Sources of the zodiacal dust cloud

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Analysis of WHAM observations was made together with **A. Kutyrev, G.J. Madsen, J.C. Mather, S.H. Moseley, R.J. Reynolds**.

A file with this presentation can be found on http://faculty.cua.edu/ipatov/gsfc2011o-zodi.ppt

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Abstract

Fractions of asteroidal particles, particles originating beyond Jupiter's orbit (including trans-Neptunian particles), and cometary particles originating inside Jupiter's orbit are estimated to be about 1/3 each, with a possible deviation from 1/3 up to 0.1-0.2. These estimates were based on the comparison of our models that use results of numerical integration of the orbital evolution of dust particles produced by asteroids, comets, and trans-Neptunian objects with different observations (e.g., WHAM observations of spectra of zodiacal light, the number density at different distances from the Sun). The fraction of particles produced by Encke-type comets (with e~0.8-0.9) does not exceed 0.15 of the overall population. The estimated fraction of particles produced by long-period and Halley-type comets among zodiacal dust also does not exceed 0.1-0.15. Though trans-Neptunian particles fit different observations of dust inside Jupiter’s orbit, they cannot be dominant in the zodiacal cloud because studies of the distribution of number density with a distance from the Sun shows that trans-Neptunian particles cannot be dominant between orbits of Jupiter and Saturn. Mean eccentricities of zodiacal particles that better fit the WHAM observations were about 0.2-0.5, with a more probable value of about 0.3. The conclusion on a considerable fraction of cometary dust is also in an agreement with our studies that showed that some former Jupiter-family comets could get orbits located entirely inside Jupiter's orbit and stay in these orbits for a long time. Most of these objects could disintegrate producing a substantial amount of dust.

Migration of dust.
Initial data and methods of integration

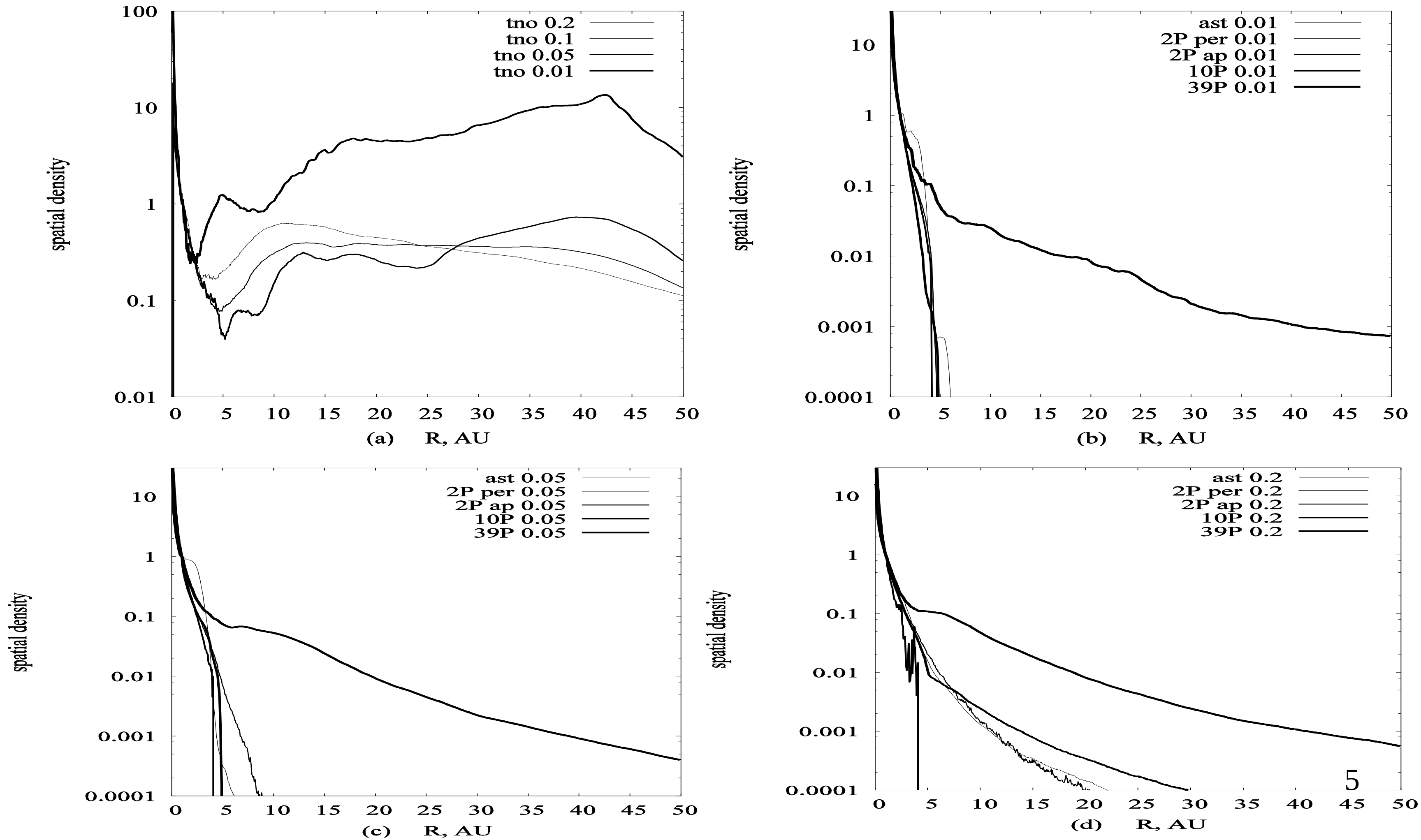
- The main sources of interplanetary dust are comets, asteroids, and trans-Neptunian bodies. Dust could be more efficient than larger bodies in delivery of organic matter to the planets.
- ***Our studies of sources of the zodiacal dust were based on comparison of some observations with our models based on results of integration of the motion of >20,000 asteroidal, cometary, and trans-Neptunian dust particles*** *under the gravitational influence of all planets* (Pluto was considered only for trans-Neptunian particles), *radiation pressure, Poynting-Robertson drag and solar wind drag. The motion of particles was integrated using* the Bulirsh-Stoer method (BULSTO) with the error per integration step less than $\varepsilon=10^{-8}$. We used the SWIFT package by Levison and Duncan (Icarus, 1994, v. 108, 18).
- ***A wide range of particle sizes (from 1 micron to several millimeters) was studied.*** We considered **β** (*the ratio between the radiation pressure force and the gravitational force*) equal to **0.0001, 0.0002, 0.0004, 0.001, 0.002, 0.004, 0.005, 0.01, 0.05, 0.1, 0.2, 0.25, and 0.4**. For silicates at density of 2.5 g/cm^3, such β values correspond to particle diameters ***d*** of about **4700, 2400, 1200, 470, 240, 120, 47, 9.4, 4.7, 2.4, 1.9, and 1.2 microns,** respectively. For water ice ***d*** is greater by a factor of 2.5 than that for silicate particles.
- In each run we took $N\leq250$, because for $N\geq500$ the computer time per calculation for one particle was greater by a factor of several than that for N=250.

Initial coordinates and velocities

- 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). Our initial data for dust particles were different from those in previous papers.
- The initial positions and velocities of **cometary** particles were the close to those of *Comet 2P Encke* (a≈2.2 AU, e≈0.85, i≈12 deg), or *Comet 10P/Tempel 2* (a≈3.1 AU, e≈0.526, i≈12 deg), or *Comet 39P/Oterma* (a≈7.25 AU, e≈0.246, i≈2 deg), or test long-period comets (e=0.995, $q=a(1-e)$=0.9 AU or q=0.1 AU, i was distributed between 0 and 180 deg, particles launched at perihelion), or test Halley-type comets (e=0.975, $q=a(1-e)$=0.5 AU, i was distributed between 0 and 180 deg, particles launched at perihelion).
- We considered Encke particles starting *near perihelion* (runs denoted as Δto=0), *near aphelion* (Δto=0.5), and when the comet had orbited for *Pa*/4 after perihelion passage, where *Pa* is the period of the comet (such runs are denoted as Δto=0.25).

Number density vs. distance from the Sun for different migrating dust particles.

Observations showed that number density is constant at 3-18 AU from the Sun [Humes D.H., J. Geophys. Res., 1980, 85, 5841]. Therefore, our obtained plots show that asteroidal dust doesn't dominate at a>3 AU, trans-Neptunian dust does not dominate at 3-7 AU, and ***a lot of dust particles located at 3-7 AU were produced by comets***.



Our model of calculations of changes of the solar spectrum after the light was scattered by dust particles

- *Based on positions and velocities of particles taken from a single run with a fixed β, we studied the variations in solar spectrum after the light was scattered by dust particles and reached the Earth.* For each such stored position, we calculated many (~10^2-10^4 depending on a run) different positions of a particle and the Earth during the period *Pr* of revolution of the particle around the Sun. All positions of particles during their dynamical lifetimes were considered.
- **Three different scattering functions were considered:**
- (1) the scattering function depended on a scattering angle θ in such a way: 1/θ for θ<c, $1+(\theta-c)^2$ for θ>c, where θ is in radians and c=2π/3 radian.
- (2) we added the same dependence on elongation ε (considered eastward from the Sun).
- (3) the scattering function didn't depend on these angles at all.
- ε is the angle with a vertex in the Earth between directions to the Sun and a particle,
- θ is the angle with a vertex in a particle between direction to the Earth and the direction from the Sun to a particle.
- The intensity of light that reaches the Earth was proportional to $\lambda^2(R*r)^{-2}$, where *r* is the distance between a particle and the Earth, *R* is the distance between the particle and the Sun, and λ is a wavelength of light.
- For each considered positions of particles, 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 the light was scattered by different particles located at some beam (line of sight) from the Earth. The direction of the beam is characterized by ε and inclination *i*. Particles in the cone of 2.5 deg around this direction were considered.

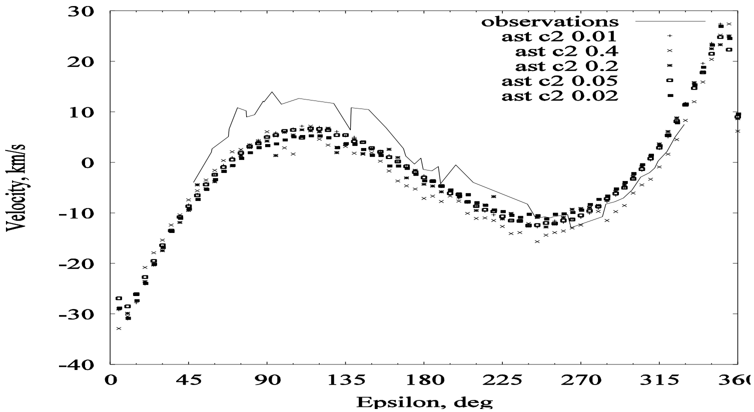
Calculation of 'velocity-elongation' plots

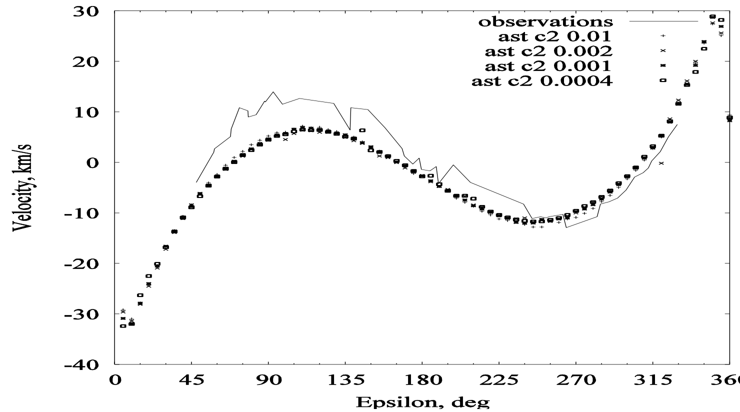
- ***Based on our plots of the intensity of the scattered light* obtained at the Earth vs. Δλ** (λ is **the length of the wave near the solar Mg I λ5184 absorption line** and Δλ=λ-λo, where λo corresponds to the minimum of solar spectrum near this line), ***we calculated the shift Δλs of the plot, which is based on our distribution of dust particles, relative to the plot of the solar spectrum.*** Considering that *v/c*=Δλs/λ (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) **were compared with those obtained by Reynolds et al. (2004) at observations**.
- Velocity-elongation plots for different scattering functions are denoted as c1 and m1 for function 1, as c2 and m2 for function 2, and c and m for function 3.
- For velocity-elongation plots presented in the poster, we considered a shift of a centroid (the 'center of mass' of the region located upper than a plot of intensity vs. Δλ and restricted by the maximum value of the intensity) for scattered light obtained at the Earth relative to the centroid for the solar light. These velocity-elongation plots are practically the same as the plots for the model when we considered a shift of the minimum of the plot of intensity of a scattered light from the minimum for the solar spectrum.
- Velocity-elongation plots obtained for different scattering functions are close to each other, exclusive for the cases when ε is close to 0.

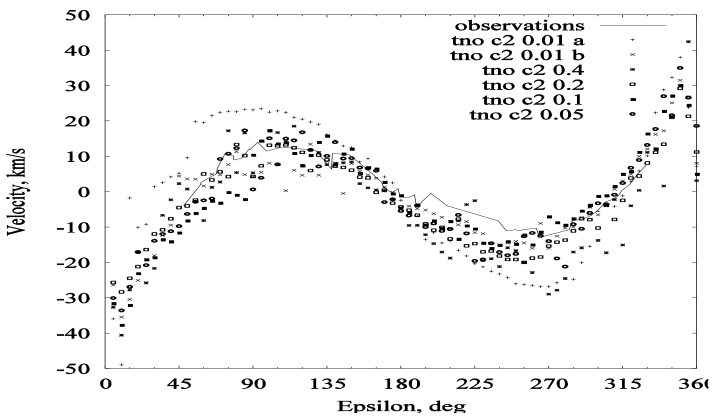
Comparison of plots of velocities of Mg I line versus elongation with the observations

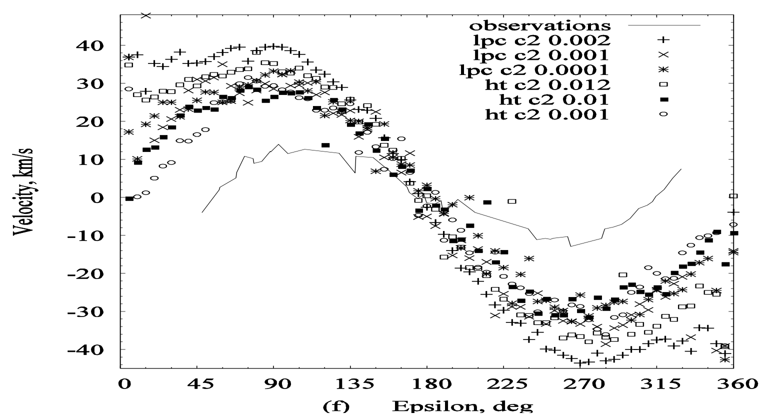
- **Ipatov, S.I., Kutyrev, A., Madsen, G.J., Mather, J.C., Moseley, S.H., Reynolds, R.J. (e.g., Icarus, 2008, 194, 269-788)** compared the plots of velocities of Mg I line (at zero inclination) versus elongation ε (measured eastward from the Sun), with the observational plots obtained by Reynolds et al. (ApJ, 2004, 612, 1206-1213).
- **The velocity-elongation plots obtained for different considered scattering functions were close to each other for 30<ε<330 deg**, the difference was greater for more close direction 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 particular attention to this interval of ε.
- In our opinion, **the main conclusion of the comparison of such curves is that asteroidal dust doesn't dominate in the zodiacal light and a lot of zodiacal dust particles were produced by comets.**
- This conclusion is also supported by the comparison of a spatial density of different migrating dust particles with the observational result that a spatial density is constant at 3-18 AU from the Sun.
- Significant contribution of cometary dust to the zodiacal dust was considered by several other authors (e.g., Zook, 2001; Grogan et al. 2001, Nesvorny et al. ApJ, 2010, 713, 816-836).

Velocity-elongation plots for asteroidal, trans-Neptunian, and cometary zodiacal dust. **For asteroidal dust, the velocity-elongation curves are below the observational curve** at elongation ε<240 deg. For trans-Neptunian dust, the observational curve is mainly inside the region covered by curves for different β, but at 180<ε<270 deg it is mainly above the trans-Neptunian curves**. For particles produced by long-period and Halley-type comets, the plot was above the observational curve at ε<180 deg** and it was below at ε>180 deg .

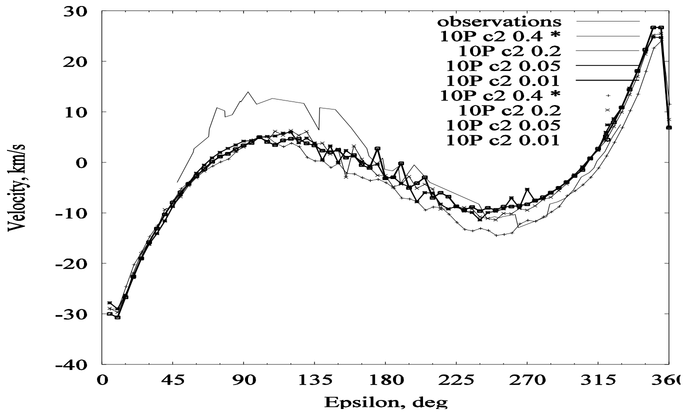


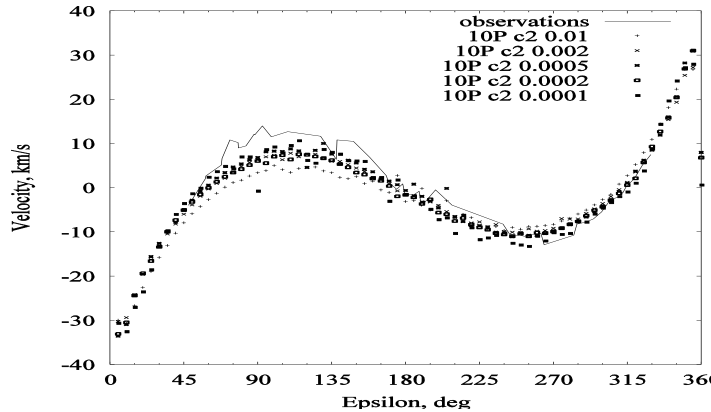


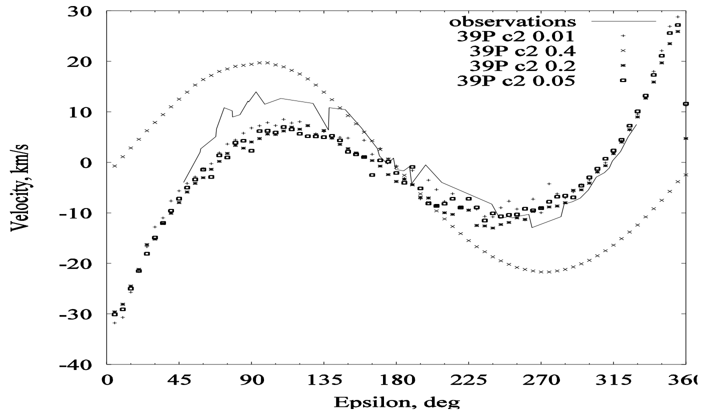


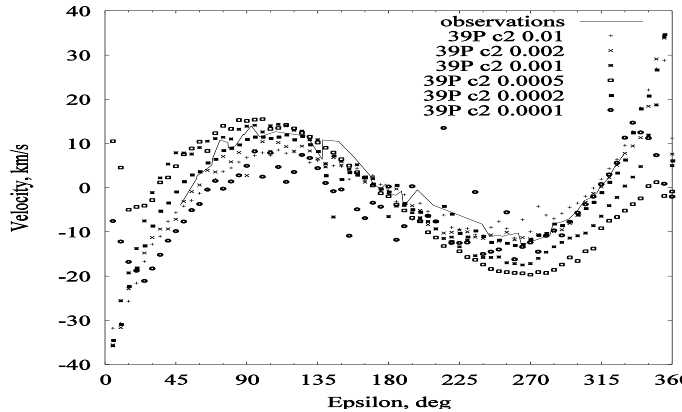


Velocity-elongation curves for particles originated from comets 10P and 39P. 10P curves are **below** the observational curve, but the difference is smaller for larger particles. *For some particles produced by comets with eccentricities ~0.25-0.5, the model curves can be close to the observational curve.*

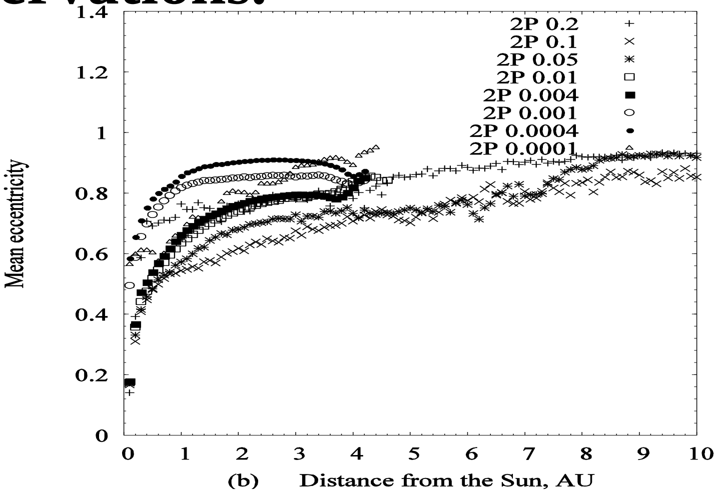


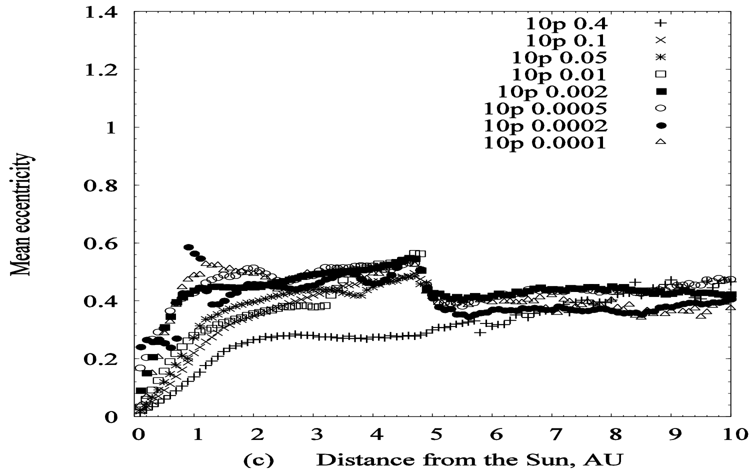


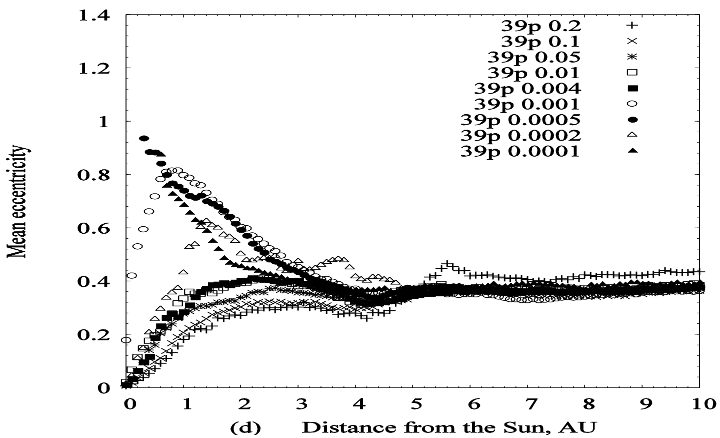


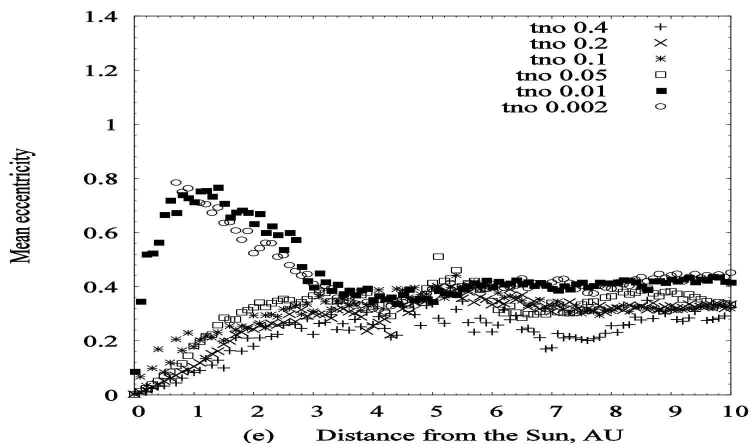


Mean eccentricity of particles at different distances from the Sun at several values of β (see the last number in the legend) for particles originated from comets 2P, 10P, 39P, and trans-Neptunian objects. **At eccentricities ~0.3-0.4, velocity-elongation plots better fit the observations.**

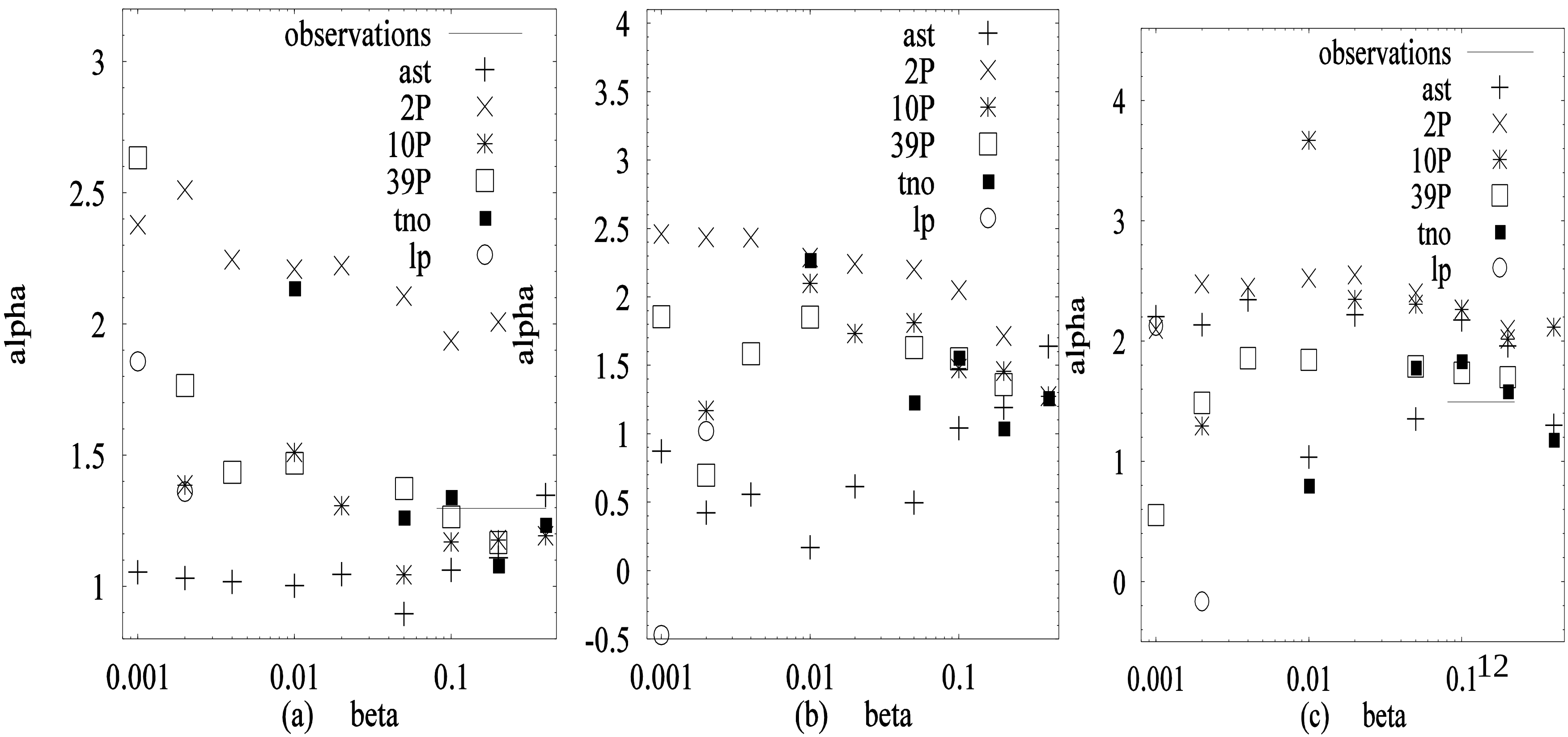








Values of α in the proportionality of number of particles *n*(*R*)~*R*^-α^ obtained by comparison of the values of the number density *n*(*R*) at distance *R* to the Sun equal to 0.3 and 1 AU (a), at *R*=0.8 and *R*=1.2 AU (b), and at *R* equal to 1 and 3 AU (c). The values are presented at several values of β for particles produced by Comets 10P and 39P (10P and 39P), from trans-Neptunian objects (tno), and from long-period comets (lp) at *e*=0.995, *q*=0.9 AU and *i* between 0 and 180 deg. *Observational values are* 1.3 for (a) and 1.5 for (c). **Comparison of model distributions of particles over *R* with observations testifies against a considerable zodiacal contribution of particles produced by comets moving in very high eccentric orbits (such as Comet 2P).**



Conclusions on sources of zodiacal cloud

- Our study of velocities and widths of the scattered Mg I line in the zodiacal light is based on the distributions of positions and velocities of migrating dust particles originating from various solar system sources. These distributions were obtained from our integrations of the orbital evolution of particles produced by asteroids, comets, and trans-Neptunian objects. The curves of the characteristic velocity of the line vs. the solar elongation obtained for different scattering functions were close to each other for directions not close to the Sun.
- The differences between the curves for several sources of dust reached its maximum at elongation between 90 deg and 120 deg. For future observations of velocity shifts in the zodiacal spectrum, it will be important to pay particular attention to these elongations.
- The comparison of the observations of velocities and widths of the zodiacal Mg I line made by Reynolds et al. (2004) with the corresponding values obtained in our models shows that asteroidal dust particles alone cannot explain these observations, and that particles produced by comets, including high-eccentricity comets (such as Comet 2P/Encke and long-period comets), are needed.

- The conclusion that cometary particles constitute a considerable fraction of zodiacal dust is also supported by the comparison of the variations of a number density with a distance from the Sun obtained with the spacecraft observations for dust particles of different origin.
- **Cometary particles originating inside Jupiter's orbit, particles originating beyond Jupiter's orbit (including trans-Neptunian dust particles), and asteroidal particles can contribute to zodiacal dust about 1/3 each, with a possible deviation from 1/3 up to 0.1-0.2.**
- *The estimated contribution of particles produced by long-period and Halley-type comets to zodiacal dust does not exceed 0.1-0.15.* The same conclusion can be made for particles originating from Encke-type comets (with e~0.8-0.9).
- The velocity amplitudes of the Mg I line (in plots of the velocity vs. elongation) are greater for greater mean eccentricities and inclinations, but they depend also on distributions of particles over their orbital elements.
- The mean eccentricities of zodiacal particles located at 1-2 AU from the Sun that better fit the WHAM observations are between 0.2 and 0.5, with a more probable value of about 0.3.