ULTRAVIOLET OBSERVATIONS OF THE ZODIACAL LIGHT AND THE ORIGIN OF INTERPLANETARY DUST GRAINS

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ABSTRACT. Surface brightness photometry of the night sky from rocket and satellite experiments shows an increase in the scattering efficiency of interplanetary dust grains in the 1500 to 3000 Å region of the spectrum. This increase is best explained by the presence of small dielectric particles with a mean radius of 0.04 microns. The most likely source of these grains is the dissolution of agglomerates of these particles which are released by comets during their perihelion passage. Many of these agglomerates have been collected in the Earth's atmosphere by high flying aircraft. Submicron particles swept up from interplanetary space may be responsible for the high altitude haze observed in planetary atmospheres.

1. Observations

Ultraviolet observations of the zodiacal light provide a sensitive test for the albedo, phase function and size distribution of interplanetary dust particles. The number of observations in this region are quite limited, however, and show considerable disagreement [1]. These observations must be obtained with instruments on rockets or spacecraft to avoid absorption by the Earth's atmosphere, and are extremely difficult due to the ten-thousand-fold decrease in solar flux between 3000 and 1500 Å. They are also complicated by large contributions from residual airglow, integrated starlight and diffuse galactic light which must be subtracted from the measurements.

Table 1 summarizes the available data for the zodiacal light intensity as a function of wavelength relative to the sun, normalized to 1 at 5500 Å [2,3]. There is good agreement among investigators that the zodiacal light is redder than the sun from 2400 to 2900 Å, with colors ranging from 0.40 to 0.90. And there is general agreement that the zodiacal light is bluer than the sun at wave-

Table 1. Zodical Light Colors [3]

Reference	Wavelength (Å)					
	1680	1800	1920	2200	2600	2900
Sudbury and Ingham (1970)					0.68	
Lillie (1968)				4.1	0.74	0.42
Lillie (1972)	16	15	6.5	0.75	0.54	0.54
Orrall and Speer (1973)	<130	<52	<18.4	0.75		
Morgan et al (1976)					0.76	
Frey et al (1977)				<1		1
Feldman (1977)	<40			0.45		0.90
Pitz, et al (1978)		0.54		0.30	0.40	
Maucherat-Joubert, et al (1979)*	~40			1		
Cebula and Feldman (1979)		<4		0.75		0.68
Tennyson, et al (1988)					0.80	0.80

* Reanalysis of Pitz, et al, (1978)

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lengths below 2200 Å, although there is a large scatter in the measurements. These differences may be due to temporal variations in the interplanetary medium as well as to different viewing geometries, observing equipment and techniques and calibration standards.

Figure 1 shows rocket and satellite data which suggests enhanced ultraviolet scattering. This scattering appears to be quite isotropic [6]. The Aerobee 4.55 data [5] were obtained on 2 September 1964 with photoelectric photometers which scanned the night sky at solar elongations from 40 to 180 degrees, while the data of [7] were obtained with a slitless spectrograph which observed the F and K corona at R=1.07 solar radii during the total solar eclipse of 7 March 1970 (three points are upper limits). The OAO-2 data [6] were obtained with the 8-inch filter photometers of the Wisconsin Experiment Package from February 1969 to March 1970 and cover elongations from 45 to 110 degrees. The Apollo 17 data [14,15] were obtained in December 1972 with an ultraviolet spectrometer which scanned the sky from approximately 6 to 180 degrees elongation while in Lunar orbit. Two versions of the OAO-2 data are shown. β Hyi has the spectrum of the sun but ζ Her is closest to the sun in color and ultraviolet flux and is the preferred solar analog. The data in Figure 1 show remarkable agreement, considering the wide variation in observing techniques and instruments which were used to obtain them. All of the observations show an increase below 3000 Å, with a steep rise below 2200 Å and an apparent peak at 1700 Å. The Apollo 17 data points have a large uncertainty, however, due to large contributions from integrated starlight and diffuse galactic light.

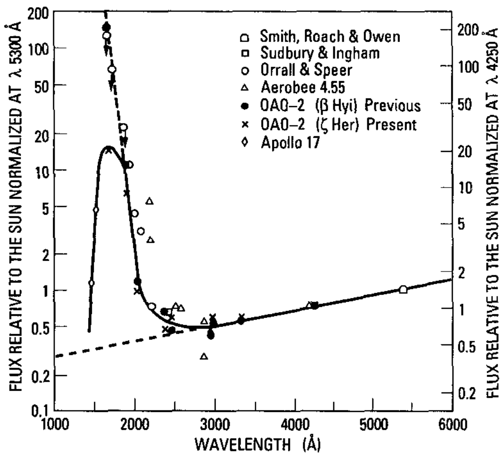

Figure 1. Zodiacal Light Spectrum

3. Analysis

Sudden increases in the scattering efficiency of particles can occur when the particle is much smaller than the wavelength of the incident radiation and the index of refraction is small (Rayleigh scattering), or when the particle is small and the index of refraction of the material is large and real or nearly so (optical resonance)[16]. The strongest resonance peak (magnetic dipole radiation) occurs near $nx = \pi$, where n is the real part of the index of refraction $m = n + ki$ and the particle size parameter $x = 2\pi a/\lambda$. Some examples of optical resonances are the 10 µm emission feature in silicates and the ultraviolet extinction feature at 2175 Å.

The optical properties of the small (0.01 and 0.10 µm radius) graphite and silicate spheres which are candidates for interstellar grains [17] were used to compute the ultraviolet scattering efficiency of these grains for comparison with the zodiacal light spectrum. Three spectral features were selected for this comparison: the onset of enhanced scattering at 3000 Å, the mid-point of the steep rise at 2000 Å, and the scattering peak at 1700 Å. The particle radii required to produce each feature are 0.0237, 0.0280 and 0.0487 µm, respectively, for graphite particles or 0.413, 0.400 and 0.407 for "astronomical silicate" particles. The rms variance of 0.0005 for silicate (versus 0.0109 for graphite) suggests silicate particles are responsible for this ultraviolet enhancement. Also, the graphite particles have a secondary scattering feature at 2200 Å, which does not appear in the zodiacal light spectrum.

Figure 2 shows the scattering efficiency required to produce the steep increase in the zodiacal light spectrum for grains of radius 0.036 and 0.057 μm. The scattering curves for non-absorbing spheres for four values of the refractive index [16] are shown for comparison. The inset in Figure 2 shows the variation of the index of refraction with wavelength required to produce the observed scattering for the two radii.

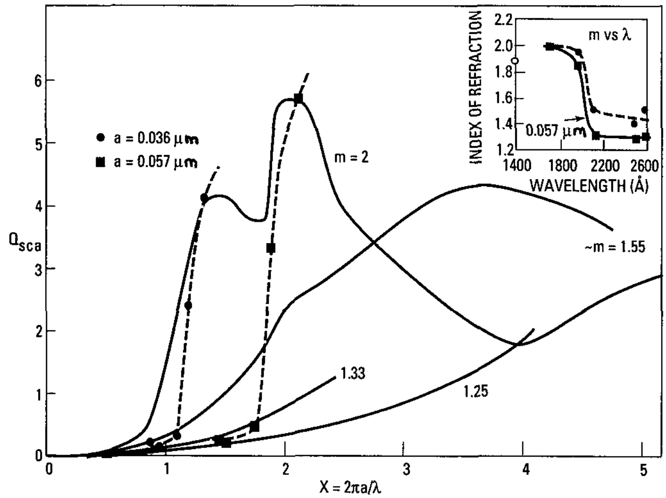

Figure 2. Scattering Efficiency of Small Grains

The peak in the m = 2 curve at x = 1.6 is a magnetic dipole resonance, and a 0.04 μm particle curve would just intersect the peak of this feature. This analysis is only valid for silicate particles [17] whose refractive index is almost entirely real (m ~ 1.73, k < 0.03 at wavelengths longer than 2200 Å, increasing to m = 2.08, k = 0.16 at 1700 Å). ("Astronomical silicate" might be classified a strongly absorbing black glass). The variation of m with wavelength in Figure 2 most nearly resembles the dispersion curve for vitreous quartz or borosilicate glass [18]. Given accurate dispersion curves it may be possible to discriminate between candidate materials for these grains.

4. Discussion

This analysis indicates the steep rise in the zodiacal light spectrum is due to a combination of Rayleigh scattering and magnetic dipole resonance in silicate particles with a mean radius of 0.04 μm. An absorption band at ~ 1400 Å must also contribute to the formation of the scattering peak at 1700 Å.

Particles of this size have a mass of ~ 10^{-15} grams, and will be pushed out of the inner solar system by solar radiation pressure in about 10^7 seconds [19]. The cosmic dust experiments on Pioneer 8 and 9 have observed such particles in hyperbolic trajectories whose apparent radiant is the sun [21]. These particles may be created from cometary fragments (from new and periodic comets) which spiral in toward the sun and partially evaporate at a few solar radii, until radiation pressure exceeds gravity and the particle is ejected radially [20].

Interplanetary particles of probable cometary origin have been collected in the stratosphere at an altitude of 20 km with U-2 aircraft [22]. These "Brownlee Particles" are fragile, highly porous aggregates of mostly submicron (<0.10 μm) polychrystalline grains. They could easily be fragmented by sputtering, differential heating or electrostatic forces in the vicinity of the sun.

Submicron particles believed to be of cosmic origin have also been collected at high altitudes (> 80 km) in the Earth's atmosphere [23]. These particles have a mean diameter of ~ 0.06 μm, with the highest concentrations found in noctilucent clouds. Other evidence for planetary sweeping of submicron particles may be found in the high altitude hazes (with optical depths of .02 to .03 in the violet region of the spectrum) observed on Mars by the Mariner and Viking spacecraft, and in the outer planets by Voyagers 1 and 2. Titan also has high altitude aerosols with a mean radius of 0.05 μm [24]. Large fluxes of dust particles were also detected in-situ by the Voyager plasma wave experiment during equatorial plane crossing at Jupiter, Saturn, Uranus and Neptune.

These observations are consistent with the current core-mantle model for interstellar and cometary grains [25] if we assume the icy coating and refractory organic mantle have been volatilized by solar radiation, leaving relatively bare silicate cores with high scattering efficiency in the 1500 to 3000 Å region of the spectrum.

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