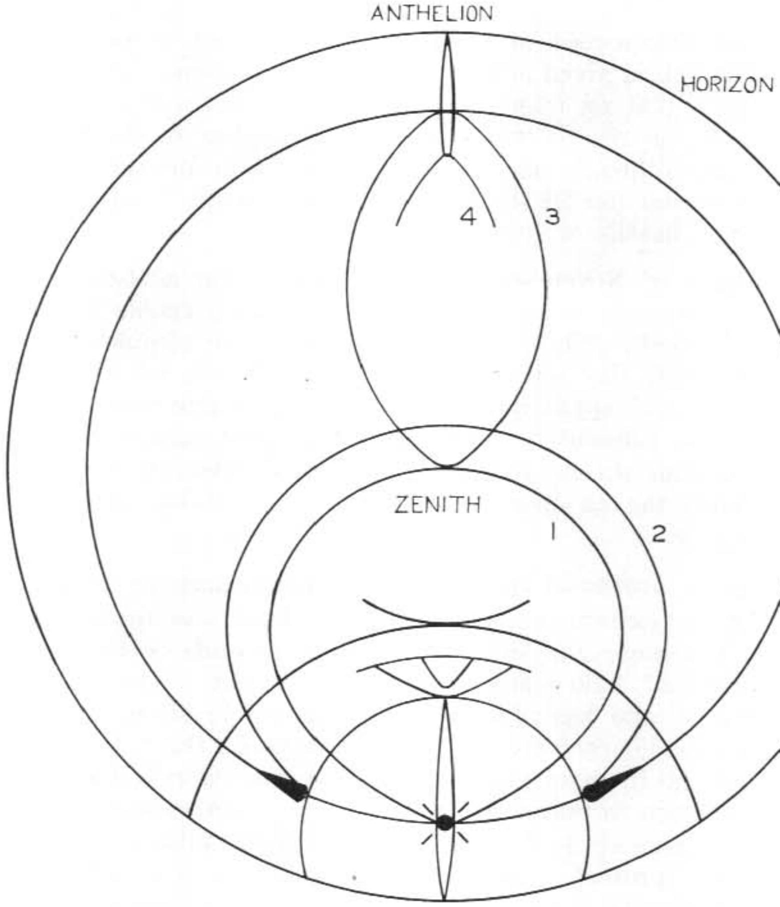


FIG. 6.—Complex display of 2400 GMT, 2-3 December, 1958; $h_s = 13.0°$.

diffuse. If completed, it appeared as though it would have met curve 2 tangentially in the solar vertical. The intensity of this curve was much greater in the vicinity of the anthelic pillar where, however, it was also more diffuse.

The peak of the display was short-lived and the break-up was sharp and fairly rapid.

It was thought at the time that curve 4 was a separate halo to the anthelic pillar; however, as already pointed out, it may have been part of the anthelic arcs formed in the manner suggested by Liljequist (1956, p. 44) who reports a similar appearance of the anthelic pillar at Maudheim on May 8, 1951, although arcs 1 - 3 were not present.

Curve 1 closely resembles the *oblique heliac arcs* described by Humphreys (1940). The theoretical zenith-sun-halo-point angles to the points of intersection of these arcs with the 22°- and 46°-halos are computed to be 55.5° and 49.0° respectively, these being in sufficiently accurate agreement with the approximate observations noted above. The theoretical arcs cross the solar-vertical at an elevation of 107° and, although this is somewhat different from the zenith point, it must be remembered that the position of the celestial zenith is very difficult to estimate without some form of instrument, especially from a bouncing Weasel!

There is no record as to whether this curve met the parhelic circle tangentially at the sun or not. The theoretical curve leaves the solar disc at an angle of almost 60° with the solar vertical.

Since the oblique heliac arcs are produced in elongated columns in their position of maximum stability—i.e., having principal axis and two prism faces horizontal—and this is also the requirement for the upper arc of Putnins (2 - 6), and for Parry's Arc, it is of interest that both these latter arcs were present during the display.

To the author's knowledge, the other arcs, 2 and 3 (and perhaps 4), have not been previously reported. Their explanation will not be investigated here.

## VI. OVERALL ANALYSIS OF OBSERVATIONS.

We first explain two terms used in the analysis. A "*halo-day*" is a day on which any form of halo appeared (we are considering only "low" halos), the time being reckoned as GMT due to the presence of the midnight sun throughout most of the observational period. An observation timed at 2400 GMT is counted as two halo-days, as it is more than likely (in the absence of contrary information) to have started well before Greenwich midnight and ended well afterwards.

A *halo-occasion* is more difficult to define as the halo form and number of components may change considerably during a single display. There may be more than one halo-occasion on the same day, and the durations of displays may differ widely. Each individual record is here treated as a separate halo-occasion.

The number of halo-occasions considered here is 27, although it was, in reality, greater than this. For instance, on three separate days the word "Halos" appears in the "Remarks" column of the Field Meteorological Observations Log, but no further details are recorded. Also, it is known that on other occasions, especially in the earlier part of the expedition, no record was kept at all.

The relative frequencies of the various halo components are given in Table 7.

Taking into account the remarks above, we see that there were at least 30 halo-occasions, all of which occurred on 20 days during the period November 21, 1958 - January 5, 1959—an interval of 46 days. Twelve of these halo-days occurred during December.

It is of interest to compare this data with that from Maudheim in 1950-51. Liljequist (1956) finds a pronounced minimum with no low-halos occurring during the months December - February. The maximum occurred in September with a mean of seven halo-days, and a secondary maximum occurred in April with a mean of five halo-days. A minimum in high-halo appearance also occurred in summer and the records of other expeditions confirm this (e.g., see summary by Sandner, 1951, 1953. There is, however, no distinction between high and low halos here). The data from Maudheim on middle-level halos indicates, however, a maximum in late spring - early summer, although the number of these halos was comparatively few. We also compare the number of occasions on which at least one, two, three, &c., halo components were recorded, with the Maudheim data for low halos. This is done in Table 8, and is shown graphically in Fig. 7.

TABLE 7.

## RELATIVE FREQUENCY OF HALO COMPONENTS.

| Halo-component. | Number of Observations. | Relative Frequency % |
|---|---|---|
| 22°-halo | 26 | 96.4 |
| 22°-parhelia | 24 | 88.9 |
| 46°-halo | 14 | 51.8 |
| 46°-parhelia | 1 | 3.7 |
| *Parhelic circle | 13 | 48.2 |
| Circumscribed "ellipse" of 22°-halo | 4 | 14.8 |
| Wegener's upper contact arc of 22°-halo | 6 | 22.2 |
| Parry's Arc (brilliant form) | 5 } 8 | 18.5 } 29.6 |
| Inverted upper contact arc of 22°-halo (Parry's Arc alone?) | 3 | 11.1 |
| Putnins' Arcs 2-6 & I-V (double upper contact arcs) | 3 | 11.1 |
| Lower contact arc of 22°-halo | 3 | 11.1 |
| Circumzenithal Arc | 7 | 25.9 |
| *Vertical pillar | 7 | 25.9 |
| Hall's Halo | 1 | 3.7 |
| Anthelion and/or pillar | 9 | 33.3 |
| 120°-paranthelia and/or pillar | 2 | 7.4 |
| 86°-antisolar halo (mock suns only) | 1 | 3.7 |
| 90°-(Hevelius') halo and/or mock suns | 5 | 18.5 |
| Zenith Arc | 1 | 3.7 |
| Arc 1 (oblique heliac arcs) | 1 | 3.7 |
| Arcs 2, 3, 4 | 1 | 3.7 |
| Halo-Occasions | 27 | 100 |

* These figures are probably unreliable, as already explained. The relative frequency of each will be greater than the values shown here.

TABLE 8.

## NUMBER OF OCCASIONS ON WHICH AT LEAST $\eta$ HALO COMPONENTS OCCURRED.

| Number of Components $\eta$ | Southern Traverse. | | Maudheim. | |
|---|---|---|---|---|
| | Number of Occasions. | Relative Frequency % | Number of Occasions. | Relative Frequency % |
| 1 | 27 | 100 | 71 | 100 |
| 2 | 25 | 92.7 | 52 | 73 |
| 3 | 19 | 70.4 | 39 | 55 |
| 4 | 16 | 59.3 | 31 | 44 |
| 5 | 12 | 44.5 | 20 | 28 |
| 6 | 10 | 37.1 | 17 | 24 |
| 7 | 8 | 29.7 | 14 | 20 |
| 8 | 7 | 26.0 | 6 | 8 |
| 9 | 6 | 22.2 | 3 | 4 |
| 10 | 5 | 18.5 | 3 | 4 |
| 11 | 3 | 11.1 | 2 | 3 |
| 12 | 2 | 7.4 | 1 | 1 |
| 13 | 1 | 3.7 | 0 | 0 |
| 14 | 1 | 3.7 | 0 | 0 |

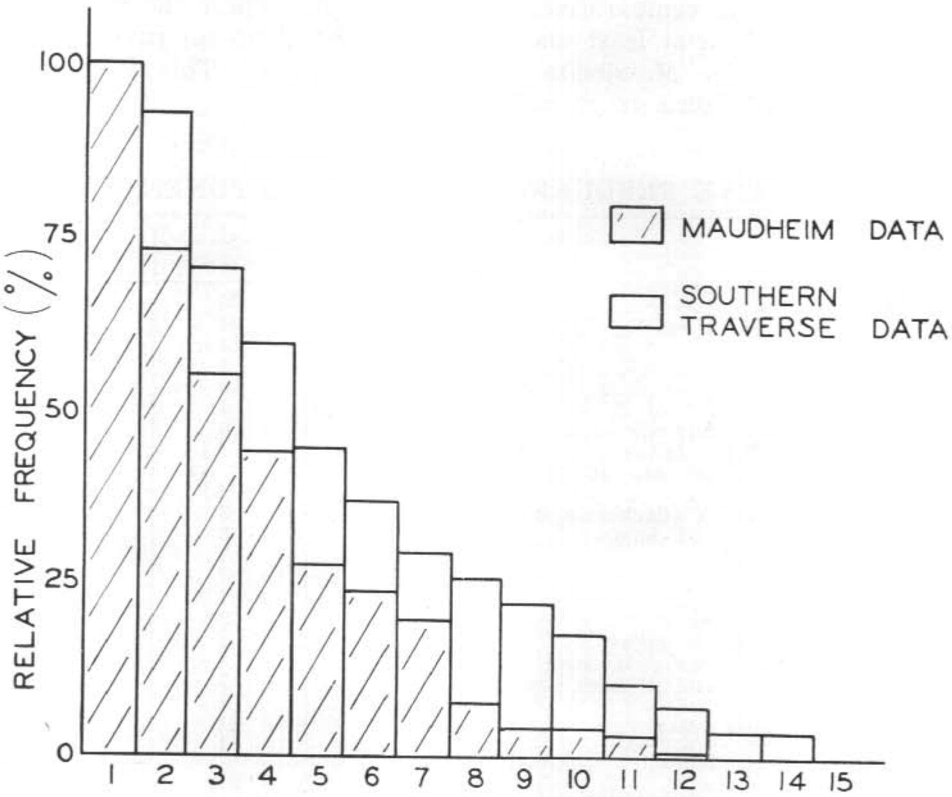


FIG. 7.—Comparison of relative frequency of at least $\eta$ halo components occurring during southern traverse with Maudheim data.

TABLE 9.

TOTAL NUMBER OF DIFFERENT HALO COMPONENTS.

| Expedition. | Date. | Number of separate components. |
|---|---|---|
| ANARE Southern Traverse .... .... .... | 1958-59 | 22, possibly 24 |
| NBSAE, Maudheim .... .... .... .... .... | 1949-52 | 16 |
| Filchner .... .... .... .... .... .... | 1911-12 | 11 |
| S.Y. Belgica .... .... .... .... .... .... | 1897-99 | 8 |
| Byrd .... .... .... .... .... .... .... | 1929-30 | 7 |
| Byrd .... .... .... .... .... .... .... | 1934-35 | 6 |

We note that the actual number of occasions on which the number of halo components was from eight or more to fourteen was somewhat greater, during this period of 46 days, than during the whole two years' observations at Maudheim. Also the total number of different components seen was at least 22, possibly 24, which is far greater than most other expeditions, a summary of some being given in Table 9.

From the components present during each display an attempt has been made to determine the relative frequency of occurrence of the four types of ice-crystal: plate, short column, elongated column, and pyramidal form. The 27 halo-occasions were examined and, on one occasion when the components present varied considerably over a period of three hours, the analysis was applied to three separate periods, resulting in 29 "halo-times". The results are given in Table 10.

TABLE 10.

RELATIVE FREQUENCY OF CRYSTAL TYPES.

| Crystal Type. | Number of Times. | % |
|---|---|---|
| Short columns .... .... .... | 27 | 93 |
| Plates .... .... .... .... | 27 | 93 |
| Elongated columns .... .... | 18 | 62 |
| Pyramidal .... .... .... .... | 6 | 21 |
| "Halo-Times" .... .... .... | 29 | 100 |

Thus it can be said that short columns and plates were present to some extent on almost all occasions while elongated columns and pyramidal forms were progressively less frequent. The best displays occurred in the presence of pyramidal and/or elongated column ice-crystals. However, although the presence of one or both of these crystal types appears to be a necessary condition for a brilliant or extensive display, the presence of elongated columns without pyramidal forms does not appear to be a sufficient condition, as some rather unimpressive displays, poor in components, were observed which nevertheless indicated the presence of this crystal type.

Some halo-forms were conspicuous by their absence. In particular, the infra-lateral tangential arcs of the 46°-halo, although apparently not a very rare halo, never appeared with sufficient clarity to be noticed. These arcs are produced by refraction through 90° prisms in horizontal columns, which are known to have been present during many of the displays (Table 10). Liljequist (1956) also notes its rarity, only four appearances occurring during the two years at Maudheim and most of these being indistinct.

Another "halo" sometimes seen is Bouguer's Halo—apparently an ordinary fog-bow. In Antarctica this has been observed with ice-crystal halos by Barkow (Sandner, 1951) and Arctowski (1902), and separately by Liljequist (1956) at Maudheim, although it is produced in very small water droplets. However, Bouguer's Halo was not observed either separately or with ice-crystal halos during the Southern Traverse.

## VII. METEOROLOGICAL DATA.

The general meteorological conditions on each halo-occasion were recorded and are given with the halo observation notes in the Appendix. Perhaps the principal item of interest is the temperature. As has already been pointed out by Liljequist, there are conflicting results from field investigations of the ice-crystal type-temperature relation, the difficulty being in determining the conditions at the level at which the ice-crystals are formed. In an attempt to allow for the temperature inversion over the ice-shelf, Liljequist has used the 9-metre level temperatures and finds a tendency for the relative number of columns over plates to increase below —27°C, whereas using the screen temperatures he finds no relation to the relative proportions of columns and plates.

The mean surface air temperature during the halo displays in our records was —24° C, with a variation from —16.5° C to —34.5° C. The mean surface air temperature during which elongated column-type displays occurred was —24° C, with extremes of —16.5° C and —30° C.

With the first appearance of the midnight sun on November 22, a cold spell commenced during which the daily maximum surface air temperature did not rise above —24°C and the minima were in the region of —35°C or lower, and which lasted until the temperatures began slowly rising on November 29. This period of low temperatures coincided with a period of unspectacular halo displays, poor in components. Apart from this, there appears to be little connection between surface air temperature and halo type.

The fact that no spectacular halos were noted during the earliest portion of the journey is possibly connected with the time taken for the seismic trains to get clear of the mountain ranges which extend inland for some fifty or so miles behind Mawson. The coastal portion of these ranges rises from blue-ice, as distinct from the permanent snow-cover of the inland ice-cap itself. These ranges, together with the generally rocky environment of Mawson, presumably have some bearing on the fact that very few, if any, "low" halos have been observed at Mawson itself, whereas the coastal station of Maudheim (71° 03′ S, 10° 56′ W) which was situated on a plane ice-shelf with an almost unbroken horizon, and some few miles from the main coastline, observed so many of them.

As regards the wind, halo-displays on the Southern Traverse were recorded with accompanying wind speeds varying from 25 knots to dead calm, the mean being 14 knots. Both wind and sastrugi directions slowly swing westwards as one moves further inland from Mawson, the wind directions varying overall from 160° to 230°, with a mean of 195°. Variation of wind direction with latitude south of Mawson is dependent on the Coriolis and katabatic effects, this latter being another of the major differences, meteorologically, between Mawson, the region in which these observations were recorded and, apparently, Maudheim. Mawson lies well within the topographical zone affected by the violent katabatic winds which, apparently, Maudheim did not; also the region where these inland halo observations were taken is beyond or very near the inner limits of this zone.

A few words might here be added concerning solar halo displays observed during a similar inland journey from Mawson in 1957-58.* Again the phenomena were at first completely novel to the members of the expedition, but after a time came to be regarded as quite commonplace. The displays do not appear to have been as extensive as those reported above from the 1958-59 Southern Traverse, and occurred in almost stationary ice-crystal suspensions on relatively calm days, usually with low solar altitudes (again the midnight sun was present) They occurred in the same or very similar areas to those seen in 1958, i.e., in the vicinity of 150 miles or more south of Mawson at altitudes between 6,500 ft. and 9,000 ft. above M.S.L.

The most common components were the 22°-halo and parhelia, parhelic circle (though rarely, if ever, was the complete 180° present; it usually faded out at about 90° from the sun), and vertical pillar. The bright area often termed a mock-sun, on the 22°-halo and vertically above the sun was fairly frequent, and occasionally what appears to have resembled a secondary parhelic circle or some form of "horizontal contact arc" through this area was observed, extending to perhaps the same azimuth as the 22°-parhelia. On one occasion the vertical pillar extended up to what was presumably the bright area at the top of the 46°-halo, although it was rather faint; however, the 46°-halo was not present, neither was the circumzenithal arc. The interval of the vertical pillar between the 22°- and 46°-halos was considerably weaker than that inside the 22°-halo. On no occasion was any of the 46°-halo, upper contact arcs of the 22°-halo, Parry's Arc or circumzenithal arc observed, although faint anthelia occurred on occasions.

It would appear that the solar halos observed during the Southern Seismic Traverse from Mawson were to some extent unusual, even for

* This information was provided by Mr. N. Collins, a member of the 1957-58 ANARE Southern Party.

Antarctica, in that many displays, some very complex, were seen over a period of one and a half months during a season when many coastal stations report a distinct minimum. However, there appears to be some evidence that these phenomena are a characteristic of the Antarctic inland during summer.

Investigation of this phenomenon should include some sort of simultaneous ice-crystal study, similar for instance to that carried out by Liljequist at Maudheim. A development which should greatly aid in this work is the quick and simple method of Schaefer for obtaining permanent plastic replicas of ice-crystals—this method is described by Mason (1957), p. 173.

## VIII. ACKNOWLEDGEMENTS.

The author wishes to thank Dr. F. J. Jacka, Chief Physicist, Antarctic Division, for his advice and encouragement in the preparation of this article, Miss J. Cummings-Wright (of the same Division), who carried out the computations and prepared the drawings, and the four other members of the 1958-59 ANARE Southern Traverse, Messrs. I. L. Adams, E. E. Jesson, D. A. Brown, and F. A. Smith for their interest in, and assistance with, the observations.

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## X. APPENDIX.

The records of the halo-observations are summarized in Table 11 and, in addition, several cases are described in more detail. A summary of the prevailing meteorological conditions is also given in Table 11. All dates and times refer to GMT.

(*a*) *November* 21, 1958: Fig. (i).—

*Time*: Commenced at 1500, ended at 1800, the peak being at about 1630 GMT.

*Location:* Mobile at 70.1° S, 62.1° E, altitude approximately 8000 ft.

*Solar Altitude/Azimuth*: 1500 : 12.0°/244°
1630 : 05.8°/223°
1800 : 01.7°/203°.

*Display:* The 22°-halo was bright with colours red, orange, yellow, white, faint-blue, the red being nearest the sun. The 46°- halo was fainter than the 22°-halo, but similarly coloured. The left (or southern) parhelion

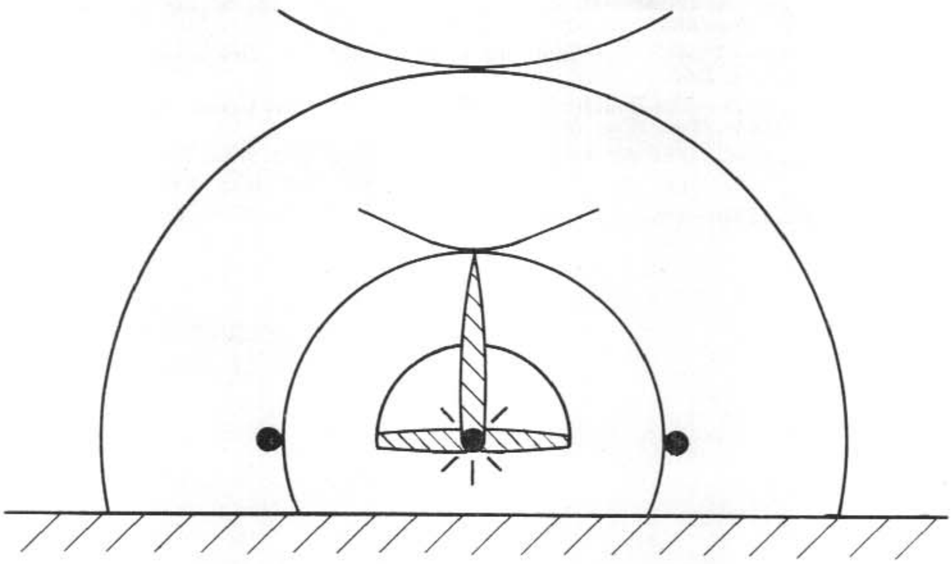

FIG. i.— 1500-1630, 21 November, 1958.

was very bright, being much brighter than the right-hand one. The upper contact arc was rather faint but distinct, the point of contact being much brighter than the rest of the 22°-halo, but not as bright as the parhelia. The circumzenithal arc was very faint, although the "point of contact" was brighter than the rest of the 46°-halo.

The parhelic circle extended for only about 10° on either side of the sun, being rather faint. It formed a closed semicircle with the very faint Hall's Halo, the radius of this halo being approximately half that of the 22°-halo, but observation being greatly impeded by the sun's brightness. The vertical sun-pillar extended from the sun up to the 22°-halo, being brighter near the sun. It apparently did not extend below the sun.

The azimuthal radii of the two major halos were measured with an astrocompass as 21° and 45° respectively.

*Notes:* By 1700 only the 22°-halo, vertical pillar, and faint portions of the 46°-halo remained, and at 1800 only partial parhelia and a bright upper portion of the 22°-halo were visible. The peak of the display was at 1630.

At 2100 (position 70° 10′ S; 62° 08′ E, alt. 8000 ft.; sun at 01.3°/161°) the display was again observed, consisting of 22°-halo and bright parhelia, with the upper portion of the halo brighter than elsewhere; parhelic circle, bright and extending to 180° on either side of the sun; and a faint anthelion.

(*b*) *November* 28, 1958: Fig. (ii).—

*Time:* 1600 - 1730 GMT.

*Location:* Mobile at 70.2° S, 62.2° E, altitude approximately 7800 ft.

*Solar Altitude/Azimuth:* 1600 : 09.2°/230°
1730 : 04.3°/210°.

*Display:* The 22°-halo and parhelia were all bright, the parhelic tails being noted as present. The 46°-halo was likewise fairly bright, having the circumzenithal arc at its summit. A brilliant vertical pillar extended from the horizon, through the sun, to the 22°-halo above the sun. At this point the lower arc of the "double upper contact arcs" met the halo, each arc being coloured with the normal solar halo spectrum of red, orange, yellow, white and bluish, with a suspicion of purple inside the red, towards the sun.

The angle enclosed by the lower arc was estimated at c.100°, each arc extending from the solar vertical to approximately the azimuth of half the radius of the 22°-halo. The interarcial separation in the solar vertical was estimated as c. 1/5 the radius of the 22°-halo.

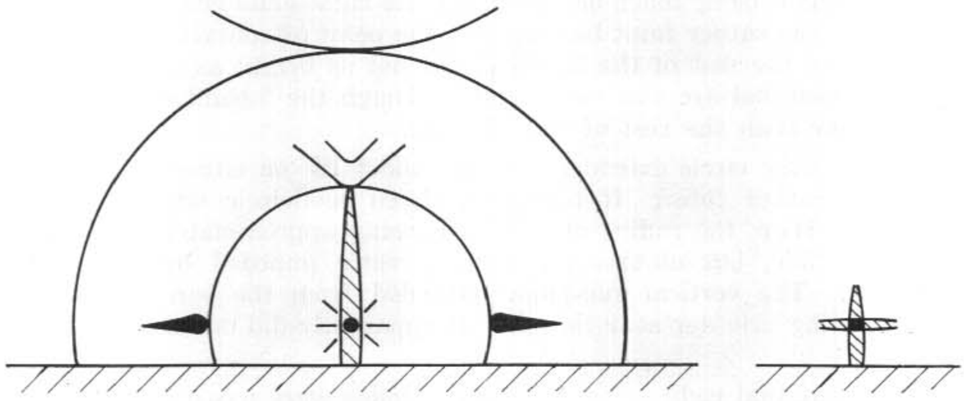

FIG. ii.—1600-1730, 28 November, 1958. Opposite Sun.

Through the anthelic point was a bright, white vertical pillar, reaching the ground. Also visible was part of the parhelic circle, the intersection of the two arcs being a " spot " of greater intensity. The parhelic circle did not exist elsewhere.

*Notes:* The display was only at its peak for a few minutes, disappearing as the cloud increased. A diffraction corona was produced in the low cloud, being extremely bright inside the 22°-halo and extending, with less intensity, to between the 22°- and 46°-halos.

(*c*) *November* 29, 1958: Fig. (iii).—

*Time:* 1345 GMT.

*Location:* Mobile at 70° 15′ S, 62° 11′ E, altitude c.7800 ft.

*Solar Altitude/Azimuth:* 19.7°/261°.

*Display:* The 22°- and 46°-halos were both very brightly coloured, and both 22°- and 46°-parhelia were present, both pairs being very bright. The vertical pillar extended from the horizon to the top of the 22°-halo, which was brilliant. From this point extended the upper contact arc which merged smoothly with Parry's Arc; both these arcs were coloured and very bright. Parry's Arc appeared to be elliptical in shape, the apex being c. 1/4 - 1/5 radius of the 22°-halo above the point of tangency of the contact arc, and the point of apparent mergence with the contact arc being of the same azimuth as c. 2/3 the radius of the 22°-halo. The extremities of the contact arc almost reached the intersection of the 46°-halo and the parhelic circle, and if produced would have done so. The intensity of the arc decreased towards its extremities. The circumzenithal arc was also present, being very brightly coloured.

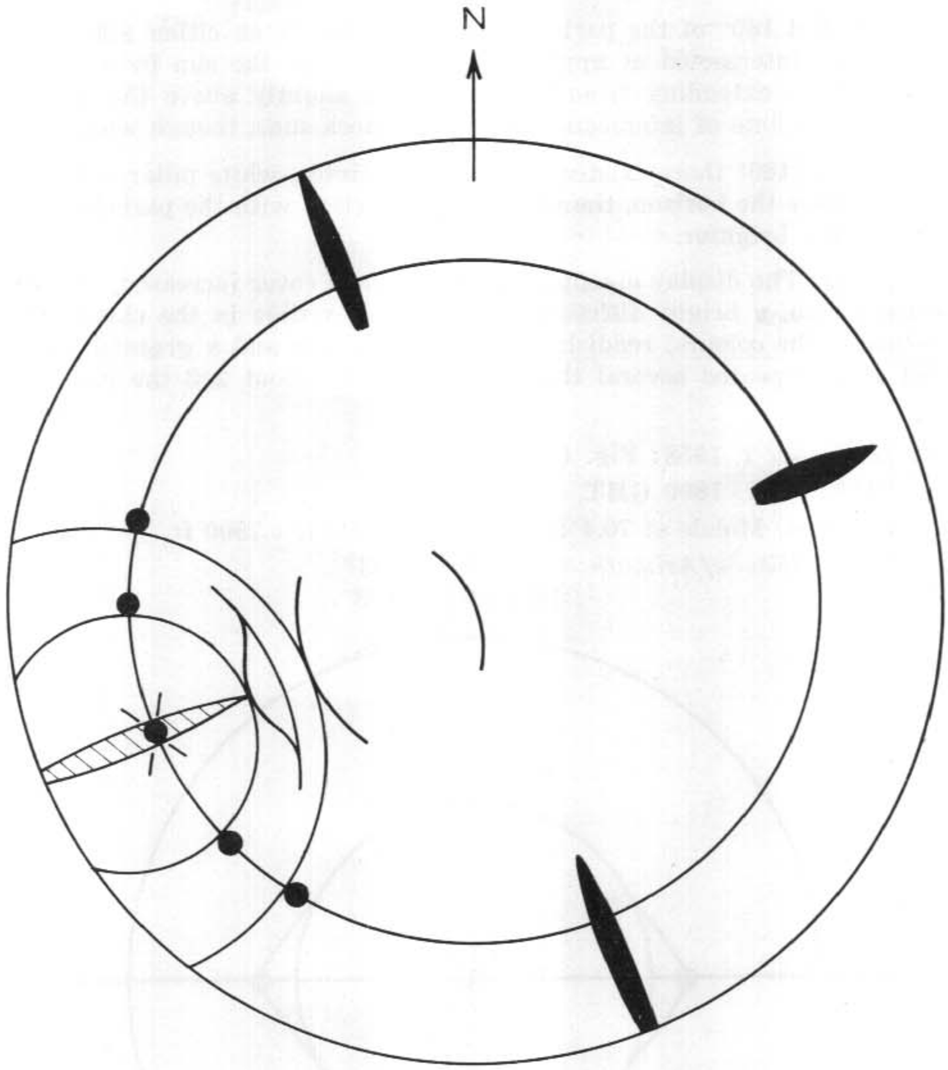


FIG. iii.—1345, 29 November, 1958.

A fairly bright, coloured arc, passing through or close to the zenith and concave to the sun was visible, the colours being very pure and distinct. Because of its position, it was difficult to obtain any estimates; however, it appeared to have approximately the same curvature as the 22°-halo.

The full 180° of the parhelic circle was visible on either side of the sun, being intersected at approximately 90° from the sun by a pair of white pillars extending from the horizon to slightly above the parhelic ring. The points of intersection resembled mock-suns, though white.

Also at 180° there existed a somewhat fainter, white pillar extending to just above the horizon, the point of intersection with the parhelic circle again being brighter.

*Notes:* The display disappeared as the cloud cover increased. On this occasion, too, a bright diffraction corona was visible in the cloud about the sun. The colours, reddish-brown near the sun and a greenish colour next were repeated several times, extending to about 2/3 the radius of the 22°-halo.

(*d*) *December* 1, 1958: Fig. (iv).—
*Time:* 0915 - 1800 GMT.
*Location:* Mobile at 70.4°S, 62° 09′ E, altitude c.7900 ft.
*Solar Altitude/Azimuth:* 0915 : 39.4°/331°
1800 : 03.9°/203°.

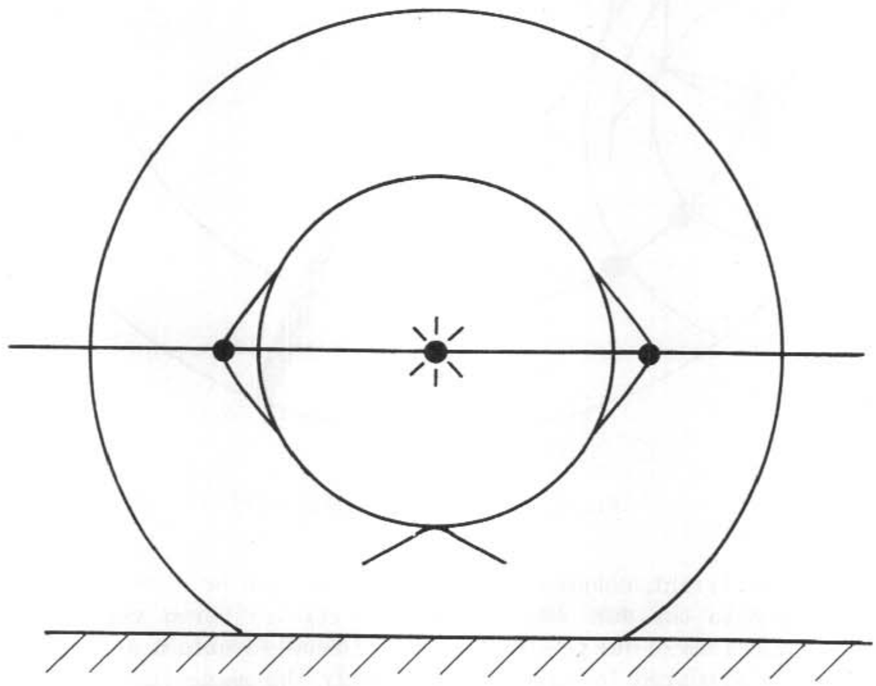

FIG. iv.—0915, 1 December, 1958.

*Display:* The azimuthal radius of the 22°-halo was measured as 29° (0915 GMT), the halo being quite bright, and having a bright and coloured lower contact arc convex to the sun. The parhelia appeared to be at the intersection of a circumscribed " ellipse ", with the parhelic circle, the azimuthal difference from the sun's vertical being measured as 34° with the astrocompass. The parhelic circle existed on both the inside and outside of the 22°-halo, but the full 180° were not present. For a short period a 46°-halo was present, although of faint intensity.

(*e*) *December* 2 - 3, 1958: Fig. (v).—

*Time:* 2400 GMT.

*Location:* Mobile at 70° 50′ S, 62° 12′ E, altitude c. 8000 ft.

*Solar Altitude/Azimuth:* 13.0°/121°.

*Display*: Both the 22°- and 46°-halos were present, together with the parhelic circle which extended for the full 180° on either side of the sun. The vertical pillar extended from the horizon through the sun, up to the top of the 22°-halo. Here also the lower arc of the double upper contact arcs met the 22°-halo. The ends of these arcs coincided with their intersection with Parry's Arc, neither intersection being a smooth mergence, as occurred between Parry's Arc and the single upper contact arc. The double upper contact arcs appeared to be elliptical or hyperbolic in shape, but not circular, the inter-arm angles being estimated as 130° for the lower arc, and 80° for the upper arc. The interarcial separation in the solar vertical was measured as 4° with the astrocompass, and the separation of the apex of Parry's Arc from the lower arc was likewise measured as 13°. The intersection of the lower arc with Parry's Arc was vertically above the 22°-parhelia. All three arcs were brightly coloured with red towards the sun.

The circumzenithal arc was also present, its " inter-arm " angle being estimated as 145°.

Extending from the sun and passing through, or in the region of, the zenith was a white curve, which intersected the 22°- and 46°- halos at approximately one-third of the quadrant arc-distance above the parhelic circle (i.e., c. 60° from the solar vertical, using the sun as centre). The curve appeared to be roughly circular, and is designated as curve 1.

Approximately parallel to this curve, and starting at the parhelia, was a second curve (curve 2) of similar colour and intensity to curve 1; however, it was not visible below the parhelia. This curve intersected the 46°-halo about midway between curve 1 and the parhelic circle.

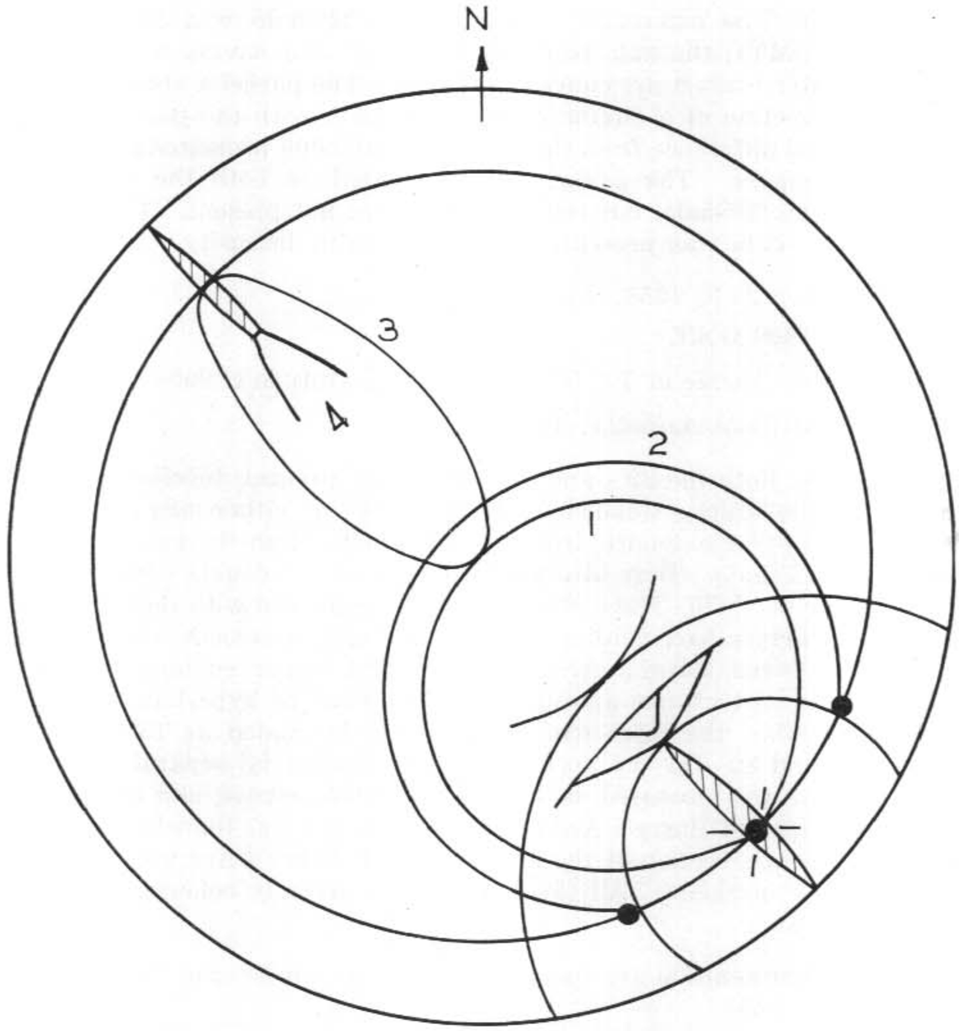


FIG. V.—2400, 2-3 December, 1958.

Extending from the horizon up to a point somewhat above the parhelic circle, in the region of the anthelic point, was a white pillar, the central point being of greater luminosity. From the anthelic point a third curve (curve 3) originated, being approximately elliptical in shape and meeting curve 1 tangentially in the solar vertical. This curve was similar in colour and intensity to curves 1 and 2. Although not bright, these curves were certainly not faint, and were quite distinct.

A fourth curve (curve 4), much fainter and more diffuse than the above three, emanated from the upper end of the anthelic pillar, producing a Y shape although the arms were concave inwards. This arc appeared to be approximately parallel to curve 3 and, if produced, may have met curve tangentially. Its intensity was greater near the anthelic pillar, although the arc was still diffuse here.

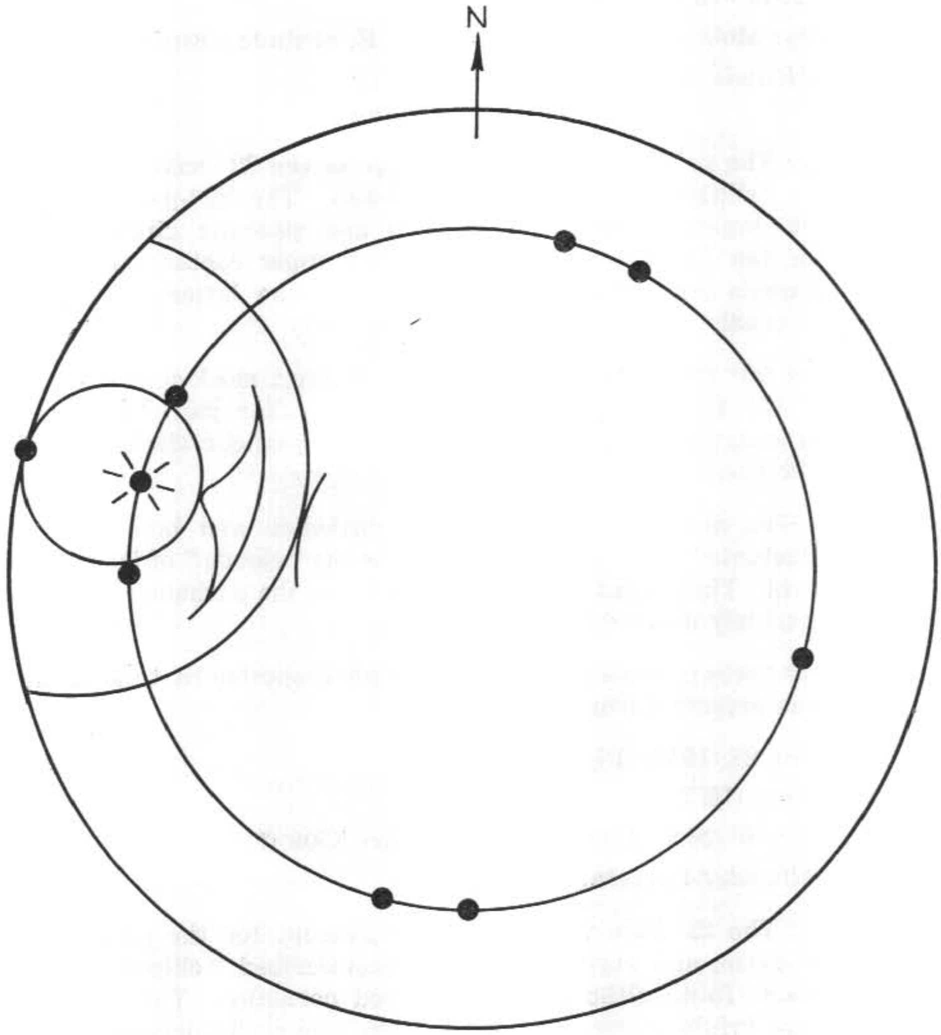


FIG. vi.—1340-1500, 11 December, 1958.

*Notes:* Although extensive, the display was not as brilliant as, for example, that of November 12. It did not last, at its peak, for very long, the break up being sharp and fairly rapid. The spectrum of the coloured arcs was, as usual, red, orange, yellow, greenish-white, and occasionally a bluish tinge, red always appearing near the sun.

(*f*) *December* 11, 1958: Fig. (vi).—

*Time:* 1340 - 1500 GMT.

*Location:* Mobile at 70° 50′ S, 61 ° 40′ E, altitude c.8100 ft.

*Solar Altitude/Azimuth:* 1340 : 22.0°/277°
1500 : 15.9°/245°.

*Display:* The point where the lower edge of the 22°-halo touched the horizon was brilliant, resembling a mock-sun. The 22°-parhelia were also present, together with the 46°-halo and parhelic circle (which extended for the full 180°), the very bright upper contact arc of the 22°-halo, Parry's Arc, and circumzenithal arc, the latter three being coloured as usual.

At about 90° from the sun were a pair of faint mock-suns, and at a further 10° -15° from the sun were a second similar pair. Both pairs appeared as somewhat brighter " spots " on the parhelic circle. At the anthelic point was a similar bright " spot ".

*Notes:* The display, particularly the anthelion and both pairs of mock-suns fluctuated in intensity and clarity as the " clouds " of ice-crystals came and went. These light " spots " and parts of the parhelic ring would at times completely disappear.

Although there is no note of it, it is strongly suspected that the vertical sun-pillar was present during this display.

(*g*) *December* 22, 1958: Fig. (vii).—

*Time:* 1430 GMT.

*Location:* 70° 26.3′ S, 61° 27′ E, altitude c.8500 ft.

*Solar Altitude/Azimuth:* 19.0°/253°.

*Display:* The 22°-halo was very bright, except for the region near the parhelic circle, and enclosed by the circumscribed " ellipse ". Here the halo became faint, although still coloured normally. The " ellipse " itself was very bright, especially near the parhelic circle; however, there were no parhelia present on this occasion. The red of the colour spectrum of the " ellipse ", as well as of the other coloured halos, was toward the sun. The vertical pillar was very bright, and extended from horizon to 22°-halo. The area on the horizon and between the ends of the 22°-halo was also exceptionally bright. Also visible was the 46°-halo.

The white parhelic circle extended for the complete 180° on either side of the sun, having anthelia, 90°- and 120°-mock suns also present for a short period.

*Notes:* In general, the halos during this display were very brilliant.

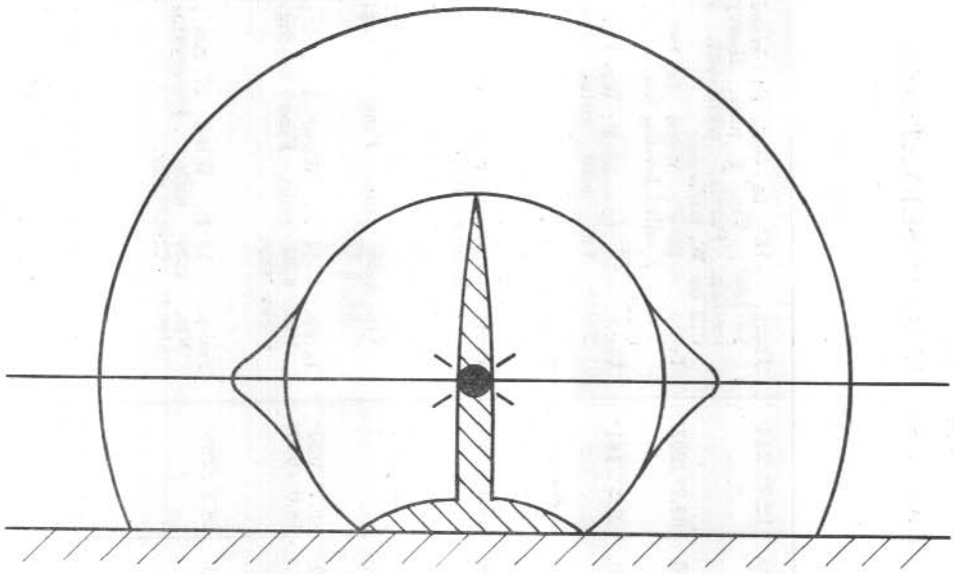

FIG. vii.—1430, 22 December, 1958.

TABLE 11.

SOUTHERN TRAVERSE HALO OBSERVATIONS.

| Date (a) | GMT (b) | Lat. & Long. (c) | Altitude above M.S.L. (ft.) (d) | Solar Altitude & Azimuth (e) | Meteorological Conditions. (f) | Halo-components Visible. (g) |
|---|---|---|---|---|---|---|
| 21.xi.58 | 1500-1800 | 70.1°S 62.1°E | c.8000 | 12.0°/244°- | Temp. —18° to —22°F; Wind 15/180°; Vis. $\frac{1}{2}$ mile. Heavy ice-fog. Partial white-out. $\frac{1}{8}$ CiS on W. horizon | See separate report. Fig. (i) |
| | 2100 | 70°10.2′S 62°08′E | c.8000 | 01.7°/203° | Temp. —28°F; Wind 15/180°; Vis. > $\frac{1}{2}$ mile? Ice-fog less thick. Clear sky. | See separate report. |
| 22.xi.58 | 2000-2300 | 70°10.2′S 62°08′E | c.8000 | 01.3°/161° | Temp. —28° to —30°F; Wind 20/200°; Vis. c.30 miles. Ice-crystals. $\frac{1}{8}$ CiS on NW. horizon. | 22°-halo and parhelia. |
| 25.xi.58 | 1200 | 70°10.2′S 62°08′E | c.8000 | 00.4°/174°-07.0°/133° | Temp. —14°F; Wind 14/210°; Vis. c.30 miles. Ice-crystals. $\frac{1}{8}$ Ac & $\frac{5}{8}$ Ci. | 22°-halo and parhelia. |
| | 2015 | 70°10.2′S 62°08′E | c.8000 | 27.7°/286° | Temp. —28°F; Wind 15/200°; Vis. c.5 mile? Ice-crystal clouds. Variable cloud all levels. Snowing nearby. | 22°-halo and parhelia. |
| 27.xi.58 | 0600 | 70°10.2′S 62°08′E | c.8000 | 01.2°/171° | Temp. —13°F; Wind 10/200°; Vis. c.30 mile. Fine ice-fog. $\frac{1}{8}$ As, $\frac{1}{8}$ CiS. | 22°-halo with very bright areas above and below sun. No parhelia. |
| 28.xi.58 | 0600 | 70°10.2′S 62°08′E | c.8000 | 38.7°/030° 38.9°/030° | Temp. —14°F; Wind 13/200°; Vis. c.30 mile. Fine ice-fog. Clear sky. | 22°-halo and parhelia, with tails. Bright areas above and below sun on halo. |
| | 1200 | 70°10.2′S 62°08′E | c.8000 | 28.3°/286° | Temp. —12°F; Wind 17/200°; Vis. c.30 mile. Ice-crystal clouds. Clear sky. | 22°-halo and parhelia, inverted upper contact arc, either elliptical or hyperbolic, & coloured. |
| | 1600-1730 | 70.2°S 62°10′E | c.7800 | 09.2°/230°-04.3°/210° | Temp. —16°F; Wind 15/180°; Vis. c.300 yds. Ice-fog and white-out; variable low and middle cloud. | See separate report. Fig. (ii). |

| | | | | | | |
|---|---|---|---|---|---|---|
| 29.xi.58 | 1345 | 70°15′S<br>62°11′E | c.7800 | 19.7°/261° | Temp. —18°F; Wind 15/200°; Vis. c.½ mile. Ice-crystal clouds. 4/8 Sc and Ac. | See separate report. Fig. (iii). |
| 30.xi.58 | 1400 | 70°17.1′S<br>62°10′E | c.8100 | 20.3°/261° | Temp. —9°F; Wind 25/200°; Vis. c.100 yds. Ice-crystal clouds. 7/8 middle and low cloud. | 22°- and 46°-halos. |
| 1.xii.58 | 0915-1800 | 70°24′-<br>70°25.2′S<br>62°09′E | c.7900 | 39.4°/331°-<br>03.9°/203° | Temp. —10° to —14°F; Wind calm to 03/220°; Vis. c.30 mile. Ice-crystals. 4/8 As. and Ci increasing to 4/8. | See separate report. Fig (iv). |
| 2-3.xii.58 | 2400 | 70°49.7′S<br>62°12′E | c.8000 | 13.0°/121° | Temp. —22°F; Wind 11/230°; Vis. c.30 mile. Ice-crystal clouds. 1/8 As in N. | See separate report. Fig (v). |
| 4.xii.58 | 0600 | 70°49.7′S<br>62°12′E | c.8000 | 39.2°/031° | Temp. —4°F; Wind 15/210°; Vis. c.30 mile. Ice-crystals? 5/8 middle cloud, 2/8Ci. | 22°-halo and parhelia. |
| | 1200 | 70°49.7′S<br>62°12′E | c.8000 | 29.1°/287° | Temp. —7°F; Wind 13/210°; Vis. c.30 mile. Ice-crystals. | 22°-halo, circumscribed "ellipse", parhelia, inverted upper contact arc of 22°-halo. |
| 9.xii.58 | 0600 | 70°49.7′S<br>62°12′E | c.8000 | 39.7°/031° | Temp. —7°F; Wind 18/200°; Vis. c.¼ mile. Ice-crystals. 3/8Ci. | 22°-halo, circumscribed "ellipse", parhelia, lower contact arc of 22°-halo. |
| | 1300 | 70°49.7′S<br>62°12′E | c.8000 | 25.0°/272° | Temp. —5°F; Wind 18/210°. Ice-crystals? 1/8 CiS. | 22°-halo and parhelia, 46°-halo, parhelic circle, vertical pillar, upper U-shaped contact arc of 22°-halo, Parry's Arc, circumzenithal arc, 90°-mocksuns, anthelion. |
| | 1800 | 70°50′S<br>70°50′S | c.8000 | 05.5°/204° | Temp. —11°F; Wind 13/200°; Vis. c.1 mile. Ice-crystals? 7/8 Sc. | Halos. |
| 11.xii.58 | 1340-1500 | 61°37′E<br>61°40′E | c.8000 | 22.0°/277°-<br>15.9°/245° | Temp. —1°F; Wind 16/190°; Vis. c.¼-½ mile. Dense ice-crystal clouds. 8/8 thin St. | See separate report. Fig. (vi). |

| Date (a) | GMT (b) | Lat. & Long. (c) | Altitude above M.S.L. (ft.) (d) | Solar Altitude & Azimuth (e) | Meteorological Conditions. (f) | Halo-components Visible. (g) |
|---|---|---|---|---|---|---|
| 14.xii.58 | 1200 | 70°50'S 61°39'E | c.8000 | 30.6°/288° | Temp. +1°F; Wind 11/190°; Vis. c.30 mile. Ice-crystals. | 22°-halo and parhelia, 46°-halo, parhelic circle (180°), 120°-paranthelia, anthelion. |
| 14-15.xii.58 | 2400 | 70°50'S 61°34'E | c.8000 | 13.6°/123° | Temp. —16°F; Wind 15/200°; Vis. c.30 mile. Ice-crystals. | 22°-halo and parhelia |
| 15.xii.58 | 1200 | 70°44.5'S 61°35'E | c.8200 | 30.7°/288° | Temp. —2°F; Wind 11/220°; Ice-crystals? 6/8 Ci and CiS. | Halos. |
| *20.xii.58 | 0400 | 68°00'S 54°04'E | c.7200 | 30.8°/076° | Temp. +1°F; Wind 25/110°; Vis. c.400 yds. Ice-crystals? 7/8 low cloud. | 22°-halo and parhelia, parhelic circle (180°) |
| 21.xii.58 | <1800 | 70°26.3'S 61°27'E | c.8500 | 06.0°/206° | Temp. —6°F; Wind 08/150°; 8/8 thin St. | 22°-parhelia. |
| 22.xii.58 | 1430 | 70°26.3'S 61°27'E | c.8500 | 19.0°/253° | Temp. +1°F; Wind 13/160°; Vis. c.30 mile. Ice-crystals. 1/8 Cu. | See separate report. Fig. (vii). |
| | 1800 | 70°26.3'S 61°06'E | c.8700 | 06.0°/206° | Temp. —13°F; Wind 08/180°; Vis. c.20 mile. Ice-crystals? 4/8 low cloud. | 22°-halo and parhelia, 46°-halo, parhelic ring, double upper contact arcs to 22°-halo. |
| 27.xii.58 | 0600 | 70°26.3'S 60°50'E | c.8800 | 39.9°/036° | Temp. —8°F; Wind 15/150°; Vis. c.10 mile. Ice-crystals. 1/8 CiS. | Halos. |
| | 1200 | 70°21.1'S 60°50'E | c.8800 | 31.6°/290° | Temp. —4°F; Wind 15/170°; Vis. c.5 mile. Ice-fog? 1/8 CiS. | 22°-halo and parhelia, 46°-halo, lower contact arc and inverted upper contact arc to 22°-halo. |
| | 1800 | 70°10.8'S 60°50'E | c.8800 | 05.8°/207° | Temp. —19°F; Wind 05/190°; Vis. c.30 mile. Ice-crystals? 1/8 As. | 22°-halo & parhelia, 46°-halo, vertical pillar, parhelic circle, upper U-shaped contact arc to 22°-halo, Parry's Arc, circumzenithal arc, 90°-mocksuns, anthelion. |
| 5.i.59 | 1200-1600 | 68.8°S 61.8°E | c.7400 | 31.6°/290°-10.9°/234° | Temp. +2°F; to —6°F; Wind 20/160° to 10/200°; Vis. c.30 mile. Ice-crystals? 2/8 middle cloud, 3/8 CiS. | 22°-halo and parhelia, 46°-halo, upper contact arc to 22°-halo. |

* This observation was made by a survey and geological team on a dog-sledging expedition from Amundsen Bay to Mawson.

L. G. SHEA GOVERNMENT PRINTER TASMANIA