DYNAMICAL ZODIACAL CLOUD MODELS CONSTRAINED BY HIGH RESOLUTION SPECTROSCOPY OF THE ZODIACAL LIGHT.

S. I. Ipatov, *University of Maryland, USA (siipatov@hotmail.com)*, A.S. Kutyrev, *NASA/GSFC, Greenbelt, MD, USA*, G.J. Madsen, *University of Wisconsin-Madison, Madison, WI, USA*, J.C. Mather, *NASA/GSFC, Greenbelt, MD, USA*, S.H. Moseley, *NASA/GSFC, Greenbelt, MD, USA*, R.J. Reynolds, *University of Wisconsin-Madison, Madison, WI, USA*.
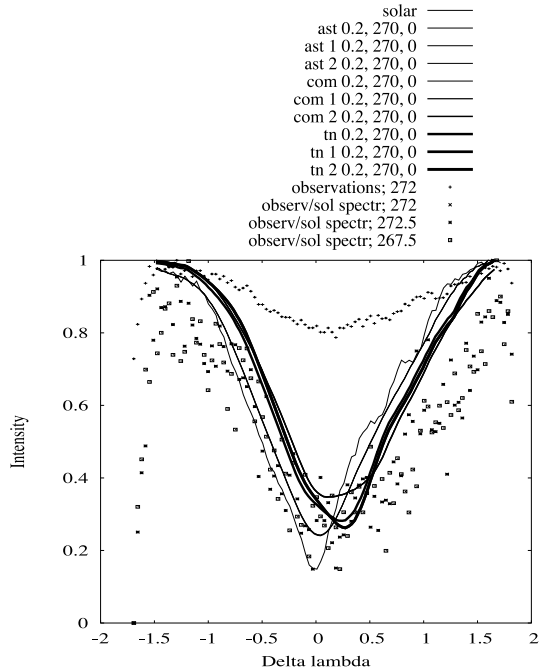

Figure 1: Dependence of the intensity of light vs its wavelength λ (in Angstrom) at β=0.2, ϵ=270°, and i=0. Zero of $\Delta\lambda=\lambda-\lambda_o$ corresponds to $\lambda=\lambda_o$=5184 Angstrom.

Introduction. We have developed a set of self-consistent dynamical models of the Zodiacal cloud, following the orbital evolution of dust particles. Three populations were considered, originating from the Kuiper belt, asteroids and comets. Using the models developed, we investigated how the solar spectrum is changed by scattering by the zodiacal cloud grains and compared the obtained spectra with the observations.

Models for migration of dust particles. Using the Bulirsh–Stoer method of integration, Ipatov et al. (2004) and Ipatov and Mather (2005) investigated the migration of dust particles under the influence of planetary gravity (excluding Pluto for asteroidal and cometary particles), radiation pressure, Poynting–Robertson drag, and solar wind drag. The initial positions and velocities of the asteroidal particles were the same as those of the first numbered main-belt asteroids (JDT 2452500.5), i.e., dust particles are assumed to leave the asteroids with zero relative velocity. The initial positions and velocities of the trans-Neptunian particles were the same as those of the first TNOs (JDT 2452600.5), and our initial data were different from those in previous papers. The initial positions and velocities of cometary particles were the same as those of Comet 2P Encke ($a\approx$2.2 AU, $e\approx$0.85, $i\approx$12°) or Comet 10P/Tempel 2 ($a\approx$3.1 AU, $e\approx$0.526, $i\approx$12°). .

For asteroidal and Encke particles, values of the ratio between the radiation pressure force and the gravitational force β varied between 0.0001-0.0004 and 0.4. For silicates, the β values 0.004, 0.01, 0.05, 0.1, and 0.4 correspond to particle diameters of about 120, 47, 9.4, 4.7, and 1 microns, respectively. For water ice, our β values correspond to particle diameters of 290, 120, 23, 11.7, and 2.9 μm. As did Liou et al. (1999) and Moro-Martin and Malhotra (2002), we assume the ratio of solar wind drag to Poynting–Robertson drag to be 0.35. The relative error per integration step was taken to be less than 10^{-8}. The simulations continued until all of the particles either collided with the Sun or reached 2000 AU from the Sun. Orbital elements were stored with a step of $\leq$20 yr for asteroidal and cometary particles and of 100 yr for trans-Neptunian particles.

Variations of the solar spectrum due to scattering by dust particles. We investigated how the solar spectrum is changed by scattering by dust particles (a detailed paper will be prepared). Positions of particles were taken from the runs discussed above. For each such stored position, we calculated $>10^3$ different positions of a particle and the Earth during the period P_{rev} of revolution of the particle around the Sun, considering that orbital elements do not vary during P_{rev}. Three different scattering functions were considered. In the first model, the scattering function depended on a scattering angle θ in such a way: $1/\theta$ for θ<c, $1+(\theta$-c$)^2$ for θ>c, where θ is in radians and c=$2\pi/3$ radian. In the second model, we added the same dependence on elongation ϵ (considered westward from the Sun). In the third model, the scattering function didn't depend on these angles at all. For all these three models, the scattering function was proportional to $\lambda^2\cdot(R*r)^{-2}$, where r is the distance between a particle and the Earth and λ is a wavelength of light. For each considered position, we calculated velocities of a dust particle relative to the Sun and the Earth and used these velocities and the scattering function for construction of the solar spectrum received at the Earth after been scattering by different particles located at some beam (view of sight) from the Earth. The direction of the beam is characterized by ϵ and inclination i. Particles in the cone of 2° around this direction were considered. In each run, particles of the same size (at the same β) and the same source (i.e., asteroidal) were studied.

Two plots of the obtained spectrum are presented in Fig. 1-2. The most thin line denotes the initial solar spectrum. Solar spectra for asteroidal ('ast') and Encke ('com') particles are practically the same for three scattering functions. For trans-Neptunian ('tn') particles for the first and the second models (e.g., denoted as 'tn 1' and 'tn 2', respectively) the plots are practically the same, but the plot for the third model (denoted simply as 'tn') is different. In the legend in the figure, the first number (0.2 in Fig. 1) denotes β, the next
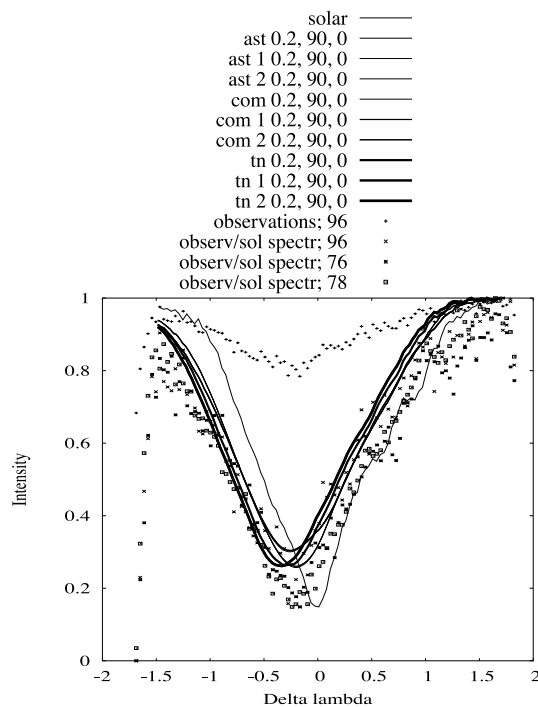
Figure 2: Dependence of the intensity of light vs its wavelength (in Angstrom) at β=0.2, ϵ=90°, and i=0. Zero of $\Delta\lambda$ corresponds to 5184 Angstrom.

number denotes elongation (in degrees), and the last number denotes inclination. For observations (made by Reynolds et al., 2004) only the value of elongation is presented in the legend. Designation "observ/sol spectr" corresponds to the case for which the plot based on the observations was stretched in such a way that the minimum became the same as that for the initial solar spectrum. The maximum value was considered to be the same (equal to 1) for all plots. The data points of observations that drop toward zero on the far blue edge of some of our spectra are an artifact of how we collect data and are not a real part of the spectrum.

The obtained spectrum (e.g., Fig. 1-2) is in general agreement with the observations made by Reynolds et al. (2004) who measured the profile of the scattered solar Mg Iλ5184 absorption line in the zodiacal light. Unlike results by Clarke et al. (1996), our modeled spectra don't exhibit strong asymmetry. As with these authors, we found that minima in the plots of dependencies of the intensity of light on its wavelength near 5184 Angstrom are not so deep as those for the initial solar spectrum. The details of plots depend on diameters, inclinations, and a source of particles. Different particles populations produce clearly distinct model spectra of the zodiacal light. For example, for i=0 and trans-Neptunian particles, the shift of the plot to the blue was greater than those for asteroidal and

Encke particles at ϵ=90°, and the shift to the red was greater at ϵ=270°. The results of modeling are relatively insensitive to the scattering function considered, the difference was greater for directions closer to the Sun. Our preliminary models and comparison with observational data indicate that for more precise observations it will be possible to distinguish well the sources of the dust and impose constrains on the particle size.

Brightness of dust particles. For asteroidal and Encke particles at i=0, about 65-89% and 70-85% of brightness was due to the particles at distance from the Earth r<1 AU (83-96% for r<1.5 AU; 80-98% for R<2 AU). For trans-Neptunian particles, 14-78%, 22-85%, 26-78%, and 40-90% of brightness was due to r<1 AU, r<1.5 AU, R<2 AU, and R<5 AU, respectively. The above ranges were caused by different values of β and ϵ and different scattering functions considered. Only a few trans-Neptunian particles in one run reached the near-Earth space, so statistics were not good and could increase the above intervals. According to Grün (1994), the intensity I of zodiacal light falls off with heliocentric distance R as $I\sim R^{-\gamma}$, with γ=2 to 2.5 and beyond about 3 AU zodiacal light was no longer observable above the background light. At $\beta\geq0.05$ the brightness of all trans-Neptunian dust particles located at R>3 AU was less by only a factor of several than that at R<3 AU, so the contribution of trans-Neptunian dust particles at d<10 μm to the zodiacal light may not be large (else zodiacal light will be observed beyond 3 AU), but this problem needs more accurate estimates. Note that it is considered that the main contribution to the zodiacal light is from particles with diameters of about 20 to 200 μm.

Velocities of dust particles relative to the Earth that mainly contributed to brightness were different for different ϵ. At i=0 they were between -25 and 25 km/s.

Our recent papers can be found in http://arXiv.org/format/-astro-ph/ .

References

Clarke, D., Matthews, S.A., Mundell, C.G., Weir, A.S. (1996) *Astron. & Astrophys.* 308, 273-278.

Grün, E. (1994) in Milani, A., Di Martino, M., Cellino, A. (Eds.), IAU Symp. 160: *Asteroids, Comets, Meteors 1993.* Kluwer Publishing. Dordrecht, Holland, pp. 367-380.

Ipatov, S.I., Mather, J.C., Taylor, P.A. (2004) in: Belbruno, E., Folta, D., P. Gurfil, P. (Eds.), *Astrodynamics, Space Missions, and Chaos, Annals of the New York Academy of Sciences*, **1017**, 66-80.

Ipatov, S.I., Mather, J.C., (2005) *Advances in Space Research*, submitted (http://arXiv.org/format/astro-ph/0411004)

Liou, J.-C., Zook, H.A., Jackson, A.A. (1999) *Icarus.* **141**, 13-28, 1999.

Moro-Martin, A., Malhotra, R. (2002) *Astron. J.* **124**, 2305-2321.

Reynolds, R.J., Madsen, G.J., Moseley, S.H. (2004) *Astrophys. J.*, in press.