NOCTILUCENT CLOUDS

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Abstract. Noctilucent clouds appear during the summertime at high latitudes near the top of the mesosphere. In this review, the observational facts about them, obtained from ground level, by rocket sounding and from orbiting spacecraft, are reviewed. The data are not sufficiently clear and unambiguous to permit dogmatic assertion about the origin and nature of the clouds. They seem to be ice particles nucleated at very low pressures and temperatures by either meteoric smoke or by atmospheric ions. Wavepatterns in the clouds may well result from quite close relations between the troposphere and the mesosphere. The very existence of the clouds leads to difficulties in explaining why there is so much water vapour at this great height in the atmosphere. To try to predict the microscopic behaviour of the cloud particles leads one into assessment of the relative importance of radiometer effects, radiation balance, Brownian movement, electric polarization and the influence of Coulomb attraction on the growth of large clustered ions. Finally, a list is given of published sources of observational data.

1. Introduction

Noctilucent clouds have a distinctive appearance. Even if the observer has but read of them, when one is seen it is immediately recognised. They become visible in the middle of a summer night and have a characteristic silvery or blue colour. They truly are ‘night shining’. It is thus a little curious that until the summer of 1885 they were not recognised for what they are, a cloud formation quite distinct from tropospheric clouds and from mother of pearl clouds. Krakatoa had exploded in 1883 and men’s attention had turned to the twilight sky because of the remarkable sunset and sunrise colours caused by the heavy burden of stratospheric dust and aerosols that resulted from the volcanic event. In June, 1885, noctilucent clouds abruptly came to the attention of observers in Russia (Tseraskii, mentioned by Astapovich, 1961), in Ireland (Anon., 1885), Germany (Backhouse, 1885) and in Czechoslovakia (Jesse, 1889). The first mention of them in the popular scientific magazine Nature (London) is by Leslie (1885), who wrote:

> Ever since the sunsets of 1883 and last year there has been at times an abnormal glare both before and after sundown. But I have seen nothing in the way of twilight effect so strange as that of Monday evening, the 6th, when about 10 p.m. a sea of luminous silvery white cloud lay above a belt of ordinary clear twilight sky, which was rather low in tone and colour. These clouds were wave-like in form, and evidently at a great elevation, and though they must have received their light from the sun, it was not easy to think so, as upon the dark sky they looked brighter and paler than clouds under a full moon. A friend who was with me aptly compared the light on these clouds to that which shines from white phosphor paint. This effect lasted for some time after 10 p.m., and extended from west to north, the lower edge of the clouds, which was sharply defined, was about 12 degrees above the horizon.

6, *Moira Place, Southampton, July* 8 — Robt. C. Leslie

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Leslie's letter shows how the noctilucent clouds of 1885 were clearly something unusual. It is plain that special attention was directed to the twilight sky in these years; why were these shining clouds not noted more frequently in previous years? It can hardly be thought that there were few before 1885. Although Bronshten and Grishin (1970) mention some earlier occasional records that might refer to noctilucent clouds, the puzzle remains.

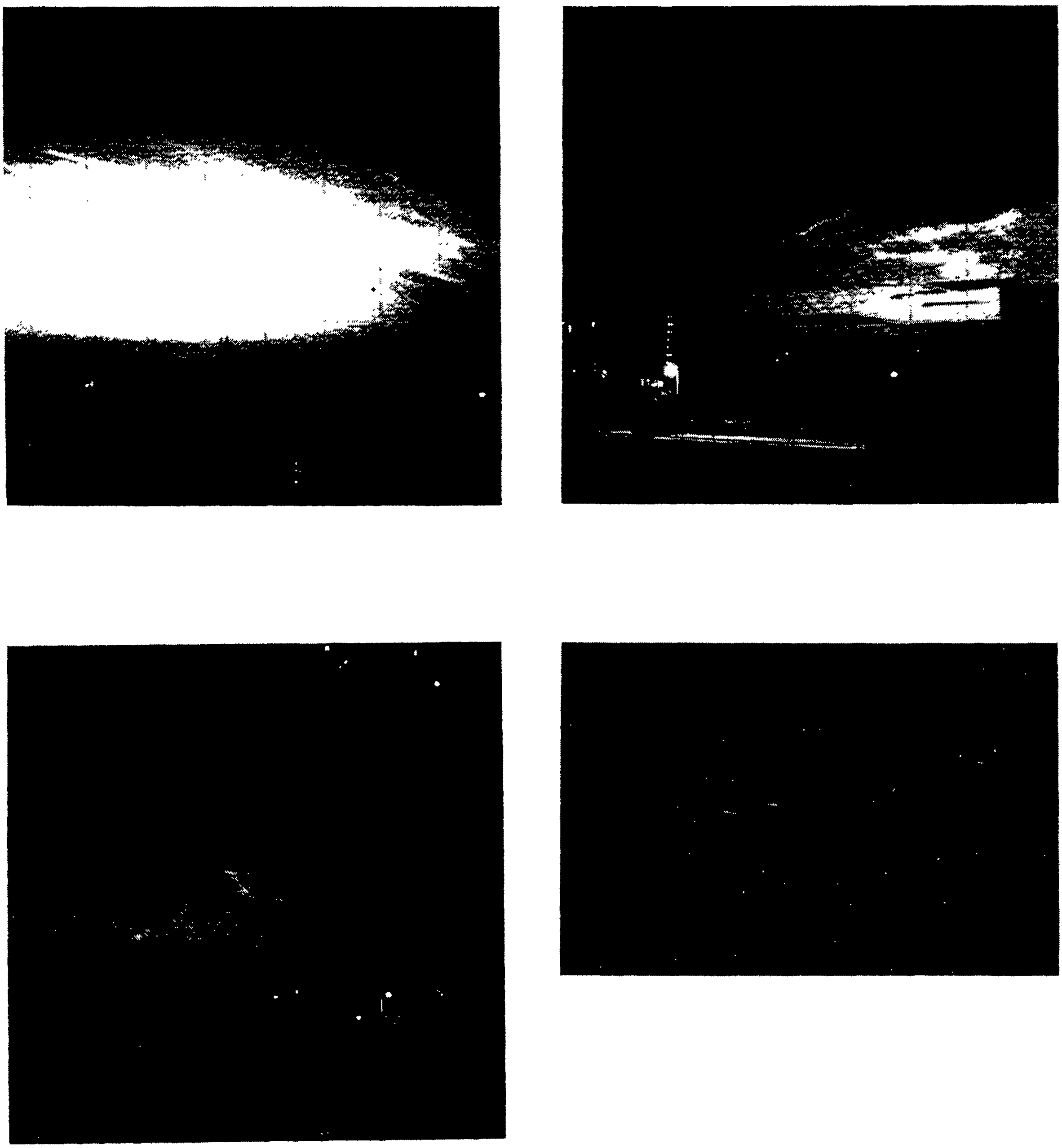

Fig. 1. Photographs of noctilucent clouds taken at Aberdeen, Scotland (57° N). *Top left*: 1975 July 4 2351 UT. *Top right*: 1974 July 11 0021 UT. *Bottom left*: 1976 Jul 20 0106 UT. These three photographs were exposed on ASA160 Ektachrome film with exposures of 8 s at a lens aperture of *f*2.8. *Bottom right*: 1978 July 28 0154 UT. This exposure was made through the eyepiece of the guiding telescope of a photoelectric polarimeter. The plus signs mark the ends of the polarimeter field of view which was rectangular, 54′ × 3.3′.

Some recent photographs of noctilucent clouds are shown in Figure 1. The characteristic wave-like forms of the clouds are well displayed; it is clear from Leslie's letter that these were the first things to be noticed about them.

In the last ninety-six years, the pace of investigation into the origin and causes of noctilucent clouds has increased. From the leisurely pace of the first half of the twentieth century, the scientific community is currently showing a marked increase in interest. Part of this increase is certainly due to research being carried out as part of the Middle Atmosphere Programme (1982–1985); part may well be because the time is ripe for another attack on the problems posed by the existence of clouds at great heights in the atmosphere.

The reader who is interested in studying the development of a research area should look at the review by Vestine (1934) contained in a paper published in two consecutive parts. The first part contains a useful catalogue of observations made during the period 1885–1933, called from:

... well-known German, English, and French scientific journals.

The post-war pace picks up with a paper by Paton (1949) concerning observations from Scotland; a good review by the same author appears fifteen years later (Paton, 1964). During this interval, Ludlam (1957) published a comprehensive review of the subject, together with some fresh observations made from Sweden. Meanwhile, there was considerable activity in the U.S.S.R. (Khvostikov, Willmann, and Grishin) and this is well-summarised in the book already referred to (Bronshten and Grishin, 1970). Many papers appear in a series of Geophysical Reports and Proceedings of International Symposia held in the U.S.S.R.: these publications, often now difficult to obtain, are listed in a separate section at the beginning of the listing of cited references at the end of this review.

In North America, the observers were encouraged at first by Currie at the University of Saskatchewan (Currie, 1962) and later also by Fogle at the University of Alaska. Fogle's work appeared as a Scientific Report to the National Science Foundation (Fogle, 1966). Much of this Report, which may not now be widely available, was published jointly with Haurwitz (Fogle and Haurwitz, 1966) and this is the most recent, truly comprehensive, review of the subject apart from the Bronshten and Grishin monograph already referred to.

I shall attempt to summarise the current state of what is known and to indicate what appear to be profitable lines of pursuit. It cannot be gainsaid that what is desperately needed for future studies are more observational data. The acquisition of the data is hindered by two factors. First, the clouds can be seen from ground-level observatories only in a relatively narrow band of latitudes and for only a couple of months in the year. Secondly, in situ observations (direct sampling of the clouds or their physical environment) requires small sounding rockets; these rockets have neither the glamour of space research programmes nor the cheapness of the routine meteorological sounding rockets which reach up to perhaps 65 km altitude. On both counts, the middle range rockets capable of penetrating the cloud layer are not favourably looked on by funding agencies.

2. Scattering of Sunlight

The clouds are seen because they scatter sunlight. To understand and to interpret the observations, it is necessary to consider in some detail what is involved in this scattering. Much of the observational data comes from measurement of the state of polarization of the scattered light and it is necessary to set out clearly what is involved both in the process of scattering and in the way in which sunlight reaches the clouds.

2.1. Polarization by scattering

In this discussion, the state of polarization of light is described through the use of Stokes parameters. The transformation of these parameters by scattering will be treated with the help of the Mueller calculus (Shurcliff, 1962). To use this calculus, one writes the Stokes parameters as a vector $\{I, M, C, S\}$ having four components; the effect of any linear transformation (e.g. scattering, or passage through a polarizing element) is expressed by sixteen coefficients of a 3 × 4 matrix, F. If the incident light has Stokes parameters I_0, M_0, C_0, S_0 then

$$\{I, M, C, S\} = F \cdot \{I_0, M_0, C_0, S_0\}.$$

The physical meaning of the individual Stokes parameters can be grasped by referring to Figure 2, a representation of the polarization ellipse. Using the quantities noted in the figure, we have the following relationships:

Ellipticity = $\tan \beta$; orientation of the major axis = χ.

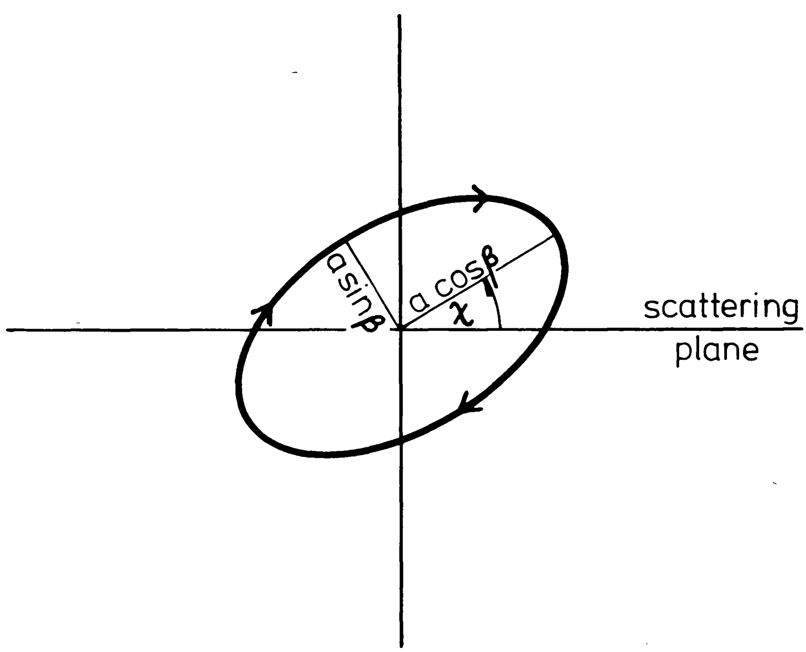

Fig. 2. State of polarization of an elliptically-polarized wave. The direction of propagation is into the page.

The Stokes parameters are:

$$I = a^2,$$

$$M = I \cos 2\beta \cos 2\chi,$$

$$C = I \cos 2\beta \sin 2\chi,$$

$$S = I \sin 2\beta.$$

If $M = +I\,(-I)$, the light is linearly polarized in (perpendicular to) the scattering plane.
If $C = +I\,(-I)$, the light is linearly polarized at 45 (135) degrees to the scattering plane.
If $S = +I\,(-I)$, the light has right-handed (left-handed) circular polarization.

Clearly

$$I^2 = M^2 + C^2 + S^2$$

and the degree of polarization of a partially-polarized light beam is given by the ratio of I to the total intensity of the beam.

Van de Hulst (1957) and Kerker (1969) discuss the form and coefficients of F in some detail, with special reference to cases of matrices for scattering media. If the particles in a scattering cloud scatter waves which have unrelated phases (that is, if the scattering in the cloud is incoherent), each coefficient in the matrix F for the cloud is the sum of the corresponding coefficients for each particle. Also, because the scattering is assumed to be incoherent, the summing for the cloud of particles is done for intensities, not amplitudes, of the scattered waves. The principle of optical equivalence enunciated by Stokes in 1852 (see Clarke and Grainger, 1971) makes clear that it is impossible to distinguish between different incoherent sums of simple waves that together form beams of light with the same Stokes parameters.

There are certain restrictions that are imposed on the matrix F by the symmetry existing in some physical situations. First, if all the scattering particles are spheres, or if they have a plane of symmetry but their axes are oriented randomly, eight of the sixteen coefficients are zero and two pairs of those that remain share the same numerical magnitude, so the matrix contains only six separate coefficients:

$$F = \begin{vmatrix} S_{11} & S_{12} & 0 & 0 \\ S_{12} & S_{22} & 0 & 0 \\ 0 & 0 & S_{33} & S_{34} \\ 0 & 0 & -S_{34} & S_{44} \end{vmatrix} .$$

In this case, there are limits on what kind of polarization of the scattered light can have. If the incident light is unpolarized, $\{I, 0, 0, 0\}$, the scattered light has Stokes parameters $\{S_{11}I, S_{12}I, 0, 0\}$. It is plane-polarized, therefore, either in the plane of scattering or at right angles to it depending on whether S_{12} is positive or negative in value. If the incident light is linearly polarized, the Stokes parameters of the scattered light are

$\{(S_{11}I + S_{12}M), S_{12}I + S_{22}M), S_{33}C, -S_{34}C\}$ and there can be circular polarization if the incident light has any degree of linear polarization in a plane oblique to the scattering plane. Naturally, if the incident light is elliptically polarized, that is, if there are both kinds of linear polarization plus circular polarization present in the incident light, the scattered light will, in general, be elliptically polarized too with neither the original orientation of axes nor with the original ellipticity being necessarily preserved.

In the general case where the cloud contains odd particles which are not randomly oriented, the matrix F is unrestricted. It should be noticed that the coefficients in F are related to both the shape and to the composition of the cloud particles and there is no way of distinguishing particles with anisotropic composition from elongated particles of isotropic material.

There are two simplifying approximations that can be made and often are made. If the particles (of arbitrary shape) are very small in comparison with the wavelength of the incident light, the Rayleigh approximation holds good. In this case,

$$F = \begin{vmatrix} 0.5\,(\cos^2\theta + 1) & 0.5\,(\cos^2\theta - 1) & 0 & 0 \\ 0.5\,(\cos^2\theta - 1) & 0.5\,(\cos^2\theta + 1) & 0 & 0 \\ 0 & 0 & \cos\theta & 0 \\ 0 & 0 & 0 & \cos\theta \end{vmatrix}$$

with all the consequent simplifications in taking the product with $\{I_0, M_0, C_0, S_0\}$ to find the Stokes parameters of the scattered light.

The second approximation is that the scattering particle is low in contrast, that is, the phase of the incident wave is negligibly changed in passing the particle. Rayleigh (1881) gives this approximation as an extension of the small-particle approximation which is valid for particles of any size and any shape provided their refractive index is close to that of the surrounding medium. To distinguish the two approximations discussed by Rayleigh in the one paper, the low-contrast case is usually called Rayleigh–Gans scattering but Kerker (1969) has suggested this would be more appropriately called Rayleigh–Debye scattering.

The Rayleigh–Gans approximation is not a good one for the case of noctilucent clouds, where the refractive index of the cloud particles is not close to unity. It is, however, useful in permitting simpler relations to be used to indicate the behaviour of full, rigorous solutions to the scattering problem. Wait (1955) has obtained the full solution for the case of scattering from an infinitely-long cylinder for which, as Rayleigh points out in his 1881 paper, one may also make use of the equations for a scatterer of finite length. Banderman and Kemp (1973) obtain expressions for the degree of circular polarization produced when unpolarized incident light is scattered from a finite right circular cylinder. They make the approximation that the relative refractive index of the cylinder is close to unity so there is a limit to the usefulness of their treatment being applied to the case of noctilucent cloud particles. Nevertheless, the behaviour exhibited by the low contrast cylinders can be useful as a guide and has been so used by Gadsden (1977). A full solution of Maxwell's equations for the case of scattering by an ellipsoid has been obtained by Asano and Yamamoto (1975) and this set of equations should be applied when testing a cloud model against observations of the scattered light. Barber and Yeh (1975) have approached the problem from a different angle and obtain general solutions using the 'Extended Boundary Condition Method'; in their paper, they give examples of scattering from several different shapes of scatterers including prolate and oblate spheroids in the resonance region, that is to say, for scatterers whose dimensions are comparable with the wavelength of light. Latimer and Barber (1978) make use of the Extended Boundary Condition Method (which is, of course, exact) to assess the worth of several approximations to solutions of the scattering from ellipsoids.

2.2. Transmission of Sunlight through the Atmosphere

As has been seen, the problem of predicting the state of polarization of light scattered from noctilucent clouds is soluble in principle. Given the state of polarization of the incident sunlight, the light that would be scattered from any model containing spheres, or cylinders, or spheroids can be calculated once the refractive index of the material (or materials) in the particles is decided. However, the sunlight that is incident on the clouds has passed obliquely through a considerable amount of the atmosphere. By the very nature of observing the clouds in twilight, some time after local sunset, the incident sunlight has entered the atmosphere, plunging fairly deeply over the terminator, and then begun to emerge before striking the clouds. There will be significant absorption along this path. In addition, there is at least the possibility of a significant contribution to irradiance at the cloud level from light forward scattered in the troposphere and stratosphere. This problem has not been solved. It is less of a problem for observations of noctilucent clouds from rockets (where the Sun may be well above the local horizon at cloud level) but it has become clear recently that the conditions for observation from orbiting spacecraft are almost as unfavourable as those for ground observation.

Rozenberg (1966) goes into considerable detail to give ways of calculating the effect of refraction, absorption (both by ozone and through molecular scattering) and the presence of aerosols on the passage of grazing rays of sunlight. The calculations are in essence simple but, on any particular occasion, the abundance of ozone near the terminator and the amount of stratopsheric aerosol are not known with precision and the results of the calculations generally, therefore, are in the nature of general guidance to interpretation rather than precise solutions. The effect on the colour of noctilucent clouds of the passage of sunlight through stratospheric ozone has been discussed by Gadsden (1975). Spectrophotometric measurements in the visible region show clearly an absoprtion band in the yellow and this band is the Chappuis band of ozone. If one tries to make allowance for stratospheric absorption of sunlight on its way up to the clouds, the result turns out that much of the blue colour of the clouds is in fact simply the colour of the incident sunlight, as modified by ozone absorption. It cannot be assumed that the cloud particles are Rayleigh scatterers because the clouds are blue. Indeed, the data taken by Gadsden on a single display in 1974 show that the clouds had a scattering cross-section that varied through the visible spectrum in a way that was very clearly not in accord with the Rayleigh approximation.

However, such measurements of the spectral radiance are difficult to correct for absorption by the atmosphere both of the sunlight incident on the clouds and of the scattered light travelling, usually very obliquely, down through the atmosphere to the observer. For this reason, more weight is generally and properly allowed to measurements of the state of polarization of the scattered light in using them to make estimates of the characteristics size of cloud particles.

3. Observations from Ground Level

There are rather close restraints imposed on observation of noctilucent clouds from ground level. The tightest of these, apart from the need to have a clear sky over the observatory, results from the geometry of twilight. The clouds are seen by scattered sunlight and need to be sunlit; the observer needs a dark sky to see the illuminated clouds. There is, therefore, a narrow range of twilight when the clouds are able to be seen from the ground.

Simple geometry, ignoring absorption and refraction of sunlight in the lower atmosphere and treating the Sun as a point source, gives the area of sky in which the clouds can be seen from any particular place. Ignoring refraction, the shadow of the Earth on a layer of noctilucent cloud lies within a circle of radius $(R + H)$, where R is the radius of the solid Earth and H is the smallest height (the 'screening height') to which sunlight is able to penetrate in its grazing passage through the atmosphere. This circle is centred a distance Y from the centre of the Earth along the antisolar axis (see Figure 3).

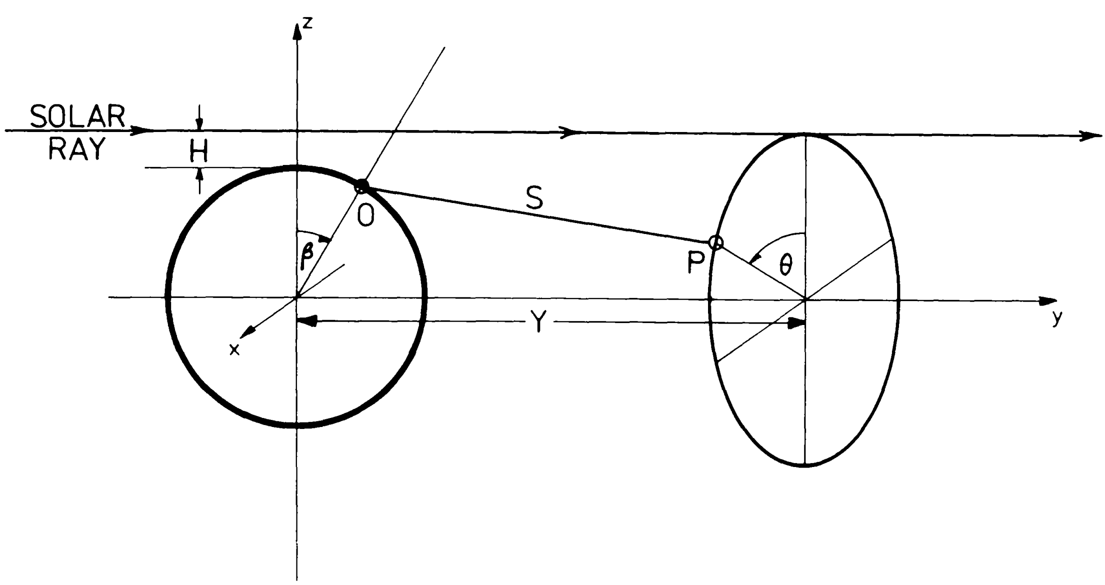

Fig. 3. The geometry of observation of the edge of the illuminated area of a noctilucent cloud display. The Sun is assumed to be a point source; the y axis passes through the centres of the Sun and the Earth. An observer at 0 defines the plane (y, z) of the solar meridian; the Sun is at a depression angle, β, at the observer. The edge of the cylindrical shadow projected into space by the Earth, increased in radius by an amount H (the screening height), is the locus of a point P distant $(R + h)$ from the centre of the Earth.

If an observer is at O, where the solar depression angle is β, he sees a point P on the edge of the illuminated area of noctilucent cloud at a slant range, S, given by

$$S^2 = (R + h)^2 - 2YR \sin \beta + R^2 - 2R(R + H) \cos \theta \cos \beta$$

and

$$Y^2 = (R + h)^2 - (R + H)^2.$$

In these equations, h is written for the height of the cloud layer. The point, P (see Figure 3), appears to the observer to be at an elevation, e, on a vertical with azimuth, a, relative to the direction of the Sun. The angles a and e are given by

$$s \sin e = Y - R + (R + H) \cos \theta \cos \beta$$

and

$$s^2 \cos^2 a = (Y - R \sin \beta)^2 + \{R \cos \beta - (R + H) \cos \theta\}^2.$$

Plots of the loci of P are given in Figure 4 for the values h = 82 km, H = 15 km, and R = 6371 km.

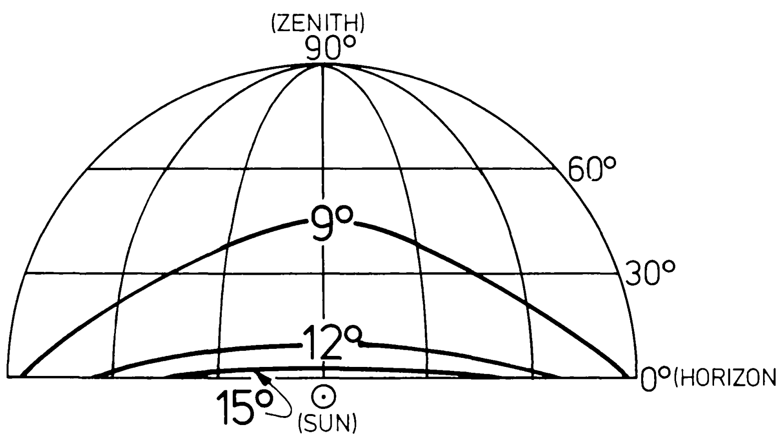

Fig. 4. The loci of P for solar depression angles of 9°, 12°, and 15° seen projected on that half of the sunward hemisphere above the observer's horizon.

3.1. Visibility of noctilucent clouds

It is clear that if the Sun is more than 12 degrees below the horizon, noctilucent clouds can be seen only close to the horizon in the direction of the Sun. If the Sun is less than 8 degrees below the horizon, in principle the clouds can be seen at the zenith and in the antisolar hemisphere. In practice, though, it is found that the twilight sky is so bright at these small solar depression angles that the contrast of noctilucent clouds is very low. Dietze (1973) has considered this progressive loss of constant as dawn approaches in some detail, as part of a wide-ranging discussion of the several factors (tropospheric turbidity, dust and ozone in the atmosphere, and visual adaptation) that affect whether an observer can see a noctilucent cloud.

Paton (1964) reports two occasions on which the clouds appeared at the zenith when the Sun was 7.7 degrees below the horizon. He shows that these observations imply a screening height of 24 or 25 km, in accord with much of his other data.

The commonest way of estimating the screening height is to measure the edge of the illuminated area of cloud. Plainly, interpreting these measurements to give a screening height depends on the cloud area having an edge resulting from the falloff of illumination rather than from there being a real edge to the clouds. Deciding whether the method is appropriate on a particular occasion is very much a decision at the time for the observer.

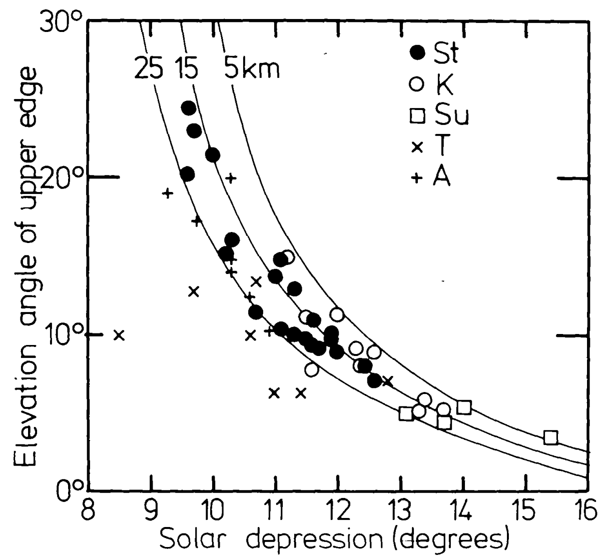

Fig. 5. Measured elevation angles of the upper edges of noctilucent cloud displays in the solar meridian. Data are shown from five observing places: Steglitz (52° N), Kissingen (50° N) and Sunderland (55° N), all given by Jesse (1896); Torsta (63° N) by Ludlam (1957); and Abernethy (56° N) by Paton (1964). The curves correspond to screening heights of 5, 15, and 25 km for a cloud height of 82 km. A point source Sun and zero atmospheric refraction have been used to calculate the curves (see text).

Jesse (1896) lists a number of such measurements made in 1885, 1886, and 1887 and the data are plotted in Figure 5. Data from Ludlam (1957) and Paton (1964) are also in Figure 5. If one remembers that the measured points should fall, if anywhere, to the left of a line corresponding to the calculated variation of position of the upper edge of the cloud with different solar depression angles, it is clear that a screening height of 15 km is as good a choice as any. This is rather lower than Paton's own estimate of 25 km but is consistent with his data. In calculating the curves shown on the Figure, no allowance has been made either for refraction of sunlight low in the atmosphere or for the appreciable solar disc. The first effect is small for a screening height (the deepest penetration of the solar rays into the atmosphere) of 15 km; it is approximately 8.5 min of arc. The second effect causes noctilucent clouds to be seen a quarter of a degree of solar depression greater than would otherwise be the case. The two effects together allow data points to fall up to 0.4 degrees to the right of the appropriate curve in Figure 5.

3.2. Latitude of observation

It can be taken as a general guide that noctilucent clouds will be seen only when the solar depression angle is between 6 degrees and 15 degrees and it is well known that the clouds are a high-latitude, summer phenomenon. This is shown clearly in the statistics given by Fogle (1966), who lists the reports of noctilucent clouds from North America for the ten years from 1956–1965. In this period, the clouds were seen during 146 twilights in the May to August period. Figure 6 gives a plot of the frequency of the reports for the latitude of the southernmost observer on any particular night. There is no list of when the clouds were not seen, that is, of nights when the sky was clear and without noctilucent clouds so it is not possible to express the data as probability of occurrence. Two things show clearly. First, the distribution with latitude contains the effect of distribution of population density with latitude; the two major peaks in the histogram correspond to Canada and Alaska. Secondly, there is a dearth of reports from the higher latitudes. This is because at these latitudes the summer night does not get dark enough for an observer to be able to see the clouds. The broken line in Figure 6 is the number of nights, at a particular latitude, that the Sun goes below a 6 degree depression angle during the months of May to August. (The sole observation of a noctilucent cloud beyond this line is that from a polar island station which reported noctilucent cloud visible on September 13.)

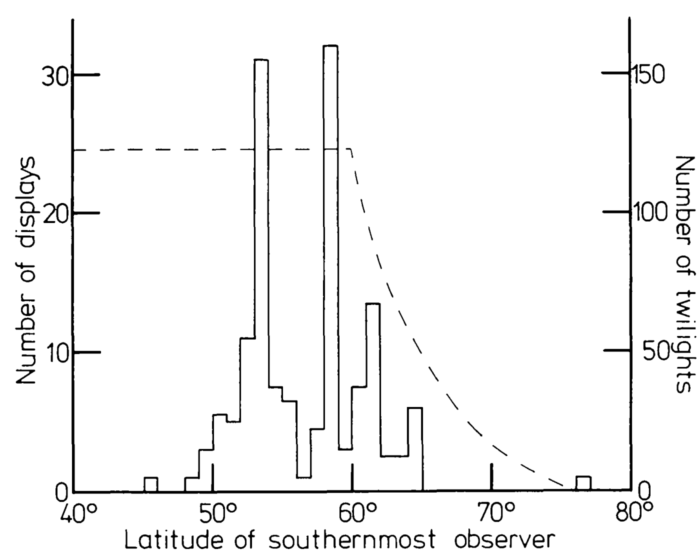

Fig. 6. Fogle's (1966) North American data for the appearance of noctilucent clouds in the period 1956–1965. The broken curve shows the number of nights in May, June, July and August when the Sun reaches a solar depression angle of at least six degrees.

It should be borne in mind that these data refer to the sighting of a noctilucent cloud; the cloud itself will, in general, be at a position some degrees further to the north of the observer. Also bear in mind that these are the latitudes of the southernmost observer; it is generally, but not invariably, the case that observers to the north with clear skies will report noctilucent cloud visible to the north of them also. A more meaningful representation of the data might be to plot them as a cumulative curve with the recognition that nothing much can be said from groundlevel observations about the occurrence of clouds at latitudes poleward of 80 degrees. The median occurrence is at 57.5 degrees latitude.

3.3. Height of Noctilucent Clouds

The height of noctilucent clouds has been measured directly, using photographic triangulation, on a number of occasions. The data are summarised in Table I, in which the average of the heights measured on each night is listed. Jesse (1896) gives the results from eight nights on which noctilucent clouds were seen, and his summary at the end of that paper can hardly be improved on even at the present day, eighty six years since it was written:

> ... dass die leuchtenden Nachtwolken bestandig und zwar von dem Jahre 1885 bis 1891 sehr nahe eine und dieselbe mittlere Hohe von 82 Kilometer gehabt haben.

The median of the observations listed in Table I is 82.9 km but this is an unimportant modification of Jesse's conclusion and may well not be meaningful. What is surprising is how rarely have measurements of height been done in the eight decades that have

TABLE I

Summary of measured heights of individual displays

Jesse (1896)	1889 Jun 22	82.9
	Jul 2	82.5
	Jul 24	85.5
	Jul 31	88.5
	1890 Jul 6	83.0
	Jul 10	81.7
	Jul 24	82.95
	1891 Jun 25	81.4
Stormer (1933)	1932 Jul 10	81.8
	Jul 24	81.1
Stormer (1935)	1934 Jun 30	82.2
Paton (1951)	1949 Jul 10	84 to 89
Burov (1959)	1958 Jun 16	82.6
Dirikis (1962)	1959 Jul 14	83.3
Dirikis *et al.* (1966)	1961 Jun 30	83.1
	1964 Jun 30	82.9
Burov (1966)	1964 Aug 2	83.2
Burov (1967)	1965 Jul 15)	(73.0 to
	Jul 19)	(96.8
Grahn and Witt (1971)	1958 Aug 10	83.7
	1965 Aug 5	84.2
	Jul 20	82.0
	1967 Jul 16	82.2
	Aug 9	83.0
	Median of 22 displays = 82.9 km	

elapsed since such measurements were first tried. The body of data is not sufficient to permit a discussion of trends, such as any systematic change as the summer progresses, or connection with lunar tides in the upper atmosphere, or with geomagnetic activity at the time, and so on.

The numbers given in Table I are, with two exceptions, the arithmetic means of the heights measured from one or more stereo pairs of photographs taken on an evening. The measured heights commonly show a spread which is larger than the estimated uncertainty in an individual measurement. Much of this spread may be due to there being a systematic variation in height from place to place in the cloud. Indeed Stormer (1933) in discussing his measured heights says:

> A stereoscopic view of the two pictures from Oslo and Kongsberg gives the impression that the clouds were arranged in two layers of different altitude. This is in accordance with the measured heights, 83 and 84 km for the points 2 and 3 and 88, 92, and 90 km for the points 4, 5 and 6.

Witt (1962) discusses the stereophotographs he obtained on the display visible over Central Sweden on the night of 1958 August 10. He had the use of precision photo-theodolites (placed at his disposal by the Bofors Company) at each end of a geodetically-surveyed baseline of length 51.5 km. He also had the good fortune to have almost perfectly clear conditions to make his measurements on an extensive, bright display. In his paper, he is principally concerned to present sections through and contour maps of the clouds and the estimated velocities of the movements in the clouds. The range of measured heights was only 4 km; the data lay in the range 81.5 to 85.5 km. (In Table I, the average of the individual heights listed by Grahn and Witt (1971) for this display is 83.7 km.) It has to be said that the work reported by Witt (1962) is the best that has ever been done on measuring the height of noctilucent clouds and, in my opinion, the quality of the work is unlikely ever to be surpassed. Reading that paper should be required of all who attempt similar observations. The published article even includes a pair of anaglyph pictures, together with red and green viewing filters, to allow the cloud pictures to be viewed stereoscopically.

These and other data show that noctilucent clouds have a varying height across the field of view and also may appear at two distinct levels in the atmosphere. There is a need for caution in interpretation of photographs. First, it must be remembered that the clouds are optically very thin (stars shine through them with little diminution in light) and the structure that may be obvious to the observer can result from the superposition of two separate clouds in the line of sight. Very wrong heights will be got from triangulation or stereogrammetry on a feature which has no real existence and which appears at different locations in space from the two observing points.

Secondly, the clouds are almost always viewed very obliquely. Bright features again may have no physical reality but arise simply from seeing a thin layer of cloud with waves in it from a direction in which the line of sight travels a considerable distance within the layer. The same favourable view may not be available to a second observer some distance from the first.

3.4. Variation in occurrence with season

Mention has been made earlier of the clouds being a summer phenomenon. This shows up clearly in the statistics of occurrence made ever since the clouds were first recognised. Figure 7 shows histograms plotted from the data in three major lists of observations.

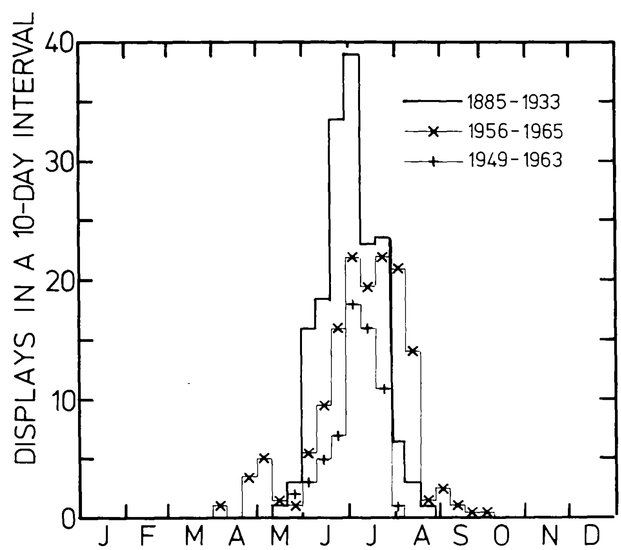

Fig. 7. The seasonal variation of noctilucent clouds in the Northern hemisphere. The 1885–1933 data are from Vestine (1934), the 1956–1965 data from Fogle (1966), and the 1949–1963 data from Paton (1964).

The period covered by the data is eighty years and the three sets of data are in good agreement. There is a 'season' for noctilucent clouds; in the Northern hemisphere, it is May to August (with a few exceptions in the North American data). The sparse observations available from the Southern hemisphere confirm that the season truly summertime; in the South, the clouds were seen in December and January (Fogle, 1965). Fogle's note drew the attention of Antarctic observers to the phenomenon and Francis, Bennett and Seedsman (1966) reported that they had seen the clouds from Mawson (68° S) in October and in February. (The solar depression angle is never greater than six degrees at the latitude of Mawson from November 6 to February 23.) Later, Kilfoyle (1968) added observations in August 1966 from the same base, Mawson, and writes:

> These sightings met the necessary conditions for the identification of noctilucent clouds given by Fogle (1964).

Kilfoyle adds that nacreous ('mother of pearl') clouds were seen on the same days. Perhaps the noctilucent clouds that Kilfoyle claims were nacreous clouds. (One is well aware, of course, of the dangers in building into the selection of data the self-justification that these clouds could not have been noctilucent clouds, i.e. clouds in the mesosphere, because such clouds do not occur in the winter.)

The same objection can be made to the winter sighting of noctilucent clouds over

Lerwick (60° N) in January. Hamilton (1964) says:

At 16:55 UT the depression of the Sun was 10° 45′. If it is assumed that the cloud was overhead and just illuminated at 16:55 and the refraction was twice 34′ (see Meteorological Glossary), then the calculated height was 91 km – somewhat higher than the mean height of 82 km in the summer – and the cloud velocity was roughly 40 m s^{-1} towards the south-east.

Reference to Figure 5 shows that such a cloud would fall well to the right of the 'acceptable' area on the plot; introducing a screening height of some kilometres and a correspondingly reduced allowance for refraction into Hamilton's calculations would put his cloud well up into the ionosphere. Impossibly high, one might say.

Kropotkina and Shefov (1975) investigate whether lunar tides in the upper atmosphere cause a temperature oscillation large enough to affect the probability of occurrence of the clouds. They take 1103 reported sightings in the months of June and July over the years from 1885 to the then present day. The data were sorted according to lunar time, smoothed with sliding blocks of 2 or 3 hr and plotted as departure of observed frequency from the average. They find a semidiurnal component of 15%, and a diurnal component of 5%. The standard deviation is, they say, not more than 5%. If one refers to the relation between rotational temperature of the hydroxyl airglow emission and lunar time (Shefov, 1967), there is an expected change in temperature of 15–20 K. The association of appearance of the clouds with the time of lunar day is thus consistent with the airglow data.

3.5. Variation in Occurrence from Year to Year

It is clear from Figure 7 that the incidence of cloud displays from year to year is by no means constant. The forty-eight years of the data from Vestine (1934) give only twice as many sightings in some of the ten-day calendar intervals as do the data for ten years from Fogle (1966). Some more recent data are replotted in Figure 8 where three

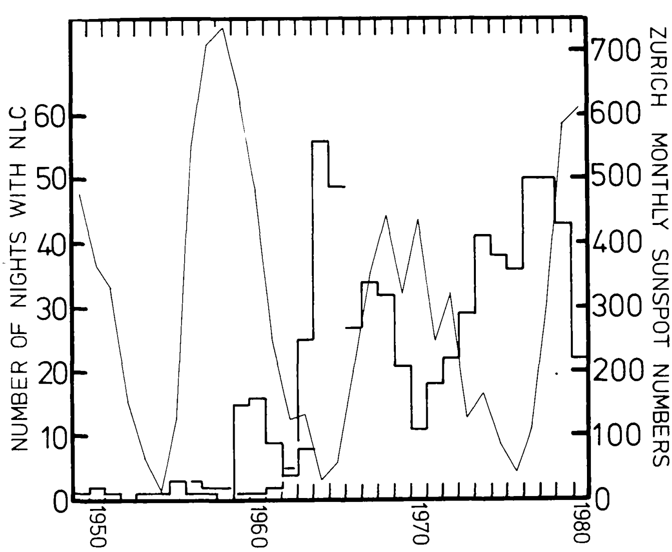

Fig. 8. The variation in number of nights with noctilucent clouds from year to year. The 1949–1963 data are from Paton (1964), the 1956–1965 data from Fogle (1966), and 1966–1980 (North European) data have been summed by Simmons (1982). The thin line shows the summer sums (May + June + July + August) of the Zurich monthly mean sunspot numbers.

histograms show the number of nights in each year when noctilucent clouds were reported. Part of the year-to-year variation must arise, undoubtedly, from changes in the density of observers or in the degree of interest in the phenomenon. In spite of these effects, though, there do seem to be real year-to-year variations; the Paton data, for example, from 1949 to 1963 were taken essentially by Paton himself from his house in Abernethy (Scotland). He was a professional meteorologist at the University of Edinburgh and one can think of no obvious reason why there should have been an abrupt increase in number of displays in 1959 after his having seen none in 1958. The later North European data, assembled by Simmons (1982), cover the period 1966 to 1980 and show two periods of decreased frequency of occurrence during these years; the summers of 1970 and 1980 were noticeably unfavourable for seeing noctilucent clouds. Simmons, who has allowed me to see his data in advance of publication, has checked the observations for the presence of wrongly-identified clouds through the use of calculations similar to those represented in Figure 5. He finds that there is a certain proportion of the reports for which either not enough information is given to confirm that the clouds would indeed have been sunlit at that time and at that place or the clouds would have been in the Earth's shadow. These account for some fraction of the data. His 'confirmed' data, though, have not been plotted in Figure 8 so as to keep consistency with the other data in the figure; but his curve of 'confirmed' clouds marches closely in parallel with the plotted curve – the fraction of rejected observations remains reasonably constant from year to year.

The two summers that have been singled out from the data in Figure 8 are in fact the two most recent sunspot maxima. The thin line plotted in Figure 8 gives the sum of the Zurich monthly sunspot numbers for the months of May, June, July, and August in each year. There does not seem to be a marked anticorrelation between noctilucent cloud occurrence and level of sunspot activity. In this connection, though, it should be remarked that D'Angelo and Ungstrup (1976) have taken some of the North American data listed by Fogle (1966) and compared the dates of occurrence of noctilucent cloud that were observed over a wide area in 1963, 1964, and 1965 with the dates when the daily sum of the magnetic K_p index fell below 10. They find that almost all the 21 cases of widely-observed clouds fell at or near a minimum in the daily sum. D'Angelo and Ungstrup point out the K_p index is a measure of the strength of the electric field in and near the auroral zone at ionospheric heights and suggest that the marked anticorrelation between K_p sum and occurrence of noctilucent clouds arises from local heating of the atmosphere by electric currents. In turn, this leads to the air temperature rising above the frost point at the height where otherwise a cloud would form. There is obviously something here that will be relevant in discussion later (Section 3.10) of the occurrence of noctilucent clouds with aurora visible at the same time above the clouds.

It is probably appropriate here to mention the correlation between mesospheric temperature and K_p found by Seshamani (1977). He took the published temperature sounding from Fort Chruchill (59° N) made over the period 1956 to 1969. He found a positive correlation (0.6; 98% significance level) between temperatures in the mesosphere, lagging 15 hr, and K_p. This was for soundings in the daytime only; there was no significance to the small negative correlation coefficient (−0.2) for nighttime soundings. He found a slope of the temperature K_p curve equal to

$$\Delta T/\Delta K_p = 9.1 \text{ K}$$

in the 81–90 km layer. If the correlation of temperature with magnetic activity occurring some hours before is a physically real effect, it is not clear why the correlation should not show up with nighttime soundings as much as with daytime ones.

3.6. Colour of noctilucent clouds

The spectrum of the light scattered from noctilucent clouds shows no features that are not present in the incident sunlight. The change in scattering cross-section through the spectrum will change the relative spectral distribution in the scattered light from that of sunlight and, in principle, this change can be measured and used in estimating the size of the scattering particles. In practice, this is neither easy to do nor exact in application. Atmospheric absorption, both of the sunlight incident on the clouds high in the atmosphere and of the scattered light passing (usually obliquely) through the lower atmosphere to the observer, has a major effect on the observed spectral distribution. Figure 9 shows some measurements of spectral radiance of noctilucent clouds from a paper by Gadsden (1975) in which the effect of atmospheric absorption is particularly obvious. The drop in radiance around a wavelength of 600 nm is caused by Chappuis absorption in stratospheric ozone. The absorption is so obvious in the

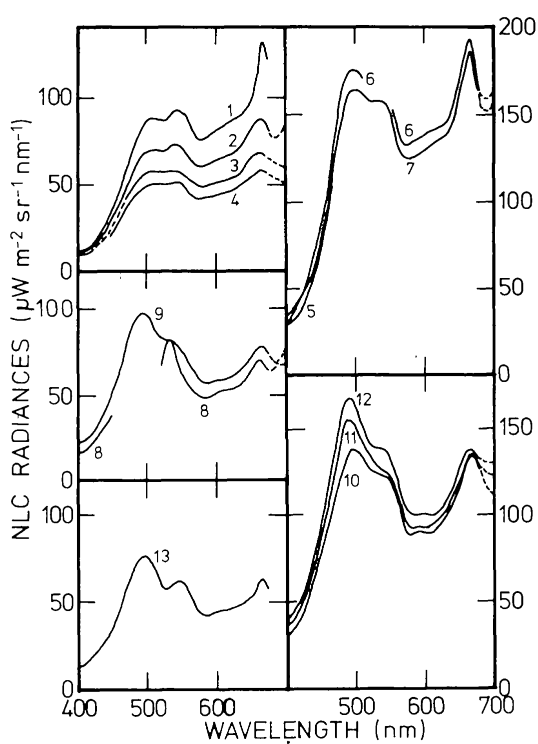

Fig. 9. Measurements of spectral radiance of noctilucent clouds observed from 57° N latitude on 1974 July 23. The numbers identify individual scans of the spectrometer and the separate boxes show scans on five separate areas of the clouds.

spectra because the sunlight incident on the clouds has passed at grazing incidence through the stratospheric ozone layer. Knowing how to correct for the effect of atmospheric absorption is the nub of the problem of interpreting these observations.

Since 1886, observers have inspected the scattered light through handheld pocket spectroscopes and noted that there was nothing out of the ordinary to be seen. The solar Fraunhofer lines are present and there are no obvious emission lines. Grishin (1956) published the first photographic spectra of the clouds. His spectrograph was a prismatic one and the spectra are rather crowded in the red but the minimum in the yellow shows up. Deirmendjian and Vestine (1959) discuss the analysis and significance of Grishin's data in some detail and conclude that there is primary scattering of direct sunlight by dielectric spheres with a maximum radius of 0.4 μm together with some night sky emission lines and bands.

Fogle and Rees (1972) were able to get spectra in the region 300 to 680 nm on two nights; on one, the cloud intensity was rather too low for a good analysis. The other night, 1969 July 22, gave usable spectra in the 300–500 nm region. Their measurements were compared with the scattering predicted from a cloud consisting of ice particles of radius 0.13 μm and gave good agreement with a column density of just under 10^9 m^{-2}; the data were, of course, corrected for both the twilight foreground light and for atmospheric absorption.

Harrison (1973) has measured the spectral radiance in the near infrared of a single cloud seen north of Calgary (Canada) on 1972 June 14. The display was the only one to appear in a series of observations throughout June and July when airglow and auroral spectra were being obtained. The spectral regions covered were 785 to 900 nm, and 2.8 to 4.2 μm. Spectra were also obtained regularly of the (4–1) band of hydroxyl, which lies in the 1.02 to 1.064 μm region (see Section 3.9). The spectra of the light scattered from noctilucent clouds showed no strong spectral absorption features. At the longer wavelengths, there was little evidence of scattered sunlight; the thermal emission from the atmosphere was predominant. Harrison points out that this is to be expected unless the radius of the scatterers was greater than 1 μm.

Veselov *et al.* (1976) report on a series of measurements made in the summer of 1974 in the spectral range 400 to 1700 nm. Because of unfavourable weather during the summer, measurements were possible only on the display of 1974 July 9. The clouds were rather faint. The results show a monotonically decreasing spectral radiance in the range covered; the scattering angle for the observation was approximately 20 degrees.

The spectra shown here in Figure 9 are the original spectral scans made on differing parts of a noctilucent cloud. Each scan. labelled in sequence from 1 to 13, took 77 to complete. The first four were of a diffuse cloud at an elevation of 4.0 degrees; the next three were made at an elevation angle of 5.0 degrees, with the entrance slit of the spectrometer aligned along the image of a bright band of cloud. Scans 8 and 9 were made of a dark region lying just above this band, scans 10, 11, and 12 were on another bright strip slightly higher in the sky at 6.0 degrees. The last scan, number 13, was on a darker region at 6.3 degrees elevation.

After allowing for atmospheric absorption on the paths of sunlight up to the particular clouds (assuming that they were at 82 km height) and the transmission of the atmosphere at the oblique directions of observation, the spectral reflectance of the clouds was found to be rather lower in the blue than would be expected if the cloud scatterers were small in size. Accepting those data as they stand, the scatterer size is found to be approximately 0.3 μm radius for a refractive index of 1.33, with a column density of approximately 4×10^7 m^{-2}. Clearly, though, the analysis stands or falls on the precision of allowing for atmospheric absorption and it is difficult to see how this can be done in a rigorous way given the unusual conditions of observation. These conditions are, first, that there are at most two or three stars visible in the twilight arch. It is not practicable to estimate atmospheric transparency from stellar observation. Second, the brightest clouds always appear fairly close to the horizon and atmospheric absorption is large. Third, except in rare cases, there are no simultaneous ozonesonde observations from a meteorological station some hundreds of kilometres from the noctilucent cloud observatory in the direction of the Sun. An average ozone distribution, appropriate to the season and to the latitude, has to be assumed for the analysis of the spectral data.

3.7. Polarization of the Light Scattered from the Clouds

It may be that no weight should be given to estimates of particle radius based on ground-level observations of the spectral distribution of the scattered light. Rather more emphasis is placed upon estimates of the size of particles from the measurements of the degree of polarization in the scattered light. Witt (1960a, b) used an ingenious camera which had two polarizing analysers in front of two objective lenses. A rotating frame allowed the operator to set the planes of the analysers (held always at ninety degrees to each other) to lie in, and perpendicular to, the previously-calculated direction of the plane of scattering. He had two pairs of filters, with effective wavelengths of 490 nm and 610 nm, that could be placed over the objectives of the camera. Photographs were obtained on the bright display of 1958 August 10, and eleven pairs of exposures with the red filters and seven pairs with the blue were used in the subsequent analysis. The brightness of the display was some two to five times greater than that of the surrounding sky and Witt therefore made no allowance for any effect of the twilit foreground. His measurements of the degree of polarization, plotted against scattering angle, showed the expected monotonic increase with increase in scattering angle from a little over 20 degrees to just over 60 degrees. The amount was consistent with scattering from dielectric spheres of radius 0.13 μm (490 nm filter) or 0.12 μm (610 nm filter) if the refractive index is taken to be 1.33.

Vasilyev (1962), Willmann (1962), and Tarasova (1962) report separately on measurements made in the U.S.S.R. They used a photographic method too, in their case with three fixed analysers. They were able, therefore, to look at the plane of polarization in the scattered light and to compare its direction with the direction of the scattering plane. Vasilyev's data extended over a rather limited range of scattering angles – between 15.5 and 20.3 degrees. In this range, he found a degree of polarization between 0.07 and 0.23, with the plane of polarization lying in the scattering plane.

Vasilyev suggests that the radius of the scatterers is 1.5 μm, with a column density of $10^6\ m^{-2}$.

Willmann, on the other hand, presents in some detail data that show results similar to that of Witt and he suggests that particle radii (for refractive index 1.33) of 0.135 μm are present. Willmann's data are extensive; there are 382 measured points listed, with an estimated precision of 0.02 to 0.04 in degree of polarization. The range of scattering angles covered by the data is 13.2 to 46.1 degrees; the degree of polarization changes from 0.02 to 0.31 over this range. Willmann finds that the direction of the plane of polarization does not lie in the scattering plane, nor at right angles, but has a systematic change with change in scattering angle. This behaviour is supported by the observations reported by Tarasova who finds that the plane of polarization lies close to the scattering plane, while the plane of polarization of the twilight sky (in the absence of noctilucent clouds) lies, as expected, perpendicular to the scattering plane.

All the measurements reported from the U.S.S.R. have been analysed with allowance for the twilit foreground. But those, and the measurements of Witt, make an initial tacit assumption that the scattered light shows only linear polarization. Gadsden (1977) reports a series of measurements of all four Stokes parameters and finds that there is a detectable amount of circular polarization in the scattered light. There seems to be a systematic change in the proportion of circular polarization with change in wavelength; the red and blue parts of the spectrum (wavelengths 400, 450, and 675 nm) show typically 0.02 to 0.08 left-handed circular polarization, while scattered light at 575 nm shows 0.00 to 0.02 of right-handed polarization. The plane of the major axis of the polarization ellipse is found to be close to the perpendicular to the scattering plane but significantly (at better than the 0.1% level) rotated a few degrees anticlockwise from the plane.

It is possible that the presence of circular polarization in the scattered light arises to a large extent from the presence of forward-scattered sunlight in the light incident upon the clouds. This would explain the absence, or small amount of reversed handedness, of circular polarization in the yellow (575 nm) results compared with the data for the blue and the red filters. The 575 nm sunlight suffers marked absorption in passage through the ozone layer (as seen, for example, in the spectra shown in Figure 9). Sunlight that is scattered in the forward direction from the troposphere near the terminator may well contain a significant proportion of linearly-polarized light. It is possible, therefore, that the sunlight incident upon the clouds in the mesopshere is unpolarized light as is usually assumed for the purposes of analysis only where an ozone absorption band stops this scattered light from reaching the clouds.

To check this point, observations were made with a television camera which had an analyser in front of its objective lens (Gadsden *et al.*, 1979). The analyser consisted of a polaroid filter fixed in position over the lens, and in front of this filter there was a rotating quarter-wave plate. A blue-green filter gave a certain amount of spectral selection. The output from the camera was recorded on tape for subsequent analysis in a video-integrator which allowed the signal from an part of the picture to be selected and displayed on a chart recorder. (This system has been called a 'post-hoc photometer'.) Taylor (1981) shows that such an analyser gives an unambiguous signal in the presence of circular polarization in the light coming from any part of the field of view. Only one display offered during the summer that this television system was operating, that of 1978 July 28. Examination of the video recording showed that on this occasion circularly-polarized light was coming from only a single small area of the clouds, with immediately adjacent areas showing none. The proportion of circular polarization was 0.005 ± 0.0013, which is small when compared with the earlier measurements (Gadsden, 1977). The distinct localisation of the area giving circular polarization argues against it having come about through tropospheric scattering contributing to the incident sunlight. The circular polarization is probably a result of the scattering process in the clouds themselves. More information is needed to decide what processes are going on; the interpretation is, in some ways, as uncertain as the interpretation of the spectral radiance measurements.

3.8. Movements seen in the cloud layer

Rather a large amount of attention, possibly out of proportion to the relevance of the data, has been paid to estimating the wind velocity displayed by the movements of noctilucent clouds. In principle, the observations are quite simple. If the height of the cloud is assumed (usually 82 km), photographs of the cloud taken at intervals can be measured to give the wind speed and direction and the period and wavelength of any waves seen in the clouds. Sometimes the measurements of movements are made from visual observations but these are really rather uncertain; the movement of the clouds across the sky is slow and their shape may change during the time embraced by the observations. Grishin (1958, 1960) has discussed these problems with some vigour and is inclined to give weight only to those estimates of speeds and directions which are got from time-lapse cinematography of the clouds. Even using still photographs made at known intervals can be deceptive, he says, and it is difficult not to agree. The problem lies partly in the optical thinness of the clouds; if there is more than one layer, or if the structure that is seen is the effect of viewing an optically thin layer obliquely, measurements of the movement of a feature across the sky can be misleading. With the large redundancy in the amount of information recorded during cinematography, it becomes simpler for the viewer to distinguish the various types of motion and to have some confidence in deciding the cause of the apparent motion.

Vestine (1934b) gives what he calls an indication of cloud movements; the direction is generally northeast or east after midnight and without a clear preference of direction for clouds in the first half of the night. The speeds average perhaps 50 m s^{-1} or so, with some speeds shown as being well above 100 m s^{-1}. A fundamental problem in interpretation is shown up by the two plots that Vestine has in this paper. In his Figure 6, the caption reads:

> Direction of movement of noctilucent clouds for various values of approximate local time.

and I read this as meaning the direction towards which the clouds appeared to be moving. But the caption under his Figure 7 reads:

The vectorial distribution of velocities of noctilucent clouds moving from various azimuths.

and this plot shows the majority of the vectors pointing towards the south and west.

Stormer (1935) measured a number of cloud photographs taken for triangulation. The display of 1934 June 30 showed:

The velocity of 80–83 m s^{-1} was from east to west. A series of waves with their crests oriented north and south appeared, the distance between successive crests being 6–9 km.

There is little doubt here about the meaning.

Grishin (1960) applied cinematography to the problem of measurement and discusses three kinds of waves that can be distinguished. These are, in his notation, small crests (type IIIa), crests (IIIb) and wavelike arcs (IIIv). The typical wavelengths of the three types are 5–10, 50–100, and > 100 km, respectively.

Witt (1962) in his seminal paper on the photogrammetry of the cloud displays in 1958 remarks that the speed of the mean horizontal flow could not be determined with certainty. In the early stage of the display, wind speeds of 80–100 m s^{-1} were obtained; these values mean that the wave structures he measured were moving at some 70–135 m s^{-1} in the frame of reference of the clouds. He found an average amplitude of the waves to be about 2 to 3 km, with locally larger amplitudes here and there. He says:

Wave motion on a smaller scale is represented by systems of parallel billows of different orientations. The appearance of the billows may remind the observer of that of tropospheric clouds or a 'mackerel sky', as sometimes seen in the literature. Analysis shows that, at least in this case, the cloud surface was continuous between the billow crests... Thus, it is reasonable to conclude that the increased brightness of the crests is due to geometrical effects rather than to a sublimation and reevaporation process... The characteristic wavelength of the billows is about 4 to 9 km with amplitudes of about 500 to 1000 m.

Haurwitz (1964), and Haurwitz and Fogle (1969), have examined the significance of the estimated speeds of the mean flow, the drift of the clouds, and the velocity of waves moving in the clouds. The physical model that is favoured by them is the occurrence of gravitational waves at an interface presumably, they say, the mesopause. An alternative is the presence of internal gravity waves which exist without the necessity of an interface. Critical to an understanding of the role of gravitational waves at an interface is reliable knowledge of the wind, wind shears, and temperature in the neighbourhood of the clouds. This knowledge is available only to a sketchy extent.

Fogle and Haurwitz (1969) present fresh data from displays observed over North America in 1965.

The data show that NLC bands are characterized by wavelengths of 10–75 km, amplitudes of 1.5–3 km, lifetimes of several hours, lengths of hundreds of kilometers, and apparent speeds of 10–30 m s^{-1}. The NLC billows are characterized by wavelengths of 3–10 km, amplitudes of 0.5–1.0 km, lifetimes of 6–24 min, and lengths of 10–40 km. Billows generally move with the display while the bands generally move in a different direction.

Grishin (1967a) discusses at some length the effects of oblique viewing on the appearance of, and movements deduced from, a transparent layer of cloud. He illustrates his argument with striking geometrical interpretations of photographs of clouds taken in the period 1956 to 1965. The pictures of the complex structure in a cloud photographed on 1951 Jul 6 are particularly striking and are well worth study. His paper is later summarised in English (Grishin, 1967b) but without the halftone reproductions.

Burov (1967) reports on a programme of stereogrammetry of the clouds made in 1964 and 1965. The base line had a length of 52 km, and was sited in Estonia at a latitude of 58° N. Heights from 73.4 to 90.6 km were measured, with velocities in the range of 18–262 m s^{-1}. Schroeder (1969a) reports on measurements made at Roennebeck in 1967. He found wavelengths in the range 9–50 km, and estimated the general motion of the clouds to be towards the southwest with velocities 35–55 m s^{-1}. The measurements were made on the display of 1967 July 4.

Grishin (1969) describes some single station photographs of a cloud display observed from Moscow on 1967 July 3. He finds a speed of movement of 30–55 m s^{-1} in a southward direction but this was for crests running behind a bright band which was at the time moving towards the west.

The in situ measurement of winds in the mesosphere at the time of a noctilucent cloud display has been done but rarely. Theon, Smith and McGovern (1969) report on the results obtained by grenade sounding carried out from eight rockets launched at high latitude sites in the summers of 1963, 1964, and 1965. Five of the flights were at times when there were clouds present, three when no clouds were seen. The wind measurements were obtained at heights up to 95 km. Temperatures were measured at the same time and these are discussed in Section 6.1; clearly the mesopause was penetrated on these flights.

The data show no very obvious effect of there being a cloud at or near the mesopause. The authors find that there is an indication (at 95% confidence level) that the clouds are associated with lower wind speeds than is the case when there are no clouds to be seen. Table II, below, is taken from their paper.

Grah and Witt (1971) tried to obtain stereogrammetric observations of noctilucent

TABLE II

Observed mesopause winds in the presence and absence of noctilucent clouds

Site Latitude	Date	Local Time	Wind vector m s^{-1} (degs.)	Cloud present?
66 N	1963 Jul 30	01:28	31 (101)	Moderate
66 N	1964 Aug 7	02:16	36 (328)	Strong
66 N	1964 Aug 16	03:13	84 (89)	Weak
66 N	1964 Aug 17	02:49	24 (352)	Moderate
71 N	1965 Aug 7	01:13	29 (267)	Strong
66 N	1963 Aug 2	01:27	96 (53)	No
66 N	1963 Aug 8	00:29	165 (32)	No
71 N	1965 Aug 9	00:10	54 (72)	No

clouds at the same time and in the same area of sky as in situ measurements of winds from the tracking of smoke puffs left by a rocket passing through the mesosphere. There are difficulties in doing such a joint experiment; on several occasions, either the rocket tracking wasn't satisfactory or there were tropospheric clouds hindering the photographers. On 1964 August 16, the stereocameras got satisfactory pictures of the smoke puffs but there was no noctilucent cloud at the time. The authors show a useful graphical comparison, though, between the wind measurements from 49 to 90 km by optical and by grenade methods.

Hines (1968) puts forward the case for interval gravity waves being the source of the wave structure in noctilucent clouds. He takes observations made over Scandinavia on 1958 August 10 – the Witt (1962) data – and relates these results to surface frontal systems. He shows that there are indications that fronts and jet streams low in the atmosphere may well account for the mesospheric wave systems. The connection is through propagation of internal gravity waves whose source lies in the weather systems at low levels. Support is added when he compares noctilucent cloud data reported by Fogle and the weather systems over North America at that time.

In a series of papers, Schroeder (1968, 1969b, 1970b, 1971, 1973, 1974) suggests that the frequency of occurrence of noctilucent clouds in any particular year is controlled to some extent by the spring transition of mesospheric winds. He points out that the clouds are seen only when the cold mesospheric circulation (with a general lifting of the air in the region) is established. The changeover, in spring, from winter to summer circulation probably occurs earlier at the lower mesospheric levels, so the start of the noctilucent cloud season will be accelerated or delayed according to whether the spring transition moves up quickly or slowly. On the other hand, the change back to the winter circulation occurs first at the top of the mesosphere and the noctilucent clouds are the first things to be stopped when this autumn transition occurs.

Scott (1974) in a separate study shows a correlation between the maximum height reached by the 10 mb surface over the North Pole during December and January and the date of the first observation of noctilucent clouds the following summer. What caused him to look into this was a tendency for the first observations of noctilucent clouds in a summer to be earlier in a summer that followed a major stratospheric warming at any time during the previous winter. He notes that the effects of a major perturbation of a stratospheric winter circulation, which will be quite smoothed out by the beginning of March, seem to persist higher up, in the mesosphere, until late in May or early June.

Grishin has suggested for some years now that there is an immediate, in the sense of a few days, connection between tropospheric weather and the occurrence of noctilucent clouds. Bronshten and Grishin (1970) give a good summary of the position; in brief, a moving ridge of high pressure is thought to launch gravity waves up into the atmosphere. The authors do not state a mechanism for the formation of the clouds when the gravity waves reach the mesosphere. There is much persuasive evidence, though, for the connection between the troposphere and the mesosphere being present even if the processes involved are none too clear.

3.9. Association with hydroxyl airglow emission

Shefov (1967) has made a long series of measurements of the nightglow emission coming from excited hydroxyl radicals in the mesosphere. The altitude of the emission is quite close to that of noctilucent clouds and the radicals are excited in the process of their formation from atomic hydrogen and ozone. The atomic hydrogen available at those levels comes largely from the photodissociation of water vapour (see, for example, the discussion by Anderson and Donahue, 1975).

There are thus two principal reasons for directing attention to the hydroxyl emission in the context of observing noctilucent clouds. The rotational levels of the radical should be in thermodynamic equilibrium with the surrounding atmosphere and the rotational temperature should therefore be the same as the local atmospheric temperature. The emission has a relatively open rotational structure and the determination of rotational temperature is therefore a relatively straightforward problem of spectrometry. Secondly, the intensity of the hydroxyl emission can be expected to be related to the water vapour content of the mesosphere although the relationship need not be straightforward because the hydrogen: ozone reaction is one of many involving both water vapour and ozone.

As one would expect, the rotational temperatures measured during the summer from Moscow (56° N) are low, in the vicinity of 160 K. When noctilucent clouds appeared, the temperature did not necessarily fall to a lower value; indeed, Shefov notes that sometime the temperatures were actually higher than usual, with a lower temperature being seen the day after the display of clouds. The intensity of the hydroxyl emission was normally up by a factor of two during a cloud display compared with the average value on other nights during the summer. He saw evidence, too, that the night following a cloud display showed a decrease in intensity, to below the average by a factor of two or three, with a recovery to the average value by the second night after a display.

Harrison (1973), observing during one summer from Calgary (51° N) in Canada, obtained data from a single display of clouds together with data from other (cloudfree) nights in June and July. He could see no particular effect of the cloud upon the temperature and intensity of the hydroxyl emission.

Shefov's results are interesting but their interpretation is subject to certain inherent difficulties. It has to be remembered that the emission comes from a considerable thickness of atmosphere – probably greater than 10 km in altitude extent. The rotational temperature is therefore a weighted average over a considerable range of temperatures. Furthermore, a change in measured temperature might as well be the result of a change in mean height of the layer as an actual change in temperature of the mesosphere. Similarly, an increase in the intensity of the emission may well result from a decrease in mean height of the emitting layer. Perhaps, then, the changes of temperature and intensity associated with cloud displays come about through the airglow layer being lower than usual in the presence of a cloud, with the layer being somewhat higher than usual on the following night.

3.10. Association with aurora

Soon after noctilucent clouds had been recognised for something rather unusual, Smyth (1886) noted the occurrence on the same evening of the clouds and an auroral arc. His description of the sky, which has published in Nature, is rather attractive and is of a literary style probably unacceptable to most scientific journals of the present day:

> On issuing, then, that night [1886 July 27], close upon twelve o'clock, from the Observatory computing-room, upon the Calton Hill, I was surprised and even startled, not at seeing a low-down coloured twilight in the north, but at the excessive strength, and glittering brightness of its colours. You might indeed have, at first sight, imagined that some great city, spread abroad over the plains of Fife was in a fierce state of extensive conflagration, so burning red was the first and lowest stratum extending along nearly 20 of the horizon. But that awful kind of redness passed quickly into lemon-yellow clouds in the stratum next above the red; and then came the silver-blue cloudlets just above the lemon-yellow, and even brighter still; but with an innocence of colour and gentleness of beauty, which at once exorcised the horrid idea of malignant flames devouring the works of man; and showed it must be something very different. ... At the same time a few stars were faintly visible; while a long streamer, of apparently white cirrus cloud, trailed over half the sky from west to east-north-east, and passed across the Polar region at a considerable altitude, having the silver-blue cloudlets and their gorgeous red basement far below, but within, its wide-enclosing sweep.

Perhaps his being Astronomer Royal for Scotland helped the Editor to accept his Letter. What is more germane to us, is that Smyth used a spectrometer at his home to look at the different parts of the sky. The red glow close to the horizon showed an emission line in the green which, by micrometer measurement and reference to a hydrogen lamp, he found was the auroral green line. With a hand spectroscope, he could see that the band of 'cirrus cloud' was simply an auroral band or arc. He saw the green line sharp and brilliant along the whole length of it. A short time later (at about 1 a.m.), the auroral band became active and showed rays. In fact, as Smyth remarks, a very fair auroral display.

The same aurora was seen by Backhouse (1886) from Sunderland; he adds the information that the noctilucent clouds were visible chiefly before the aurora appeared and after it vanished; he says there is no reason to suppose there is any connection between the two phenomena. The comparison by D'Angelo and Ungstrup (1976) of Fogle's data of occurrence of the clouds over North America and the daily K_p sum has been mentioned earlier (Section 3.4). The observations described above suggest that the connection between auroral activity and the probability of occurrence of noctilucent clouds is not a simple one.

The appearance together of the clouds and an aurora has alsways caught the attention of observers. On 1950 July 24, Paton (1950) photographed from Abernethy (56° N) an auroral arc with base at 10 degrees elevation and noctilucent clouds reaching 5 degrees elevation beneath the arc. The geographical positions of the two must have been very close. The clouds were watched and photographed from just after 22:00 UT until they disappeared into the dawn at about 03:09 UT. The display extended over the sky and at 00:50 UT covered an area between azimuths 345 and 85 degrees, up to an elevation angle of nearly 25 degrees. Meanwhile, the aurora had vanished or had been extinguished by the brilliant light of the clouds.

In a later paper (Paton, 1953), the aurora is described as developing sunlit rays in the early part of the night. At about 02 : 05 UT, turbulence appeared in the eastern part of the cloud display and within a quarter of an hour, the clouds became

> ... quite chaotic in structure ... though as the photograph shows, the parallel horizontal bands were still visible. Among some twenty displays of noctilucent cloud that have been observed since 1939, this is the only occasion when such turbulence has been seen. That it occurred soon after a brilliant aurora may be significant.
>
> Did it arise from some thermal effect associated with aurora or was it merely the turbulence that would be expected near the earth-shadow boundary? At all events, it persisted unabated until the clouds vanished against the brightening sky at 03 : 09 GMT. Sunrise was at 04 : 02 GMT.

In a typed note found among James Paton's papers (Byrne, 1963), another simultaneous occurrence of aurora and noctilucent clouds is reported from Lerwick (60° N) in the Shetland Isles. On the night of 1963 July 30, the clouds were first noticed at 22 : 45 UT, towards west–north–west, covering about one-sixteenth of the sky. The elevation is given as 18 degrees in the north–west, 26 degrees in the west. At midnight, the clouds were barely discernible but by then there was an auroral arc visible towards the north–north–east, maximum elevation of 6 degrees. At 03 : 00 UT, the arc had rays and the noctilucent clouds were becoming brighter. The cloud was in the same position as at 22 : 45 UT, but had become more patchy and less fibrous than before.

Fogle (1966) arranged for a special observing programme in western Canada in the summer of 1965. Noctilucent clouds and aurora were observed together on thirteen nights. On seven of the nights, they were in the same part of the sky. The general effect of the aurora was a decrease in the area and intensity of the clouds (on two occasions, they vanished) and a decay of their 'well-ordered structure'. Fogle suggests the possibility of auroral heating at or below the mesopause.

Schroeder (1970), on the other hand, saw no unusual changes in the clouds when aurora occurred on two nights in July 1963. The observations were made from Ronnebeck (53° N).

In summary, it is not clear what effect an aurora has upon clouds below it in the mesosphere. The examples mentioned above seem to refer to clouds and aurora at the same, or very similar positions; one should remember that the aurora base is probably some 20 to 25 km higher in the atmosphere than the clouds. There seems to be no doubt about the statistical relationship between magnetic activity and the likelihood of seeing clouds but the detailed, individual occurrence, behaviour is not all of a kind.

3.11. Lidar measurements

The only observations of noctilucent clouds using a laser appear to be those of Fiocco and Grams (1969). The laser emitted 100 ns pulses containing 2 J, with a maximum pulse repetition frequency of 0.5 s^{-1}. Observations were made from Kjeller (60° N) on 21 nights in July and August, 1966. Noctilucent clouds were overhead on five evenings and present in the sky on a further four nights. Thus there were twelve nights for comparison on which no noctilucent clouds were seen.

The measurements show that the 60–70 km altitude region contains an appreciable amount of particulate material. They found that the noctilucent cloud layer was at an altitude lying fairly close to 74 km. They report on changes in height of a particular cloud; in a period of 90 s, the height changed from 75 to 73 km. The geometrical thickness of the cloud appeared to be 0.5 km, with an optical thickness of approximately 10^{-4}. The photoelectron statistics of the data are poor, though, and the upper atmosphere scattering layers appear marginally above the returns from a dust-free atmosphere. It will be noted that the height given for this cloud is somewhat lower than what is generally found by triangulation on other clouds.

3.12. Miscellaneous observations

Fast and Fast (1981) have seen noctilucent clouds in unusual conditions. They were in the small village of Krasnoyarka (55° N) to view the total solar eclipse of 1981 Jul 31. They saw noctilucent clouds on the evening before the eclipse and again for some six minutes during and after totality. The clouds were horizontal streaks extending about 30 to 40 degrees in azimuth and no higher than 5 or 6 degrees in elevation. They were seen in the azimuth of the eclipsed Sun (approximately 35° elevation), below the corona. The total phase had a duration of 84 s and the clouds, which were first noticed after totality had started, were visible for four to five minutes after third contact. The Fasts say that the noctilucent clouds were confidently identified by more than ten observers who had experience of noctilucent cloud observations. The scattering angle for the observation lay between 30 and 40 degrees, rather similar to what is often the case during normal twilight observations.

A bright 'noctilucent cloud' was seen and photographed from Tucson (32° N) in the U.S.A. by Meinel, Middlehurst, and Whitaker (1963). The height calculated from the time that the cloud vanished in twilight was 71 km. The figure is corrected for refraction but no mention is made of any screening height. The authors remark that similar clouds have been seen on many occasions from Tucson; the days always coincide with the launch of a space vehicle from Vandenberg Air Force Base in Southern California. They conclude that these clouds are the exhaust clouds of rockets.

Similar observations are reported by Benech and Dessens (1974). On two occasions, 1971 February 23 and 1972 March 18, a mesopsheric cloud was nucleated by the exhaust of a rocket passing through the region. The launch site was at Landes (44° N) in France; the cloud was formed a little to the north of the site, at close to 45° N, on each occasion. Very little water was released by the rocket engines but a cloud which grew briefly was seen and the photographs of the cloud certainly show an appearance reminiscent of noctilucent clouds. The cloud on the second occasion was measured by triangulation and it lay between 79 and 92 km altitude.

4. Observations in Situ

Sounding rockets have been used with some success in studying the cloud region, and the clouds themselves. Measurements of ion composition and of wind and temperature sensing are discussed in Section 6; in addition to these measurements, a considerable amount of effort has been put into collecting the particles in the clouds (sampling) and to studying the scattering of sunlight from the clouds with scattering angles (usually 90 degrees or thereabouts) unattainable in practice from ground level.

4.1. Scattering and polarization of light

It appears that Witt (1969) was the first to fly a photoelectric photometer or polarimeter through a noctilucent cloud. He found a distinct layer, with a sharp lower boundary, on both ascent and descent of the rocket. There were problems with illumination of the polarimeters by the Sun but data were successfully obtained from both channels. The effective wavelength of the radiation was 366 nm on one channel and 534 nm on the other. The scattering angle was 86 degrees. The layer was entered at 82.4 km altitude, and the rocket seems to have broken clear of the layer by about 84.4 km. The ratio of the radiances at the two wavelengths (534 : 366 nm) was at least 2.5. There was a high degree of linear polarization, and if the cloud particles were scattering as monodisperse dielectric spheres of refractive index 1.33, an upper limit of 0.2 μm in radius was indicated. The column abundance of such particles was found to exceed $10^8\ m^{-2}$.

Witt was involved in another rocket sounding from Kiruna (69° N) the following year (Witt *et al.*, 1976). For this flight, the wavelengths chosen for the polarimeters were 256 and 536 nm. Both instruments sensed a scattering layer at altitudes between 85.5 and 89 km on both ascent and descent. The 256 nm polarimeter signal was affected to a considerable extent by fluorescence from upper atmosphere nitric oxide. The strength of the scattered light at 536 nm from the layer amounted to roughly one-half that from molecular scattering at 85.5 km. The data do not refer to noctilucent clouds but rather to a scattering layer somewhat higher than where the clouds are seen usually. Witt *et al.* deduce an upper limit to particle radius of 0.05 μm. These may well be the particles available for nucleation of noctilucent clouds when the temperature or humidity is right. The scattering would have been caused by a column abundance of approximately $10^9\ m^{-2}$; for a layer thickness of 3 km, the mean particle density density becomes $3 \times 10^5\ m^{-3}$.

Witt *et al.* (1971) give a report on two flights from Kiruna in 1971 using more ambitious polarimeters. These involved measurements at seven wavelengths (214, 309, 366, 453, 536, 589, and 762 nm) and there were a number of other instruments (airglow infrared photometers, nitric oxide ionisation chamber, solar irradiance photometer, ion collector, and Faraday rotation). The preliminary results from the polarimeters showed noctilucent clouds on both flights. On the July 31 flight, the layer was between 82 and 83 km; the following night, the cloud layer was rather higher, at 85–87 km. At 453 nm, the degree of polarization was a little higher than that expected from molecular scattering.

Rossler (1972) has made measurements of the scattered radiance in a cloud from a rocket launched from Kiruna at 00:40 UT on 1970 August 10. There was clear evidence of a scattering layer at 82.5 km with integrated radiances (at 470 and 600 nm) of $0.1\ W\ m^{-2}\ sr^{-1}$. A flight on 1969 August 14, ‘in the case of no noctilucent clouds’, had showed a scattering layer at 83 km altitude with the same radiance at a wavelength of 460 nm. Rossler fits his data with a model containing two classes of scatterers, Aitken nuclei of radii between 0.03 and 0.05 μm and particles ('Junge particles') with larger radii in the range 0.1 to 1 μm. The derived number of particles in all three cases lies close to 500 m^{-3} for the larger particles and 10^6 m^{-3} for the smaller, Aitken, particles. De Bary and Rossler (1974) return to the analysis of the data from the 1970 August 10 flight (the one with a cloud present) and give the results listed in Table III for scattering at three heights, viz. just above, in, and just below the cloud. There are differences, as one one would expect, between the relative numbers of the two groups of particles at the different heights.

TABLE III

		Particle numbers (m^{-3})			
	Scattering	600 nm		430 nm	
Height (km)	angle (deg)	Aitken	Larger	Aitken	Larger
87	85	2×10^4	40	5×10^3	50
82	77	5×10^5	250	3×10^5	500
74	77	4×10^5	30	4×10^5	150

As part of a campaign to launch particle collectors through noctilucent clouds (see next section), Tozer and Beeson (1974) obtained polarimetric data from four flights over Kiruna. The instrument on each of the flights had two channels sharing a common entrance pupil (through the use of a split fibre optic bundle). Filters gave effective wavelengths of 540 and 410 nm. The published data include upward looking radiances at 250 m intervals in height between 60 and 101 km. The better data were obtained from the latter two flights which were separated by 31 minutes around local midnight on the night of 1972 August 1. On both these flights, the rocket passed through a bright noctilucent cloud which lay between 83.3 and 84.4 km. On all four flights (i.e. including the first two in the series, on 1971 July 31 and August 1), a weakly-scattering layer was seen low down, at around 68 km altitude. This confirms the observations of Fiocco and Grams (1969), discussed in Section 3.10, who detected layering in this region with a ground-based laser. The polarimetric data of Tozer and Beeson are summarised in Table IV, which is taken directly from Table I in their paper.

There was no penetration of a noctilucent cloud on the flight on 1971 August 1.

Gadsden (1978) has scaled the data plotted from the 1973 flights to give volume scattering coefficients, from numerical differentiation, at altitudes from well below to well above the cloud layer. The 410 nm data in particular gave very convincing scattering data and comparison with expectations based on molecular scattering in the atmosphere below the cloud layer was good. The rocket data can be used to obtain the ratio of the radiances at the two wavelengths, and the derived ratio of the volume scattering

TABLE IV

Flight and wavelength (nm)	Altitude of NLC (km)	Total brightness (10^{-10} W m^{-2} sr^{-1} A^{-1})	Degree of polarization	Scattering angle (deg)
1971 Jul 31				
(Ascent)				
540	82.0–83.4	212	0.96	80
410	81.9–83.4	288	0.87	80
(Descent)				
540	82.9–83.7	231	0.95	81
1973 Aug 1				
(1st Ascent)				
540	83.3–84.2	600	0.88	78
410	83.3–84.2	1725	0.78	78
(2nd Ascent)				
540	83.4–84.4	1000	0.94	84
410	83.4–84.7	3100	0.79	84
(2nd Descent)				
540	83.2–84.7	957	0.80	74
410	83.3–85.1	2613	0.71	74

coefficients for the region below the cloud was found to be 0.30, in good agreement with the value 0.33 expected from molecular scattering. The scattering in the cloud layer gave a ratio, using the same data, of 0.33, in accord with Witt's statements that the degree of polarization in a cloud is similar to that obtained from light scattered from clear air. Tozer and Beeson summarise their data by suggesting that the cloud particles are principally less than 0.13 μm in radius, with a number density in the cloud of approximately 10^6 m^{-3}.

4.2. Collection of samples of cloud particles

For a period of about ten years, starting in 1962, a considerable effort was made to obtain samples of the particles in a noctilucent cloud. Two successful flights, on August 7 (no noctilucent cloud) and August 11 (noctilucent cloud), were launched from Kronogard (66° N) in northern Sweden (Hemenway *et al.*, 1964). Collecting surfaces were exposed between 75 and 98 km altitudes during the ascent of each rocket. The second flight, made with noctilucent clouds over the launch site, showed a column abundance of particles at least one thousand times greater than on the first flight, in the absence of clouds.

Each rocket carried a variety of particle collectors and the particles were analysed (after postflight recovery) by electron diffraction, neutron activation and electron beam techniques. Some evidence was found for water in the collected specimens; a significant fraction of the particles showed the presence of a volatile coating, presumably ice, at the time of collection. The ice, if that is what it was, had sublimed or melted and evaporated before examination of the collectors.

Hemenway *et al.* summarise the findings from the collection of experiments as follows:

(1) The nuclei of noctilucent cloud particles are extraterrestrial origin.

(2) These nuclei have an integral size distribution of the form $N = \mathrm{Ad}^{-p}$; $3 < p < 4$.

(3) The size distribution of nuclei cuts off sharply at about 0.05 microns diameter.

(4) A significant fraction of the particles were ice coated when collected.

(5) The layer concentration in the sampled layer (75–98 km) is at least one thousand times greater in the presence of clouds than when they are not seen.

(6) The particle concentration in a vertical column through the cloud display of 11 August 1962 was greater than 8×10^{10} particles per square meter.

(7) If the particle density (number per unit volume) decreased exponentially with height then the scale height is about 2 km.

There seems to be a relation between the size of the coated particles and the size of the solid nucleus seen inside many of them. The larger nuclei appeared to have attracted thicker coats of volatile material. The size distribution of 93 coated particles is shown in Figure 10, where the distribution of radii of the complete particle (nucleus + halo) is shown separately from that of the radii of the nuclei.

Two different preparations of nitrocellulose collectors were used. Both had 20 nm thick films for substrate; one type had a thin overcoat of aluminium, the other was coated with a layer of fuschin dye (Soberman *et al.*, 1964).

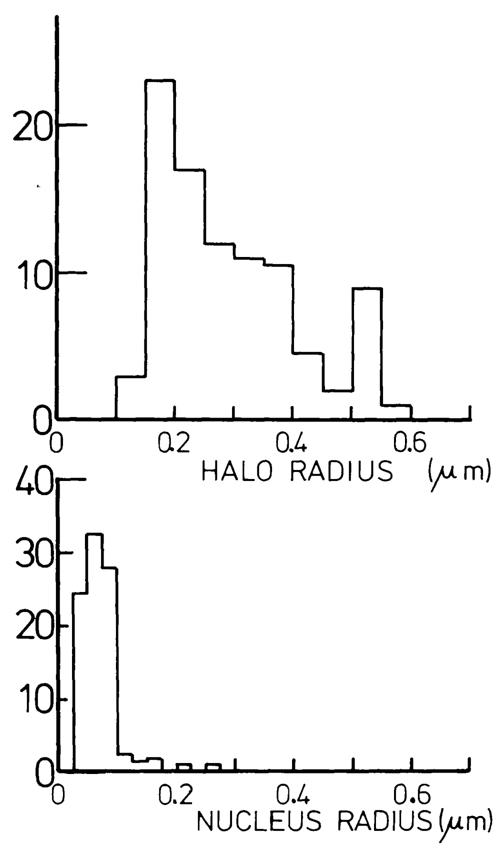

Fig. 10. Histograms of particle radii based on 93 particles found on a nitrocellulose film flown through a noctilucent cloud (Hemenway *et al.*, 1964). The upper plot is the radii of particles showing haloes, the lower plot the radii of their solid nuclei.

Hemenway, Fullam *et al.* (1964) discuss the samples obtained with these films in some detail; they present cumulative distributions of sizes of the particles found on one each of the detectors. Their data have been replotted here in Figure 11 as size distributions rather than cumulative plots.

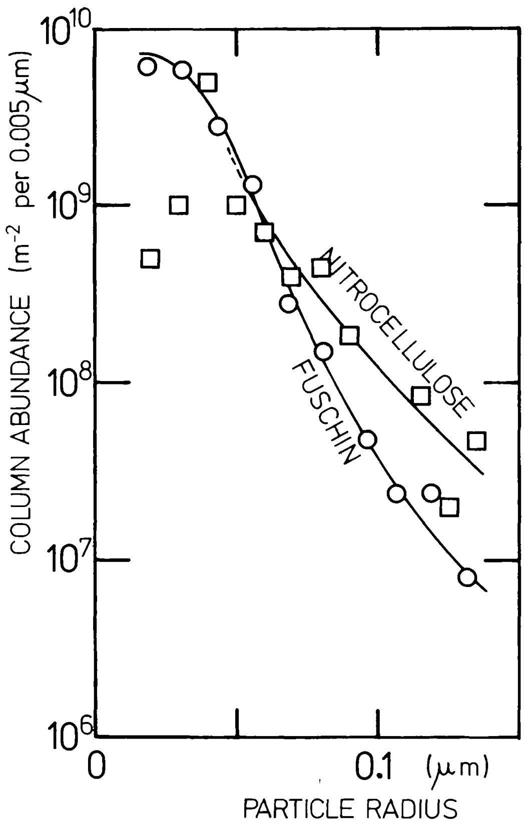

Fig. 11. Logarithmic plots of the size distributions found from two different collectors flown through a noctilucent cloud (Hemenway *et al.*, 1964).

Calcium film collectors were also flown (Linscott *et al.*, 1964). These consisted of a package of evaporated layers on a lucite substrate. From the lucite outwards, there was first a layer of lithium fluoride approximately 100 nm thick, then a layer of aluminium (5 nm) and a relatively-thick layer of calcium which was in turn covered by 5 nm of aluminium and a layer of paraffin. The whole sandwich was topped with a layer of silicone oil. The detector was judged, after tests, to be capable of detecting ice crystals at least down to 0.25 μm radius; metallic and abrasive particles 0.1 μm and upwards in size were fired with speeds of around 800 m s^{-1} at the layer in tests and only those particles larger than 10 μm were found to rupture the calcium film.

Results were obtained from four such surfaces, two on each flight. The surfaces from the second flight (in the presence of noctilucent cloud) were clearly different both from the controls and the surfaces carried on the first flight. There was a variable density of the calcium film and examination under phase contrast illumination showed a coarse texture to the exposed film. Laboratory tests using a radio-tagged water spray at low temperature and pressure suggested that the slight changes in reflection and transmission arose from approximately 1.5×10^{-5} kg m^{-2} of moisture. If the density of haloed particles on the nitrocellulose collectors referred to above (4.5×10^{9} m^{-2}) is taken as the relevant number of cloud particles for the calcium film detector, each cloud particle had 3×10^{-15} kg of water associated with it (corresponding to a sphere of radius 0.9 μm).

Witt (1969) tried to repeat the observation of haloed particles on a flight in 1967, which was launched through a noctilucent cloud display. The collector was a collodion film shadowed with palladium for electron microscope examination. The limit of detection was particles of radius less than 5 nm yet only two particles were found on 4 mm^2 of the film.

Hemenway, Hallgren and Schmalberger (1972) flew rockets from Kiruna (68° N) in northern Sweden during the summers of 1970 and 1971. The payloads included 'Pandora' collectors (Hemenway and Hallgren, 1970); these had the capability of inflight shadowing of films for subsequent electron microscopy. Much of the doubt about the origin of the particles is removed thereby. There is a clear signature of two shadows to indicate particles that were acquired before the interval between two evaporations using separated sources of the shadowing material. Again, two-component particles were collected. There was an electron-opaque core surrounded by low-density material in a rounded coating. In the 1970 collections roughly 70% of the particles were of this type, compared with but 15% from flights the following year. In both years the remaining particles were mostly single, submicron irregular particles of high electron optical density.

In a later paper, Hallgren, Hemenway *et al.* (1973) discuss the 1970 flights and present the data in a little more detail. The haloed particles accounted for 85% of the total collected and were clearly round or elliptical droplet-like particles of low electron density with varying amounts of high density material in their centre. The particles did not appear to be the same type as were seen in the 1962 flights but the authors say that a difference in shadowing technique may account for this. The concentration of particles was about ten times greater than was seen on a similar flights from midlatitudes (at White Sands, 32° N, in the U.S.A.) and a hundred times less than was seen on the noctilucent cloud penetrations in 1962.

Hallgren, Schmalberger and Hemenway (1973) report on the 1971 flights carrying 'Pandora' collectors. There were two flights, on July 31 and August 1; the first successfully penetrated a cloud, the second missed. In these and other collections, examination of the composition of the solid particles that were acquired showed the presence of remarkable amounts of elements of high atomic number; this is used to identify the particles as of extraterrestrial origin.

Farlow *et al.* (1970), (see also Ferry and Farlow, 1972) have flown a different type of collector through a noctilucent cloud. In the flight of 1968, launched from Fort Churchill (59° N) in Northern Canada, the arms bearing the electron microscope screens began to open at 55 km altitude, rather lower than was planned, and trouble was experienced with damage to the screens. Farlow and Ferry are not sure that the collection was from a noctilucent cloud but they did see a considerable increase in numbers of collected particles over and above what they expect in flights at midlatitude.

Their solid-particle collector was scanned first at a magnification of 4000 and they identify six distinct types of particle; only one (their type 2) was regarded as being of upper atmosphere origin. Figure 12 shows the size distribution of these particles; it is possible that the absence of particles of radius less than 0.025 μm, and the drop in numbers of particles of radii less than 0.05 μm arises from the difficulty of detecting and identifying particles of this size, even though the magnification was increased to 15 000 to make the counts upon which Figure 12 is based.

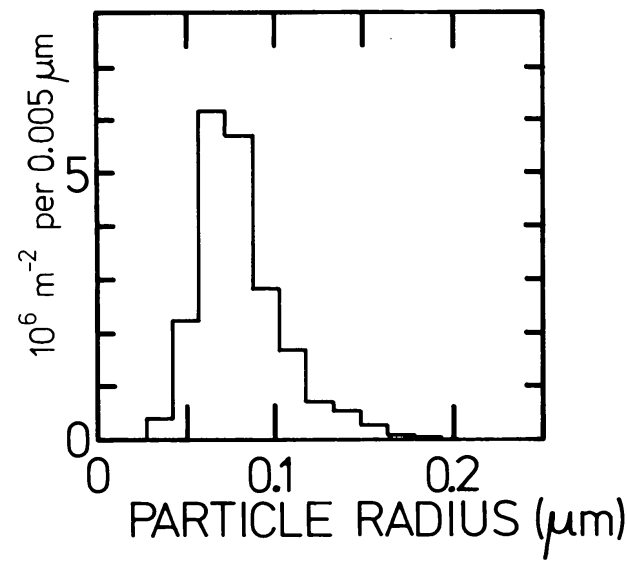

Fig. 12. Size distribution of so-called 'Type 2' particles found on collectors flown though a noctilucent cloud (Farlow *et al.*, 1970).

The water-droplet collecting surfaces that were flown showed no impacted particles. These surfaces were 50 nm layers of polyvinyl alcohol laid onto a 50 nm film of nitrocellulose. The alcohol is insensnsitive to humidity but highly soluble in water. A droplet, or ice crystal which subsequently melts, dissolves part of the film and leaves it at the edge of the drop during evaporation of the water, causing a raised rim or crater in the film.

Farlow and Ferry (1972) concluded that the particles they collected on the 1968 flight were indeed noctilucent cloud particles which had been uplifted to mesospheric levels from lower in the atmosphere. That is to say, they question the cosmic origin of the cloud particles or nuclei. Two further flights were made, also from Fort Churchill, in the spring of 1970, before the start of the noctilucent cloud season. The purpose was to measure the cosmic dust at the same latitude as the noctilucent cloud flight but before any uplift of low level particles had occurred. They found only a few dozen particles on the collecting surface where before they had several thousand.

Collectors and detectors of rather different type to those described above have been flown on a series of rockets launched into noctilucent clouds by a group at the Max-Planck-Institut in Germany. There were flights in 1968 from Fort Churchill

(Fechtig and Feuerstein, 1970) and in 1969 from Kiruna (Fechtig *et al.*, 1971). The following year, (Rauser and Fechtig, 1972), more data were obtained from a flight through a weak noctilucent cloud and in 1971 there were flights from White Sands (32° N) in April and Kiruna (68° N) on July 31 and August 1. Neither of the last two flights apparently penetrated a noctilucent cloud although both were made 'in the presence of' clouds.

The dust collectors used on the flights had clean and highly polished silver, aluminium and copper surfaces, some of which were shielded by a grid, some millimetres in front, supporting a 0.2 μm nitrocellulose film. A second type of particle detector consisted of a concave hemisphere of tungsten which acted as a grounded anode. The amount of charge released on the impact of a particle and the rise time of the pulse measured at a central cathode (−50 V) could be used to estimate both the speed and the mass of the particle.

The collector from the 1970 flight which penetrated a noctilucent cloud showed 290 penetration holes (diameters ranging from 1 μm to 50 μm) on 1.62×10^{-4} m^2. (This corresponds to 1.25×10^6 m^{-2} particles of radii greater than 1.5 μm.) Electron microscopy of an area equal to 25.4 mm^2 showed 5 accumulations of small particles ranging in radius from 0.025 to 0.1 μm, corresponding to a total of 5×10^6 m^{-2}. The collectors and detectors were exposed at 61 km altitude on the upleg of the flight, through apogee of 114.3 km, and closure took place at 99.5 km on the downleg. Some ring structures (with radii up to 15 μm) both with and without central particles were noted. These did not appear on the control surfaces and Rauser and Fechtig interpret these as

> ... probably produced by the impact of droplets or dirty ice crystals during flight. Vibration tests carried out on the collector films showed no holes comparable with those found on the flight samples.

Rauser and Fechtig (1973) summarise their findings as follows:

> ... particles in the micrometre and submicrometre range which are entering the atmosphere are decelerated to very low velocity (0.5–1 km s^{-1}) by the time they reach about 100 km altitude. However, the velocity profile between 70 and 100 km altitudes is very different from earlier model calculations. An explanation ofthe observed velocity profile is that particles falling through the cold summer mesopause are able toagglomerate or absorb condensable constituents like H_2O, CO_2 and related clusters as found in these-altitudes ... The existence of noctilucent clouds, therefore, may partly be explained by the presence of those particles in the region of minimum temperature which would correspond to the maximum of their mass x density phase.

5. Observations from Satellites

In 1972, Donahue *et al.* (1972) announced the discovery of a thin scattering layer over the poles of the Earth which appeared to have a mean altitude of 84.3 km (Donahue and Guenther, 1973) and to be a summertime phenomenon. The similarity to noctilucent clouds was obvious and was made immediately by the discoverers.

The layer was detected and measured with a photometer on board the orbiting geophysical observatory OGO–6. The photometer was designed to measure the airglow layers of atomic sodium and atomic oxygen (the 589.0 + 589.6 nm and the 557.7 nm emissions). It was a horizon scanning instrument, with a field of view corresponding to about 5 km in height at an altitude of 100 km. The scattering layer was seen on all satellite passes above 80 degrees latitude from 1969 June 5, the day of launch. The signal appeared to come from a thin layer which was clearly separated from the airglow layers higher in the atmosphere and was much more intense than was expected of an airglow layer. The signal stood out clearly above the scattering from the atmosphere just above and just below the layer; from the examples given in the paper, it looks as though the scattered intensity from the layer at 84 km is as much as that from the atmosphere some 20 km lower.

Analysis of the radiance suggested that the layer had a vertical optical depth of approximately 5×10^{-5}; if the scatterers were ice particles of spherical radius 0.13 μm, the authors calculated that there must have been approximately 6×10^{10} m^{-2}. This is a hundred times or more than is seen in noctilucent clouds at lower latitudes and the suggestion of Donahue *et al.* is that clouds seen at lower latitudes from ground level are a weak sporadic manifestation of the persistent polar layer. They observed the recurrence of the layer over the north pole in the summer of 1970 and its appearance over the south pole in late 1969.

These cloud densities imply a quite large water content in this part of the atmosphere; this point has been taken up by Reid (1975) and by Gadsden (1978). It is difficult, in some ways, to see how the atmosphere can provide enough water vapour to make the amount of ice that is implied by the observations. The situation is exacerbated by Hummel (1977) who reports that the concentrations of scatterers estimated by Donahue and his colleagues need to be increased by from five to seven times because an incorrect scattering cross section was used in the calculations.

Hummel (1975) and Hummel and Olivero (1976) have used the date from OGO–6 to confirms that the ice crystals had radii no larger than the assumed radius of 0.13 μm. This conclusion has been attacked by Gadsden (1978) on the grounds that their estimate of radius was made by taking the ratio of radiances of the scattering layer at the two (airglow) wavelengths available from the photometer data. The data are shown in Figure 13. There is too much spread in the measured ratio to allow any worthwhile conclusions to be drawn from these data. The great scatter in the plotted points comes about from the characteristics of the photometer; each channel, the oxygen and the sodium photometers, viewed the layer sequentially, not concurrently. The interval between consecutive observations at each wavelength is 74 s; taking a ratio of the radiance at one wavelength to the mean of the radiances at the other wavelength measured just before and just after involves comparing three distinct regions of the scattering layer separated through satellite motion over a line approximately 600 km in length along the track. The layer is unlikely to show uniformity of radiance along this.

Donahue and Guenther (1973) report some interesting statistics of the height of the layer. The average is 84.3 km and there is some indication that this progressively decreases as the summer season progresses (with a drop of 1.5 km in the three weeks before the solstice). There is a systematic dawn: dusk variation at 70–75 degrees

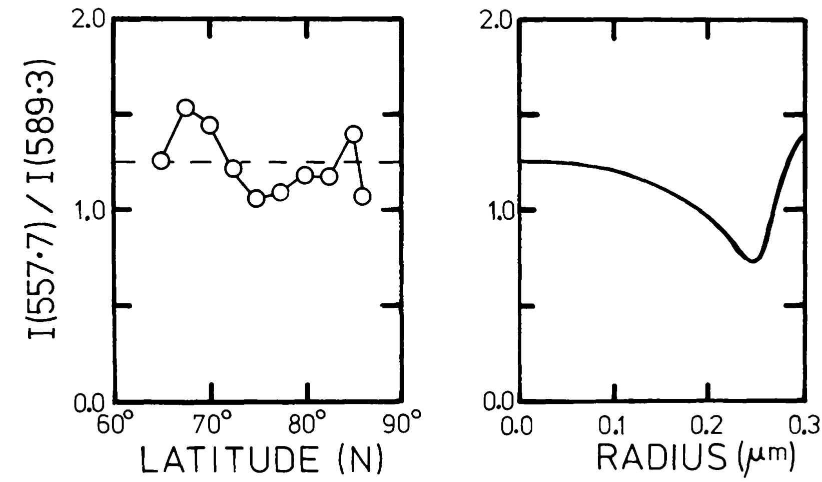

Fig. 13. On the left, the ratio is plotted as averages over 2.°5 intervals in latitude. The data are from OGO-6 and are those used by Hummel (1975) and Hummel and Olivero (1976). The broken line shows the ratio (1.256) expected for scatterers of vanishingly-small radius. The right-hand plot is of the ratio calculated using Mie theory for dielectric spheres of refractive indices 1.305, 1.304 (i.e. ice at 133 K) with radii up to 0.3 μm; scattering angle = 80°.

latitude. The average of the measured heights was 85.3 ± 0.8 km in the afternoon (local time 14 : 10–16 : 30) and 82.7 ± 0.6 km in the morning (05 : 12–05 : 38).

5.1. Visual observations

These photometer observations have been confirmed to some extent by visual observations on board the U.S.S.R. and U.S.A. space laboratories. On one orbit of Voshkod-2 (Lazarev and Leonov, 1973) a sharply-defined blue-gray layer was seen at 1.5 degrees distance above the nighttime horizon. The apparent height of the layer was deduced to be 80 km and there was perceptible absorption of starlight passing through the layer.

Packer and Packer (1977) give a brief report of observations by Weitz on Skylab-2. Noctilucent clouds were seen on four occasions during the 28-day flight by Weitz; they were seen always at dawn and in the direction of the rising Sun. They were never seen after the Sun had risen. Packer and Packer write:

> The clouds were bright, as conjectured, and formed a thin bright line just above the earth horizon when first detected. As the spacecraft approached, the thin line appeared to become broken, and finally two to four patchy, thin, stratified clouds were visible. Their lateral angular subtense was of the order of 5°, and as the spacecraft drew nearer, the clouds appeared to rise above the earth horizon, finally vanishing into the airglow. The sightings were made ... during the last week in May and the first week in June 1973 near 50° north latitude and 10–40° east longitude.

This astronaut was particularly impressed by the spectracular views of the horizon and specially by those at twilight. He spent as much time as his duties permitted in watching the view.

A considerable amount of attention was paid to observation of noctilucent clouds from the Salyut series of spacecraft. Willmann *et al.* (1977) report 27 occasions when the cosmonauts saw noctilucent clouds. They were the same clouds reported from ground level in widespread sightings from Northern Europe and the northern U.S.S.R. at the times of passage of Salyut-4. Views both edge-on and showing cellular (horizontal) structure were got from the spacecraft.

5.2. Instrumental observations

On the same Salyut-4 craft, there were four near infrared photometers available for horizon scanning (Avaste *et al.*, 1977). The effective wavelengths were 1.35, 1.9, 2.2, and 2.7 μm; the photometer at the shortest wavelength (1.35 μm) showed a plateau in the plot of radiance against distance above the horizon while there was no indication of the noctilucent clouds at 1.9 μm. On another occasion, the 1.9 μm channel showed a clear peak in radiance corresponding to a layer at about 80 km. The relative and absolute radiances at 1.35, 1.9, and 2.2 μm showed, from observations for a scattering angle of 80 degrees, that the vertical optical thickness of the clouds was in the range 5×10^{-5} to 10^{-4}.

Belyaev *et al.* (1979a) report on measurements of the spectral radiance of noctilucent clouds in the visible region. The data come from a small spectrometer on board Salyut-4 with a rapid scan in wavelength. Measurements were obtained as the spacecraft flew past (on a track between 40 and 50 degrees north latitude) noctilucent clouds at around 60 degrees latitude. The authors show a plot of relative radiance from 400 to 800 nm for three scattering angles, $22° \pm 7°$, $47° \pm 8°$, and $51° \pm 5°$. In the red, at about 740 nm, the radiances are in the ratio 1.0 : 0.71 : 0.46; at 400 nm, the ratios are quite different, 1.0 : 0.47 : 0.26. It will be noted that the ratios are not in the proportions of $(1 + \cos^2 \theta)$ but there could well have been problems in sighting the entrance slit of the spectrometer during a spectral scan. The ratio of radiances is not necessarily evidence of a forward-scattered component in the scattered light.

The same data are discussed in a later paper by a different set of authors, Belyaev *et al.* (1979b). They note that the data are uncorrected for absorption by the lower atmosphere of the sunlight incident upon the cloud and that the field of view of the instrument was larger than the projected area of the clouds. Belyayev *et al.* (1981) return to these same spectral data and give absolute calibrations for them. They conclude that there is a satisfactory fit with cloud particles having an effective radius of 0.7 μm, with a cloud density of 6×10^6 m^{-3}. Alternatively, a distribution of particles sizes is considered which is described by the function Ar^{ν}, over a range of sizes from $r_{\min} = 0.025$ μm to $r_{\max} = 1.9$ μm, with $\nu = -3.5$.

Avaste *et al.* (1981) describe the results of microphotometring some of the Salyut-6 photographs of noctilucent clouds seen at the horizon, in the direction of the Sun. The data show quite a marked degree of forward scattering in the clouds; there is a clear brightening of the scattered light when the azimuth relative to the solar azimuth is less than 5 degrees. It will be recalled that Weitz's observations on Skylab were also indicative of a marked degree of forward scattering. It is difficult to reconcile this with a model of particle sizes which contains no particles of radius greater than 0.13 μm.

In a recent review paper, Avaste *et al.* (1980) summarise much of the U.S.S.R. data obtained from the Salyut missions and list the following conclusions drawn from the visual observations and photography from space:

(1) Photography and visual observations from space enable one to determine the NLC on a global scale. In particular, the investigations performed on board 'Salyut-4' revealed that in summer in the Northern hemisphere NLC often completely covered the latitudinal belt north of 45°. Similar observations aboard 'Salyut-6' ascertained that in summer in the Southern Hemisphere there also exist extensive NLC fields, but they are shifted more southward: the NLC belt is south of 53–55° S.

(2) Photometric investigations as well as visual observations revealed that in both hemispheres the mesopause often has a complex structure (sometimes there exist two- and three-layered NLC fields).

(3) These observations allow one to make sound estimates of the spatial-temporal characteristics of NLC fields as well as the morphogical features of their evolution.

(4) The photometric investigations from space also confirm that in the NLC layer there exist particles whose radius exceeds 10^{-5} cm. The NLC in the Southern Hemisphere probably consist of smaller particles than those in the Northern Hemisphere.

Willmann *et al.* (1981) discuss the results of the Salyut-6 observations in the southern hemisphere in conjunction with simultaneous rocket soundings for temperature. The data refer to the period of December 1977 to February 1978. Noctilucent clouds were seen each day between 23 December and 2 February. There were resistance wire measurements (Izakov *et al.*, 1967) of atmospheric temperature and wind velocities obtained from tracking of 'window' ('chaff') at altitudes from 78 to 83 km. Some 14 rocket flights were made from a launch site at 68° S in the period from 7 December to 7 March. It is clear that the rocket soundings did not penetrate to sufficiently high levels to allow the mesopause to be properly defined. On the majority of the flights, the minimum in temperature was not traversed. The authors show a summary of the temperature data for the height interval 78–84 km. The average, (68° S), shows the temperature falling from 156 K at 78 km to 129 K at 84 km, with a lapse rate increasing over the same range from 7.0° km^{-1} to 26.5° km^{-1}.

Avakyan *et al.* (1981) discuss Salyut-6 observations which show a scattering layer at 80–95 km altitude above the equator. This layer was seen by four astronauts in the period 1979 June 25 to July 5; they had seen noctilucent clouds at high latitudes on the same orbits. The equatorial layer was estimated, in a preliminary way, to have a vertical optical thickness of 10^{-4} to 10^{-3}; assuming particles of radius 0.3 μm, there were from 0.1 to 1 m^{-3}.

6. Environment

The region of the atmosphere in which noctilucent clouds are formed is one of very low pressure in comparison with the pressures at which other types of clouds are formed. The physical processes of importance in discussing noctilucent clouds are correspondingly modified in relative importance. First of all, the mean free path in the region is very much bigger than the particle size in the cloud and the physical conditions are those of the Knudsen regime rather than those of a fluid. It may help in visualizing the local conditions to list some of the relevant properties of the atmosphere. Table V lists the mean free path of air molecules, their mean velocity, the number density and the flux passing a plane surface. In calculating the values given in the table, the cross-sectional area of a molecule was taken as 4.417–19 m^2, in accordance with viscosity data, and the mass of an air 'molecule' was set equal to 4.845–26 kg.

TABLE V

Kinetic properties of the atmosphere: model for illustrative purposes

z (km)	T (K)	p (Nm^{-2})	λ (mm)	c (ms^{-1})	N (m^{-3})	n_x ($m^{-2}\,s^{-1}$)
70	220	7.67	0.83	400	2.53×10^{21}	2.53×10^{23}
75	195	3.44	1.65	376	1.28×10^{21}	1.20×10^{23}
80	165	1.36	3.5	346	5.98×10^{20}	5.17×10^{22}
85	140	0.456	8.9	319	2.36×10^{20}	1.88×10^{22}
90	152	0.143	31.	332	6.82×10^{19}	5.66×10^{21}

6.1. Atmospheric temperature

It is a fact that the temperature around the mesopause seems to be the same when noctilucent clouds are present and when they are not. This is shown very clearly in the rocket soundings made at Kronogard (Sweden) and at Barrow (Alaska) during the summers of 1963, 1964, and 1965. Witt (1968) gives the results of six flights in 1963 and 1964, four of which were made with noctilucent clouds present, two in their absence. The data, redrawn here as Figure 14, extend from below 40 km altitude to

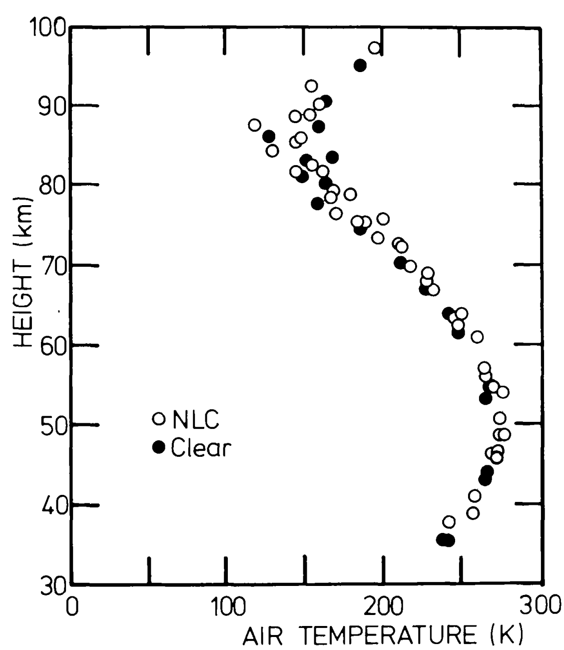

Fig. 14. Temperature of the upper atmosphere measured by acoustic (grenade) sounding over Kronogard (66° N). Four flights were made with noctilucent clouds present: 1963 July 29 (23 28 UT); 1964 August 7 (00 16 UT), August 16 (01 13 UT), August 17 (00 49 UT). Two flights were made into a clear sky: 1963 August 1 (23 27 UT), August 7 (22 29 UT). The data have been redrawn from the figure given in Witt (1968).

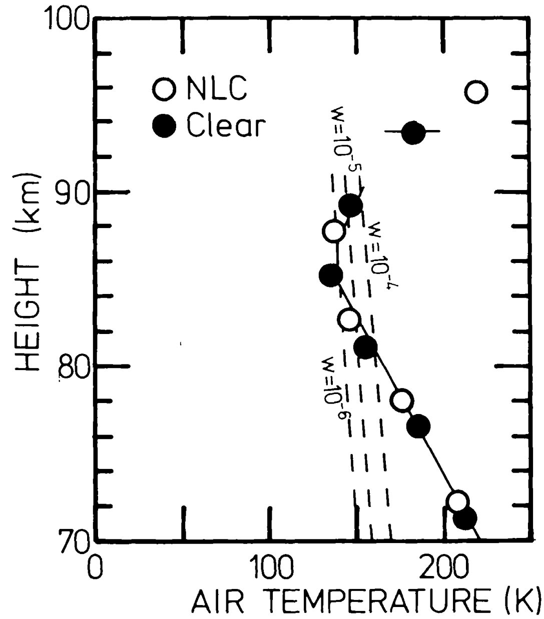

Fig. 15. The acoustic sounding data from two flights over Barrow (71° N) in 1965: August 7 (11 13 UT) with noctilucent cloud present and August 9 (10 10 UT) into a clear sky. The solid line shows the temperatures adopted for illustration in the text. The broken lines are corresponding frost points for three water vapour mixing ratios, w, set equal to 10^{-4}, 10^{-5}, and 10^{-6}.

nearly 100 km and show clearly that the atmospheric temperature is not obviously different during a cloud display from what it is without a display. The same thing shows in the Barrow data (Smith *et al.*, 1967) which are plotted here in Figure 15. These latter data form the basis for the model temperatures used in Table V. The model pressure used is based on a reference pressure at 80 km taken equal to that given in the CIRA 1965 reference atmosphere (COSPAR, 1965) for July 1 at 60 degrees north latitude.

When one considers the presence of water vapour in the atmosphere, there are unusual constraints imposed upon cloud behaviour through the very low temperature of the region and the low number density of both the air molecules and the embedded water molecules.

6.2. D-REGION

The region in which the clouds form is part of the ionospheric D-region. The atmosphere is partly ionized and contains large numbers of free electrons, positive (and some negative) ions and, of particular interest, ions on which numbers of water molecules have clustered, Reid (1977) has discussed in some detail how these different species of charged particles interact. He finds that the electron density at 80–85 km altitude can be expected to be about 1.0×10^9 m^{-3} under normal, daytime conditions. (Normal, in the context, means without a flux of high energy electrons being precipitated from the magnetosphere. Much of the high midlatitude area at which noctilucent clouds occur is also one of high geomagnetic latitude and as such is open to fluxes of high energy particles.) Arnold and Joos (1979) report the results of flying mass spectrometers on three rocket ascents launched from Andoya (in northern Norway) and Kiruna (in northern Sweden). On two of the flights, with enhanced electron fluxes, the electron density at 82 km was found to be 2.0×10^{10} and $6.6 \times 10^{9}\ m^{-3}$, respectively, compared with $3.0 \times 10^{9}\ m^{-3}$ on the third flight when the electron fluxes were close to their background level for daytime.

The ionic chemistry of the region predicts that the principal positive ions in the region will be hydrated NO^+ ions (the positive ion of nitric oxide with anything from one to seven or more water molecules adhering to the initial ion). Reid shows that the relative amounts of the different hydrated ions will depend on both the temperature and the humidity of the atmosphere, as would be expected. Arnold and Krankowsky (1977) have used measurements of the hydrated ion to estimate that the water vapour mixing ratio in this region is close to 4.0×10^{-6} (by volume). The flights from which their data were taken were made at latitudes of 68 and 69 degrees north latitude. The rockets were launched in May and in August and the measured temperature at 82 km was 170 K on the May flight and 166 K in August.

Goldberg and Witt (1977) flew a rocket-borne mass spectrometer on a day when noctilucent clouds had been seen over the launch site the previous night. Their data showed hydrated ions and they draw attention to the presence of ions which are possibly water clusters surrounding Fe and FeO initial ions. Whether this is something that is peculiar to the atmosphere where noctilucent clouds have formed or whether it is a coincidence with enhanced meteor influx is something which awaits more flights under these special conditions.

Johannessen and Thrane (1974) report the results of the flight of a mass spectrometer through the mesosphere over northern Norway in the month of August. Up to 84 km, water clustered onto a proton dominated the ion composition. There was an abrupt transition in the region 84–86 km, and the dominant ions above that region were found to be NO^+ and O^+ with negligible water clustering. The results are of particular interest because the rocket payload included ionization chambers which were used to estimate the temperature of the atmosphere from the extinction of solar Lyman-alpha. The temperature showed, on this occasion, two minima (a double mesopause) at 80 km (145 K) and at 85 or 86 km (150–155 K).

6.3. Dust

In a recent paper, Hunten *et al.* (1980) set up a model of the stratosphere and mesosphere in which they calculate the amount of dust and smoke that may be present consequent on the ablation of meteors. Using a distribution of meteor velocities that has a mean of 14.5 km s^{-1}, they calculate that the majority of the meteoric material is deposited between the heights of 75 and 95 km. They point out that the ablated material is unlikely to be in the form solely of boiled-off molecules; there will be 'smoke' particles in the meteoric wake. These particles act as nuclei for the aggregation of some of the meteoric material. These form a significant source of solid particles, presumably of silicaceous material, at the top of the mesosphere. This is, of course, the region that contains the whole phenomenon of noctilucent clouds and they suggest that these solid particles may well be an important source of nuclei for the clouds. It is clear that the solid material itself cannot account for the clouds; the scattering cross-section of the material is far too small to account for the amount of sunlight scattered in a noctilucent cloud and, indeed, Hunten *et al.* estimate that the amount of sunlight scattered by the material is undetectable.

The numbers of nuclei that are present, according to the calculations, are critically dependent on the assumption of initial particle size in the meteor smoke. It is assumed that a mass influx of 1.0×10^{-15} kg m^{-2} s^{-1} is distributed among identical smoke particles of radius r_0. Clearly, then, the number of initial nuclei is inversely proportional to r_0^3 and the steady-state dust particle concentration in the source region will vary quickly as the chosen value of r_0 is changed. For $r_0 = 0.2$ nm, there will be a dust concentration at 85 km of greater than 5.0×10^{10} m^{-3}; when r_0 is set five times larger (1.0 nm), the dust concentration falls to 3.0×10^9 m^{-3}. For the rather large initial radius of 10 nm, the dust concentration is down to approximately 1.0×10^6 m^{-3}. Coagulation is probably not very important in the 80–90 km region; by the time the dust has settled to 60 km, however, there are particles of radii up to several nanometres however small the value of r_0 that has been assumed.

6.4. Water Vapour in the Mesosphere

Estimates of the amount of water vapour present in the vicinity of the mesopause usually put it at a few parts per million (Anderson and Donahue, 1975; Arnold and Krankowsky, 1977). Rather larger amounts have been given by the groundbased microwave measurements of Radford *et al.* (1977); the altitude distribution of atmospheric water vapour is got from mathematical inversion of the line profile of an atmospheric emission line. Because of both pressure broadening and Doppler (thermal) width, the contribution to the centre of the line profile seen at ground level is mainly from water vapour at high altitudes while the water vapour lower in the atmosphere contributes to the entire profile. Mixing ratios are found to be as high as 15 ppm by volume in the 60–80 km region; the data do not give estimates any higher than 80 km. Recent work reported by Olivero (Olivero *et al.*, 1981) gives 10 ppm at 65 km as typical of the atmosphere over the Eastern U.S.A. (that is, at midlatitudes).

Fiocco and Grams (1971) discuss the possible effect of extraterrestrial dust (particles of minute radius that are stopped high in the atmosphere without ablating) sifting down into the mesopause region and sweeping water from the lower thermosphere down to just below the mesopause. They note that the meridional trajectories of dust entering the atmosphere are likely to give a dust layer at roughly 70 km in high latitudes. Indeed, laser soundings have shown just this. Fiocco and Grams suggest that the dust particles provide efficient nucleation of water vapour at region above the mesopause and that the dust particles, with adsorbed water, simply scavenge water vapour in the upper levels down to below the mesopause, where the temperature is high enough to evaporate the water or ice from the dust. There may well be, therefore, an unusual amount of water vapour in the mesosphere at high latitudes which will not be seen in measurements made at midlatitudes. Laser soundings from southern Norway (Fiocco and Grams, 1969) do indeed show increased scattering from the high atmosphere near 65 km at

74 km. The association with noctilucent cloud being seen overhead is not good, however. In spite of the 74 km layer appearing on one night concurrently with a noctilucent cloud, that layer shows up in the summer's observational summary (21 nights of observations: no noctilucent cloud on 12 nights, noctilucent cloud overhead on 5 nights and present elsewhere in the sky on a further 4 nights) as statistically above the signal fluctuations on only two nights, each without any noctilucent cloud display.

6.5. Radiation

Deirmendjian and Vestine (1958) consider the absorption and emission of radiation by cloud particles in sunlight. Using a very simple model, they find that the equilibrium temperature of an ice particle is greater than 273 K. This conclusion was criticized by Bronshten (1970) who considers the radiative equilibrium of a submicron particle which is irradiated both by the Sun and by thermal radiation from the Earth and its atmosphere. Cooling of the particle takes place by radiation and conduction through the ambient atmosphere. He finds that the equilibrium temperature of an ice particle at 80 km altitude is 170 K, taking the local atmospheric temperature to be 160 K. This applies only if a particle has a radius no greater than 1 μm.

Fiocco *et al.* (1975) have tackled the radiative transfer calculations independently, using an aerosol model involving refractive indices rather larger than is the case for ice, or water. In the visible, the refractive index is taken to be 1.65 and has an appreciable imaginary part in the near infrared (i.e. there is infrared absorption). At 45 degrees north latitude, summertime, they find an excess of particle temperature above ambient (atmospheric) temperature equal to 175 K for 0.5 μm particles at 92 km. With the particle radius down to 0.01 μm, the excess reduces to between 1 K and 10 K in the 80–90 km height interval.

Such temperature excesses are not applicable to case of ice particles. Baybulatov and Ivaniya (1976) show that the temperature excess at 80 km is rather less than 10 K for all particles of radii up to several micrometres. The difference between these numbers and those of Fiocco *et al.* comes from taking ice as being much more of a dielectric than the rather absorbing, high refractive index, material that Fiocco *et al.* considered.

In a second paper, Baibulatov and Ivaniya (1977) consider in more detail the region of occurrence of noctilucent clouds and the temperatures of particles at these heights. They calculate the temperature excess both for pure ice particles and for layered particles – ice with a core of absorbing material. The temperature of small particles (radii up to 0.1 μm) is essentially identical to the air temperature up to altitudes of close to 85 km. In this region, the temperatures of larger particles are higher in the summer and lower in the winter than the air temperature. In the case of the particles with a core, the effect of the core is marked if it occupies more than about one-seventh of the radius of the particle. The particles with a large central core have to be much smaller than 0.1 μm radius if they are not to have a large temperature excess.

Olivero and Bevilacqua (1979) take account of the latent heat of sublimation or condensation when an ice crystal is changing its size. This is plainly a more realistic model than any of the others. In general, an ice crystal suspended in the atmosphere will not be constant in size; while it is growing, there will be a temperature increase above the steady-state condition and vice versa. The water vapour mixing ratio in the region of existence of the particles is of paramount importance. Olivero and Bevilacqua find that when $w = 10^{-6}$, the ice particles will exist only in a very narrow range of height, approximately 0.5 km thick. This range of height increases to 2 km for $w = 10^{-5}$, and 8 km for $w = 10^{-4}$.

7. Physics of nucleation and Growth

7.1. Rates of growth

For our purposes, probably the most interesting numbers are those relating to the speed of growth and sublimation of an ice crystal. The shape is probably not spherical; the departure from sphericity can be allowed for by using the concept of an inscribed sphere, which is given the radius R. If the surface area and volume of the crystal are A and V, two shape factors may be defined as

$$a = A/4\pi R^2$$

and

$$b = 3V/4\pi R^3.$$

If the mass flux of water molecules per unit area at the surface of the crystal is given by $g(T)$ at temperature T, then the rate of increase in mass of the crystal is clearly

$$\mathrm{d}m/\mathrm{d}t = 4\pi R^2 a \,\{g(T_1) - g(T_2)\}\, m$$

in which T_1 is the temperature of the atmosphere and T_2 is the temperature of the crystal. The mass of a single water molecule is written m. The value of $g(T_1)$ is given simply by the product of the water vapour mixing ratio, w, with the value of n_x (see Section 6) in Table V. The value of $g(T_2)$, the flux of water molecules evaporating from the crystal at temperature T_2 is found, for any T_2, by calculating n_x for the saturation vapour pressure of water at temperature T_2.

The saturation vapour pressure over ice at these exceedingly low temperatures requires to be estimated; it is too low to be measured with precision in the laboratory. Resort is made to the Clausius–Clapeyron relation

$$L_T = RT^2 \,\mathrm{d}(\ln p)/\mathrm{d}T$$

in which L_T is the latent heat of vaporization of ice at temperature T; p is the vapour pressure over ice, and R is the universal Gas Constant. If C_p^s, C_p^g are the specific heats at constant pressure of ice and water vapour, respectively, then

$$L_T = L_0 + \int_0^T (C_p^g - C_p^s)\,\mathrm{d}T.$$

The specific heat of water vapour, C_p^g, at low temperatures is listed by Eisenberg and Kauzmann (1969) and we can use the Giauque and Stout (1936) values for C_p^s, with 616 Nm^{-2} for the value of p at 273 K. Numerical integration of the Clausius–Clapeyron equation in steps of 10 K gives values of p which are closely approximated by the following simplified version of the Kirchhoff formula:

$$\ln p = 28.548 - 6077.4/T$$

in which p is in Nm^{-2}. If we now write ρ (912 kg m^{-3}) as the density of ice, the rate of change of radius of the inscribed sphere can be written

$$dR/dt = (aM/b\rho)\,\{g(T_1) - g(T_2)\}.$$

There are two limiting cases for the rate of change of radius with time: first, the maximum rate of evaporation is when $g(T_1) = 0$, that is, when the cloud particle falls into a perfectly dry region of the atmosphere. The values of dR/dt in this case are indepedent of the atmospheric model and are related to the temperature of the particle only. Some numerical values are given in Table VI.

TABLE VI

Maximum possible rate of evaporation and time taken for disappearance of a sphere of initial radius equal to 0.1 μm

T (K)	(dR/dt) (m s^{-1})	Time
130	2.23×10^{-14}	52 d
150	1.05×10^{-11}	2.6 hr
170	1.17×10^{-9}	85 s
190	4.74×10^{-8}	2 s

Similarly, there is a maximum rate of growth that occurs when $g(T_2) = 0$, that is, when the temperature of the cloud particle is sufficiently low that the rate of evaporation of water molecules from its surface is negligibly small. In this case, it is necessary to take account of the humidity of the atmosphere.

The water vapour mixing ratio (volume : volume) in the upper atmosphere during noctilucent cloud displays is not known (see below) but is thought to be in the range, say, 2.0×10^{-6} to 2.0×10^{-5}. With these numbers, and the model atmosphere given in Table V, it is possible to calculate values for the rate of change of radius of the inscribed circle and these are given in Table VII. (Only the atmospheric conditions at 85 km are considered; at the other levels listed in Table V, evaporation rather than growth takes place except with rather high values of the water vapour mixing ratio.) The third column in Table VII shows the time taken for a spherical cloud particle to grow to a radius of 0.1 μm.

TABLE VII

Values for the rate of change of radius of a spherical crystal for particular values of the water vapour mixing ratio, w

$T = 140$ K; $p = 0.456$ Nm^{-2}		
w	$(\mathrm{d}R/\mathrm{d}t)$ (m s^{-1})	Time (h)
2.0×10^{-6}	1.23×10^{-12}	23
5.0×10^{-6}	3.08×10^{-12}	9
1.0×10^{-5}	6.16×10^{-12}	4.5
2.0×10^{-5}	1.23×10^{-11}	2.3

7.2. Nucleation of Ice

Two things are involved in having a rate of formation of embryonic particles that is large enough to account for the presence of a visible cloud. The partial pressure of water vapour must be high enough to reduce a free-energy barrier to an acceptably-small level. There must be sufficient nuclei present to maintain a source of embryos against their loss by growth and consequent falling out of the saturated region. The degree of saturation, S, at any height in the atmosphere is simply the ratio of the local partial pressure of water vapour to the saturated vapour pressure over ice at the temperature, T, at that height.

As a cloud particle grows, there is a change in the free energy, G, of the particle-vapour system. In the absence of any electrical charge on the embryo, there are two terms in the expression for the rate of change of G with change in radius (cf. Hobbs, 1974):

$$\mathrm{d}G/\mathrm{d}r = 8\pi\sigma ar - 4\pi\rho br^2 RT \log_e S/M$$

in which M is the molecular weight of water and σ is the ice-vapour surface energy. If there should be an extra proton on the embryo, the Coulomb forces on an approaching water molecule cause an extra term to appear in the equation:

$$\mathrm{d}G'/\mathrm{d}r = \mathrm{d}G/\mathrm{d}r - \alpha\rho e^2/8\pi\varepsilon_0^2 mr^2$$

in which $\alpha(1.606 \times 10^{-40}$ Cm NC$^{-1})$ is the polarizability of a water molecule; $\rho(932$ kg m^{-3} at 130 K) is the density of ice; $e = 1.602 \times 10^{-19}$ C; $\varepsilon_0 = 8.854 \times 10^{-12}$ Fm^{-1}; and $m = 2.99 \times 10^{-26}$ kg, the mass of a water molecule.

The first equation may be integrated immediately; $\mathrm{d}G'/\mathrm{d}r$ may be integrated with the value of G' set to that of G for very large particles. The resulting curves of G (light lines) and G' (bold lines) are plotted in Figure 16. A temperature of 130 K is assumed and 0.109 J m^{-2} is used for the surface energy. In obtaining the expression for G', no account is taken of a water molecule changing its orientation as it approaches the charged embryo; there is then no need to take account of the permanent dipole moment of water in the expression for $\mathrm{d}G'/\mathrm{d}r$.

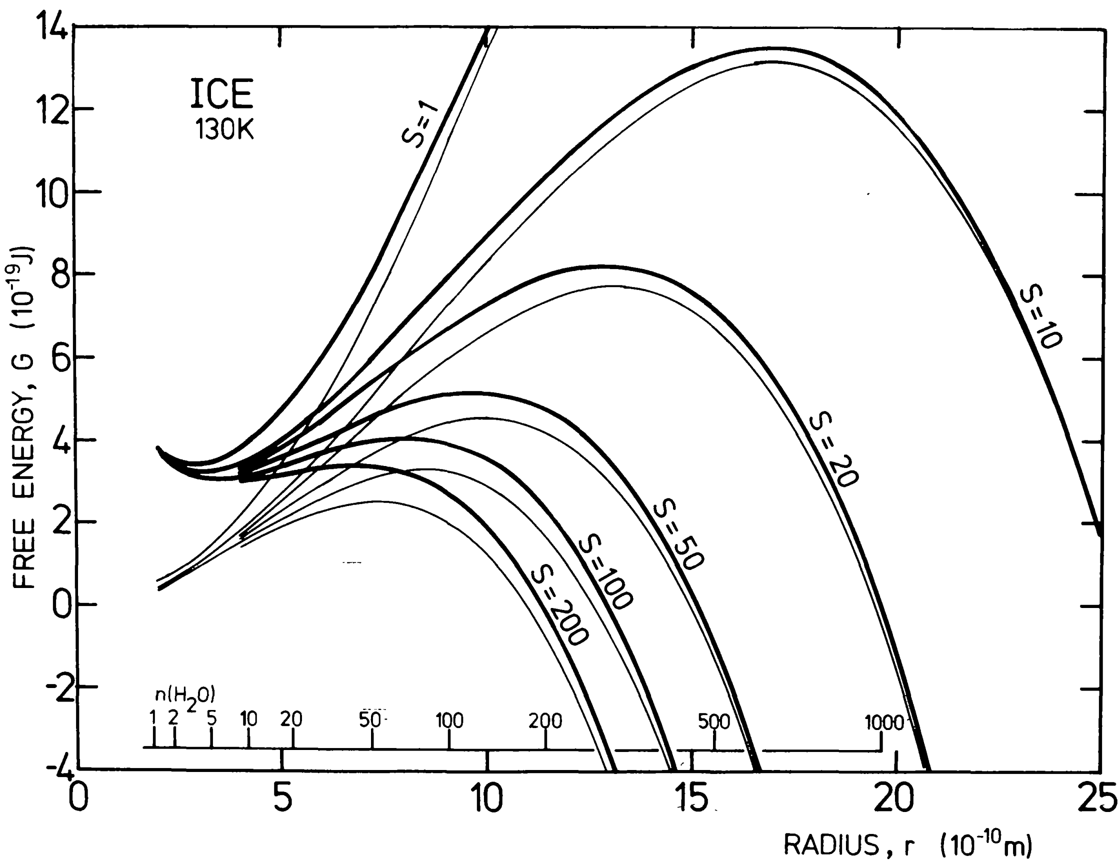

Fig. 16. Variation of free energy (G) with radius (R) for a number of saturations (S). The light lines are for an uncharged embryo (i.e. homogeneous nucleation), the bold lines refer to an embryo containing a charge of $\pm 1.6 \times 10^{-19}$ C. The physical properties of the particle are those relevant to ice at a temperature of 130 K.

The existence of a large energy barrier is seen in Figure 16; as the partial pressure of water vapour is increased, leading to a corresponding increase in the saturation, S, the energy barrier decreases. Note that the presence of a positive charge on the embryo not only decreases the height of the energy barrier slightly but confers stability on an embryo containing several water molecules which has a free energy somewhat larger than that of an uncharged (unstable) embryo of similar size.

The sensitivity of the energy barrier to S, and thus indirectly to the temperature T, means that the statistical probability of an embryo having sufficient energy to pass the barrier (and reach the size at which steady growth follows) is extremely sensitive to temperature. In any particular set of temperatures at the top of the mesosphere it follows that nucleation will occur effectively only at the height which shows the lowest temperature. But nucleation at a good rate does not necessarily mean that a visible cloud will form. Having got past the energy barrier and started to grow, the infant cloud particle must survive long enough to grow to a size where it can scatter light effectively. This last condition means that there has to be a sufficiently-large water vapour pressure for the particle to become large before it falls out of the saturated region. Therefore, to some extent the conditions for, first, nucleation and then growth are not related. One needs a low temperature to give high S for there to be nucleation; then the atmospheric layer immediately below the nucleating layer needs to be wet enough to allow the particles to grow. In summary, the nucleation occurs, if at all, at the mesopause. If the mesopause is broad, i.e. it consists of a layer of constant temperature rather than showing a distinct minimum in the temperature-height curve, nucleation will occur at the bottom of that layer, where S will be largest. The variation of S with height must always show a sharp maximum unless there is a pronounced increase in water vapour mixing ratio with increase in height. This is unlikely to be the case.

7.3. Settling of the Cloud Particles

Once nucleated and over the free energy barrier, the infant particle grows and begins to fall at ever increasing speed as it grows. It falls, in most cases, through a region where the temperature is increasing in the downwards direction. The saturation, S, is therefore decreasing downwards and at some height S becomes equal to unity. Therafter, the particle falls through increasingly-unsaturated air and sublimation takes place quickly. The fall speed gets smaller as the particle size gets smaller; the shrinking particle lingers in the region just below the frost point level and the base of a noctilucent cloud must be very close to the level at which S is unity. If there were to be a precise measurement of temperature at the base of a noctilucent cloud, it would be possible to deduce with some reliability what the water vapour mixing ratio was at that time and that place.

The cloud particles are not necessarily spherical; Reid (1975) has calculated the fall speeds of submicron particles, both for spheres and for cylinders. He assumes specular reflection of atmospheric molecules from the particle surface. A better assumption is to allow for diffuse reflection with accomodation (Epstein, 1924) and Reid's estimates of the fall speed should be decreased by about 40% in consequence. For the non-spherical particles, one should regard them as tumbling rapidly through the operation of Brownian movement (Einstein, 1906).

The clouds are seen by scattering of sunlight. The particles are therefore in intense, directed, radiation and may show radiometer effects, or photophoresis, as discussed by Orr and Keng (1964) for stratospheric particles.

Some calculations based on these general ideas but applied in a simple way are given by Gadsden (1981). In these calculations, estimates of particle size distributions are made which may prove helpful in assessing observational data. It seems likely that water vapour mixing ratios as high as 10^{-4} would be needed to provide cloud particles as large as 0.6 or 0.7 μm in radius.

8. Concluding Remarks

It would seem not to be exaggerating to suggest that what is needed to advance our understanding of the processes of formation, growth and disappearance of noctilucent clouds is more, and perhaps different, data. It is clear that there is not good agreement on what the characteristic size of a cloud particle is, what the nuclei of the particles are, what shape they have, how much water is available in the mesosphere and if there are close ties with the lower atmosphere.

Some emphasis should be placed on the consequences of modelling with cloud particles that are too small. For very small particles, the amount of water vapour needed to give a particular amount of scattered light is inversely proportional to the cube of the radius. To some extent, when one observes a noctilucent cloud, one sees what one expects. At scattering angles close to 90°, there will be little circularly-polarized light and small particle (Rayleigh) scattering is likely to predominate. At small scattering angles (as when one looks from a spacecraft towards the rising Sun), forward scattering from larger particles may be dominant.

Some promising lines of investigation are:

(1) In situ sampling of the clouds with simultaneous photometry of the scattered light on board the same rocket.

(2) As a sine qua non of all rocket experiments, there should be a determination of atmospheric temperature from the same vehicle. Just where on the temperature profile in the atmosphere do noctilucent clouds form? If right at the mesopause, the particles must be very small. If some kilometres below the mesopause, the cloud particles will have had time to grow appreciably.

(3) Ground level observations of twilight scattering to monitor changes in the stratospheric aerosol burden occurring during the summer at high latitudes might well show a possible source for increased water vapour content in the mesosphere.

(4) Are there systematic changes in height of the cloud layer associated with changes in the hydroxyl temperature and intensity? Only a series of stereogrammetric measurements in conjunction with the airglow measurements can give the answer to this.

(5) What are the relations between perceived wave motions and the atmospheric flow in which they appear? Is there a connection between these and the weather pattern at ground level?

Other lines of enquiry, equally profitable, will suggest themselves to the reader. It is my hope that this review, which cannot pretend to be comprehensive, will offend none through omission. It is, after all, simply my view of the subject and I am aware of its inadequacy. I should like to record my gratitude to Ben Fogle and James Paton who between them helped me to study these fascinating and beautiful clouds. Particularly I should like to acknowledge the help from Paton's family who have allowed me to take into my personal care the extensive library of reprints that he had built up through contacts with his many friends around the world.

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