# Noctilucent Clouds

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## *Abstract*

Knowledge of noctilucent clouds is reviewed, and fresh observations made in Sweden are described. The conditions under which the clouds may be seen are calculated and compared with observations; it appears that the clouds are formed only in the summer in high latitudes. The sizes and concentrations of the cloud particles are inferred, and the probsem of their composition and origin is discussed. The clouds are not likely to be formed by condensation of water vapour, but are more probably dust clouds derived from great eruptions, very large meteorites, and from interplanetary space. Evidence of dust in the stratosphere is assembled, and the processes by which it appears in visible clouds are discussed.


## 1. Introduction; the properties of noctilucent clouds

In high latitudes during summer months tenuous high clouds occasionally become visible about an hour after sunset. Only clouds high in the stratosphere can remain in sunshine so long after the sun has set on the ground.

Such clouds, called 'luminous night-clouds' or *noctilucent clouds*, were first studied systematically by Jesse, in Germany, and by Tseraskii, in Russia, in 1885 and later years. It is probable that similar clouds had been observed previously, but the published accounts are not sufficiently definite for this to be certain (see ARAGO, 1854, and SCULTETUS, 1949, who discusses an observation by Lavoisier). There are numerous reports of bright noctilucent clouds in 1885, 1886 and 1887, but in succeeding years there were fewer observations and the displays became weaker, and since 1894 the clouds have been observed only intermittently. A valuable review of published reports was made by VESTINE (1934), and more recently STØRMER (1933, 1935) and PATON (1954) have on several occasions observed and measured the height of the clouds.

The problem of the nature of the clouds is still unsolved. In this paper some new observations are described, previous reports are summarized, and theories of the composition and formation of the clouds are discussed, with the aim of stimulating more widespread and thorough observations during the approaching International Geophysical Year.

### a) *The form and colour of noctilucent clouds*

In general appearance noctilucent clouds resemble a thin, decayed cirrostratus, without any of the fallstreak forms characteristic of many ice clouds (Figs. 1—3). They tend to occur in extensive sheets, although the part of the sky in which they can be seen is often restricted to a narrow segment above the horizon. The most careful classification of the forms of noctilucent clouds is that of GRISHIN (1955); he distinguishes the following:

1. The *nebula*, or flare. Between the more prominent details of other forms there is frequently a nebulous, very tenuous and structureless veil, shining faintly with a delicately white or bluish light. According to Grishin the flare often can be detected by an experienced observer as a slight luminescence of the twilight sky, and may appear a half to one hour before clouds with a definite structure.

2. *Bands*. Diffuse-edged, long streaks, known as bands, are more or less straight or gently

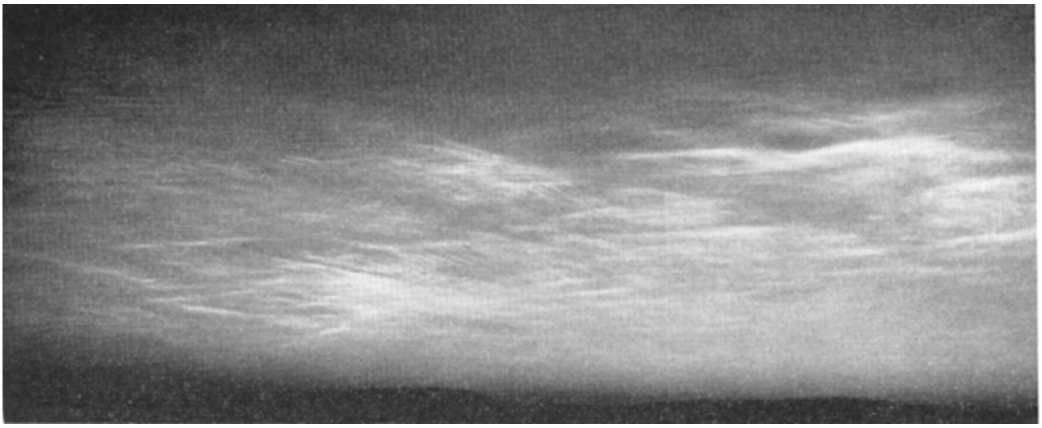

Fig. 1. Noctilucent clouds in the northern sky, Torsta, 13 August 1955, 0025 hours. A dark "shadow" can be seen above a bright detail in the upper right of the picture.

Fig. 2. Noctilucent cloud billows, Torsta, 13 August 1955, 0155 hours (photograph by F. Singleton).

curved, and sometimes hundreds of km long. They occur in extensive groups, the individuals of which are roughly parallel. They are persistent, with inappreciable change of detail. Smaller *streaks*, with twists or bends, may lie across the bands or branch out from them.

3. *Billows.* When the noctilucent clouds extend above low elevations, groups of rather sharply-defined billows may be seen. The distance separating pairs of billows is about 10 km. The billows tend to lie across the direction of the bands, but their alignment may differ noticeably in neighbouring parts of the sky. When the billows lie across a band part of the material of the band becomes gathered into the billow crests; at other times billows form within the flare. In contrast to the bands, the small streaks and billows may change their form and arrangement, or appear and disappear, within several minutes.

The colour of the clouds is usually white; at high elevations they are often silvery, having a slight bluish tinge, while near the horizon they become yellowish, or even orange. Sometimes more closely-spaced *serrations* are seen, which to the unaided eye present an almost continuous cloud. Grishin also distinguishes individual wave-like curves or distortions in parts of noctilucent clouds, and

4. *Eddies*, usually of slight curvature, which may be seen in bands, serrations, and sometimes in flares. The eddies extend over very variable arcs, even to complete rings or vortices with dark centres.

Grishin's classification was developed during observations made in the years 1948 to 1953; in the last year a time-lapse film of noctilucent clouds was made, which clearly showed the wave-like form and evolution of many of the structural details. No satisfactory impression of the nature of the internal motion and transformations shown by these clouds can be gained except by the help of such films.

According to Helmholtz, Størmer, and Astapovich (see KHVOSTIKOV, 1952), their spectrum is similar to that of daylight; the Fraunhofer lines are clearly present, and there are no emission lines. The light from the clouds is evidently simply scattered sunlight, but with some excess of blue compared with red. PATON (1954) once observed a slow change of colour in portions of a noctilucent cloud from a vivid blue to white.

Occasionally the clouds are strikingly bright. In 1885 and 1886 they were bright enough at times to cast shadows and to allow the reading of ordinary print outdoors. A report in 1908 (WHIPPLE, 1934) speaks of 'an extraordinarily strong light, magical and very imposing in the fair summer night'. PATON (1951) mentions a display during which notes could be written without artificial light. Nevertheless the clouds are usually very tenuous, causing hardly any dimming of stars seen through them. During moderate displays in Sweden the clouds were photographed on fine-grain panchromatic film (speed 28° Sch.) with exposures varying from about 1 sec, with a solar depression of 6°, to as much as 100—500 sec, with a solar depression of 11—12.5°, at an aperture of *f* 5.6. The clouds are seen clearly through blue filters, but fade in red filters, and the latter, so useful in the photography of cirrus, should not be used when photographs are taken of noctilucent clouds.

The light of the noctilucent clouds is quite strongly polarized, in the same sense as the light of the sky. This property is sometimes useful in distinguishing faint noctilucent clouds from cirrus feebly illuminated by scattering from the twilight sky.

### b) *The occurrence of noctilucent clouds*

According to previous accounts noctilucent clouds are observed only at places lying between latitudes of about 45° and 62° N (see, e.g. PATON, 1954). However, they were observed on ten nights during the months July and August, 1954 and 1955, at the field-station of the International Institute of Meteorology (Stockholm), which is at Torsta, near Östersund in central Sweden, and in latitude 63°15′ N. On some occasions the clouds were seen in the northern sky down to elevations of 1 to 2° above the horizon, corresponding to distances of 800 to 900 km. These clouds therefore extended northwards at least into the vicinity of North Cape, in latitude 71° N (only in the clean air so often enjoyed in this part of the world could it be expected that clouds would be visible at such a distance). The previous lack of reports from north of 62° N is therefore probably due to the scarcity there of keen observers.

It may equally be wondered if the complete lack of reports during some years reliably indicates the absence of the clouds. The decrease in the number of accounts after 1887 may have been due partly to waning interest. PATON (1954) remarks that the records from Ben Nevis Observatory, where hourly observations were made from 1883 to 1904, show that noctilucent clouds were frequently seen and noted as 'pearly cirrus', 'shining with a silverly blue light'. Paton himself, observing during the period 1939 to 1955, saw noctilucent clouds at least once each year, except in 1942 and 1944 (private communication). If these observations are added to those of Størmer, Malzew (quoted by STØRMER, 1935), and SPANGENBERG (1949), we find that only in these two years are reports missing in the years since 1932. It seems likely, therefore, that the clouds occur at least somewhere in high latitudes every summer, that often they are not seen for want of suitable weather conditions or interested observers, and that occasionally they are abnormally widespread and intense, compelling attention. The exceptional periods seem to be 1885—1892, 1908—1911, 1932—1935, and, possibly, 1953—1955.

The clouds have been seen in the northern hemisphere from late May to the middle of August, and, according to Vestine (who does not, however, quote references) in the southern hemisphere in the period of the year about six months later.

Fig. 4, from Vestine's review, shows that the clouds have been observed more frequently after than before the summer solstice.

During strong displays the clouds have appeared as early as 15 minutes after sunset over a large part of the sky, extending to near the SE horizon. As the sun sinks lower the illuminated area of the clouds recedes to a zone above the twilight arch, on either side of the vertical through the sun. This zone moves with the sun's vertical into the northern sky, where at midnight the upper edge of the illuminated area has reached a minimum elevation, and towards sunrise into the northeast before extending again across the zenith and fading away about half an hour before sunrise. In less striking displays the clouds appear in the northwest about an hour after sunset, and fade in the northeast about the same time before sunrise. Only rarely have the clouds been seen at elevations higher than 10°.

Except in very intense displays, the clouds have been seen more frequently after than before midnight, even though the number of observers is likely to have been less at the later hours. In the period 1889—1894 the clouds were observed on 6 occasions before, and on 33 occasions after midnight.

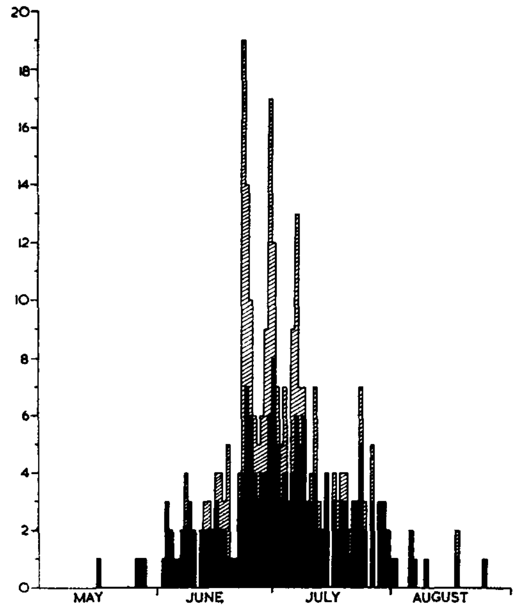


Fig. 4. Total number of times noctilucent clouds have occurred on a given date, 1885—1933 (solid histogram); total number of reports of noctilucent clouds on a given date (hatched histogram). (After Vestine, 1934.)

### c) *The height of noctilucent clouds*

Tseraskii in 1895, and Pokrovskii in 1897 (see Khvostikov, 1952), Jesse (1896), Størmer (1935) and Paton (1949) have measured the height of noctilucent clouds by photography from the ends of long base-lines. Tseraskii obtained an approximate height of 79 km, and Pokrovskii a value of 82 km. Jesse used a base-line 35 km long; in the summer of 1889 he determined the height of 108 cloud details identified on simultaneously exposed pairs of plates, and obtained an average of 82.8 km. When these were combined with another 179 measurements made in the following summer, the mean became 82.1 km; the individual values varied from 79 to 90 km.

Størmer used his network of auroral cameras, which provides base-lines of 47, 65 and 105 km. On two occasions in 1932 he measured mean heights of 81.8 km (18 measurements) and 81.1 km (19 measurements). On another occasion in 1934 he obtained a mean height of 82.2 km from 41 measurements which varied from 78 to 85 km.

Paton also used auroral cameras on an occasion in 1949, with a base-line 27.6 km long, which, however, was unfavourably orientated with respect to the clouds, lying almost N—S; he measured a height of about 89 km.

The measurements are thus very consistent. Estimates based on the angular elevation of the nearest discernible details, and the assumption that they are lit by rays which graze the earth, give smaller height varying between about 30 and 70 km.

### d) *The velocity of noctilucent clouds*

Jesse made a number of measurements of the movement of noctilucent clouds and found it

a.

b.

Fig. 3. Noctilucent clouds in NNE, 9 August 1955, 2340 hours (a), and 10 August 1955, 0010 hours (b).

to be almost always from some point between N and E, and to be rapid, with speeds of up to 100—200 m/sec (ARCHENHOLD, 1928). In 1932 Størmer observed the clouds to be moving from NNE at 44—55 m/sec, and in 1935 estimated a movement from E at about 80 m/sec. STØRMER (1935) quotes a measurement made in Russia in 1925 of a motion from 013° at 229 m/sec. KHVOSTIKOV (1952) mentions measurements in Russia of speeds varying from 50 to 135 m/sec.

According to Jesse's data the motion before midnight is usually from NE, while after midnight it tends to be from ENE. STØRMER (1933) suggests that the changes in velocity may occur near the earth's shadow.

## 2. Summary of observations at Torsta, 1954 and 1955

In the following summary of observations made at Torsta, near Östersund, a note is included of occasions when the clouds were not seen although sought under apparently favourable viewing conditions. The times quoted are in Swedish clock time (G.M.T. plus 1 hour), which within a few minutes is also the local time. The sun's declination is given in brackets following each date of observation. Cloud velocities are derived from theodolite observations, on the assumption that the cloud height is 80 km. Figures following bearings refer to elevations above the horizon.

*18—19 July 1954* (21.0°)

The clouds were first noticed in the NE, 20° at 2322, and later appeared in various places between NNW and E, up to 30°. Billows were aligned E—W. About 0040 four successive measurements gave the following velocities: 003° 55 m/sec, 021° 70 m/sec, 009° 66 m/sec, 011° 65 m/sec.

The clouds were also observed in Stockholm from 2400 to 0100, between N and NNE (fig. 5).

*20—21 July 1954* (20.8°)

A good display occurred after 2300, covering practically the whole sky north of the zenith, mainly as very long irregular streaks aligned N—S. Some billows in the east had the same alignment. At 0012 the clouds were visible in the NNW down to 6°, where they gleamed silver behind a rayed purple light extending up to about 10°; one measurement gave a velocity of 345° 86 m/sec. At 0035 the clouds extended to 18° above the SSW horizon; the display faded at 0200.

Fig. 5. Noctilucent clouds in NNE, from Lidingö, Stockholm, 19 July 1954, about 0030 hours (photograph by Hans Höfer).

*24 July 1954* (20.0°)

The clouds did not occur before 2330.

*29—30 July 1954* (18.9°)

Some clouds were barely visible beyond stratocumulus, just E of N, 5°, at 2345. Later long streaks and billows appeared in the NE, about 10°.

*16—17 August 1954* (13.9°)

Noctilucent clouds appeared at 2300 in an arch extending from WNW to NNE, with minimum and maximum elevations of 2.2 and 7° (where they faded sharply into a deep blue-black sky) in the NNW at 2335, and were still visible at 0010. One measurement at 2342 gave a velocity of 053° 55 m/sec.

*17, 19 and 22 August 1954* (13.6, 13.0, 12.0°)

The clouds were not present before 2400.

*18 August, 1954* (13.3°)

The clouds were not present before 2300.

*29 August 1954* (9.6°)

The clouds were not present before 2200.

*18—19 July 1955* (21.0°)

Between 2345 and 0035 faint streaks were visible near the zenith, down to 40° in the S and down to 10° between W and NNE. No appreciable movement of the streaks could be seen over the open sights of the theodolite during a ten-minute period.

*23—24 July 1955* (20.0°)

At 2340 faint streaks lying N—S appeared in NE and at about 30° in the SE a faint streak was aligned E—W. At 2400 faint patches with billows appeared in SE, 60°; motion 355° 70 m/sec. At 0015 further streaks appeared in NW, 25° and ENE, 15°. Another measurement of the motion, more reliable than the first, gave 022° 80 m/sec. At 0110 the display had faded, but two long faint streaks were still visible in the E, 25°.

*25—26 and 26—27 July 1955* (19.7 and 19.5°)

No noctilucent clouds before 0030.

*27—28 July 1955* (19.2°)

At 2250 a thin streak appeared in N-NNE, 3°; soon another appeared at 6°, and a patch of billows formed just below 3°. At 2325 the clouds had extended up to 7.5°; they gave a strong impression of forming and dissolving with a life of about 20 min. From 2345 to 0040 there were only traces, from NNW to NNE, 3.5 to 4.6°.

*29—30 July 1955* (18.8°)

No clouds present before 0030.

*31 July—1 August 1955* (18.3°)

At 2245 pale streaks became visible in NNE, 7°; gradually they became brighter and more extensive; the longest streaks were aligned towards ENE, gradually bending towards NNW at low elevations, with many shorter streaks and some billows lying across their length. By 2330 the clouds extended from NNE to ENE, 1.7 to 10°. Immediately above bright streaks the sky was darker, as though they cast a shadow. At 2350 the motion was measured as 344° 36 m/sec. At 0019 and 0023 two further measurements in the same part of the sky, apparently no less reliable, gave 238° 45 m/sec and 243° 38 m/sec. The alignment of a billow was measured to be along 293°. After midnight the display became weaker, and only traces remained at 0040.

*2 August 1955* (17.8°)

Clouds not present before 2315.

*9—10 August 1955* (15.8°)

Noctilucent clouds appeared in the N at 2330, and by 2350 extended from NNE—ENE, 2.0 to 5.0°. Two measurements of the motion gave 325° 13 m/sec (at 2400) and 341° 16 m/sec (at 0025). By 0040 the clouds extended from 3.2 to 13.4°, but were fainter; throughout this period they were very sharply limited in the NNE. At 0145 traces remained in ENE, 11 and 6°. The clouds are illustrated in Fig. 3.

*12—13 August 1955* (15.0°)

Clouds first observed at 2330; at midnight they extended from NNE to ENE, up to 4.3°; half an hour later they had spread into the N, with traces also in the NW, and the upper margin had increased to 6.2°. The area of clouds continued to shift westwards and the upper margin to rise; at 0135 the clouds extended between NNW and NNE and up to 12.8°. There were many groups of beautiful billows (Figs. 1, 2), and again marked 'shadows' occurred immediately above some of the brighter streaks (Fig. 1). After 0200 the clouds faded and shrank in extent, only traces in the NW remaining at 0225. Measurements of the motion gave the following results:
0100: 031° 36 m/sec; 0130: 052° 26 m/sec and 049° 60 m/sec; 0150: 054° 90 m/sec.

The acceleration seemed real, for in the later stages the motion in the field of the theodolite was obviously more rapid than previously.

*21—22 August 1955* (12.1°)

Noctilucent clouds absent.

*23, 24, 25, 26 August 1955* (11.4 to 10.4°)

Noctilucent clouds absent before 2330.

**General remarks**

Altogether during these two summers there were observed 2 faint, 3 moderate and 5 bright displays. It is remarkable that between successive displays the clouds are sometimes not to be seen under apparently perfect viewing conditions. Possibly on some of these occasions a watch, although maintained until about midnight, was not kept long enough, for in accordance with previous experience there is a clear tendency for the displays to be more marked after than before midnight. The clouds also are usually visible for a longer period after than before midnight.

It is noticeable that the clouds occur predominantly in the part of the sky which is east of N, and even for them to first appear there before midnight, when of course the sun lies west of N. On some occasions the clouds are clearly limited in extent, their boundaries not being determined simply by the border of the earth's shadow.

It is not easy to make a reliable measurement of the cloud motion by theodolite, because of the difficulty of finding a suitable detail which retains its identity and sharpness for more than a minute or two. Some of the prominent details, for example the bright places where two streaks cross or fuse, may not move with the wind velocity.

### 3. Conditions under which noctilucent clouds may be observed

It has been supposed that observations of the clouds are restricted to the summer months in middle and high latitudes because only then do the geometrical conditions allow the clouds to remain in sunshine for substantial periods after sunset on the ground. In low latitudes throughout the year the sun sinks rapidly below the horizon, greatly restricting these periods in which the clouds are suitably illuminated. The variation of viewing conditions throughout the seasons and over the earth can be calculated under some assumptions, as described in the following paragraphs.

An observer at o (Fig. 6) is considered able to see any clouds lying at the 80 km level over an arc extending in the vertical through the sun between angular elevations *a*, *b*, when the sun's apparent depression below the horizon is $\alpha$. The sunlight grazes the earth at the point *G*,

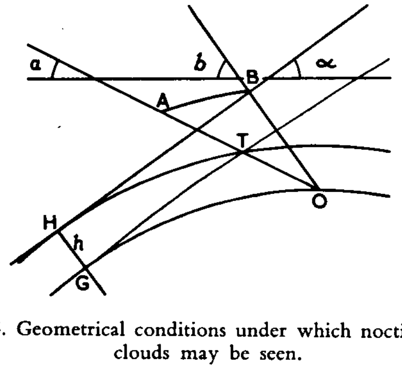


Fig. 6. Geometrical conditions under which noctilucent clouds may be seen.

but it is supposed that the light is much attenuated in a layer extending above the ground to a height *h*, so that only rays above that which grazes this layer at *H* illuminate the clouds sufficiently for them to become visible. On the other hand, it is assumed that the clouds cannot be seen beyond the point *A* because in the line of sight a part of the main scattering layer is still in direct sunshine, and the cloud details are swamped in the flood of scattered light which produces the twilight arch.

The angles *a* and *b* are functions of the sun's depression $\alpha$, and of the heights assumed for the clouds and the top of the main scattering layer. They may be determined by calculating the paths through the atmosphere of the rays along *OA* and *OB*, and of the rays *GT* and *HB* which graze the earth's surface and the main scattering layer. Because these rays have long paths through the atmosphere it is necessary to consider the earth's curvature, and at the same time normal atmospheric refraction can be taken into account (although it is relatively unimportant).

It is desirable to determine a value of *h* from observations of the upper and lower boundaries of noctilucent clouds. Størmer (1933, 1935) has determined from his observations the height of the earth's shadow at the position *B* of the upper edge of the clouds. Although he neglected refraction he in this way obtains a close approximation to *h*, with results varying from 29 to about 50 km. Only the minimum values are likely to be significant, because on some occasions there may be no clouds extending into the position *B*; nevertheless in six measurements made on each of two occasions Størmer obtains values which rather consistently lie between 30 and 45 km. This astonishing result implies either that there is very substantial attenuation of sunlight even well in the stratosphere, or that the clouds do not quite extend to the position of the earth's shadow.

I have calculated values of *h* for the rays which illuminated the nearest and furthermost details of the clouds observed at Torsta, assuming the cloud height to be 80 km and taking into account refraction, with the results shown in Table 1. These confirm Størmer's values, and suggest that only rarely are the nearest details in a position corresponding to a value of *h* smaller than 30 km. The values of *h*

**Table 1. Least height *h* above the ground of rays illuminating nearest and farthest details of noctilucent clouds**

| Date | Time | Sun's depression, deg. | Azimuth and Elevation of clouds, deg. | *h*, km |
|---|---|---|---|---|
| Nearest details: | | | | |
| 18.7.54 | 2400 | 5.7 | 360,30 | 54 |
| 21.7.54 | 0035 | 6.0 | 90 | 45 |
| 16.8.54 | 2335 | 12.8 | 330,07 | 12 |
| 19.7.55 | 0005 | 5.7 | 180,40 | 43 |
| 23.7.55 | 2400 | 6.8 | 90 | 34 |
| 27.7.55 | 2325 | 7.5 | 360,07.5 | 69 |
| 31.7.55 | 2330 | 8.5 | 360,10 | 55 |
| 9.8.55 | 2350 | 10.8 | 040,05 | 37 |
| 10.8.55 | 0025 | 11.0 | 031,06.3 | 34 |
| | 0040 | 10.7[1] | 035,13.4 | 10 |
| 13.8.55 | 0040 | 11.4 | 033,06.3 | 32 |
| | 0115 | 10.6 | 015,09.9 | 30 |
| | 0140 | 9.7 | 007,12.8 | 29 |
| | 0215 | 8.0 | 353,10.0 | 45 |
| Farthest details: | | | | |
| 19.7.54 | 0025 | 5.7 | 360,04 | 12 |
| 21.7.54 | 0015 | 6.0 | 340,06 | 16 |
| 16.8.54 | 2335 | 12.8 | 320,02.2 | 55 |
| 19.7.55 | 0005 | 5.7 | 360,10 | 16 |
| 27.7.55 | 2330 | 7.5 | 360,03.0 | 18 |
| 31.7.55 | 2330 | 8.5 | 020,01.7 | 23 |
| 9.8.55 | 2350 | 10.8 | 023,03.3 | 38 |
| 10.8.55 | 0025 | 11.0 | 023,02.9 | 37 |
| | 0040 | 10.7 | 024,03.2 | 36 |
| 13.8.55 | 0040 | 11.4 | 006,01.2 | 32 |
| | 0115 | 10.6 | 360,01.7 | 31 |
| | 0140 | 9.7 | 007,01.8 | 26 |
| | 0215 | 8.0 | 344,01.6 | 25 |
| | | | 008,04.7 | 25 |

[1] (very faint)

corresponding to the farthermost visible details seem significantly less, and bearing in mind that the minimum values are likely to be more significant, I have used a value of 16 km in the following calculations. It must be supposed, however, that the appropriate value may often be twice as much, with the effect of restricting the visible area of the clouds. It should be noted that the scattering of indirect light which limits the visibility of the clouds is that which occurs in the lower stratosphere, and that in the troposphere only attenuation by concentrations of haze or obscuration by clouds are likely to interfere with observations.

Fig. 7 shows the relations between the sun's apparent depression $\alpha$ and the angles *a* (for a value of $h = 16$ km) and *b* ($h = 30$ km), and Fig. 8 shows the relation between the distance of noctilucent clouds at 80 km and their angular elevation, used in the derivation of Fig. 7. This diagram shows that the clouds are likely to be visible only when the sun lies between about 5° and 16° below the horizon.

## 4. Variation of conditions of viewing according to latitude, season, and time of day

The true depression $-\gamma$ of the sun is a function of latitude, $\phi$, sun's declination $\delta$, and apparent solar time, $\tau$, according to the equation:

$$\sin \gamma = \sin \phi \sin \delta + \cos \phi \cos \delta \cos \tau \qquad (1)$$

For a given latitude a diagram can be constructed with apparent solar time as ordinate

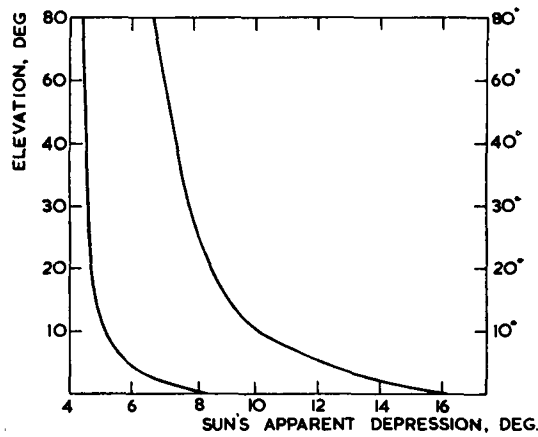


Fig. 7. Angular elevation of upper and lower borders of region, above sun's azimuth, in which noctilucent clouds may be seen, as a function of the apparent depression of the sun.

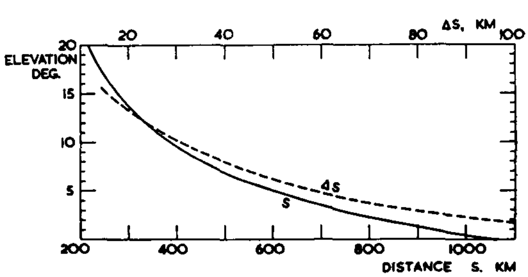


Fig. 8. Distance S of noctilucent clouds 80 km above the level of the observer, as a function of elevation above the horizon, and the change ΔS in S due to a change of 1° in the elevation.

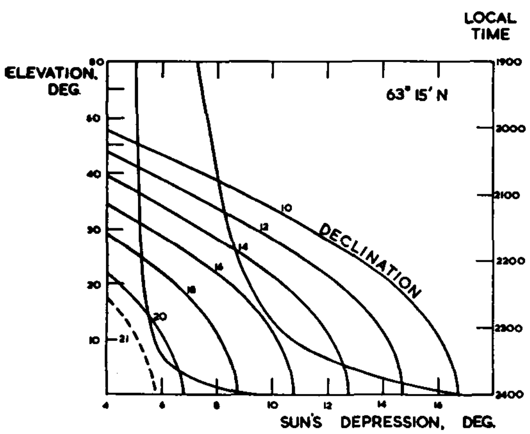


Fig. 9. Diagram for finding upper and lower border of noctilucent clouds on sun's azimuth for an observer in latitude 63° 15′ N, as a function of the sun's true depression (assuming 0.6° of refraction at the horizon), or as a function of local time and sun's declination.

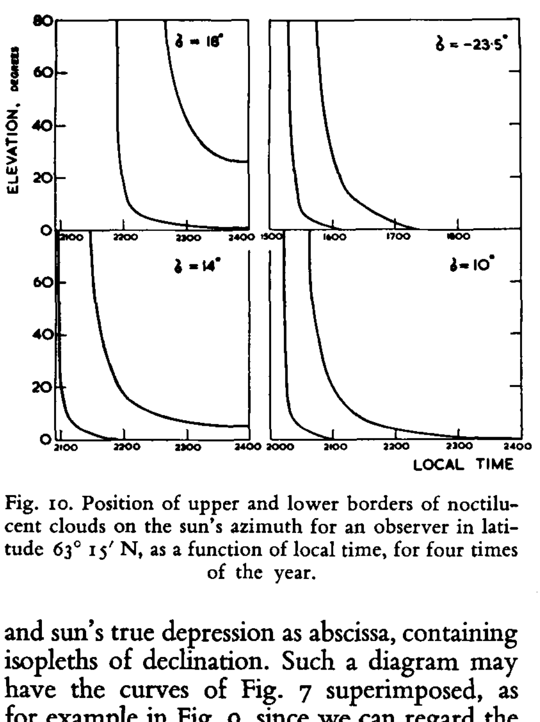


Fig. 10. Position of upper and lower borders of noctilucent clouds on the sun's azimuth for an observer in latitude 63° 15′ N, as a function of local time, for four times of the year.

and sun's true depression as abscissa, containing isopleths of declination. Such a diagram may have the curves of Fig. 7 superimposed, as for example in Fig. 9, since we can regard the true sun's depression to exceed the apparent by 0.6°, and it can then be used to find the elevations in the vertical through the sun where noctilucent clouds should be sought, as a function of season and apparent solar time. (The apparent solar time is found from the following relation: apparent solar time = G. M. T. + (4 min. for each degree of longitude east of Greenwich)—(the equation of time). Values of $\delta$ and of the equation of time are tabulated for each day of the year in the Nautical Almanac.) The diagram is used by determining the point corresponding to a given declination and time; the vertical through this point intersects the *a*, *b*- curves in two points defining the lower and upper borders of the part of the sky above the sun in which noctilucent clouds may be seen.

The form of the *a*—*b* curves in Fig. 7 implies that in the vertical above the sun the upper and lower borders of the visible area of clouds pass rapidly through the zenith, but descend rather slowly as they approach the horizon. This is illustrated in Fig. 10, which shows the position of these borders with time of day for several seasons in latitude 63° 15′ N. These diagrams also show the most favourable season for viewing to be near mid-summer.

As a measure of an observer's opportunity of seeing noctilucent clouds it is reasonable to consider the total period during which a cloud at an elevation of 10° on the sun's azimuth is suitably illuminated. From Fig. 9 it is seen that during this period the true depression of the sun changes from 5.75 to 10.7°; the period can therefore be calculated from eq. (1) by inserting these values of $-y$, for particular latitudes and seasons. In this way we derive Fig. 11, which shows the length of the viewing period (before midnight) throughout the year in latitude 63° 15′ N. Over most of the year the period is nearly an hour, rising sharply to a peak of nearly three hours at a declination of 15°, and abruptly falling to zero at declinations exceeding 21°, corresponding to one month before and after the summer solstice, when the sun even at midnight is less than 5.75° below the horizon. At rather lower latitudes mid-summer is the most favourable viewing season, as shown in Fig. 12. In this diagram the curves show the variation of the viewing period (before midnight) for two months after the summer solstice, in latitudes 63° 15′ N, 56° N, 50° N and 30° N. In the lower latitudes the period changes little throughout the year, and amounts to between a half and three quarters of an hour.

Such a period must be considered ample for an attentive observer to detect the clouds if they are present. Nevertheless according to

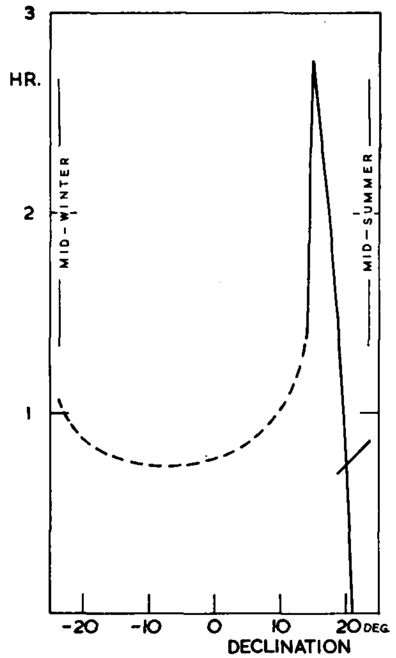


Fig. 11. Period before midnight during which noctilucent clouds on the sun's azimuth and at an elevation of 10° above the horizon are continuously visible, as a function of the sun's declination. The long curve is for an observer in latitude 63° 15′ N, and is drawn continuously over the season in which the clouds have been seen from Torsta. The short intersecting curve is the corresponding one for the latitude 50° N, and extends over the season in which the clouds have been reported from places between the latitudes 49° and 52° N.

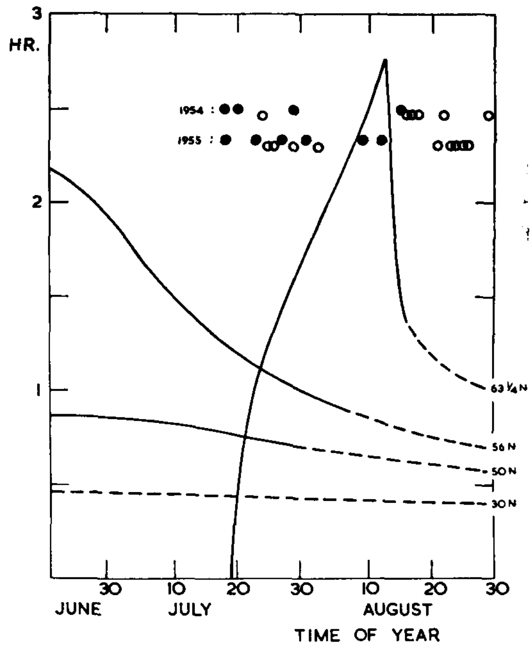


Fig. 12. Period before midnight during which noctilucent clouds on the sun's azimuth and at an elevation of 10° above the horizon are continuously visible, as a function of time of year. The continuous parts of the curves show the season during which the clouds have been observed at Torsta ($63^{1}/_{4}$° N), Edinburgh (56° N), and at places between 49 and 52° N (50° N). The circles in the upper part of the diagram show the occasions when the clouds have been seen at Torsta (blocked-in circles), or not seen under apparently favourable viewing conditions (open circles).

Vestine the clouds have never been reported from latitudes lower than 45°; apparently the reports from as far south as this were made in Russia on an exceptional occasion, that of the fall of the Great Siberian Meteorite, in 1908, which is further discussed below. If this occasion is excluded it seems that there are very few reports from south of 50° N, and if we consider also that the clouds seen in places near this latitude have rarely extended more than a few degrees above the northern horizon, then the presumption is strong that noctilucent clouds do not exist in latitudes lower than about 55°.

In Figs. 11 and 12 the curves are drawn as continuous lines over the season within which reports of the clouds have been made. The Torsta observations were used for the curve corresponding to latitude 63° 15′ N, Mr. Paton's (Edinburgh) observations for 56° N, and all those listed by Vestine from places between 49 and 52 1/2° N for the curve appropriate to 50° N. Evidently the observations of the clouds at Torsta and at Edinburgh cease when the viewing conditions, judged on this criterion, are still more favourable than ever occur in rather lower latitudes. At Torsta on clear days in mid-winter clouds 10° above the horizon would be visible for a whole hour in the morning and again in the afternoon, at times when they could hardly escape attention. It may also be significant that the clouds have been seen at Torsta rather later in the year than has ever been found at Edinburgh. On the basis of this evidence I conclude tentatively that the clouds, in addition to occurring mainly after rather than before mid-summer, are restricted in southern extent to about latitude 55° in July and to about 70° N in the latter part of August, and do not occur in these regions in seasons other than the summer. These circumstances suggest some meteorological control of their appearance.

## 5. The size and concentration of the particles in noctilucent clouds

The noticeable degree of polarization in the light from noctilucent clouds indicates that

$$\pi r < 0.5\ \mu,$$

where $r$ is the predominant radius of the particles in the clouds. On the other hand, the scattering of light by the particles cannot be that which occurs in the Rayleigh regime, for if so the clouds would appear blue. They are observed to be white, although sometimes tinged with blue. This shows that

$$\pi r > 0.025\ \mu,$$

and combining these indications we have

$$10^{-6} < r < 10^{-5}\ \text{cm}.$$

In Sweden it was found that when the sun was about 6° below the horizon, the exposure needed to photograph the clouds on fine-grain panchromatic film (speed 28° Sch.) was about 5 sec at $f$ 5.6; if, however, the sun's depression was about 12°, the exposure needed was about 200 sec. It can be assumed, then, that an exposure of about 100 sec at this aperture is a measure of the brightness of typical clouds. This information allows the likely concentration of the cloud particles to be inferred, in the following manner.

It is assumed that the scattering particles are disposed in a layer of depth $h$, illuminated by the sun at an angle of incidence $\Theta$. If a fraction $f(h)$, $\ll 1$, is scattered from a vertically incident solar beam, then a fraction $f(h)$ sec $\Theta$ is scattered from the beam incident at an angle $\Theta$. Then the scattering fom a unit area of the cloud surface is independent of $\Theta$ and equal to $s \cdot f(h)$, where $s$ is the flux/cm² in the solar beam. If the particles are small, half of the scattering is forward, and half backward.

If the cloud surface is assumed to scatter according to Lambert's law, its brightness $B_c$ is independent of the direction of view and

$$B_c \sim s \cdot f(h)/2.$$

Over a surface of snow, or some other nearly perfect scatterer, which is illuminated vertically, the fraction of the incident beam scattered backwards is unity; thus if $B_s$ is its brightness, $B_c \sim s$, and

$$B_c/B_s = f(h)/2.$$

We now suppose that the ratio of the brightness of these surfaces is given by the inverse ratio of the exposures needed to photograph them, which from our experience is about $10^{-6}$, corresponding to exposures of 100 sec at $f$ 5.6 and 1/200 sec at $f$ 32, respectively.

The scattering cross-section of particles in the size range inferred above is approximately equal to their geometrical cross-section $\pi r^2$, so that if $n$ is their concentration we have

$$f(h) = hn\pi r^2 = 2 \times 10^{-6}.$$

The depth $h$ of the layer occupied by noctilucent clouds is likely to be several km; for example, if the billows represent a convective process similar to that which produces the billows of tropospheric clouds, the depth of the layer involved is approximately $d/2.7$ (SCORER, 1951), where $d$ is the separation of the billows, observed to be about 10 km. The billows, therefore, are likely to occur in a layer about 4 km deep, while the denser and much broader streaks and bands are probably even thicker. If we assume a value of about 6 km for $h$, then

$$n h \pi r^2 = 2 \times 10^{-6}, \text{ and}$$
$$n \approx 10^{-12}/r^2, \text{ or}$$
$$n \approx 10^{-2}/\text{cm}^3 \text{ if } r = 10^{-5}\ \text{cm},$$
$$n \approx 1/\text{cm}^3 \text{ if } r = 10^{-6}\ \text{cm}.$$

The corresponding space-densities of the material, assuming a particle density of 2.5, would be $10^{-16}$ and $10^{-17}$ g/cm³, respectively. These estimates can be regarded as representative of average conditions, and as unlikely to be in error by more than one power of ten. It would be very desirable to make better estimates by accurate quantitative study of particular clouds.

## 6. The substance of noctilucent clouds

Noctilucent clouds may be true ice clouds, or their particles may be composed of some other material.

In the ozone layer, and at higher levels up to about 55 km, the saturated vapour pressure of water at the rather high temperatures encountered exceeds the air pressure, and a condensation of vapour is therefore impossible. At still higher levels, however, the temperature falls with increasing height, to reach a minimum at a kind of second tropopause at about 80 km, approximately the level of noctilucent clouds, and a condensation is possible there if the air is moist enough and the temperature sufficiently low. In the lower stratosphere of middle latitudes the air is practically always very dry, and water clouds are never observed apart from the exceptional wave clouds sometimes formed over the Norwegian and some other mountains in winter. The soundings of the British Meteorological Research Flight have shown that 3 to 5 km above the tropopause the frost-point tends to become constant at about $-115°$ F ($193°$ A), corresponding to a relative humidity of less than 1 % (MURGATROYD AND OTHERS, 1955). If such air from these levels were raised or stirred up to the 80 km level, the mixing ratio, of order $10^{-3}$ g/kg, would be preserved, and the vapour density would become about $3 \times 10^{-14}$ g/cm$^3$ (at 80 km the air density is about $3 \times 10^{-8}$ g/cm$^3$ (WHIPPLE, 1952)). If this value is to exceed the saturated vapour density over ice, so that a condensation could occur, then the air temperature would need to be lower than about $145°$ A (accepting a value of the saturated vapour density extrapolated to this temperature from a formula regarded as thoroughly reliable in the range $173°$ to $273°$ A: O.M.I., 1951). Temperatures at the 80 km level have been deduced from instruments carried on rockets and from observations of meteors, and although they cannot be regarded as particularly accurate and were obtained mainly in latitudes lower than those in which the clouds are seen, they suggest a mean temperature of $220°$ to $230°$ A. WEXLER (1950) considers $170°$ A as a likely minimum value, and at this temperature the saturated vapour density is about $10^{-9}$ g/cm$^3$. It must therefore be said that a condensation in the 80 km level could be expected only if the temperature there became abnormally low, or if the air were abnormally humid, containing a large proportion of water vapour; nevertheless if the clouds there are regarded as very rare phenomena, the possibility of their representing a condensation cannot quite be excluded on these grounds.

A further circumstance makes it seem improbable. The rapid changes of the internal details of the clouds and the presence of billows suggest that the layer in which the clouds occur is well stirred and has a strong lapse-rate; since the layer is a few km deep, the temperature in its upper parts must be twenty degrees or so below that in the lower part. As the saturated vapour pressure decreases very rapidly with temperature, the space-density of the condensate in a cloud extending through such a layer must be nearly the saturated vapour density at the lower surface, that is, at the condensation temperature. Even if this temperature were as low as $145°$ A, the corresponding mean density of the ice cloud would be of the order of $10^{-14}$ g/cm$^3$, two or three orders of magnitude greater than the values deduced from the optical properties of the clouds.

Finally, the deduced concentrations of the cloud particles suggest a nucleated rather than a homogeneous condensation, so that if the clouds are regarded as ice clouds it is still necessary to consider upon what nuclei the particles formed. It is therefore natural to consider seriously other theories of the constitution of the clouds, which attribute them to concentrations of dust derived from the earth's surface or from outer space.

## 7. Noctilucent clouds and volcanic explosions

It has been suggested that the intensity and prevalence of noctilucent clouds in the years 1885 to 1894 are to be related to the eruption of Krakatoa in August 1883. There is no doubt that vast quantities of dust are introduced into the lower stratosphere by eruptive clouds. The final paroxysmal eruptions of Krakatoa occurred on the night of August 26, but already in the early afternoon the captain of the British ship *Medea*, over 75 miles away, could see the enormous cloud over the volcano, and from angular measurements estimated the height of its top as 17 mi, and later as 21 mi (34 km) (Report of the Krakatoa eruption, 1888). Since the wind at these levels carried the cloud away from the ship (towards the west), there is no reason to suppose that these are overestimates. Dust from the eruptive cloud spread across the earth and within three months was visible in western Europe as a tenuous layer even in full daylight, which produced spectacular twilight phenomena. Estimates of the height of this dust cloud, based on the sun's depression when the red glow faded from the cloud, varied between about 15 and 30 km, the higher values being obtained mainly in the early history of the cloud, and the lower values after some months; amongst the observers was Jesse, who found mean heights of 12—15 km, later becoming 10 km.

Similar, though less dense clouds of dust were recently observed at such heights by aircraft over western Europe in July and August 1953 (JACOBS 1953), following an eruption in Alaska, and again in April and May of 1955, following an eruption in Kamchatka (BULL and JAMES, 1956). The appearance of the clouds and estimates of their height were also recorded by ground observers (LUDLAM, unpublished). It therefore seems likely that dust from volcanoes is injected mainly into the lower stratosphere, but it must be supposed that a sufficient proportion to account for the appearance of noctilucent clouds could become diffused up to much higher levels.

It is remarkable that the first observations of noctilucent clouds in the years 1885—1894 were not made until 2 years after the arrival of the volcanic cloud in Europe, and Vestine points out that the period 1880—1887 was one of strikingly frequent and brilliant displays of comets and meteors, and that the great eruption of Katmai, in 1912, was not followed by any increase in the frequency of reports of noctilucent clouds. On the other hand, SPANGENBERG (1949) has tried to associate more frequent reports in the years 1932—1935 with an eruption in the Cordilleras in 1932, which threw up a cloud to 25 km. However, major volcanic eruptions occur sufficiently often for some to lie within any chosen period, and the reports of noctilucent clouds are made so unsystematically and depend so much on favourable weather in a particular short season, that it is hardly surprising no close relation can be demonstrated between volcanic activity and the occurrence of the clouds.

## 8. Noctilucent clouds and meteor showers

On the morning of June 30, 1908, a great meteorite fell in Siberia; its mass has been estimated at some tens of thousands of tons, and the explosion it produced was recorded by barographs in England. During the same night an unusually brilliant display of noctilucent clouds was reported by many observers in Russia, Sweden, Denmark, Germany and England. G. A. Clarke, at Aberdeen, observed the sudden arrival of the tenuous clouds, accompanied by a marked brightening of the twilight, about two hours after sunset. From this observation WHIPPLE (1930) deduced the eastward speed of the cloud movement to have been about 85 m/sec, supposing the cloud to have originated in the trail of the meteorite. Apparently it was on this exceptional occasion that noctilucent clouds were reported (over Russia) from as far south as latitude 45° N (VESTINE, 1934); no references to the clouds or to unusual twilight brightness could be found in the meteorological logs in the U.S.A., and no such reports were made in southern Europe.

A witness of the Great Siberian Meteorite said that it left in the atmosphere 'a light bluish trail', and the smaller streaks left by meteors large enough to be seen in daylight also have the pale silvery colour which is characteristic of noctilucent clouds; evidently, therefore, the particles in meteor trails have about the size of those composing the clouds. This conclusion is supported by the work of FESSENKOV (1949), who has discussed the properties of the trail left by another large meteorite, of estimated mass a few hundred tons, which also fell in Siberia, on 12 February 1947. Broken material was found in small craters, and with the help of mine detectors many small pieces, including a multitude of spheres of radii 15—20 $\mu$ produced by thin sprays of solidifying iron, were found in the soil. At first the trail left in the atmosphere was about 1.5 km in diameter, and was so dense as to obscure the sun, but soon afterwards, as it diffused, the sun shone through as a red disc. The particles were therefore noticeably more transparent to red than to blue light. From these observations Fessenkov deduces that the diameter of the particles must have been less than $10^{-5}$ cm, and that their concentration in the original trail was about $7 \times 10^5/\text{cm}^3$; since the total volume of the trail was originally about 70 $\text{km}^3$, it contained nearly 200 tons of iron. If the particles had diameters considerably smaller than $10^{-5}$ cm, these figures for the space density and total mass would be substantially increased. Since if noctilucent clouds are supposed to contain particles of diameter $10^{-5}$ cm their concentration would be about $10^{-2}/cm^3$, such a trail could diffuse horizontally to a diameter of 7,000 km before the mean particle concentration fell below that inferred for noctilucent clouds. Although the denser parts of a large meteorite trail lie below the 80 km level, clearly such trails could form a significant source of the substance of noctilucent clouds, divided into particles of the appropriate size. The particles are presumably produced by condensation of material boiling away from the incandescent meteorite, and perhaps also by the crumbling of its substance into the component cosmic particles. The much larger spherules sometimes found are drips from the molten but unvaporized parts of meteorites which reach the ground, and characteristically have radii of some tens to hundreds of microns.

Meteorites of the great size of those discussed above are very infrequent. Recently BOWEN (1953) has claimed that there is a very close relation between the occurrence of noctilucent clouds and recurrent meteor showers. Bowen compared the dates of the prominent annual meteor showers of June and July, according to LOVELL and CLEGG (1952), with the dates of maximum frequency of reports of noctilucent clouds, according to the diagram of VESTINE (1934) (Fig. 4). This diagram contains two curves, one of which shows, for reports collected by Vestine from the period 1885—1933, the total number of years in which reports have been made on particular dates, and the other of which shows the total number of reports on particular dates. The latter curve was alone considered by Bowen; it has several peaks which in seven cases out of eight correspond to or precede by 1 or 2 days the dates quoted for the prominent meteor showers. Some authors have since supposed that in this way Bowen has established a relation between the two phenomena. However, WHIPPLE and HAWKINS (1956) state that the dates of the principal meteor streams used by Bowen are inaccurate, and that when more modern data are used the only notable coincidence with the dates of the maxima on Vestine's curve occurs on June 30, corresponding to a weak meteor stream. On this date Vestine's curve indicates 17 reports, which an examination of his lists shows to contain probably 12 from the occasion of the fall of the Great Siberian Meteorite on June 30, 1908. Thus there is good reason to discount even this coincidence. Nor is the correspondence improved by considering Vestine's curve which shows the number of years, rather than the number of observers, when the clouds have been recorded, which might be regarded as the more appropriate curve to discuss. On this curve 5 occasions, and one the other curve 7 reports, would be sufficient to produce a peak, so that the significance of those shown in the diagram must be regarded as very doubtful. Moreover, it must be realized that the observations which it summarizes were made over a large range of latitudes, within which the viewing conditions vary considerably from place to place on the same date. For example, even excluding the peak of June 30, Vestine's diagram shows that the observations are notably most frequent about the end of June; however, if a sufficient number of observations from high latitudes were included, this maximum would disappear, for near midsummer the clouds there are invisible, even if present. Evidently only an extended series of observations in one locality or latitude, including reports of occasions when no clouds could be seen in apparently favourable viewing conditions, can provide a satisfactory basis for relating the occurrence of the clouds to any other phenomena.

The observations made in Sweden (Fig. 12) suggest that within the best viewing season there are clear nights when the clouds are definitely not observed, separating the occasions when they are seen. The occurrences are not obviously related to any meteor streams; the principal stream at this season is that of the Perseids, which begin to arrive about August 6 and reach a maximum between about August 10 and 14. This meteor shower, in common with the others, is spread over a few days, and cannot be associated with a particular date (LOVELL, 1954). On the basis of the available evidence, therefore, it cannot be concluded that there is any clear relation between the occurrence of noctilucent clouds and the arrival of meteor showers.

## 9. The accretion of interplanetary particles by the earth

The rate of arrival of visible meteors during the major showers rises by only a factor of about 2 above that of the sporadic meteors (LOVELL, 1954), so that the showers can be neglected in comparison with the sporadic meteors as a possible source of the material of noctilucent clouds.

Visible meteors are produced by particles of mainly stony or iron-nickel composition, and of radius exceeding about 100 $\mu$, which enter the atmosphere at speeds of some tens of km/sec and become incandescent. Particles smaller than this are also fused, but emit too little light to be visible to the unaided eye, while particles of radius less than a few microns are decelerated in the atmosphere without reaching melting-temperatures (1 200—1 700°A) (WHIPPLE, 1950, 1951). The larger meteorites leave trails which often are visible for some minutes or even longer as a dark smoke, or, under favourable lighting, as pale streaks closely resembling the noctilucent clouds. It seems, also, that many meteors, particularly the fainter ones, have a low density (0.2 to 1.0 g/cm$^3$), and disintegrate under aerodynamic pressure and heating by a progressive crumbling (JACCHIA, 1955), so that they are regarded as porous and fragile structures, probably consisting of mineral fragments embedded in ices of such substances as $H_2O$, $CO_2$ and $NH_3$. However, particles of the size ($10^{-5}$ to $10^{-6}$ cm) inferred to predominate in noctilucent clouds must be supposed to enter the atmosphere either directly with this size, or to be produced in the atmosphere by condensation of vapourized material in the wakes of meteorites having dimensions which exceed several microns. The visible paths of most meteors lie between heights of about 100 and 50 km above the ground, so that their condensation products are distributed over a layer extending somewhat above and below the level of noctilucent clouds.

The fall-speeds of small particles at these levels have been estimated by LINK (1950), using Stokes Law with Millikan's correction; he obtained values proportional to the particle radius $r$ and density $\delta$, and inversely proportional to the air density $\varrho$. At the 80 km level he found a fall speed of a few cm/sec for particles of radius $10^{-5}$ cm. On the other hand, the mean free path of the air molecules at this height is about 4 mm, and therefore so much greater than the particle sizes that it seems preferable to use Knudsen's (1934, p. 33) empirical data for the resistance $K$ of rarified air to the motion of a sphere. He measured $K$ in air at pressures extending down to 0.14 dyne/cm$^2$, and expressed his results by a formula

$$K = 6\pi\eta r v(1 + 0.683\varkappa + 0.354\varkappa/e^{1.845\varkappa})^{-1},$$

where $\eta$ is the coefficient of viscosity and $\varkappa = \lambda/r$, $\lambda$ being the mean free path obtained from the expression

$$\lambda = \sqrt{(\pi/8)}\eta/0.30967p\sqrt{\varrho_1},$$

where $p$ is the pressure and $\varrho_1$ is the density at 1 dyne/cm$^2$.

If $\varkappa \ll 1$ the formula reduces approximately to

$$K = 6\pi\eta r v\varkappa, \text{ and hence}$$

$$v = \varkappa v_s,$$

where $v_s$ is the Stokes Law fall-speed.

At the 80 km level we may assume $T = 200°A$, $\eta = 1.3 \times 10^{-4}$ g/cm sec, and $p = 17$ dynes/cm$^2$; with $\varrho_1 = 1.74 \times 10^{-9}$ g/cm$^3$ we then have $\lambda = 0.37$, and for particles of density 2.5 g/cm$^3$

$$v = 4.2 \times 10^6 r^2 \varkappa.$$

If $r = 10^{-5}$ cm, $x = 3.7 \times 10^4$ and $v = 16$ cm/sec.
If $r = 10^{-6}$ cm, $x = 3.7 \times 10^5$ and $v = 1.6$ cm/sec.

These estimates differ by less than 50% from values deduced from ordinary kinetic theory of gases (Witt, private communication).

These values incidentally lend some support to the upper size limit deduced for the particles of noctilucent clouds on optical grounds, for it seems inconceivable that the clouds could possess persistent identifiable details if the fall speeds of their particles reached values in m/sec.

Given these fall speeds and the inferred space-density of noctilucent clouds, we can compute the density in space of meteoritic material sufficient to provide the source of the clouds and compare this with the density believed to exist, since meteoritic material arrives from interplanetary space with speeds within the range of about 11 km/sec (the speed of fall due to the earth's gravitation) and about 70 m/sec (compounded of the earth's orbital speed about the sun and the speed of escape from the sun at the distance of the earth).

From the observed properties of visible meteors, the size distribution of the particles over the range of radii from about 50 $\mu$ to 0.5 cm can be inferred. On the basis of this size distribution law, extrapolated to include both smaller and larger meteorites, LOVELL (1954) estimates the annual accretion of meteoritic material by the earth to amount to about 500 tons, corresponding to an average density in interplanetary space of between $10^{-25}$ and $10^{-24}$ g/cm$^3$.

If material in the higher concentration were to enter the earth's atmosphere at 32 km/sec, and were wholly converted into particles of radius $10^{-6}$ or $10^{-5}$ cm, settling at their terminal speeds, its density at the 80 km level would become $2.10^{-18}$ or $2.10^{-19}$ g/cm$^3$, respectively. If these values are compared with those deduced for noctilucent clouds composed of such particles (about $10^{-17}$ and $10^{-16}$ g/cm$^3$, respectively), we see that they are smaller by nearly one to three orders of magnitude. Although the magnitudes of the compared quantities are each liable to be in error by as much as one power of ten, the values obtained for the density of the meteoritic material are likely to be too high rather than too low. The available evidence therefore cannot be considered with any confidence to present ordinary meteorites as a sufficient source of the material of noctilucent clouds. Other possible sources must also be considered.

### 10. The zodical light cloud

There is some evidence that in the meteor showers the numbers of very small particles are even less than indicated by extrapolation of the size distribution law amongst the visible meteors. One probable reason is that the small particles in meteorite swarms become separated from the larger. On the other hand there is also reason to suppose that the accretion of sporadic micrometeorites, too small to produce visible meteors, is very much greater than this law would suggest. This evidence comes mainly from the study of the sun's outer corona and the zodiacal light.

The zodiacal light is a wedge of diffuse, feeble light pointing upwards from the horizon along the position of the ecliptic during the dark hours, when the depression of the sun exceeds about 17°; in intensity it is comparable with the light of the Milky Way (see, e.g., MINNAERT, 1940). It can be seen easily on clear, moonless nights in low latitudes, where it is always steeply inclined to the horizon, but it is more difficult to observe in middle and high latitudes.

The intensity of the light increases towards the sun, and VAN DE HULST (1947) suggested that this increase extends continuously into the outer corona of the sun. The light of the corona is composed of two parts, a *K*-component which is highly polarized and contains no spectral lines, and an *F*-component which has little or no polarization and contains Fraunhofer lines. The *K*-component decreases very rapidly in intensity away from the sun, but the *F*-component intensity decreases more slowly, and dominates the outer corona. The zodiacal light also contains the Fraunhofer lines, and both it and the *F*-component of the corona are attributed to scattering and diffraction of sunlight by a cloud of interplanetary particles disposed as a rather shallow disc lying in the plane of the ecliptic. At the time of van de Hulst's suggestion the only measurements available were those of the intensity of the zodiacal light in the range of solar elongations from 40 to 180°, and those of the intensity of the F-component of the corona, out to about 1° 20′ from the sun. Recently, however, RENSE and others (1953) have measured intensities in the range of solar elongations from 5 to 13° (from an aircraft flying at 10 km during a total solar eclipse); their results confirm van de Hulst's suggestion, forming a smooth link between the measurements of the corona and the zodiacal light.

ALLEN (1946) showed that the intensity of the outer corona and the zodiacal light, and also the distribution of intensity with solar distance and wavelength, could be explained by the diffraction and scattering of sunlight from particles of radius about $10^{-3}$ cm, whose concentration, assumed inversely proportional to the distance from the sun, is about $3 \times 10^{-15}$/cm$^3$ at the distance of the earth, representing a space density of about $6 \times 10^{-23}$ g/cm$^3$. His measurements in the outer corona showed no indication of Rayleigh scattering such as would be produced by much smaller particles; on the contrary, there was some evidence of a reddening of the *F*-component near the sun. Recently BLACKWELL (1952) found a considerably greater increase towards the sun in the infra-red than in the violet, indicating the presence of particles of radius larger than about $2 \times 10^{-3}$ cm. Van de Hulst assumed a size distribution of the scattering particles similar to that of meteoritic material, and a uniform concentration of the particles, considering that the increase of intensity towards the sun is due to the form of the scattering function, rather than to changes in the particle concentration. Since part of his scattering and diffracting material is distributed in larger, less efficient particles, he deduces a space-density, of $5 \times 10^{-21}$ g/cm$^3$, which is considerably greater than the value of about $6 \times 10^{-23}$ g/cm$^3$ corresponding to Allen's result. If van de Hulst's figure is accepted as probably more realistic and the thickness of the dust cloud perpendicular to the plane of the ecliptic is about 0.1 AU, the total mass of the particles within the earth's orbit becomes $5 \times 10^{12}$ tons, or about $10^{-9}$ times the mass of the earth.

It is interesting to consider the origin and fate of this material. WHIPPLE (1955) considers four possible sources, of which only asteroidal collisions and cometary disintegrations appear significant. Of the particles which are produced in these ways those of radius less than about $2 \times 10^{-5}$ cm are expelled from the solar system by the radiation pressure of sunlight. Larger particles spiral towards the sun under the Poynting-Robertson effect (see, for example, WYATT and WHIPPLE, 1950), at a cosmically rapid rate. Whipple deduces that to balance this loss and to maintain the outer corona and zodiacal light at their present brightness a source of about 1 ton/sec of meteoritic material is required, and quotes Fessenkov as having previously arrived at a similar conclusion by a less general theory. This figure may be compared with PIOTROWSKI's (1953) estimate of between 20 and 600 tons/sec of pulverized material which is produced by collisions between the bodies in the asteroidal belt. Probably, however, the bulk of this material is in the form of rather large fragments. According to WHIPPLE (1954) most of the small particles producing photographic meteors are derived from cometary debris (according to Whipple's model, a comet nucleus is composed of solid particles embedded in "ices" of substances such as $H_2O$, $NH_3$ and $CO_2$, which are partially vapourized on approach to the sun, so that the comet progressively disintegrates during successive orbits). Whipple estimates that particles in the debris of size greater than $10^{-2}$ cm are exposed to a high probability of destructive collisions (particles of size larger than this are also unlikely to escape accretion with Jupiter during their passage of its orbit, according to ÖPIK, 1951), but that the cometary source of material for the zodiacal light cloud could readily amount to about 3 tons/sec, which is sufficient to sustain the cloud.

The available astronomical evidence, though rather tenuous, is thus consistent with the presence of an interplanetary dust cloud, in which the particles have radii mainly in the range $10^{-3}$ to $10^{-2}$ cm, and whose concentration corresponds to a space density of about $5 \times 10^{-21}$ g/cm$^3$. Such particles entering the atmosphere would be expected to produce very faint telescopic meteors in numbers about $10^4$ greater than would be deduced from extrapolation of the size distribution law for meteors visible to the unaided eye. So far this great increase has not been demonstrated, but indirect evidence does suggest that the previously accepted accretion rates of meteoritic material are too small. For example, the impacts of small particles (of size a few microns) upon high-altitude rockets are greater than was anticipated (see WHIPPLE, 1952, p. 22), and so also is the abundance of iron and nickel in deep-sea sediments (PETTERSON and ROTSCHI, 1950; the significance of these deposits has been questioned, however: see, for example, ÖPIK, 1955), and the rate at which magnetic material of presumably meteoritic origin falls to the ground (THOMSEN, 1953; here also, however, the origin of the material is not certain: SCHAEFER, 1955, attributes most of it to industry).

If the estimate of the composition of the zodiacal light cloud is accepted, and the particles are supposed to evaporate in the high atmosphere and subsequently condense into particles of radius $10^{-6}$ or $10^{-5}$ cm, the space densities of these particles at the 80 km level estimated on the previous reasoning would be as follows:

for $r = 10^{-6}$ cm, space density $= 10^{-14}$ g/cm$^3$;
for $r = 10^{-5}$ cm, space density $= 10^{-15}$ g/cm$^3$.

Both these values exceed the space densities inferred for noctilucent clouds ($10^{-17}$ and $10^{-16}$ g/cm$^3$, respectively). Since we have used van de Hulst's rather than Allen's estimate of the density of the zodiacal light cloud, and since a proportion of its particles would be small enough to escape boiling in the atmosphere, the values are likely to be too high rather than too small. Nevertheless it may be concluded that interplanetary dust is a possible source of the material of noctilucent clouds. It also seems possible that if this dust contained a substantial proportion of iron, or if it were charged by solar radiation, it might enter the earth's atmosphere preferentially in high latitudes, thereby locally increasing in concentration.

## 11. Dust in the high atmosphere

Other evidence is available to suggest the presence of considerable quantities of dust in the stratosphere. For example, observations of the earth's shadow during lunar eclipses suggest that the atmosphere contains obscuring matter to levels well within the stratosphere, which LINK (1950) has proposed to be meteoritic dust extending from a height of 50 to 100 km down to the ground. Photographs of Mars and of Venus give ultra-violet images greater, by 3—6% and 2% respectively, than the infra-red images. According to LINK (1950), Fessenkov and Menzel have proved that an explanation in terms of molecular diffusion is not possible, and the discrepancies are tentatively explained by the presence of similar meteoritic dust layers. The smaller gravitational constants on these planets lead to a level of meteorite fusing which is farther above the ground than on earth, favouring a deeper dust layer. On the other hand on Jupiter, for example, the layer could be only some tens of km deep and could not produce noticeable effects. BOUSKA and SVESTKA (1950) have collected measurements of the size of the earth's shadow on the moon during lunar eclipses; the mean from 33 observations shows the shadow to be larger than the earth by about 2%, individual values varying from 1.7 to 2.5%. Bouska and Svestka were unable to find any significant relation between the enlargement and the declination of the sun or moon, the parallax of the sun, or the solar activity, but do claim a correlation with the occurrence of meteor showers.

From an analysis of observations of solar intensity at Mount Wilson in the period 1908—1920, ZACHAROV (1952) deduces an annual increase in atmospheric absorption by a few per cent over about four weeks including the latter half of August, which he associates with the arrival of the Perseids in

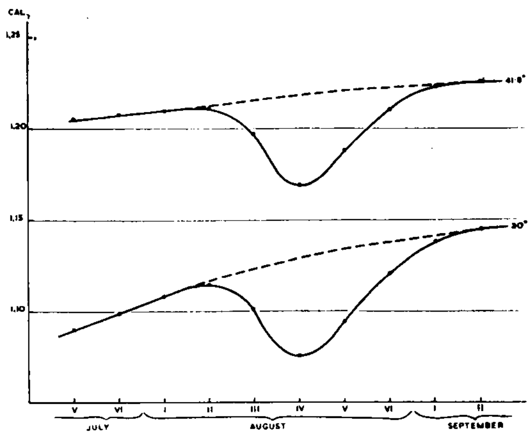


Fig. 13. Average solar intensity for each 5 days for a sun's elevation of 30° (lower curve) and 41.8° (upper curve), from 3282 and 2239 observations made at Yakutsk (1931—42), Pavlovsk (1913—37), Kursk (1928—35), Rostov (1930—37), Tbilissi (1928—37), Tashkent (1926—37) and Samarkand (1931—37). After Kalitin (1944).

mid-August. KALITIN (1944) showed that a similar decrease in the solar intensity at the same time of year is evident in the actinometric measurements of a number of widely-separated stations in Russia (Fig. 13); the coincidence is extraordinary. Presuming the effect is produced by the entry of a dust cloud into the atmosphere LINK (1955) infers the particle radius to be about $10^{-5}$ cm, and that the dust arrives at about the rate deduced above for accretion with the zodiacal light cloud. However, since the optical density of such a cloud would be several orders of magnitude greater than that of noctilucent clouds, it seems remarkable that its annual arrival is not a visible and celebrated event. Dust clouds from the catastrophic eruptions of Krakatoa (1883), M. Pelée (1902) and Katmai (1912), produced more prolonged decreases in solar intensity of about the same amount, but equally produced twilight phenomena of abnormal intensity (GRUNER and KLEINERT, 1927). Among these phenomena the purple light, which is attributed to particles, of dimensions a few microns, in the lower stratosphere, is especially enhanced in such disturbed periods. It may be significant that Fig. 14, taken from GRUNER and KLEINERT (1927), shows that abnormally intense purple lights are notably more frequent in August (when, however, convective lifting of dust from the ground is intense) than at other times of the year. Although, therefore, the evidence of Zacharov and Kalitin may need some other interpretation, their suggestions deserve further investigation. It may be noted that the recovery of the actinometer measurements after four weeks would suggest, if the disturbance is due to the arrival of a dust cloud, that the dust is substantially precipitated from the atmosphere within this period.

Direct confirmation of the presence of dust concentrations in the lower stratosphere comes from aircraft observations (e.g., PACKER and LOCK, 1950), and the photometric twilight observations of BIGG (1956) provide a strong indication of the persistent presence of concentrations of dust below the 80 km inversion. PENNDORF (1954) has assembled observations of particle concentration at various levels in the troposphere which show that the strong decrease with height ceases above about 4 km, and that thereafter the ratio between the concentration and the air density (a ratio we might expect to be preserved during the stirring of air to different levels) tends to increase with height, suggesting that at least a proportion of the particles in the upper troposphere have a source at a higher level. This result receives some support from the particle concentrations observed to occur in water clouds at the cirrus levels and in the spectacular mother-of-pearl clouds which occasionally form some 25 km above the Norwegian mountains. From coronae seen on freshly-forming cirrus I deduced that the concentration of ice crystals in the clouds is about $7/cm^3$ (LUDLAM, 1956). Since these clouds were formed in moderately strong updraughts this probably also represents practically the total concentration of condensation nuclei at these levels, in accord with the values inferred by Penndorf from flight measurements of solar radiation. Thus at the cirrus levels (about 10 km) the ratio $C = n/\varrho$, where $n$ is the concentration of small particles, has a value of about $7/5 \times 10^{-4}$/g, or $1.4 \times 10^4$/g. An observation by Størmer (1948) of the angular radius (15°) of the first red ring of a lunar corona in mother-of-pearl clouds, indicates spherical cloud particles of diameter about 2.5 $\mu$. At the temperature of these clouds (about −80° C) the concentration of water condensed during a rise of a few hundred metres above the condensation level amounts to about $10^{-10}$ g/cm³; if this is divided uniformly (as justified by the purity of the diffraction colours) amongst droplets of the appropriate radius, their concentration becomes about 1/cm³. Since these wave clouds are also produced in updraughts of at least moderate strength, we can equally assume this value to represent the total concentration of condensation nuclei. At 25 km the air density is approximately $6 \times 10^{-5}$ g/cm³, so that here the ratio $C$ becomes $1.6 \times 10^4$. At the level of the noctilucent clouds the air density is about $3 \times 10^{-8}$ g/cm³, and the inferred concentrations of particles vary from $10^{-2}$/cm³ (for a radius $10^{-5}$ cm) to 1/cm³ (radius $10^{-6}$ cm), corresponding to values of $C$ of $3 \times 10^5$ to $3 \times 10^7$. These values are rather higher than those deduced for the 10 km and 25 km levels, but the latter are so nearly the same and sufficiently close to the lower estimate for the 80 km level to encourage the view that the distribution of dust throughout the stratosphere is consistent with the existence of efficient mixing movements, and not inconsistent with a meteoritic source.

The occurrence of stirring motions in the lower stratosphere, where the air is statically very stable, and even in the upper stratosphere, where the air is stable for dry adiabatic ascent and condensation is impossible, is consistent with the uniform composition of the atmosphere but is difficult to reconcile with the usual thermodynamical arguments. RAKIPOVA (1947), however, has pointed out that dust

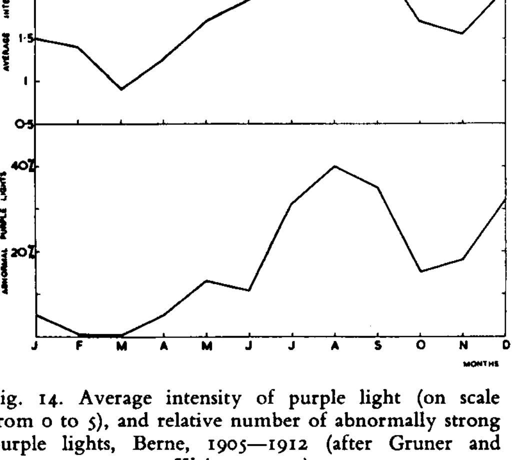


Fig. 14. Average intensity of purple light (on scale from 0 to 5), and relative number of abnormally strong purple lights, Berne, 1905—1912 (after Gruner and Kleinert, 1927).

clouds may be agencies for producing upward movement of air, by intercepting sufficient sunshine to become appreciably warmed. Air containing a dust cloud could thus commence to rise through a clearer environment, and, since it could carry its dust with it, may remain warmer and more buoyant than the surroundings. In these circumstances vertical movements are possible in statically stable, even isothermal atmospheres. Rakipova calculates the concentrations of dust particles required to produce significant effects and finds, for a radius $10^{-5}$ cm, a concentration of $1/cm^3$ at 80 km and about $10/cm^3$ at 30 km. These estimates may be obtained in the following way. At the 80 km level, for example, where the air density is $3 \times 10^{-8}$ $g/cm^3$, solar energy is intercepted by particles (assumed to have a low albedo) at the rate of about $N\pi r^2$ $cal/cm^3$ min, where $N$ is the concentration of particles of radius $r$, or about 200 $Nr^2$ $cal/cm^3$ hr. If this energy is communicated to the surrounding air it is sufficient to warm it at the rate of about $10^3$ $Nr^2/\varrho$ °C/hr, or about $2 \times 10^{10}$ $Nr^2$ °C/hr at the 80 km level, so that for $r = 10^{-5}$ cm and $N = 1/cm^3$ the rate of heating becomes appreciable and equivalent to a temperature rise of 2° C/hr. In a lapse-rate of 6° C/km this could correspond to a vertical movement of a km in 3 hours, at a speed of about 1/3 m/sec. Evidently for this process to be important the concentration of particles would need to be at least two orders of magnitude greater than that deduced to occur in noctilucent clouds ($10^{-2}/cm^3$ for $r = 10^{-5}$ cm). Since meteoritic material is unlikely to enter the atmosphere in a uniform stream, such high concentrations may sometimes occur in clouds which, if sunlit for a sufficient period, could by this means rise several km to the 80 km level. Above the base of the inversion there, the ascending speeds would be substantially reduced, and insufficient to lift the particles of the cloud, whose fall speeds amount to at least several cm/sec, so that the ascent would cease.

Particles which settle from the stratosphere into the troposphere aggregate with the condensation nuclei derived from the earth's surface and become involved in precipitation processes. The observations quoted above suggest that in the upper troposphere, where the total concentration of nuclei is about $10/cm^3$, solid meteoritic particles may often outnumber the nuclei of terrestrial origin. In the lower troposphere, where their concentration could not be significantly greater, they could comprise only an insignificant fraction of the condensation nuclei, although, in view of their silicate components, they might conceivably be an important source of freezing nuclei in clean air masses (on the other hand SCHAEFER, 1955, found that particles of magnetic dust collected in the open air, and particles from the smoke of a fused *metallic* meteorite, were not particularly effective ice nuclei).

## 12. The formation of noctilucent clouds

Some of the observations made in Sweden, particularly when noctilucent clouds developed after midnight, strongly suggested that the clouds formed within periods of several minutes in regions which previously, although apparently favourably illuminated, contained no discernible details. GRISHIN (1955) has remarked that the featureless "flare" can often be detected before the appearance of definite clouds, and thus also implies that clouds may form in the field of view, not necessarily simply arriving from places in which they already existed, or being revealed by improving viewing conditions.

The readiest interpretation of the formation in a restricted layer of clouds having definite details is in terms of a condensation process in air which is ascending or otherwise being chilled. However, we have already discussed difficulties in the way of this explanation. To reiterate, a condensation can occur only if the air were much moister or much colder than we have reason to expect, and even then the brightness of the clouds would suggest the condensation to be only partial, while the problem of accounting for the condensation nuclei would remain. If, moreover, the clouds were to appear by the growth of their particles, their first details might be expected to have a distinct blue colour which becomes steadily more white. Such a change of colour has only once been reported (PATON, 1954) and cannot be regarded as characteristic. Equally, then, it seems unlikely that the clouds become visible by a condensation (at vapour pressures below the saturation value) upon hygroscopic components of the nuclei.

If condensation of water vapour plays no part in the formation of the clouds, it must be considered how dust, probably present throughout the stratosphere, can become so disposed to produce distinct clouds which are always measured to be at a height of about 80 km. It seems likely that the formation of a *haze top* at the level of the inversion there is essential.

Pronounced haze tops are common in the troposphere, and are usually associated with inversions; in a layer of steep lapse-rates beneath the inversion particles of dust or other nuclei are stirred up from their sources near the ground, but above the base of the inversion stirring movements are suppressed by the strong static stability, and the concentrations of the particles are suddenly reduced by a factor of 10 to 100. Moreover, beneath the inversion the relative humidity increases with height, so that the size of the particles, which are all more or less hygroscopic, reaches a maximum at the haze top; immediately above, the air is usually very dry and the particles there are inappreciably swollen by condensation, so that the presence and distribution of water vapour are important in sharply defining the top of the haze layer. When wave motions disturb the layer, concentrations of haze become visible from below to an observer who looks along low angular elevations, for then adjacent lines of sight pass through layers of appreciably different optical thickness (Fig. 15). Patterns of dark haze billows are seen against a twilight background, or, if the haze top is still illuminated, bright billows are seen separated by darker spaces. Such billows are a feature of the dust cloud in the lower stratosphere, which cannot be seen overhead, but only at rather low elevations.

It is probable that the details of noctilucent clouds are produced in a similar way by disturbances in a haze top at the 80 km inversion.

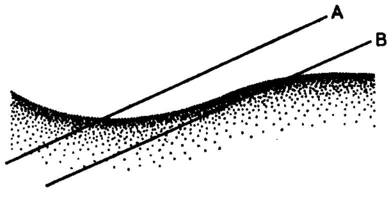


Fig. 15. A haze layer with a sharply-defined and undulating top presents visible features at low elevations, for there are marked differences in optical thickness along adjacent lines of sight, such as A, B.

It would not be surprising if all the sharply-defined clouds, which are naturally those selected for measurement, were necessarily associated with the haze top, and that other clouds are present which are considerably lower, but have more diffuse edges, and whose height is therefore never determined. The distinct "shadows" which sometimes seem to be cast by the denser cloud features (Fig. 1) almost certainly represent irregularities in a haze top, for the optical thickness of the clouds is so small that they could not possibly cast real shadows.

The production of a haze top at 80 km seems to require the ascent of dust clouds from below. WEXLER (1950) has discussed observational evidence of very steep, even superadiabatic lapse rates, in the layer between about 55 and 80 km. These arise during the daytime by solar heating of the ozone layer; although the ozone is concentrated at lower levels, the diurnal temperature change has a maximum at about 50 km (JOHNSON, 1953). It must be considered that the noctilucent clouds are observed only at a season and in latitudes such that a very prolonged heating of the ozone layer has occurred: at mid-summer in high latitudes the sun does not set on the top of the ozone layer. At this season, therefore, convective movements are particularly likely, and we may suppose that the ascending motions will occur preferentially in dust clouds. Consequently a concentration of dust may arise beneath the 80 km inversion, where the dusty air loses its buoyancy and spreads horizontally. If the dust has entered the stratosphere from below, as in eruptive clouds, a pronounced haze top is readily produced. If it has arrived from interplanetary space as the condensation product of fused meteors, it is not possible to assess the change of concentration which occurs across the 80 km inversion without information on the accumulation which occurs in the convective layer and on the levels at which the condensation takes place. Bright meteors produced by particles of mass several grams arriving at about 40 km/sec are first visible at a height of about 100 km and disappear at about 70 km; larger particles are able to penetrate to lower levels, and so considerable proportions of their condensation products are introduced below the 80 km level. This circumstance would help in the production of a well-defined haze top; on the other hand, estimates of the evaporation of particles of the small size inferred to compose the zodiacal light cloud, based upon the considerations summarized by WHIPPLE (1943), indicate that they must be evaporated entirely above the 80 km level. It therefore seems likely that only meteorological processes could account for the formation of a haze top or a marked concentration of small particles near the 80 km level.

It is interesting that dust clouds, which in sunlight may cause an appreciable warming of air, may equally be responsible for a significant cooling of air when they lie in the earth's shadow. Since the long-wave radiation emitted by the earth and its atmosphere has an equivalent black-body temperature of about 245° A, a particle in the high atmosphere (which radiates in all directions but receives radiation from the hemisphere below) is in radiative equilibrium at a temperature of about $245/2^{1/4}$, or 206° A. The air temperature in the upper stratosphere, at least to within a few km of the 80 km inversion, exceeds this value, so that dust clouds may behave as a cooling agent and promote sinking motions. Conceivably, in the high latitude summer, when the earth's shadow moves mainly latitudinally, there may be a tendency for a circulation in the vicinity of the shadow, in the layer from 50 to 80 km, as a result of a predominance of ascending motions in a belt a few hundred km broad in the sunlit region, and of descending motions in a similar belt inside the earth's shadow. Such a circulation would involve a component of the motion at the 80 km level directed away from the sun, as seems to be observed in the motions of noctilucent clouds.

## 13. Conclusion

It appears very unlikely that the condensation of water vapour plays any part in the formation of noctilucent clouds. They are probably composed of small solid particles, which may enter the stratosphere from below during major volcanic eruptions, or which may be produced in the stratosphere by the condensation of gases in the wakes of meteors. During the high latitude summer steep lapse rates develop in the upper stratosphere because of the prolonged heating of the ozone layer, and convective motions, possibly aided by solar warming of particle clouds, distribute the particles throughout a layer extending up to the 80 km inversion. Irregularities and wave disturbances in the top of the dusty layer produce visible clouds. The clouds may appear predominantly in regions near the earth's shadow at midnight, when adjacent belts of the atmosphere remain for some hours on either side of the shadow, so that a circulation is established in the upper stratosphere in which the sunlit air rises and the shadowed air sinks. This circulation and the haze top at 80 km which favour the appearance of the clouds may not develop in other latitudes and seasons because of the absence of steep lapse rates and because of the rapidity with which the earth's shadow moves through the atmosphere. The tendency for clouds to appear after rather than before midnight may be related to the diurnal variation in the accretion of interplanetary particles, but this and some other cloud properties need more thorough investigation. Noctilucent clouds may interest astronomers as evidence of the accretion of interplanetary material, and are important to meteorologists as indicators of atmospheric processes affecting the stratosphere, and as reminders that a considerable proportion of the condensation and freezing nuclei of the upper troposphere may arrive from outer space.

In future observations of noctilucent clouds it will be important to record occasions when they are absent in apparently favourable viewing conditions. It would be most desirable to establish a network of observing stations, to examine the true areal extent of the clouds and the simultaneity or otherwise of their appearance in different parts of the world. The ethereal beauty of the clouds on the rare occasions of good displays is a recompense for many hours of attentive but fruitless observing.

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