DYNAMICAL ZODIACAL CLOUD MODELS. S. I. Ipatov, *University of Maryland, College Park, MD, 20742; Space Research Institute, Moscow, Russia*, A. S. Kutyrev, *NASA/GSFC, Greenbelt, MD, 20771*, G. J. Madsen, *Anglo-Australian Observatory, P.O. Box 296, Epping, NSW 1710, Australia*, J. C. Mather, S. H. Moseley, *NASA/GSFC, Greenbelt, MD, 20771*, R. J. Reynolds, *University of Winsconsin-Madison, Madison, WI.*

Introduction: Using the WHAM spectrometer, Reynolds et al. [1] measured the profile of the scattered solar Mg Iλ5184 absorption line in the zodiacal light. Below we compare the rotation curves, i.e., plots of velocities of Mg I line (at zero inclination) versus elongations ε (measured eastward from the Sun), based on our models of the distribution of dust in the solar system, with the curves considered in [1].

Model: We integrated [2-3] the orbital evolution of about 12,000 asteroidal, cometary, and trans-Neptunian dust particles under the gravitational influence of planets, the Poynting-Robertson drag, radiation pressure, and solar wind drag, varying the values of the ratio β between the radiation pressure force and the gravitational force from $\leq$0.0004 to 0.4 (for silicates, such values correspond to particle diameters between $\geq$1000 and 1 microns). The considered cometary particles started from comets 2P, 10P, and 39P. A few hundred of particles were considered in each run. In our runs orbital elements were stored with a step of d_t of $\leq$20 yr for asteroidal and cometary particles and 100 yr for trans-Neptunian particles. The relative error per integration step less than 10^{-8} was adopted. The integration continued until all of the particles either collided with the Sun or reached 2000 AU from the Sun.

Algorithm of calculation of variations in solar spectrum after the light was scattered by dust particles: Ipatov et al. [4-5] studied how the solar spectrum is changed by scattering by dust particles. Positions of particles were taken from the runs of migration of dust particles. For each such stored position, we calculated many ($\sim 10^2$-10^4 depending on a run) 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 [3]. 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 scattering by different particles located at some beam (line of sight) from the Earth. The direction of the beam is characterized by elongation 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.

Variations in solar spectrum caused by scattering by dust particles: The plots of the obtained spectrum Mg Iλ5184 absorption line at ϵ=90° and ϵ=270° are presented in [4]. The obtained spectrum is in general agreement with the observations made by Reynolds et al. [1]. The details of plots depend on diameters, inclinations, and a source of particles. Different particle populations produce clearly distinct model spectra of the zodiacal light. For example, for trans-Neptunian particles, the shift of the plot to the blue was greater than those for asteroidal and 2P/Encke particles at ϵ=90°, and the shift to the red was greater at ϵ=270° (for i=0). The results of modeling are relatively insensitive to the scattering function considered, the difference was greater for directions closer to the Sun.

Based on our plots of the intensity of the scattered light obtained at the Earth vs. $\Delta\lambda$ (λ is the length of the wave near the solar Mg I λ5184 absorption line and $\Delta\lambda$=λ-$\lambda_\circ$, where $\lambda_\circ$ corresponds to the minimum of solar spectrum near this line) we calculated the shift $\Delta\lambda_s$ of the plot, which is based on our distribution of dust particles, relative to the plot of the solar spectrum. Considering that v/c=$\Delta\lambda_s/\lambda$ (where v is a characteristic velocity of particles and c is the velocity of light), we calculated the characteristic velocity of particles at different elongations. The plots of this velocity vs. elongation (the angle with a vertex in the Earth between directions to the Sun and a dust particle) at zero inclination are called rotation curves. The curves obtained in our runs are similar to those obtained with observations [1]. Examples of such curves are presented in [3, 6]. Many more curves will be presented in our paper which is now in preparation. In one model, we considered a shift of the centroid (the center of mass of the region located upper than a plot of intensity vs. $\Delta\lambda_s$ and restricted by the maximum value of the intensity) for scattered light obtained at the Earth relative to the centroid for the solar light. In another model, we considered a shift of the minimum of the plot of intensity of the scattered light from the minimum for the solar spectrum. Both models give similar results. A brief comparison of rotation curves obtained in our runs with the observations were made in [5]. Now we discuss this comparison in more detail.

The rotation curves obtained for different considered scattering functions were similar for 30<ε<330°; the difference was greater for directions closer to the Sun. The difference between different plots for several sources of dust was maximum at ε between 90 and 120 deg. For future observations of velocities of the zodiacal light, it is important to pay attention mainly to this interval of ε.

The comparison of the observed rotation curves with the curves for the models for dust particles of different sizes (for different values of β) produced by asteroids, comets (2P/Encke, 10P/Tempel 2, 39P/Oterma), and trans-Neptunian objects allowed us to make some conclusions about sources of zodiacal dust particles. For asteroidal dust particles and particles produced by comets 39P and 10P, rotation curves are relatively close to each other at $\beta<0.2$. Asteroidal, trans-Neptunian, and 2P particles populations produce clearly distinct model spectra of the zodiacal light.

For asteroidal dust, the rotational curve was below the observational curve by several km/s at $\varepsilon<240°$, the greater difference was at $60<\varepsilon<150°$. The plots obtained at different β were close to each other, especially at $\beta<0.01$.

For trans-Neptunian dust, the curves were different at different β. It may be caused by small statistics as only a few trans-Neptunian particles in each run entered inside Jupiter's orbit. The observational plot was mainly inside the region covered by plots for different β, but at $180<\varepsilon<270°$ it was mainly upper than the trans-Neptunian curves.

The curves for 10P particles depend on β, but less than for 39P and trans-Neptunian particles. For 10P and 39P particles, rotation curves were lower than those for observations at $\varepsilon<160°$ and $60°<\varepsilon<150°$, respectively. For 39P particles at $\beta>0.01$ the difference with observations was smaller than for 10P particles. At $\beta<0.002$ the results for 39P particles differed on β, and this may be caused by a small number of particles that entered inside Jupiter's orbit. The region covered by these curves includes the observational line.

The rotation curves corresponding to particles produced by comet 2P at perihelion were relatively close to each other for different β and were close to observations at $\varepsilon>180°$. Unlike the asteroidal dust, for 2P particles starting at perihelion, the modeled velocities of MgI line were a little higher than observed velocities at $60°<\varepsilon<180°$. So the combination of a larger fraction of 2P dust particles with a smaller a smaller fraction of asteroidal particles can match the observational curve.

For particles produced by comet 2P at aphelion, the difference between the rotation curves obtained at different β could exceed 10 km/s and the observational plot was inside the region covered by plots for different β. These curves are located mainly above than the observational curve, in contrast to asteroidal and 10P curves which are mainly below the observational curve.

The main conclusion of the above comparison is that asteroidal dust doesn't dominate in the zodiacal light and a lot of zodiacal dust particles were produced by high eccentricity comets (such as comet 2P Encke). This result is in agreement with our studies of dynamics of Jupiter-family comets [3, 7, 8] which showed that a lot of small former cometary objects can move in orbits with high eccentricities inside Jupiter's orbit. Most of these objects are not yet discovered. Our comparison [3] of the spatial density of migrating dust particles with the observational result that a spatial density is constant at 3-18 AU from the Sun also testifies that the fraction of cometary dust particles is significant (can be dominant) inside Saturn's orbit. Note that conclusions on significant fractions of cometary dust in the near-Earth space were made earlier by several scientists (see references in [3]).

Conclusions: Comparison of velocities of particles obtained in our runs with the results of observations show that asteroidal dust particles alone cannot explain these observations, and particles produced by high-eccentricity comets (such as Comet 2P/Encke) are needed for such explanation.

Several our recent papers are presented at astro-ph and at http://astro.umd.edu/∼ipatov.

References: [1] Reynolds R. J., Madsen G. J., Moseley S. H. (2004) *Astrophys. J.*, *612*, 1206-1213. [2] Ipatov S. I., Mather J. C., and Taylor P. (2004) *Annals of the New York Acad. of Sciences*, *1017*, 66-80. [3] Ipatov S. I. and Mather J. C. (2006) *Advances in Space Research*, in press. [4] Ipatov S. I. et al. (2005) *LPSC XXXV*, abstract #1266. [5] Ipatov S. I. et al. (2005) *BAAS*, late abstracts of AAS 206 Meeting, #34.08. [6] Madsen G. J. et al. (2005) *Abstracts of the conference "Dust in Planetary Systems" (Sept. 26-30, 2005, HI)*, 111-112. [7] Ipatov S. I. and Mather J.C. (2003) *Earth, Moon, and Planets*, *92*, 89-98. [8] Ipatov S. I. and Mather J.C. (2004) *Annals of the New York Academy of Sciences*, *1017*, 46-65.