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An unusual Parhelion at Calcutta

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(*Received 13 January 1954*)

ABSTRACT. The meteorological conditions leading to the appearance of a parhelion at Calcutta, accompanied by a partial halo have been investigated. From the angular elevation of the sun, the distances from the sun of the parhelion and the partial halo at the times of their appearance and disappearance have been computed. The study leads to the inference that incipient cirrus is mainly composed of hexagonal ice crystals with their sides vertical in a field of light to moderate winds. The distribution of such crystals is orderly and the deviation of light through them is a minimum.

1. Introduction

A well-formed parhelion was observed at Calcutta on the morning of 20 June 1953. As this optical phenomenon is of rare occurrence in the tropics and as there does not appear to be any record of its having been observed at this place, it has been felt worthwhile to investigate the meteorological conditions leading to its appearance. An attempt has also been made to compute the actual distance of the parhelion and the associated partial halo along the great circle through the sun from the angular elevation of the sun at the times of appearance and disappearance of the phenomenon. The computed values have been compared with those visually estimated. The results are discussed with reference to the structure of the cloud that gave rise to the phenomenon.

2. Description of the phenomenon

The phenomenon was noticed at about 0615 IST at Dum Dum (Lat. 22°38′N, Long. 88°28′E). The estimated elevation of the sun at the time was 18° above the horizon. A bright spot was observed towards the left of the sun at about the same altitude. It was circular and of the same dimensions as the sun but had an ill-defined periphery. It was estimated to lie at a horizontal azimuthal distance of 24° from the sun. It was tinged orange on the edge nearer the sun and greenish at the outer edge. An arc of light extended vertically across this spot through a point about a degree to the right of the spot. It was symmetrical with respect to the spot and was about 5° in total altitudinal extent. This arc was also faint and was concentric with the sun. Its concave edge was coloured orange and it was greenish on the outer edge. No other spectral colours were distinguishable in between. The time of sunrise on that day was 0450 IST. The phenomenon lasted upto 0630 IST. By this time the spot waned and the vertical arc waxed in brightness. The angular distance between the sun and the spot appeared to have increased by a degree above what it was at the time of its first appearance. The phenomenon faded out completely by 0635 IST. A sketch showing the details of the observation is reproduced in Fig. 1.

The same phenomenon was also independently observed at Barrackpore airfield (Lat. 22° 47′N, Long. 88°21′E) at about the same time. The details of the observation at this place were in agreement with those in Fig. 1. The actual time of disappearance of the phenomenon here was not recorded but it was not seen at 0630 IST, which is a routine time of observation. It might have vanished earlier.

3. Accompanying meteorological conditions

The sky was thundery on the preceding day up to midnight. It was later covered with 5/8 of stratus and stratocumulus but no high cloud was seen. This cloud gradually dissolved away by the time of sunrise. Cirrus began to appear at about 0430 IST and rapidly covered the western half of the sky by 0530 IST. The amount and disposition of the cloud was more or less the same upto 0630 IST, whereafter the cloud gradually dissolved away. The estimated height of the cirrus was 35,000 to 40,000 ft. The temperature in that layer of the atmosphere as revealed by the radiosonde ascent at 2030 IST on 19 June 1953 was —35° to —40°C. The Rawin ascent at the same time showed that the wind speed in this layer was 15-20 knots. The freezing level was 17,400 ft a.s.l.

4. Theory

Parhelia are formed as a consequence of the refraction of sunlight through a layer of air containing a large number of broad hexagonal snow crystals, which have their sides vertical. These bright spots appear in the direction of maximum light or minimum refraction of the rays from the sun, at about the same altitude as the sun on either side. In the case of refraction of light with the interior ray parallel to the principal plane of a crystal, the angle of minimum deviation D_0 is given by the well-known equation.

$$\text{Sin } \tfrac{1}{2}(A+D_0) = \mu \sin \tfrac{1}{2} A \qquad (1)$$

where A is the angle between the alternate sides of the ice crystal and μ is its refractive index. The value of D_0 determines the angular distance of each of the parhelia from the sun. Such a simple relationship is, however, possible only when the sun is on the horizon.

When the sun is at an elevation h above the horizon, the incident skew rays will not lie in planes normal to the intersection of the faces of the prism. In the case of skew rays, therefore, equation (1) will not be valid. If, for a skew ray, the angle between the internal ray in the crystal and its principal plane is k, Pernter and Exner (1922) have shown that the azimuthal distance D_h of each of the parhelia from the sun is given by the expression

$$\text{Sin } \tfrac{1}{2}(A+D_h) = \mu \frac{\cos k}{\cos h} \sin \tfrac{1}{2} A \qquad (2)$$

It can be shown further from geometrical considerations that $\sin h = \mu \sin k$, from

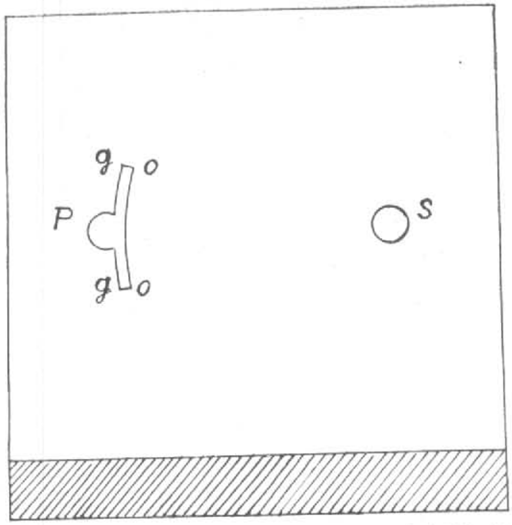

Fig. 1. Parhelion and partial halo observed at Calcutta on 20 June 1953. (Not to Scale)
S : Sun, P : Parhelion, O : Orange, g : Green

which
$$\text{Cos } k = \frac{(\mu^2 - \sin^2 h)^{\frac{1}{2}}}{\mu} \qquad (3)$$

Substituting (3) in equation (2), we get

$$\text{Sin } \tfrac{1}{2}(A+D_h) = \frac{(\mu^2 - \sin^2 h)^{\frac{1}{2}}}{\cos h} \sin \tfrac{1}{2} A \qquad (4)$$

For a hexagonal prism, A=60° and the refractive index of ice crystals for white light nearly equals 1·31. Equation (4) can, therefore, be rewritten as

$$\text{Sin} \frac{60 + D_h}{2} = \frac{(1 \cdot 716 - \sin^2 h)^{\frac{1}{2}}}{2 \cos h} \qquad (5)$$

The above expression yields only the angular azimuthal distance from the sun subtended at the place of observation. The *actual* angular distance on the arc of a great circle passing through the sun and the parhelia can be evaluated from the right spherical triangle formed by the three sides: zenith to sun; zenith to mid-point between sun and a parhelion; and this mid-point to sun ($\frac{1}{2}\triangle_0$). The angle thus formed at the zenith is $D_h/2$. It is easily seen that

$$\text{Sin } \tfrac{1}{2}\triangle_h = \cos h \sin \tfrac{1}{2} D_h \qquad (6)$$

5. Results

The elevation of the sun at 0615 IST when the phenomenon first made its appearance has been computed from the time of sunrise with the help of the nautical almanac to be 17°. At 0635 IST, when the phenomenon disappeared, the sun's elevation worked out to be 21°30′. With the help of these data and equations (5) and (6), the values of D_h and $\triangle_h$ have been computed. The results so computed are shown in Table 1 together with the estimated values.

TABLE 1

Distances between sun and parhelion at times of appearance and disappearance

Time of Obsn. (IST)	Elevation of sun above horizon	Azimuthal distance from sun to spot (D_h)		Calculated circum-zenithal distance from sun to spot ($\triangle h$)
		Calculated	Estimated (Correct to a degree)	
0615	17°	23°46′	24°	22°42′
0635	21°30′	25°6′	25°	23°12′

The close correspondence between the estimated and computed values of D_h at the times of appearance and disappearance of the observed bright spot leaves little doubt that the bright spot was the parhelion. The vertical arc of small extent lying to the right of the parhelion can be identified as part of the halo of 22°, concentric with the sun. Its actual distance from the sun varies with the altitude of the latter. Pernter and Exner (1922) have shown that for solar elevation within 10° of the horizon, the halo of 22° and the parhelia are practically superimposed. At greater altitudes, they are distinctly resolved. For an altitude of 17°, the halo of 22° would occur at a disance of 58′ nearer the sun. The fact that the vertical arc to the right of the sun in the present case was observed to be about a degree nearer the sun than the parhelion confirms the inference that this arc is part of an incomplete halo.

It is worth noting that in the case of the phenomenon reported here, only one parhelion and a small fraction of the halo alone had made their appearance. This is ascribable to the manner of distribution of the ice-cloud which gave rise to it. The cirrus cloud was mostly concentrated towards the left of the sun. Paucity of refractive material to the right of the sun must have been responsible for the non-appearance of the symmetrical parhelion to the right. It must be for this same reason that the circumzenithal arc did not manifest itself in association with the parhelion and the partial halo although the other conditions that obtained at the time were in favour of its appearance.

6. Structure of the cirrus cloud

(*a*) *The nature of the ice crystals*—The cirrus clouds appear to have formed as a consequence of the convective upwelling of moisture above the freezing level following the thundery activity on the preceding night. Radiative cooling of the moisture that lifted up to the cirrus level must have been an important cause for the commencement of formation of the cloud only after dawn. Such cooling, which attains its apex by dawn, perhaps resulted in the vapour pressure equalling or slightly exceeding the equilibrium value. Granting the presence of crystalline nuclei in the air, such as of silica or quartz grains, which should be plentiful in an industrial area like Calcutta, the water vapour tends to sublimate directly on these crystalline nuclei into hexagonal forms as soon as the vapour pressure exceeds the equilibrium value at low sub-freezing temperatures. Bentley (1937) has shown that, under such conditions, the ice crystals that are produced are the smaller and more solid hexagonal type. These crystals gradually develop into hexagonal discs of snow, float horizontally and constitute the cirrus clouds formed at low temperatures.

The winds and temperatures at different altitudes above sea level at 20,000 ft and aloft determined by Radar and Rawin (Indian Daily Weather Report, 1953) soundings at 2030 IST on 19 June 1953 which are the available data nearest the time of appearance of the parhelion, are shown in Table 2.

It is seen from Table 2 that at the estimated altitude of the cirrus cloud of between 35,000 and 40,000 ft, the winds were least, thereby providing more favourable conditions for the growth of ice crystals in that layer of the atmosphere. The temperatures were also

TABLE 2

Winds and temperatures above 20,000 ft on 19 June 1953

Altitude in ft a.s.l.	Upper winds		Temperature below 0°C
	Direction (degrees)	Speed (knots)	
20,000	100	25	5
25,000	100	27	10
30,000	100	24	21
35,000	110	20	28
40,000	110	17	41
45,000	060	23	—

considerably below the freezing point being of the order of—35°C. There was no development revealed by the synoptic charts after the ascents to suggest that the same conditions did not persist till dawn next day.

The question may be asked whether the appearance of the halo, however partial, does not suggest the presence of the short columnar type of crystals also in the cloud. If there were an admixture of such crystals, one should expect to see a well-formed halo all round the sun through the cloud, whose intensity would depend on the proportion of such crystals. That what manifested itself was only a short length of the halo precludes the possibility for the existence of columnar crystals in the cloud.

The conditions at the cirrus level on this day were then such that hexagonal ice crystals must have formed abundantly. These must have grown into relatively thin snow flakes, constituting the cirrus clouds. The snow flakes would have descended slowly through the light to moderate wind, warming up with descent, and would have evaporated away completely by 0635 IST.

(*b*) *The orientation of the crystals*

(*i*) *Shape of the parhelion*—For the occurrence of parhelia, the refracting edges of the ice crystals must be vertical, so that the maximum light is deflected in the direction of minimum deviation. If the orientation of these crystals is random, all possible deviations from minimum to maximum would occur, resulting in the parhelion being drawn out into streaks, which may extend for an elevation of the sun of 15° to 20°, over an arc parallel to the horizon of more than 20° (Humphreys, 1940). However, as the observed parhelion was roughly circular in shape and was not drawn out into streaks, it may be concluded that the orientation of the crystals was orderly and not random.

(*ii*) *Colour of the parhelion*—As μ for ice varies from 1·31 for yellow to 1·317 for violet light, the parhelion should manifest all the spectral colours starting with red at the end nearer the sun. In the case under study, only orange and green colours were seen at either edges but otherwise, the parhelion was practically white. This suggests that there were slight changes in the orientation or inclination of the crystals, causing rays of different colours to blend together in the central region. As the diameter of the parhelion was about the same as that of the sun, such changes in the orientation could not have been more than about 1 degree.

(*iii*) *The partial halo of 22°*—In the absence of the columnar type of the crystal, a halo would appear when the refracting edges of the hexagonal crystals are oriented at random, as would happen at the windy cirrus level. The effect produced by fortuitously directed snow crystals must be more or less symmetrically distributed on all sides of the exciting luminary. The fact that in this case, only a small fraction of the halo, less than 5° in total altitudinal extent, was all that had appeared, implies that the maximum deviation of the refracted rays could not have exceeded $2\frac{1}{2}°$ on either side of the line joining the sun to the parhelion. With respect to a crystal through which the sun's rays suffered this extreme value of $2\frac{1}{2}°$ of refraction, the effect is as if the sun had shifted up or down by a certain distance about its actual altitude; in other words, as if h had increased or decreased in such a way as to cause that deviation of $2\frac{1}{2}°$ more or less. This change in h has been computed with the help of equation (5) and found to be $\pm 4° \ 10'$ of the true altitude of 17° at the time of appearance of the parhelion. The maximum deviation of the refracting edges of the crystal on either side of the vertical should, therefore, have been within 5° on either side. Such deviation must have been caused by the light to moderate wind, prevailing at that level, setting the crystals in oscillation about the mean position through an amplitude of 5° or less. The number of such crystals would, however, have formed only a small fraction of those with their sides vertical, judging from the relative faintness of the halo.

(*iv*) *Changes in orientation with time*—It has been pointed out that, with progress of time, the arc of the halo waxed and the parhelion waned in intensity. Hexagonal crystals would fall slowly in calm air. Wind, however slight, would tend to make them oscillate about their vertical equilibrium position. As already discussed, a small proportion of the crystals would have oscillated about the vertical through an angle of within 5° in order to produce the observed arc of halo. It is seen from Table 2 that the wind speed increases with decreasing altitudes. It may, therefore, be inferred that, with the progress of time, the crystals descended into the more windy lower levels with consequent rapid increase in the proportion of such oscillating crystals.

(*c*) *Rarity of the parhelion in the tropics*—The rarity of the parhelion in the tropics must be attributed to the general absence of high clouds with an orderly distribution of hexagonal crystals. Convective clouds extend in the tropics even upto an altitude of 50,000 ft, as recent reports of high flying Jet aircraft (Rao, 1954) show. They also reveal that turbulence is encountered even in clear air at those high altitudes. Strong winds at that level are another important cause for disarray of the ice crystals in cirrus clouds. The present investigation shows that genuine cirrus clouds, which form sufficiently early in the day in winds less than 20 knots are composed, at least when they are incipient, of a majority of hexagonal crystals aligned with their sides vertical.

It is, however, worth emphasising in this context that the rarity with which parhelia are noticed in the tropics by the unaided eye does not provide by itself an index of the unusualness of the phenomenon, in view of the fact that well-developed cirrus and cirro-stratus clouds are not of infrequent occurrence in the tropics. The "Mock Sun" is certainly less frequent than "Mock Moon" but this circumstance is not entirely the result of greater turbulence during the day than at night. If observation is made through a suitable filter or by adoption of any other procedure, which effectively reduces the glare of the sunlight, it is possible that parhelia may be found to occur less infrequently than they are by gross visual observation.

7. Conclusions

The above discussion leads to the following conclusions on the structure of the cirrus cloud, which gave rise to the parhelion and the partial halo—

(*i*) Cirrus clouds, which form at low sub-freezing temperatures are composed mainly of hexagonal crystals. Radiative cooling may be an important factor in the formation of such clouds after dawn in the absence of any major disturbance in the atmosphere.

(*ii*) Even in light to moderate winds of 15–20 knots, such crystals tend to orient themselves with their sides vertical.

(*iii*) Some of these crystals are set into oscillation about the vertical by light to moderate winds. The proportion of such crystals is, however, small and the amplitude of oscillation within 5 degrees.

(*iv*) With increase in wind speed, the proportion of such oscillating crystals increases rapidly.

(*v*) The rarity of parhelia in the tropics is attributable to the general absence of an orderly array of ice crystals in the cirrus clouds, on account of turbulence and strong winds.

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