5 Polarimetry

5.1 Introduction

In principle, the problem of predicting the state of polarization of light scattered from noctilucent clouds is solvable. Given the state of polarization of the incident sunlight, the light that would be scattered from any model containing spheres, cylinders or spheroids can be calculated once the composition and the refractive index of the material (or materials) in the particles is determined. 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, plunged fairly deeply over the terminator and then begun to emerge again 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 forward-scattered light in the troposphere and stratosphere. This problem has not yet 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).

The degree of polarization will not be changed by passage of the light down through the lower atmosphere after scattering from the clouds. If one knows the state of polarization of the light illuminating the clouds (usually this is assumed to be unpolarized light) and if one knows the optical properties of the cloud particles, measurement of the polarization of the light from the clouds can give estimates of the particle sizes in the clouds. In such an analysis, many of the problems associated with knowing the atmospheric absorption and refraction on any particular occasion are avoided.

The state of polarization of light is described through the use of Stokes parameters. The transformation of these parameters by scattering can be treated with the help of the Mueller calculus (Shurcliff 1962). In using this calculus, one writes the Stokes parameters as the Stokes vector {I,M,C,S} having four components. The effect on the vector of any linear transformation (e.g. that caused by scattering, or by passage of the light through a polarizing element) is expressed by 16 coefficients in a 4×4 matrix, F. If the incident light has Stokes parameters I, M, C, S then the Stokes vector that results from the operation of the linear transformation is simply the product of the matrix F with the Stokes vector of the incident light. That is

$$\{I,M,C,S\} = F \cdot \{I, M, C, S\} \qquad (5.1)$$

The physical meaning of the individual Stokes parameters can be grasped by referring to Fig. 5.1, a representation of the polarization ellipse. Using the quantities marked on the diagram, we have the following relationships: Ellipticity = $\tan\beta$; orientation of the major axis = χ.
The Stokes parameters are

$$I = a^2\,; \qquad (5.2a)$$
$$M = I\cos 2\beta\cos 2\chi; \qquad (5.2b)$$
$$C = I\cos 2\beta\sin 2\chi; \qquad (5.2c)$$
$$S = I\sin 2\beta. \qquad (5.2d)$$

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°) to the scattering plane.

If S = +I (−I), the light has right-handed (left-handed) circular polarization.

The angle χ is given by $\tan^{-1}(C/M)$. Clearly,

$$I^2 = M^2 + C^2 + S^2 \qquad (5.3)$$

for a fully polarized light beam. The degree of polarization of a partially polarized light beam is given by the ratio

$\sqrt{M^2 + C^2 + S^2}/I$.

The principal attraction of handling the analysis of polarized light through the Stokes vector approach is that the Stokes parameters obey the algebraic laws of addition. That is to say if two incoherent beams of light, described individually by the two Stokes vectors,

$$\{I_1,M_1,C_1,S_1\}\;,\;\{I_2,M_2,C_2,S_2\}\;, \qquad (5.4)$$

are combined into one beam of light, the Stokes vector of that combined beam will be

$$\{I_1 + I_2,\; M_1 + M_2,\; C_1 + C_2,\; S_1 + S_2\}\;. \qquad (5.5)$$

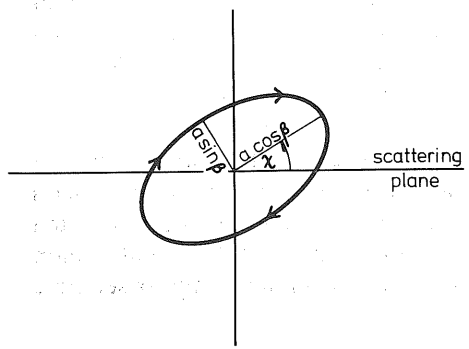


Fig. 5.1. Representation of the state of polarization of a light beam showing elliptical polarization. The direction of propagation is *into* the page

This property is of special application in observing noctilucent clouds. The clouds are seen in twilight and there is, therefore, an appreciable foreground of light scattered in the lower atmosphere. Measurements are made of part of a noctilucent cloud together with measurement of an adjacent part of the twilight sky, which has no noctilucent cloud behind it. The two sets of measurements are separately reduced to give Stokes parameters. The difference between the two sets of parameters gives the Stokes vector of the noctilucent cloud, freed of the foregound light.

Then follows the analytical stage: given the scattered light, {I,M,C,S}, from observation and assuming that the light which illuminates the cloud, $\{I_0,M_0,C_0,S_0\}$, is known, can one deduce the scattering matrix, F, involved in (5.1)?

Van de Hulst (1957) and Kerker (1969) discussed the form and coefficients of the matrix F in some detail, with special reference to cases of matrices for scattering media. If the particles in 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.

5.2 Polarization by Scattering

The amount of light scattered from a region varies with the size of the scattering angle, θ, and (in the case of non-spherical or anisotropic scatterers) with the azimuth, ϕ, of the direction of the scattered light. These angles and the orientation of the scatterer are measured relative to the scattering plane which is defined as the plane containing the direction of the incident light and the point, P, at which the scattered light is detected. The scattering angle, θ, is zero in the direction of travel of the incident light (forward scattering) and 180° (back scattering) if the scattered light travels antiparallel to the incident light.

The radiance of the scattered light is related to the irradiance of the incident light through a scaling factor $(1/k^2r^2)$ in which k is the wave number $2\pi/\lambda$, and r is the distance between the scatterer and P. Only rarely is the magnitude of this scaling factor needed or used in the analysis of the polarization of light scattered from a noctilucent cloud and it will not be discussed further.

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, 8 of the 16 coefficients are zero and two pairs of those that remain share the same numerical magnitude, so the matrix contains only six separate coefficients:

$$F = \begin{matrix} S_{11} & S_{12} & 0 & 0 \\ S_{12} & S_{22} & 0 & 0 \\ 0 & 0 & S_{33} & S_{34} \\ 0 & 0 & -S_{34} & S_{44} \end{matrix} \quad . \qquad (5.6)$$

this case, there are limits to the type of polarization that the scattered light can ive. If the incident light is unpolarized, {I,0,0,0}, the scattered light has Stokes irameters $\{S_{11}I, S_{12}I, 0, 0\}$. It has plane polarization, therefore, either in the ane of scattering or at right angles to it depending on whether S_{12} is positive negative in value. If the incident light is linearly polarized, the Stokes irameters of the scattered light are $\{(S_{11}I + S_{12}M), (S_{12}I + S_{22}M), S_{33}C, -S_{34}C\}$. iere can be circular polarization if the incident light has any degree of linear larization in a plane oblique to the scattering plane. Naturally, if the incident ght is elliptically polarized, that is, if there are both kinds of linear polarization us circular polarization present in the incident light, the scattered light will, in neral, be elliptically polarized too with neither the original orientation of axes r the original ellipticity being necessarily preserved.

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

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

$$F = \begin{matrix} 0.5(\cos^2\theta + 1) & 0.5(\cos^2\theta - 1) & 0 & 0 \\ 0.5(\cos^2\theta - 1) & 0.5(\cos^2\theta + 1) & 0 & 0 \\ 0 & 0 & \cos\theta & 0 \\ 0 & 0 & 0 & \cos\theta \end{matrix} \qquad (5.7)$$

ith all the consequent simplifications in taking the product with $\{I_o,M_o,C_o,S_o\}$ find the Stokes parameters of the scattered light.

The second approximation is that the scattering particle is low in contrast, at is, the phase of the incident wave is negligibly changed in passing the irticle. Lord Rayleigh (1881) gave this approximation as an extension of the iall-particle approximation which is valid for particles of any size and any ape provided their refractive index is close to that of the surrounding medium. distinguish the two approximations discussed by Rayleigh, the low-contrast se is usually called Rayleigh-Gans scattering, but Kerker (1969) has suggested is should be more appropriately called Rayleigh-Debye scattering. The ayleigh-Gans approximation is not recommended for the case of noctilucent ouds, where the refractive index of the cloud particles is not close to unity. It however, useful in permitting simpler relations to be used to indicate the haviour of full, rigorous solutions to the scattering problem.

Wait (1955) has obtained the full solution for the case of scattering from an finitely long cylinder for which, as Rayleigh pointed out in 1881, one may also

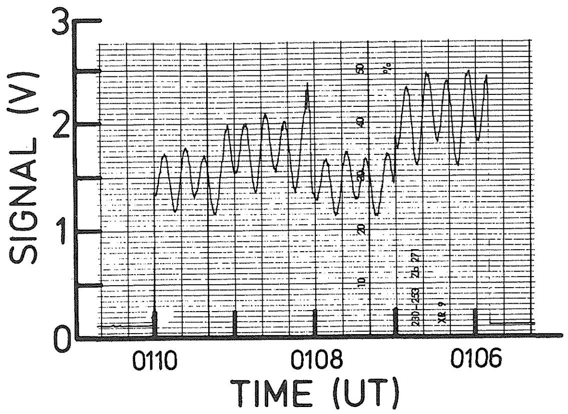


Fig. 5.2. Polarimeter recording of light scattered from a noctilucent cloud observed on June 29, 1984 at 0106 UT. The effective wavelength of observation is 440 nm and the angle of scattering is 47°. The field of view was centred at 11.5° above the horizon, azimuth 60°. Two strips of the cloud were observed (change is field of view at 0107 and 0108 UT) and the difference in radiance is clear. The dark signal at this time was 0.12 V and is shown on the record up to 0105:40 UT and after 0110 UT

Estimation of $\{I_0, M_0, C_0, S_0\}$ can be done by analyzing the photomultiplier signal for the D.C. level and the 2β and the 4β variations. An alternative, which has been used for several years, is to record the signal as integrals over successive 22.5° intervals of the retarder rotation and to solve four sets of four simultaneous equations set up in the form:

$$\begin{aligned} a_{11}I + a_{12}M + a_{13}C + a_{14}S &= B_1; \\ a_{21}I + a_{22}M + a_{23}C + a_{24}S &= B_2; \\ a_{31}I + a_{32}M + a_{33}C + a_{34}S &= B_3; \\ a_{41}I + a_{42}M + a_{43}C + a_{44}S &= B_4. \end{aligned} \tag{5.13}$$

The coefficients a_{ij} are estimated through calibration of the entire system. The telescope is pointed at a uniformly bright screen and a large polaroid and quarter-wave retarder are placed over the telescope objective. By rotation of the quarter-wave retarder in front of the objective, a series of B_i sequences is recorded for four distinct states of polarization. These are chosen to be the three orientations of linearly polarized light (vertical, horizontal and 45° in between) together with circularly polarized light.

Thus, the sets of the B_i refer to

$$\begin{aligned} &B_1\text{: } C_0 = S_0 = 0;\ M_0 = I_0; \\ &B_2\text{: } C_0 = S_0 = 0;\ M_0 = -I_0; \\ &B_3\text{: } M_0 = S_0 = 0;\ C_0 = I_0; \\ &B_4\text{: } M_0 = C_0 = 0;\ S_0 = I_0. \end{aligned} \tag{5.14}$$

The polarizer and retarder used in the calibration are not *ideal* polarizing elements although they are good. Use of a second (fixed) polaroid over the objective permits the assessment of their actual polarizing properties. These experimentally determined properties are used to adjust the above calibration (which was based on assuming ideal polarizers) to take the less than ideal properties into account. Finally, the state of polarization of the illuminated screen is estimated using the almost calibrated telescope and allowance is made for the slight degree of polarization that is almost certainly present; an iteration is practical and leads quickly to self-consistency in the calibration process.

5.4 Polarization Measured from Ground Level

Witt (1960) used a 35-mm stereoscopic camera which had two polarizing analyzers in front of the two objective lenses. A rotating frame allowed the operator to set the planes of the analyzers (held always at 90° to another) 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 and 610 nm that could be placed over the objectives of the camera. Photographs were obtained on the bright display of Aug. 10, 1958 and 11 pairs of exposures with the red filters and 7 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 foreground twilight. His measurements of the degree of polarization, plotted against scattering angle, show the expected monotonic rise when the scattering angle increased from slightly over 20° to just over 60°.

Figure 5.3 has been redrawn from Witt's paper; the lines show the degree of polarization calculated from Mie theory, assuming no polarization in the light incident upon the clouds. The calculations were made using complex refractive indices appropriate for ice particles at a temperature of 130 K, viz.

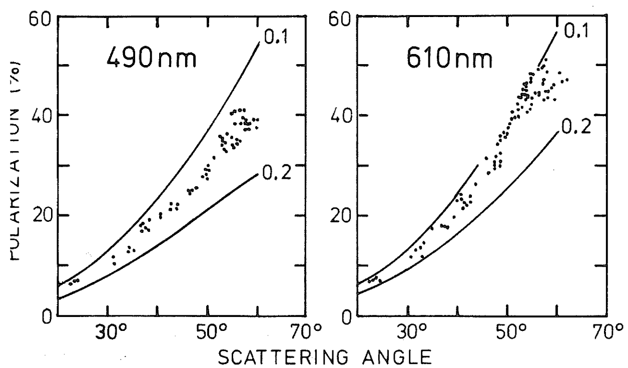


Fig. 5.3. Degree of (linear) polarization measured by Witt during observations of a noctilucent cloud on August 10–11, 1958. The *lines* plotted are the degree of polarization calculated from Mie scattering theory for ice spheres of radii equal to 0.1 and 0.2 μm, assuming that the cloud was illuminated by unpolarized light (Redrawn from Witt 1960)

$$F_{mie} = \begin{vmatrix} 2.180 & 0.520 & 0 & 0 \\ -0.520 & 2.180 & 0 & 0 \\ 0 & 0 & 2.108 & 0.193 \\ 0 & 0 & -0.193 & 2.108 \end{vmatrix} . \quad (5.16)$$

There are now two more coefficients appearing in the array, off the diagonal. The degree of polarization of the scattered light with unpolarized incident light is lower than with Rayleigh scattering (23.9% instead of 41.5%) and circular polarization is present when the incident light is obliquely plane-polarized. Incident light {1,0,1,0} gives elliptical polarization in the scattered light, {2.180,–0.520,2.108,–0.193} ; the direction of polarization is at a smaller angle (7°) to the 45° plane and there is 8.9% circular polarization present.

As we have seen, Willmann (1962) observed a change in azimuth of the plane of polarization with a change in scattering angle (Fig. 5.5). Is it possible that this comes about because there is partial linear polarization in the illumination of the noctilucent cloud? Such a state of affairs could come about by there being an appreciable contribution to the illumination on the cloud from sunlight scattered off the lower atmosphere. In this case, however, one would expect the measured polarization azimuths to show some symmetry about the direction of the solar meridian but there is no sign of this in the data.

All the measurements reported from the USSR have been analyzed with allowance for the foreground twilight. But those, and the measurements of Witt, make an initial tacit assumption that the scattered light shows only linear polarization. Gadsden (1977) reported a series of measurements of all four Stokes parameters.

The results for the degree of polarization are plotted against scattering angle in Fig. 5.6. In redrawing this graph, the distinction between different wavelengths has been removed. The line shows the degree of polarization expected for a spherical scatterer with a radius equal to a small fraction of a wavelength. The measurements have been corrected for the twilight foreground by measuring only the brighter features in a noctilucent cloud that have a dark region lying immediately next to the feature. The dark region is measured

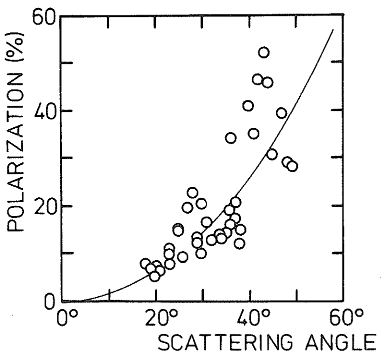


Fig. 5.6. The degree of polarization measured by Gadsden during 1974, 1975 and 1976. The *line* plotted behind the points is the degree of polarization expected for small spheres of ice with radii equal to λ/63 (Redrawn from Gadsden, 1977; the distinction between observations at 400, 450, 575 and 675 nm wavelengths has been removed)

mmediately after the measurement of the bright region. Normally this involves omparing areas of sky only a few minutes of arc apart. In the case of a bright tripe, the fainter regions on each side of the stripe are measured to give oreground subtraction.

There is often a certain amount of "super-polarization" present, that is, the legree of polarization is greater than that expected for Rayleigh scattering.

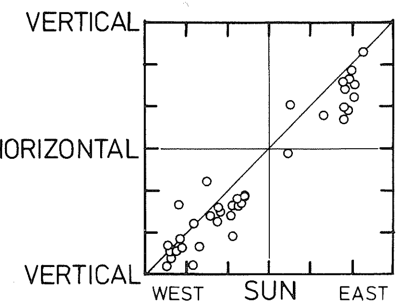
The results for the direction of the major axis of the polarization ellipse (Fig. .7) do not verify Willmann's measurements. The direction is always within 45° of the perpendicular to the scattering plane although there appears to be a ystematic, small anticlockwise rotation of direction away from perpendicularity (that is, anticlockwise on *both* sides of the solar meridian).

The results also show that there is a detectable amount of circular polarzation in the scattered light and that there seems to be a systematic change in he proportion of circular polarization with change in wavelength. The red and blue parts of the spectrum (wavelengths 400, 450 and 675 nm) show typically .02 to 0.08 left-handed circular polarization, while scattered light at 575 nm hows 0.00 to 0.02 right-handed polarization.

With reference to the principles of symmetry that underlie the theory of the cattering, matrix F shows that circular polarization can be present in the cattered light as a result of any or all of three causes:

. If the incident light is unpolarized and there is a preferred orientation for the (non-spherical) scatterers;
. If the incident light contains some circularly polarized light;
. If there is some light linearly polarized in a direction oblique to the scattering plane.

t is possible that the presence of circular polarization in the scattered light arises o a large extent from the presence of forward-scattered sunlight in the light ncident upon the clouds. This would account for the absence, or small amount



ig. 5.7. The measured directions of the major axes of the polarization ellipses, from observations 1 1974, 1975 and 1976 (Gadsden 1977). The *points* are plotted against the orientation of the cattering plane, which is vertical (90°) on the meridian of the Sun and increases towards 180° for oints in the sky to the *east* of the Sun and decreases to 0° for points in the sky to the *west* of the Sun. ecause the Sun is below the horizon, there is no part of the sky for which the scattering plane lies orizontally (0° or 180°)

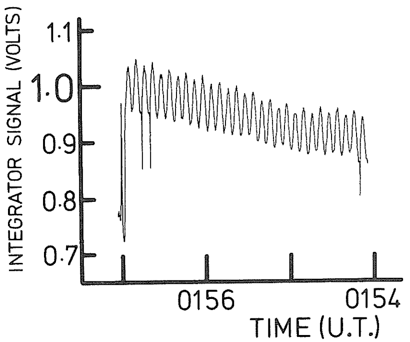


Fig. 5.9. Post-hoc photometry of a video recording; the alternating height of maxima is a clear indication of the presence of circular polarization in the light scattered from a noctilucent cloud (Gadsden et al. 1979)

themselves. More information is needed to elucidate the processes occurring; the interpretation in some ways shares the uncertainty of interpretation of the spectral radiance measurements.

5.5 Measurements of Polarization from Rockets

At first sight, it is a simple task to make in situ measurements from a sounding rocket passing through a noctilucent cloud. The facts of ballistics complicate things. Above the stratosphere, the flight of a sounding rocket is very nearly ballistic; the motors of the rockets that are used normally burn for only the first few kilometres (if that) of the flight. For the rest of the flight, the rocket is just a pointed cylindrical box of instruments and radio transmitter, with fins at one end. It will be spinning on its long axis at a few revolutions per second for stability. The rocket casing also processes, with a cone angle of perhaps 10° or 20°. The time actually spent passing through a cloud is short: if the apogee is 100 km, the rocket will pass through the whole interval from 80 to 90 km in less than 20 s. If the apogee is 150 km, the time is halved. On the way down, the rocket normally falls tail first; air drag is not enough to make it turn over until it returns the stratosphere.

It appears that Witt (1969) was the first to project a photoelectric polarimeter through a noctilucent cloud. There were problems with illumination of the polarimeters by the Sun but data were successfully obtained at two wavelengths (366 nm on one channel and 534 nm on the other). The scattering angle was 86°. The noctilucent cloud was entered at 82.4 km altitude, and the rocket seems to have broken clear of the layer by about 84.4 km. 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.

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. Witt et al. deduced an upper limit to the particle radius of 0.05 μm. These may well be the particles available for nucleation of noctilucent clouds when the temperature or humidity is suitable.

Witt et al. (1971) reported 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 ionization 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 higher, at 85–87 km. At 453 nm, the degree of polarization was a little higher than that expected from molecular scattering.

As part of a campaign to launch particle collectors through noctilucent clouds (see Chap. 6), Tozer and Beeson (1974) obtained polarimetric data from four flights over Kiruna. The instrument on each of the flights contained two channels sharing a common entrance pupil by the use of a split fibre optic bundle. Filters gave effective wavelengths of 540 and 410 nm. The polarimetric data of Tozer and Beeson are plotted in Fig. 5.10. There was no penetration of a noctilucent cloud on the second flight, Aug. 1, 1971, so the data came from three flights, ascent and descent on two, ascent only on one.

At the large scattering angles involved, the degree of polarization is close to 1.0 until the scatterer radius becomes greater than approximately 0.1 μm. The Tozer and Beeson results indicate that scatterers as large as 0.2 μm are most unlikely to be present. However, it should be recalled again that the calculations giving the reference curves in Fig. 5.10 assume that the incident light is unpolarized. The rocket flights occurred during the middle of summer nights at Kiruna, in northern Sweden, so the illumination conditions are similar to those applying to ground level observation of noctilucent clouds.

Heintzenberg et al. (1978) discussed the extraction of the median radius, the largest radius and the width of the distribution of particle sizes in a cloud from inversion of observations of the Stokes parameters I and M. They reported observations made at four wavelengths, 214, 366, 453 and 536 nm. Scattering angles, θ, for observations from "our recent rocket launchings from northern

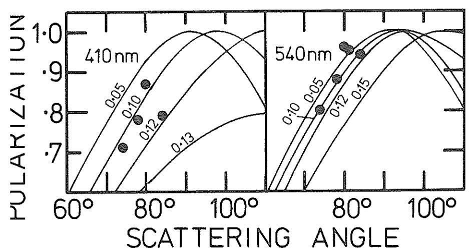


Fig. 5.10. The polarization measurements of Tozer and Beeson (1974) made with rocket-borne photometers. The degree of polarization is plotted against scattering angle for two wavelengths (410 and 540 nm) and the *lines* are values calculated from Mie scattering theory for ice crystals of radii close to 0.1 μm

Sweden" lay between 70° and 90°. Data are plotted for one flight and show a degree of polarization at 214 nm lying between 0.55 at $\theta = 70°$, and 0.65–0.89 for $\theta = 90°$. There was, however, apparently some optical interference present in this channel and the authors stated that the measured degree of polarization is to be regarded as a lower limit. The results from the three longer wavelengths show the measurements clustering closely together, running from about 0.74 ($\theta = 70°$) to 0.90–0.97 for $\theta = 90°$. Figure 5.10 shows that these degrees of polarization indicate typical radii around 0.1 μm. The analytical inversion technique used by Heintzenberg et al. (1978) gives a maximum radius of 0.075 μm with the most likely radius lying in the range 0.06 to 0.075 μm.

5.6 Conclusions About Cloud Particle Sizes

In a similar way to the caution expressed in Section 4.6, but for different reasons, there remains uncertainty about the conclusions to be drawn from the polarization data. If the irradiation on noctilucent clouds is unpolarized, the presence of polarization directions slant to the scattering plane and the presence of some degree of circular polarization suggest that there are cloud particles large enough (radii > 0.2 μm), or appreciably non-spherical or anisotropic, in the cloud. The *amount* of polarization that is measured points unequivocally to there being no cloud particles larger than approximately 0.1 μm in radius.

On the other hand, if the irradiation of the clouds is assumed to be partly polarized, evidence of rotation of the polarization plane and of circular polarization may no longer be used to infer the presence of the larger particles. Equally so, in this case, the high degree of polarization is no longer immediately interpretable in terms of the *absence* of the larger particles.

Bohren (1983) considered these problems and concluded that because he could not find a mechanism to orient larger scatterers (> 0.1 μm radius), that the circular polarization that has been measured must arise from there being some proportion of polarization in the light incident on the noctilucent cloud. Bohren thus accentuated the effect of multiple scattering on the irradiance of the cloud layer and rejected the alternative interpretation of larger, non-spherical scatterers. Gadsden (1983) to some extent justified the deduction of scatterers with radii greater than 0.1 μm by invoking Brownian rotation of non-spherical scatterers with observational selection to provide an apparent preference in the axial direction of the scatterers.

Perhaps the conclusion to be drawn at this stage concerning the characteristic size of the scatterers, larger or smaller, is to be expressed in the two words that can be the verdict of a jury in Scotland: "Not Proven!"

6 Rocket-Borne Sampling

6.1 Introduction

As seen in preceding chapters, the optical data have given conflicting, and to some extent contradictory, information on the characteristic size of the particles making up a noctilucent cloud. Given this situation, the answer would seem to be to go up to a noctilucent cloud and collect some of the particles for laboratory examination.

This is a difficult technical problem, however. The rocket vehicle is likely to be travelling supersonically through the cloud and there will be shocks around the casing and spreading from the nose cone. Simply collecting the cloud particles on trays may therefore be difficult because the airflow may stop the particles from reaching the trays. Local turbulence may cause the particles to spill out of the trays.

For aerodynamic stability, the collectors cannot be exposed until the rocket is in the upper atmosphere. Sometimes the collectors are deployed on arms extending from the casing in order to place them beyond the turbulence and shocks near the skin of the casing; air drag on the collectors when deployed in the lower atmosphere would pose unacceptable mechanical problems. Thus, collectors must be *deployed* or *uncovered* at the right time (height) and *retracted* or *covered* in time for the descent through the lower atmosphere.

In addition, the collectors must be recovered; either a sealed package has to be parachuted separately to a soft landing down range from the rocket launch or the spent rocket casing has to be found and the collector package recovered.

The principal remaining difficulty, after all the flight problems, is in identifying those particles which have been collected from the noctilucent cloud. There will inevitably be contaminant particles (appearing similar to the cloud particles) which have lodged in the collectors before, during or after the flight.

The problems have been overcome by several experimenters and the results of their successful flights are discussed in this chapter. Overcoming the problems has led to several ingenious techniques for tagging the particles that we are interested in. Describing these techniques must also be included in the discussion of the results just as the general discussion of polarized light was necessary for interpreting the optical data.