A Note on the Stratospheric Infrared Sky Radiance

R. M. MACQUEEN[1]

The Johns Hopkins University, Baltimore, Md.

7 October 1967

A thorough study of the circumsolar stratospheric sky at balloon altitudes, based on a series of measurements of the sky radiance at wavelengths 0.44 and 0.52 μ, and at various angular positions from the solar center from 1.7° to 58° has been presented (Newkirk and Eddy, 1964), hereafter referred to as NE. Their data analysis is based upon work by Sekera (1956) and Diermendjian (1957, 1959) on the theory of radiative transfer in a turbid atmosphere.

During a stratospheric balloon flight at an altitude of 28 km on 9 January 1967 for the purpose of observing the outer solar corona in the near infrared, at wavelength 2.2 μ, we made observations of the sky radiance relative to that of the mean solar disk at scattering angles 3°–4.3°. These data, obtained at constant balloon altitude, and over small angular spread, are limited in their usefulness in relation to the problem of stratospheric aerosols. We can, however, draw some conclusions concerning their interpretation.

If the zenith sky radiance is measured relative to that of the sun, the theoretical problem reduces to that of the evaluation of the parameters in the equation

$$\frac{B^j}{B_\odot}=\omega_\odot N_0(h)C^j(\phi)+\epsilon, \tag{1}$$

where we use the notation of NE, with B^j and $B_\odot$ the zenith radiances of the sky and sun, respectively (j refering to the jth polarization component); $\omega_\odot$ is the solid angle subtended by the sun; and $N_0(h)$ arises from the use of a particle size distribution of the form

$$N(r,h)=N_0(h)\left(\frac{r}{r_2}\right)^{-\delta}, \tag{2}$$

where

$$\delta=0, \quad r\leq r_2,$$
$$\delta>0, \quad r>r_2.$$

$N(r,h)$ is the particle concentration in a column of unit cross section above the height h. In (1), $C^j(\phi)$ is given by

$$C^j(\phi)=\frac{\lambda^2}{8\pi^2}\int_{r_1}^{r_3} i^j(r,\phi,\lambda)\left(\frac{r}{r_2}\right)^{-\delta}dr, \tag{3}$$

with $i^j(r,\phi,\lambda)$ the Mie intensity function for the jth polarization component. Finally, ϵ is the sky radiance due to particulate scattering of material whose radii are small enough that they may be considered to scatter with the Rayleigh phase function. This includes all particles whose size parameter $\alpha=2\pi r/\lambda$ is less than about 1.25, corresponding to radii of about 0.1 μ, for visible light. NE present arguments that lead them to adopt $\delta=3.5$ for altitudes greater than 15 km, and use $r_1\sim0.01\ \mu$, $r_2\sim0.1\ \mu$, and $r_3\sim3\ \mu$, on the basis of direct sampling of particles by Junge *et al.*, (1961).

Using values for the Mie function for $m=1.33$, the analysis yields $N_0(h)$, and the number density of various size particles (radii 0.07–2.0 μ). At 24 km, the two flights of NE give $N_0(h)$ to be $\sim5\times10^6$ and $\sim7.5\times10^6$ cm^{-2} per micron Δr (see Fig. 1), and the number of particles whose radii are 2 μ is found to be $\sim7.5\times10^{-5}$ and $\sim9.5\times10^{-5}$ cm^{-3}, respectively. We note the fact that the integrand of $C^j(\phi)$ is peaked in a region corresponding to a matching of the incident wavelength and particle radius, i.e., at $\alpha\sim5$. Their analysis, then, is most

[1] Present affiliation: High Altitude Observatory, National Center for Atmospheric Research, Boulder, Colo.

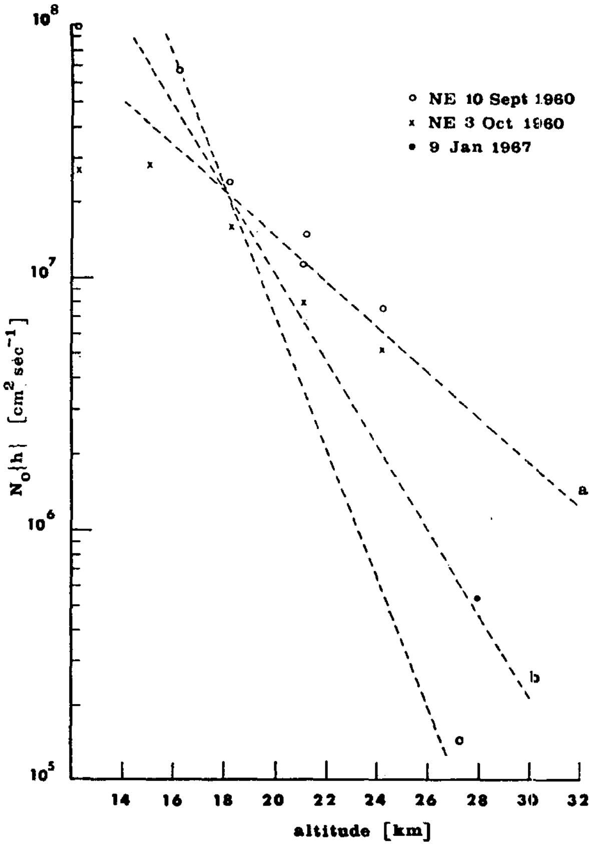

FIG. 1. $N_0(h)$ vs altitude, as determined from the two flights of Newkirk and Eddy (1964), and for the flight of 9 January 1967. The latter datum is calculated assuming the size distribution parameter $\delta=3.5$. Curves labelled a, b, c illustrate the predicted behavior of $N_0(h)$ for certain values of the eddy diffusion coefficient: a, 10,000 $cm^2\ sec^{-1}$; b, 5000 $cm^2\ sec^{-1}$; c, 2000 $cm^2\ sec^{-1}$.

sensitive to particles whose radii are distributed near those whose radii are $\sim 0.5\,\mu$. As an example, for particles whose radii are $\sim 2.5\,\mu$, i.e., $\alpha\sim 30$, the integrand has a magnitude of only about 3% that corresponding to $\alpha\sim 5$. We expect that measurements in the visible region of the spectrum would be relatively insensitive to particles whose radii are large. The direct sampling experiments are also weak in this area; for example, Junge *et al.* (1961) report distressingly large variations in the relatively small number of particles in the size range above $1\,\mu$ in the collections during their flights.

We have measured the mean infrared sky radiance to be $2.0\times 10^{-10}\ B_{\odot}$, corrected to zenith. From NE, who used the tables of Coulson *et al.* (1960), we estimate the contribution to our measured sky radiance by the pure molecular sky to be $0.2\times 10^{-10}\ B_{\odot}$. Hence, the aerosol component of the sky radiance is $1.8\times 10^{-10}\ B_{\odot}$, or about nine times the radiance of the molecular sky at this infrared wavelength. At 24 km, the same ratio was about 2, at a wavelength $0.44\,\mu$, from the data of NE.

In the case of our radiance measurement in the

TABLE 1. Calculated values of $N_0(h)$, the particle size distribution, from Eq. (1), using the aerosol radiance observations of this paper and Mie function tabulations for $m=1.33$, for various values of the size distribution parameter δ.

δ	$N_0(h)$ (cm^{-2} per micron Δr)
3.5	5.4×10^5
5.0	3.7×10^6
8.0	1.2×10^9

infrared, the major contribution to the integral $C^j(\phi)$ occurs for particles of radii $\sim 2\,\mu$, i.e., for $\alpha\sim 6$. We measure only the total intensity; both the $j=1$ and $j=2$ components. We have two variables in $N_0(h)$ and δ, and they cannot be separated by our data.

Using values for the Mie function (Penndorf, 1962; Gumprecht *et al.*, 1952) for $m=1.33$, and our observed aerosol radiance, we have calculated from (1) some sets of the parameters $N_0(h)$ and δ. These are presented in Table 1, and we may compare the results of the previous visible wavelength and these infrared measurements.

In Fig. 1 we have plotted $N_0(h)$ from the two flights of NE, and also from this infrared measurement, assuming that $\delta=3.5$. On the basis of the decrease in particle concentration with altitude found by NE for various values of the eddy diffusion coefficient, we may infer the behavior of $N_0(h)$ at the higher altitudes. Such behaviors are seen in Fig. 1 as dashed lines, and in this manner we may estimate the eddy diffusion coefficient in the region 24–28 km as approximately 1800 $cm^2\ sec^{-1}$.

In the 20–24 km region of the stratosphere, NE found that an eddy diffusion coefficient in the range $2000<D<10{,}000$ $cm^2\ sec^{-1}$ could be specified.

It is to be noted from the results presented in Table 1 that the set of the parameters $N_0(h)=3.6\times 10^6$ and $\delta=5.0$ also lead to plausible results, and indeed imply an eddy diffusion coefficient of 10,000 $cm^2\ sec^{-1}$ for the 24–28 region. The implication that there would hence be relatively fewer $\sim 2\,\mu$ sized particles than predicted by Eq. (2), with $\delta=3.5$, cannot be disproved by past data, for the reasons cited.

The data from this flight cannot resolve the question. Physically, the eddy diffusion coefficient would be expected to decrease with altitude in the stratosphere; in this respect the $\delta=5.0$ case seems less reasonable. Resolution of the question awaits more data, preferably over a wide spectral range, and as a function of altitude, in the manner of that done by NE.

Finally, we note that in the observations the solar aureole as viewed at $2.2\,\mu$ wavelength changes little in radiance out to angles of 3.2° from the solar center, a result that has been anticipated (Newkirk and Bohlin 1963). We infer less than a 2% change over this angular range. For the (possible) larger values of the parameter δ, if applicable, the change in radiance is less.

In summary, the prime contributors to our measured infrared stratospheric sky radiance are aerosols in the

2-μ radius range; a knowledge of these particles is lacking from visible wavelength radiance measurements and from direct sampling methods. We advance possibilities that allow correlation of these measurements with those of Newkirk and Eddy (1964). If currently advanced parameters are assumed correct, then an eddy diffusion coefficient $\sim$1800 cm^2 sec^{-1} may be deduced for the 24–28 km region of the stratosphere. The intensity of the aureole in the infrared is flat out to scattering angles of 3.2° to within 2%, confirming previous estimates.

Acknowledgments. We acknowledge the useful comments of Gordon Newkirk, Jr., the High Altitude Observatory, concerning this work, and thank W. G. Mankin of this Laboratory for helpful discussions. This project was supported by NASA Grant NGR-21-001-044 and Air Force Contract AF49(638)-1432, and the writer acknowledges support through National Science Foundation Grant GA641x.

REFERENCES

Coulson, K. L., J. V. Dave and Z. Sekera, 1960: *Tables Relating to Radiation Emerging from a Planetary Atmosphere with Rayleigh Scattering.* Berkeley, University of California Press 548 pp.

Diermendjian, D., 1957: Theory of the solar aureole, Part I. *Ann. Geophys.*, 13, 286–306.

——, 1959: Theory of the solar aureole, Part II. *Ann Geophys.*, **15**, 218–249.

Gumprecht, R. O., N.-L. Sung, J. H. Chin and C. M. Sliepcevich, 1952: Angular distribution of light scattered by large drops of water. *J. Opt. Soc. Amer.*, **42**, 226–231.

Junge, C. E., C. W. Chagnon and J. E. Manson, 1961: Stratospheric aerosols. *J. Meteor.*, **18**, 81–107.

Newkirk, G. N., and D. Bohlin, 1963: Reduction of scattered light in the coronograph. *Appl. Opt.*, **2**, 131–140.

——, and J. A. Eddy, 1964: Light scattering by particles in the upper atmosphere. *J. Atmos. Sci.*, **21**, 35–60.

Penndorf, R., 1962: Angular Mie scattering. *J. Opt. Soc. Amer.*, **52**, 402–408.

Serkera, Z., 1956: Recent developments in the study of the polarization of the sky light. *Advances in Geophysics*, Vol. **3**, New York, Academic Press, Inc., 43–103.