Sampling of noctilucent cloud particles

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ABSTRACT

Sampling of noctilucent cloud particles by means of sounding rockets has been successfully carried out from northern Sweden in the Summer of 1962. Two successful flights were achieved, one in the presence of noctilucent clouds and one when no such clouds could be visually observed from the ground or from aircraft. The collecting surfaces were exposed between the altitudes of approximately 75 and 98 kilometers during ascent only. The particle concentration in a vertical column through the noctilucent cloud display is found to be greater than 8×10^{10} particles per square meter which is at least one thousand times greater than in the case when no clouds were observed. The integral size distribution of the cloud particles is of the form $N = Ad^{-p}$ where $3 < p < 4$. A significant fraction of the collected cloud particles had a volatile coating prior to collection. The particles were analyzed by electron diffraction, neutron activation, and electron beam microprobe techniques. Electron-beam microprobe analysis has given evidence for iron particles with high nickel content. Calcium films were used as indicators of moisture associated with the collected particles. Study of the exposed and unexposed films flown in the sampling experiments has revealed evidence for moisture. Laboratory simulation of a ring- or halo-patterns found in the electron microscopic examination of the noctilucent cloud particles has been attempted. This was done by impacting ice-coated nickel particles on collecting surfaces similar to those used in the sampling experiment. Ring patterns similar to those observed on the rocket sampling surfaces have been produced. The primary conclusions are that the cloud particles are probably of extraterrestrial origin and that a significant fraction appears to have been coated with terrestrial ice. Plans for future experiments are briefly outlined.

Introduction

The first scientific measurements of noctilucent clouds date from the 1880's, when JESSE (1896) in Germany and Tserasski and Pokrovski (KHVOSTIKOV, 1952) independently in Russia established the unusual height of the clouds by baseline photography. These observations were made during the extraordinary conditions of the upper atmosphere following the eruption of the volcano Krakatoa in 1883. Jesse's height values range from 78 to 90 km with a mean of about 82 km. He also found that the clouds moved predominantly from the North-East to the South-West with speeds up to 200 m/s. Similar results were obtained by the Russian observers. These data have been confirmed and refined by subsequent investigations. (STØRMER, 1935; PATON, 1949; BUROV, 1959; WITT, 1962). It is clearly established that noctilucent clouds appear at the mesopause with a well defined lower boundary at about 80 to 85 km. A gross cloud drift exists, predominantly from a direction between North and East, with speeds to the order of 100 m/s. Wave patterns are often observed in the clouds, with wavelengths ranging from 5 to 50 km and amplitudes from 0.5 to 4 km. The wave crests may propagate with or against the gross cloud drifts, with phase velocities which depend on the wavelength. Fig. 1 shows a strong display of noctilucent clouds photographed in Sweden in 1958.

Soon after the earliest observations, Helmholtz obtained spectra of noctilucent clouds. These spectra exhibited Fraunhofer absorption lines, from which it is inferred that the light from the clouds is scattered sunlight. The bluish-white color of the clouds led to the con-

[1] In alphabetical order.

FIG. 1. Noctilucent cloud display photographed from the Torsta observing site in Sweden on August 11 1958, at 2350 local time, in direction 10° east of north and 10° angle of elevation.

clusion that the light was scattered by particles with radii smaller than the wavelengths of visible light. This was confirmed by the discovery of the polarization of the light from the clouds. More recent polarization and spectral measurements (DEIRMENDJIAN and VESTINE, 1958; WITT, 1960; VILLMANN, 1962) have shown that indeed the particles are in the Mie scattering size range. Since the degree of polarization is relatively high at large scattering angles, it was assumed that if the particles follow a size distribution law of the type $dN(r)/dr = Ar^{-p}$, the exponent p must be greater than 3.

In the past most observations of noctilucent clouds have been reported from the eastern hemisphere. Most of these sightings were made in the summer twilight at latitudes above 50° North. The latitudes at which the clouds have been observed range from 45° N to 80° N. Recent systematic studies in Alaska (FOGLE, 1962) have shown the presence of the phenomenon in the Western hemisphere at high latitudes.

Reported observations in the Northern hemisphere range from April to October. The time of greatest frequency of displays of noctilucent clouds falls in the months of July and August. The sightings appear to be more frequent at the later dates at higher latitudes. It has been reported that more sightings have been during the morning hours than before midnight (LUDLAM, 1957; PAVLOVA, 1962).

The apparent connection between the cataclysmic eruption of Krakatoa and the first scientific observations of noctilucent clouds led to the speculation of a volcanic origin of the cloud particles (LUDLAM, 1957). The greater frequency of noctilucent cloud sightings as compared to the frequency of large-scale volcanic eruptions led to the gradual abandonment of the volcanic hypothesis. The large-scale observations of the bright displays that followed the fall of the Tunguska meteorite in Siberia in 1908 lent weight to the hypothesis that the clouds were of meteoric origin. The meteoric hypothesis has thus far persisted.

The discovery of a temperature minimum at the altitude now labelled the mesopause gave support to the hypothesis that the clouds were due to condensation of water vapor to form ice particles (HUMPHREYS, 1933; KHVOSTIKOV, 1952). The condensation hypothesis includes the possibilities of spontaneous condensation as well as sublimation upon solid particles. The condensation hypothesis gained weight with the rocket observations of very low summer temperatures at the high-latitudes mesopause (STROUD *et al.*, 1960). The possibility of ice cloud information at these altitudes has been discussed theoretically by HESSTVEDT (1962).

To discern the real nature of noctilucent cloud particles, it was decided to attempt sampling of the particles in situ. Techniques for high-altitude particle sampling utilizing rockets have been recently developed (HEMENWAY & SOBERMAN, 1962). An international cooperative research program was organized for the purpose of carrying out this experiment. Four rockets were launched during August, 1962, from the Kronogård range (66° N, 19° E) in Northern Sweden. Two of the rockets were fired in the presence of noctilucent clouds and two when no such clouds could be observed visually from the ground or from aircraft. Two of the flights were successful, one in the presence and one in the absence of clouds. The collected samples were recovered and subsequently analyzed in laboratories on both sides of the Atlantic.

A large number of diverse contributions were necessary to the successful accomplishment of this program. To permit full recognition of these contributions, the description and discussion of the techniques of sampling and analysis have been divided into the sequence of papers that follow.

Summary

From the following papers (ref. A–E) it appears that the nuclei of noctilucent cloud particles are not of terrestrial origin. A substantial upward flux extending from the tropopause to the mesopause would be necessary to raise submicron terrestrial particles to that altitude. However, this is neither consistent with the observed increase of particle concentration with height near the mesopause nor with the absence of any layer in the stratosphere with an observed particle mixing ratio as high as found in noctilucent clouds. Such a mechanism has neither been observed nor proposed. As to the particle composition, we can only note that the data available are not inconsistent with extraterrestrial origin.

The evidence indicates that a fraction of the particles were ice coated at the time of collection. This conclusion is drawn from the halo or ring structures seen on the nitrocellulose collection surfaces (ref. B), the simulation of these ring structures with ice coated particles (ref. E), and the interaction of the cloud particles with the calcium collection surface (ref. D). The ice coatings are probably due to water vapor of terrestrial origin. It is far easier to raise water molecules to the mesopause than submicron particles. That the ice coatings are associated with the cloud phenomena is demonstrated by the absence of both ring structure and calcium interactions on the surfaces that were flown on flight I when no noctilucent clouds were present.

The particle concentrations measured by the two successful flights (Flight I—no visible evidence of clouds; Flight II—visible clouds) were significantly different. The rocket attitude data from I indicate that this rocket remained vertical within 6° (ref. A). The data available suggest that flight II (through the clouds) had a much larger angle of attack. This is inferred from the differences in particle numbers seen in the two collection cans from flight II. The explanation offered for this latter difference is that when a large angle exists between the axis of the rocket (or the normal to the collection surfaces) and the relative velocity vector of the rocket with respect to the ambient particles, then portions of the collection surface can be temporarily shielded. Also, those particles which do enter the collection port and impact the collection surfaces will be distributed over an area which varies with the cosine of the angle. These effects will decrease the number of particles per unit area observed on the collection surfaces relative to the number per unit area in a vertical column through the cloud. It was established (ref. A) that aerodynamic effects were negligible in the particle size range of interest and that the rocket took an almost vertical path through the clouds. From the foregoing we can conclude that the largest values obtained from flight II for the number of particles per unit area on the collection surfaces represent only a lower limit to the true number which were in the display of 11 August, 1962. Yaw effects appear to have been more severe in the cloud case (flight II) than the known non-cloud case (flight I) and these would only decrease the difference in particle concentrations between the two cases. Indeed, from the particle concentrations (8×10^{10} m^{-2}) and particle size distribution $N = Ad^{-p}$; $3 < p < 4$ observed from the cloud flight, there is theoretical justification to believe that the clouds would be visible even if no ice coatings were present on the particles. Moreover, the exponent of the size distribution is consistent with the high degree of polarization observed at large scattering angle.

A further inference can be drawn from the difference in the particle numbers found in the two collection cans flown through the clouds (flight II). As previously mentioned, this difference is attributed to the pitching and yawing of the rocket. If the rocket spin were rapid as compared to the change in particle concentration with height, then the particle numbers collected by the two cans should have been "averaged out". Thus with the observed difference one concludes that the above condition was not fulfilled. Using the data available, it is possible to construct a crude picture of the vertical profile of particle concentration with height in the clouds. For this we must assume a spin rate for flight II (since no magnetometer data exist for the time in question during this flight). As is mentioned in paper A, a mean value of 0.1 revolutions per second is obtained from the data of the other three flights. From the data of paper B, we find the difference between the particle numbers in the two cans to be approximately a factor of 4. This difference should have occurred during the time of $\frac{1}{2}$ revolution or about 5 seconds. During 5 seconds the rocket rose approximately 3 kilometers. If it is further assumed that the particle concentration varies exponentially with height, from the foregoing one arrives at a scale height of roughly 2 kilometers. Considering the assumptions necessary for this calculation this result should be viewed with caution.

The aerodynamic effects have been discussed and shown to be negligible for particles greater than 0.005 μ diameter. This indicates that the cut-off in the particle size distributions (paper A) at about 0.05 is not due to collection efficiency. This cut-off appeared well above the limits of resolution of the electron-microscopic scanning techniques used. Whether this cut-off is a property of the clouds or of the particle source is still unanswered. The existence of such an effect in the extra-terrestrial flux due to solar radiation pressure has been hypothesized many times.

In summation, the conclusions and inferences that have resulted from this investigation are as follows:

1. The nuclei of noctilucent cloud particles are of extra-terrestrial origin.
2. These nuclei have an integral size distribution of the form $N = Ad^{-p}$; $3 < p < 4$.
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 particle 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 kilometers.

The present experiments have given some insight into the nature and composition of noctilucent cloud particles. However, the mechanism of the cloud formation remains unknown. It now appears that noctilucent clouds could result from one of two mechanisms or a combination of the two. The first would be an enhanced injection of extra-terrestrial material which increases the particle concentration in the mesopause. The second would be a meteorological phenomenon which resulted in wide spread updraught winds strong enough to slow down the fall velocity of the extra-terrestrial material which is normally settling through this region. This slowing down would also lead to an increase in particle concentration. These hypothesized vertical movements could also provide sufficient water vapor to cause the ice coatings on the particles which seem to be a feature of the clouds. Recent evidence regarding the mesopause temperature in the presence and absence of the clouds seems to favour the meteorological explanation though not necessarily to the total exclusion of the enhanced injection mechanism.

It is hoped that the future experiments in this program will resolve many of the questions which are still open. Specifically, another series of rocket samplings of noctilucent clouds are planned for the summer of 1964. In these experiments, it is hoped that better attitude and trajectory data will be obtained. With such data, the particle concentration in the clouds can be better defined. Further, it is planned to use sampling devices which can measure the particle concentration as a function of height in the clouds. This latter information may yield new insight into the mechanism of the cloud formation. It is hoped that better composition information will result from the inclusion of sampling surfaces designed specifically for small particle composition analysis. New analyzing instruments which are currently being developed may improve these data.

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