DEVELOPMENT OF A NEW INTERPLANETARY DUST MODEL

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ABSTRACT

The interplanetary dust complex is described by several dynamic populations of particles. New populations are tested against diverse observations. The new populations differ essentially from those adopted in earlier meteoroid models and are tied to long-term dynamics of the interplanetary dust. The data set used for validation of the model include infrared emission observations with COBE DIRBE instrument and impact counts with the dust detectors aboard Galileo and Ulysses spacecraft. It is found that under reasonable assumptions about sources, dynamics and composition of the interplanetary dust both remote observations and in-situ measurements can be reproduced by a combination of the new populations quite well.

Key words: interplanetary meteoroids; models.

1. THE DIVINE METEOROID MODEL

Divine [5] constructed an empirical model of the interplanetary meteoroids which attempted to match the variety of observations like zodiacal light measurements, impact detectors on various spacecraft, radar observations and lunar impact counts. In this model, the interplanetary dust cloud was assumed to be symmetric with respect to the ecliptic plane and the line of poles, and all grains in the cloud were assumed to be in Keplerian orbits around the sun with no perturbing forces. Statistical description was adopted and distribution in space and velocities was introduced. Due to the symmetries, dimension of the problem was reduced to three, with the full 6-D number density being a function of three independent variables, the perihelion distance r_p, eccentricity e and inclination i. A separable form was chosen for the number density:

$$n_6(x, y, z, v_x, v_y, v_z) = \frac{r_p^{3/2} N_1(r_p) p_e(e) p_i(i)}{2\pi (GM_\odot)^{3/2} e} \qquad (1)$$

velocity (v_x, v_y, v_z) in the ecliptic reference frame. The functions N_1, p_e and p_i were represented with tables of values at appropriate abscissas, and interpolation was applied between the abscissas. Distribution in mass was separated from distribution in space and velocities.

Definition (1) allows for derivation of fluxes, spatial number densities, and line-of-sight brightness integrals in a straightforward way, e.g. integration of (1) over all velocities yields spatial number density, which, in turn, under certain assumptions on grain optical properties, can be integrated over a line-of-sight to model observations at visual and infrared wavelengths.

Divine [5] incorporated in the model results of a radar meteor survey, several in-situ dust experiments, zodiacal light observations and lunar microcrater data. He began with radar meteor data and already had to introduce two populations each in the form (1) since the data did not support separability. Three more populations were introduced in order to reproduce in-situ flux measurements with dust experiments on Pioneer 10 and 11, Helios-1, Galileo and Ulysses.

The construction of the model was in principle as follows. The sum of all population contributions to the modelled observations was not allowed to exceed the measured values. A new population was often added to the model when a new data set was incorporated (e.g. the inclined population to match the Helios data). In order to compensate for high observational biases, a relatively weak criterion of convergence was applied (O is the observed value, C is the calculated prediction):

$$\text{Residual} = \frac{\log(C/O)}{1 + \log(C/O)} \qquad (2)$$

The Divine model gained popularity and some modified versions of the original model were used for more recent zodiacal dust observations [3] and space debris characterisation [1].

However, the Divine model design has some caveats. When the data are incorporated, a non-linear ill-defined problem has to be solved which costs extensive computa-

Proceedings of the 3rd European Conference on Space Debris, ESOC, Darmstadt, Germany, 19 - 21 March 2001
(ESA SP-473, August 2001)

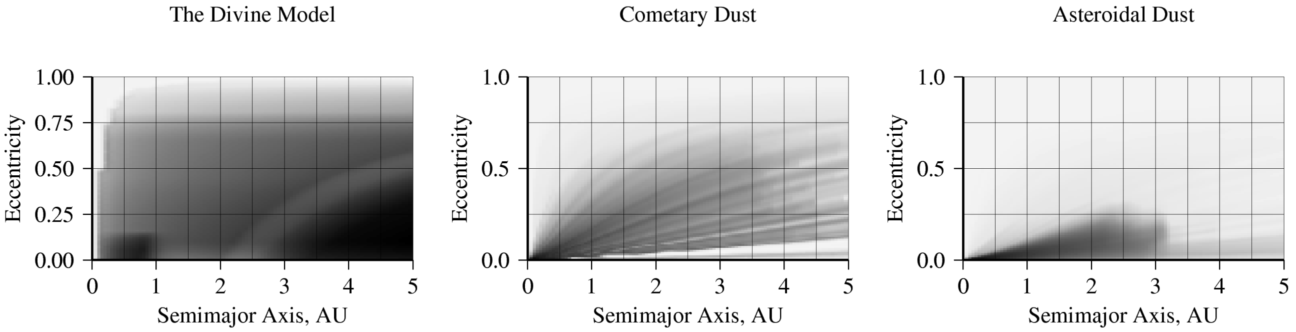

Figure 1. Comparison between the Divine model and the distributions of dust ejected from Jupiter family comets and asteroids, and spiralling towards the sun under the Poynting-Robertson drag. The Divine model distributions are calculated for the grain mass of 10^{-9} g, or a few microns in size. Three populations dominate at this size. The population in the background of the plot is the “Core” population, the dense region in the right bottom corner shows the “Asteroidal” population. There is a pronounced gap at the perihelion distance $r_p \approx 2$ AU between “Core” and “Asteroidal” populations. The patch in the left bottom corner shows the “Inclined” population.

sitates evaluation of nested integrals each time a parameter of the model is changed (well above 50 parameters in the Divine model). So far the only way to decrease computational costs has been reduction of prediction accuracy, i.e. employment of low-order quadrature formulae in approximation of the integrals numerically. When an update of the model is constructed, non-trivial and often manual work is necessary to find the first approximation. Finally, separability of the real dust distribution in the form established by (1) is supported neither by observations nor by long-term particle dynamics. Figure 1 shows disagreement between 2D distributions in semimajor axis and eccentricity for the Divine model and for the dust evolving under Poynting-Robertson (P-R) drag. It is seen that a good fit of the P-R drag-dominated dust distribution would require tens of Divine’s populations. Evolution of dust orbits under planetary perturbations, including both gravitational scattering and resonances, does not allow for separation of variables in Eq. (1) either. Source distribution is also non-separable.

In summary, we emphasise that the Divine model employed Keplerian dynamics to constrain the distribution of meteoroids in coordinates and velocities. Observations made by different methods were incorporated in the model, and a tool for the description of the interplanetary meteoroid environment was developed which allowed to estimate fluxes on arbitrary surfaces in the solar system. But improvement of the Divine model design is necessary to let the long-term dynamics further constrain distributions of interplanetary dust.

2. A NEW INTERPLANETARY DUST MODEL

New model design admits many — a number well above Divine’s five — populations with the distribution functions defined a-priori. Each population is constructed in order to represent a possible structure of the interplanetary dust cloud in accordance with long-term evolution of dust grain orbits. For example, the orbits of dust parti-

taken into account). Consequently, distribution of these particles in semimajor axis and eccentricity should look analogous to the distributions of cometary or asteroidal particles in Fig. 1. For the P-R drag taken alone, inclination distribution and mass distribution can be separated. The inclination distributions represent latitudes of sources of dust, and the mass distributions are determined by production rates and grain lifetimes.

As follows from the above example, distribution functions of the new populations may not be separable in the form suggested in (1). The distributions may be rather complicated, but since their relative profiles have been fixed, each of them add only one unknown parameter to the model — a normalisation factor. Each prediction C_j for the observation O_j may be described as a linear combination of the normalisation factors x_i

$$O_j \approx C_j = \sum_{j=1}^{N} w_{ij} \cdot x_i, \quad j = 1, \ldots, M. \qquad (3)$$

where w_{ij} is the contribution of i-th population to j-th observation. To determine the normalisation factors x_i, a linear inverse problem has to be solved. For both Gaussian and Poisson noises relevant to typical line-of-sight observations and in-situ impact counts, respectively, standard procedures exist to find the most likely values of x_i given the biased observations O_j. Note the inverse problem still may be ill-defined, since the existence of a solution depends on the choice of the population distributions.

The new model design has several advantages over the previous one. The amount of computations needed to adjust the model to the observations is decreased substantially since the observables are in linear relationships with the normalisation factors. Each individual observation — no matter whether it is a line-of-sight brightness measurement or in-situ impact count — may be expanded in a weighted sum of individual population contributions (3). This is done once only when a new population is introduced or a new observation is incorporated in the model, and then standard procedures can be applied to solve the

This is especially cumbersome when the inverse problem is solved through trial-and-error iterations.

The new design allows for an easy and comprehensive extension of the model: To add a new population or to modify an old definition, it is sufficient to expand observations in sums of weighted population contributions, and to re-adjust each population's norm using standard procedures. It is also straightforward to add new data sets. The procedure is to properly describe the response function w_{ij} of an instrument and the conditions of the observations, to calculate population contributions to the observed values and to re-adjust the normalisation factors.

Employment of long-term dynamics gives credibility to the model predictions where no observation data is available, i.e. the model-based extrapolations of existing measurements should, in general, be more reliable than in the Divine model which extrapolated measurements in a somewhat arbitrary way.

2.1. New populations

We introduced an experimental set of populations in order to test the new approach against infrared observations with COBE satellite and in-situ impact counts made by dust detectors on board Galileo and Ulysses. Of the ten wave bands covered by the COBE DIRBE experiment, we used the four centred at 4.9, 12, 25 and 60 micrometers where thermal emission of zodiacal dust dominates over other radiation sources such as stars at the shorter wavelengths, galactic infrared background at the longer wavelengths, and the cosmic infrared background. Since the data sets cover mostly small grains of radii below 100 μm, we used two different distributions in semimajor axes and eccentricity determined by the P-R drag for the grains ejected by comets and asteroids (see Fig. 1 for examples of the distributions of cometary and asteroidal dust particles). In this work, we did not account for the difference between the orbits of parent body and small dust particle subject to direct radiation pressure force. All asteroids and comets were assumed to generate dust at equal rates.

Inclination distributions for the new populations were defined as follows. We introduced sets of populations for cometary and asteroidal dust distinguished by parameters σ of the inclination distributions in the form:

$$f(i)di = \frac{1}{\sqrt{2\pi}\sigma} \exp\left\{-\frac{i^2}{2\sigma^2}\right\} \sin i di \qquad (4)$$

where σ were taken from 2° to 30° in steps of 2°. This is done in order to approximate the actual inclination distribution of dust which may differ from the distribution of visible dust sources (e.g. as a result of mean-motion resonances with planets).

Mass distributions were taken in the form $f(m)dm = m^{-\gamma+1/3}dm$ where γ is the slope of the mass distribution of ejecta from sources and the $1/3$ comes from

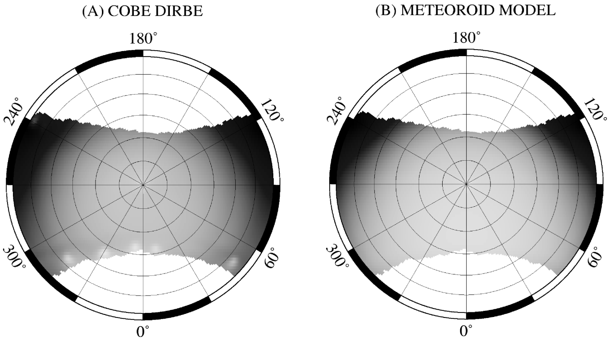

Figure 2. Thermal emission map at 12 μm as seen by COBE DIRBE (a) and predicted by the interplanetary meteoroid model (b). DIRBE's observations obtained in ecliptic southern and northern hemispheres were mapped onto one hemisphere and averaged. Reference frame is rotating synchronous to Earth's orbital motion. The centre shows thermal emission in the direction of the ecliptic North (or South) pole, 0° corresponds to anti-Sun direction.

grains live longer and spiral towards the sun slower). Note that this form of the mass distribution is valid in a limited mass range only where the P-R drag dominates particle dynamics. In order to test different possibilities, $-\gamma + 1/3$ was given values out of the set $\{-1.2, -1.27, -1.30, -1.33, -1.36, -1.4, -1.5\}$ which is centred around the expected ejecta mass distribution slope with $\gamma = 5/3 = 1.66$ [7].

Modelling of thermal emission of the interplanetary dust requires a knowledge of temperatures of zodiacal dust which depend on grain size, composition and distance from the sun. We used the approach suggested in [8] and calculated volume emissivities for astrosilicate and graphite grains for all mass distribution slopes γ. Mie theory was applied with the optical constants from [6]. In contrast to [8] who searched for a spatial number density to fit to observations, we derived spatial number densities from the distributions in orbital elements. This makes the spatial number density consistent with Keplerian dynamics, and through the definition of populations, with the long-term dynamics.

As a result of our assumptions described above we define 630 populations (2 source classes × 15 inclination distributions × 3 grain materials × 7 mass distribution slopes) which give 630 unknown parameters x_i. This is well above the number of parameters in the Divine model, yet the solution of the inverse problem is obtained faster, and at much higher accuracy of model calculations.

3. A FIT TO INFRARED OBSERVATIONS

The COBE DIRBE instrument accomplished a survey of the sky confined to the solar elongations larger than 60° and smaller than 135°. Based on this survey, weekly averaged sky maps were produced which we processed as moving the slight asymmetry of the zodiacal cloud with respect to the ecliptic plane which is seen in the data but which is not present in the formulation of the model. Ecliptic longitudes of the Earth at each observation were subtracted from the ecliptic longitudes of the observation directions so that all observations were reduced to a single location of the Earth. Multiple observations of the same positions on celestial sphere were averaged. Figure 2A shows the emission of the dust particles in 12 μm wave band.

Normalisation factors for all 630 populations were then iterated using the L-BFGS-B algorithm [2] to fit the model to the data, with the Gaussian function describing the distribution of errors of measurements

$$\text{Residual} = \sum_j \frac{(O_j - C_j)^2}{\sigma_i} \qquad (5)$$

where C_j are weighted sums of all population contributions to the i-th observation each corresponding to a line of sight from the map on Fig. 2A. The results are shown in Fig. 2B for the 12 μm wave band. Agreement with the observations in the other wave-bands at 4.9, 25 and 60 μm was good as well, so that both the spatial number densities and the spectrum of interplanetary dust were well matched by the model.

In our future work we plan to improve the representation of the infrared observations as follows. Asymmetry of zodiacal cloud with respect to the ecliptic plane can be introduced in the model by a simple transformation from the ecliptic plane to the model's symmetry plane.

4. A FIT TO IN-SITU IMPACT COUNTS

Dust experiments on-board spacecraft usually yield a sequence of impact events accompanied by inferred grain properties, spacecraft locations and velocities, as well as detector orientations. Based on similarity of observation conditions at the time of impacts (e.g. orientation of the detector, heliocentric distance, spacecraft velocity) the impacts can be sorted in bins to resolve fluxes of particles moving on different orbits. Description of the instrument response function is necessary to reproduce the impact counts in the model. In an ideal situation when the instrument response function is well known, Poisson statistics (coming from the well-known Poissonian distribution) can be applied to adjust the model to the observed impact counts:

$$\text{Residual} = \sum_j (C_j - O_j \ln C_j). \qquad (6)$$

Application of the Poisson statistics to dust experiment data yields only moderately successful results. Dikarev et al. [4] construct a model based on the same principles, and using slightly different population definitions (which include dust scattered by planets) they show that Galileo and Ulysses data can be reproduced reasonably

the Galileo data set, i.e. impacts of classes 0 and 1. This may be an indication of incompleteness of our current model or biases in the data set itself.

The calibration of dust detectors usually leaves large uncertainty factors. For example, the accuracy of mass determination with the dust detector system (DDS) installed on Galileo and Ulysses, according to ground calibration, is one order of magnitude. Impact velocities are believed to be known within a factor of 2 only. The detection threshold of the old Pioneer 10 and 11 dust experiments was calibrated at impact velocities of one to two kilometres per second and then extrapolated to the actual interplanetary velocities of tens of kilometres per second. The uncertainty of the latter measurements is difficult to estimate.

5. CONCLUSION

We propose a new interplanetary meteoroid model design in order to incorporate knowledge of the long-term dust dynamics. The new model is composed of populations defined a-priori. Each population represents a possible structure of the zodiacal cloud, distribution functions are derived based on theory. The normalisation factors are model parameters to be solved for. In this design, the inverse problem becomes linear with respect to the solve-for parameters. It allows to solve the inverse problem much faster than previously [3,5], less manual work is necessary at the stage of formulation of the model, and the transition from theoretical studies to the engineering model becomes more transparent.

We use COBE DIRBE remote observations and Galileo and Ulysses impact counts to confirm the applicability of the new design of a meteoroid model. Simple distribution functions of interplanetary dust populations are defined and used as an example. Data and model predictions are shown to be in a reasonably good agreement.

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