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Dynamic Populations of Dust in Interplanetary Space[1]

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Abstract. Information on the dynamics of interplanetary dust is obtained by observations of radio-meteors, zodiacal light, thermal infrared emission, and by measurements with in-situ detectors on board Earth satellites and deep spaceprobes. These methods are sensitive to different meteoroid sizes (mm- to sub-micron sized) and refer to different regions of space. Bigger particles ($> 10^{-9}$ g) move on bound Keplerian orbits and are dynamically dominated by solar gravity, while the trajectories of particles smaller than 10^{-10} g are strongly influenced by radiation pressure and electromagnetic interactions. Modelling interplanetary dust is done by dividing the whole meteoritic complex into dynamically distinct populations. Divine's (1993) model identifies five dynamically different populations of interplanetary meteoroids: bigger particles are described by the "core", and "asteroidal"-populations, intermediate sizes by the "halo"-population, and small particles are included in the "eccentric" and the "inclined"-populations. The intermediate and the small particle populations, in particular, have to be redefined for several reasons: new data are available which require the consideration of hyperbolic orbits and the inclusion of radiation pressure and electromagnetic forces. New small particle populations are interstellar dust and beta-meteoroids.

1. Introduction

Dust in interplanetary space has various appearances and can be detected and analysed by an number of techniques. Huge surveys of radio meteor orbits observed by the Harvard-Smithsonian radar have been published by Southworth and Sekanina (1973). Recent surveys with the Adelaide radar are reported by Baggaley (1995). IDPs collected in the atmosphere give cosmochemical information (composition and structure, Brownlee, 1995 and Bradley, 1995) which is not considered in this review. The size distribution of dust at 1 AU distance from the sun is documented in lunar microcrater records (Grün et al., 1985). Zodiacal light observations form the Earth and from spacecraft (Leinert and Grün, 1990, Levasseur-Regourd, 1995) demonstrate the spatial distribution of dust in the inner solar system. Observations of the thermal emission give evidence for dust in the outer solar system (Low et al., 1984, Hauser, 1995). Measurements of dust particles by in situ detectors on interplanetary spaceprobes suggest new

[1] Dedicated to Neil Divine

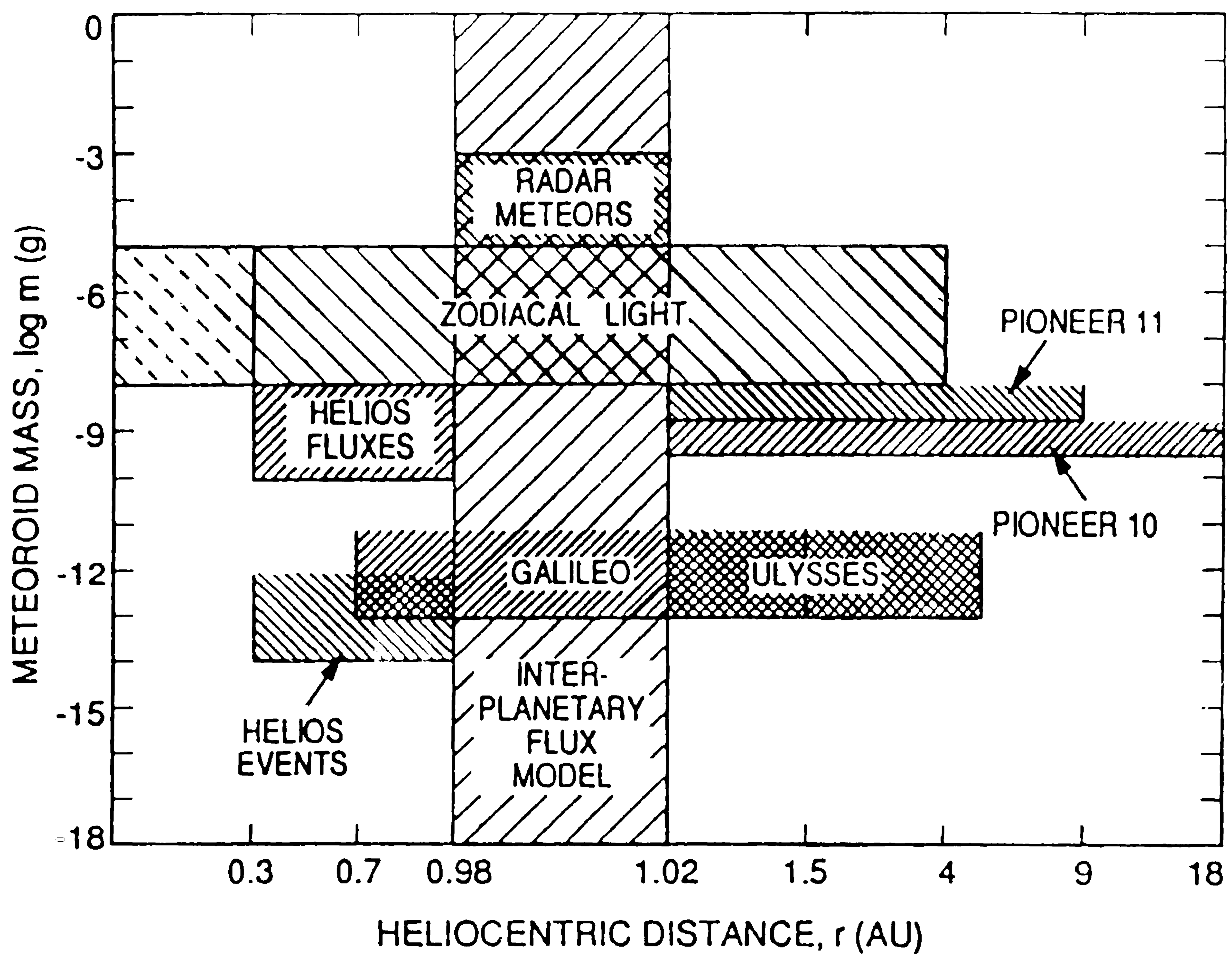


Figure 1. Mass and heliocentric distance range of the data sets used in the model (after Divine, 1993).

populations of dust (e.g. interstellar dust or dust emitted from the Jovian system, Grün et al. 1993, Baguhl et al., 1995) which are not easily identified at the Earth's distance. Fig. 1 shows the mass and heliocentric distance ranges of the dust data sets which are considered in this analysis. It is noted that only at 1 AU the whole mass range is covered and that a wide heliocentric distance range is only covered from 10^{-14} to 10^{-7} g.

The ultimate goal of modeling the interplanetary dust cloud is to provide a representation similar to an evolutionary tree of life, giving an accurate description of each species and showing the evolution of all species. The full evolutionary picture of interplanetary dust would involve a complete understanding of sources including comets, asteroids, planetary systems and interstellar dust, and processes like dynamical evolution (gravitation, radiation pressure and electromagnetic interactions), collisions (destruction and generation of fragments), and sublimation and sputtering. We are far from a complete understanding of all these effects. A first attempt to look at the combined effects of collisions and Poynting-Robertson evolution of dust from the asteroid belt was made by Durda et al. (1991) and Gustafson et al. (1991). A recent study of the interplay between planetary scattering and the Poynting Robertson effect (Jackson and Zook, 1989) led to the discovery of the Earth's resonant ring (Dermott et al., 1994).

We review a dynamical model (Divine, 1993) of dust in interplanetary space. It describes the present state and makes no statements concerning sources, sinks and evolution of the zodiacal cloud other than what can be derived from the orbits directly, e.g. an interstellar origin. It will not include information on optical properties (albedo and polarization) of dust as derived from zodiacal light observations (e.g. Levasseur-Regourd et al., 1991 and Levasseur-Regourd, 1995), because the dynamical relevance of optically different populations of dust has not yet been evaluated. In the next section we describe methods of dynamical modeling and in the third section the data sets and the corresponding dynamical populations of the Divine model are discussed. In the final section new developments and future work on the inclusion of new data sets and the redefinition of populations is outlined.

2. Modeling

The goal of dynamical modeling is to describe for each position in space the spatial density of dust and the directional flux as a function of the orbital elements and their distributions for a specific dust population. All dynamical modeling to date includes only solar gravity as operative force. In addition, rotational symmetry of the dust cloud is assumed (which is well supported by observations), i.e. the longitudes of node and arguments of pericentrum are uniformly distributed. Therefore, the spatial dust density depends only on distance r from the sun and latitude λ above symmetry plane (here the ecliptic plane). Kessler (1981) gives the spatial density N of a particle with the orbital elements perihelion distance r_1, eccentricity e, and inclination i:

$$N(r,\lambda) = \frac{(1-e)^{3/2}}{2\pi^3 r r_1 \sqrt{(r-r_1)[(1+e)r_1 + (1-e)r(\cos^2\lambda - \cos^2 i)]}} \qquad (1)$$

An early application of dynamical dust modeling was the interpretation of spatial dust densities which were obtained from zodiacal light observations in terms of distributions of orbital elements. Haug (1958) and later Banderman (1968) derived an integral which transforms distribution functions of orbital elements, $D(r_1, e, i)$, into spatial densities at any given position in space, where $D(r_1, e, i)$ is the number of meteoroids having perihelion between r_1 and $r_1+\mathrm{d}r_1$, eccentricity between e and de, and inclination between i and di. If the distribution function is separable $D(r_1, e, i) = D_1(r_1)\ D_e(e)\ D_i(i)$ then the relative spatial density $n(\lambda)$ at latitude λ is given (cf. Leinert and Grün, 1990):

$$n(\lambda) = \int_{i=\lambda}^{\pi/2} \frac{D_i(i)di}{\sqrt{\sin^2 i - \sin^2\lambda}} \qquad (2)$$

For $D_i(i) = \sin i$ and using the substitution $\mathrm{x}=\frac{\cos i}{\cos\lambda}$, the result is an isotropic distribution of dust, $n(\lambda) = \text{const.}$ and hence, $D_i(i)/\sin i$ describes the deviation from isotropy.

In order to calculate the flux one has to know the spatial density and velocity of the dust. The components of the velocity vector in sperical coordinates are:

$$v_r = \pm\sqrt{\frac{GM_o}{r^2 r_1}(r - r_1)[(1+e)r_1 - (1-e)r]} \quad (3)$$

$$v_\varphi = \sqrt{\frac{GM_o r_1}{r^2}(1+e)} \quad (4)$$

$$v_\lambda = \pm v_\varphi \sqrt{\cos^2\lambda - \cos^2 i} \quad (5)$$

where GM_o is the solar gravitation. The two solutions for v_r correspond to out- and inward velocities and the two solutions for v_λ correspond to up- and downward velocities.

Divine (1993) derived a formulation of the dust flux which allows us to model the response of an arbitrarily-oriented spacecraft detector of a given sensitivity to the meteoroid flux. In a first step the relative velocity v_D between a dust particle at velocity v and the detector v_{DB} is calculated. Next the angle γ between the detector orientation and the relative velocity vector is evaluated. The angular sensitivity of the detector response is described by the function $\Gamma(\gamma)$. The mass threshold m_t of the detector is described by

$$m_t = m_o(\rho_0/\rho)^\delta (v_0/v'_D)^\alpha \quad (6)$$

where m_0, v_0, ρ_0, δ, and α are constants of the mass, speed and densitiy sensitivity, and v'_D is the relevant component of the impact speed. From these quantities a dimensionless weighting function η_D is derived

$$\eta_D = \Gamma H_M \quad (7)$$

where $H_M = \int_{m_t}^{\infty} dm H_m$ is the cumulative mass distribution at mass m_t. With these definitions, the cumulative flux at mass m_t can be calculated

$$J_M = \frac{1}{4\pi}\sum_{l=1}^{4}\int_0^{\pi/2} d\chi N_1 \sin\chi \int_{e_\chi}^{1} de \frac{p_e}{\sqrt{e - e_\chi}} \int_{|\lambda|}^{\pi-|\lambda|} di \frac{p_i \sin i}{\sqrt{\cos^2\lambda - \cos^2 i}} (\eta_D v_D)_l \quad (8)$$

with the auxiliary variable $\chi = \sin^{-1}(r_1/r)$ and N_1 a radial distribution function, p_e a distribution function of eccentricities, and p_i a distribution function of inclinations. The summation over l corresponds to the four cases for the relative velocity: in/out and up/down. Matney and Kessler (1995) show that Divine's distribution functions N_1, p_e, and p_i correspond to the traditional distribution functions

$$N_1 = \frac{D_1}{r_1^2} \quad (9)$$

$$p_i = \frac{D_i}{\sin i} \quad (10)$$

$$p_e = (1-e)^{3/2} D_e \tag{11}$$

3. Populations and Data Sets

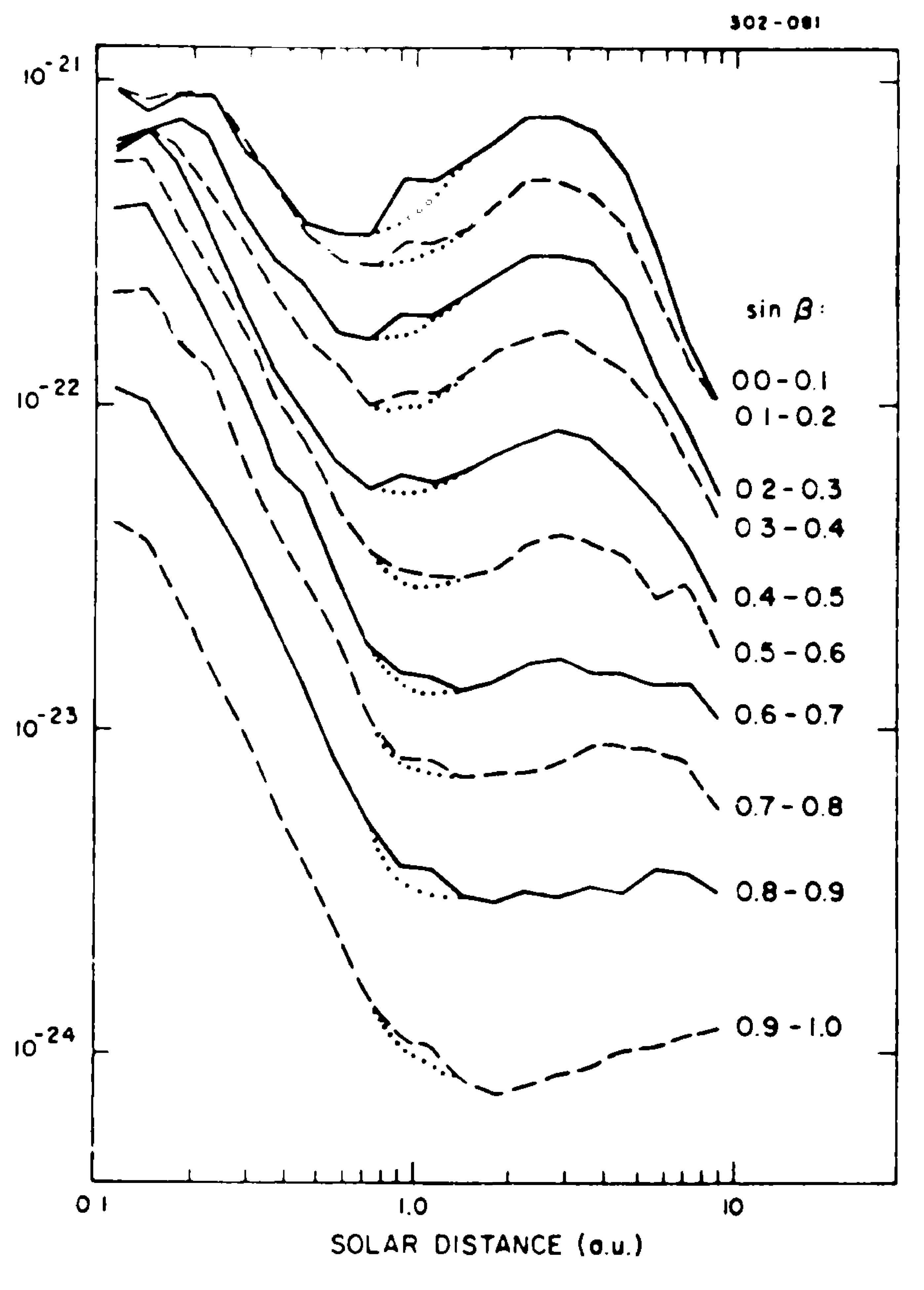
In his original model Divine (1993) identifies five distinct dynamical populations which describe satisfactorily a comprehensive data set on interplanetary dust (see Fig. 1). Divine does not maintain that the description by the five populations is unique, but his solution was based on a large number of trial-and-error iterations. However, if new data become available a modified set of populations may better fit the observations. In this section we will describe these original populations and show how these populations are represented in the data sets.

The **asteroidal** population represents the biggest particles (mean particle mass: 10^{-3} g), it peaks at 2 AU and has low eccentricities and inclinations. The **core** population covers a wide mass range (mean particle mass: 10^{-5} g), its density increases towards the sun and has also low eccentricities and inclinations. The **halo** population (mean particle mass: 10^{-7} g) dominates in the outer solar system (> 2.5 AU) and has an isotropic inclination distribution. The **inclined** and **eccentric** populations represent small particles (mean particle masses: 10^{-8} g and $10^{-13.5}$ g), in the inner solar system (< 1 and < 2 AU) and have low eccentricities and high inclinations and high eccentricities and low inclinations, respectively.

A backbone of the data responsible for Divine's populations is the Harvard Radar Meteor Survey described by Sekanina and Southworth (1975). This data set of particles above 10^{-4} g mass provides distributions in perihelion distances, eccentricities and inclinations. This data has been weighted for observational selection effects. Fig. 2a shows the radial space density of meteor particles which was corrected for unobservable orbits (Southworth and Sekanina, 1973). It displays a bimodal distribution with a minimum density inside 1 AU. Divine represents this data by two populations: the core population which shows a steady increase towards the sun and the asteroidal population peaking in the asteroid belt. Fig. 2b shows the two model populations.

The cumulative mass distribution of meteoroids was obtained from the interplanetary flux model (Fig. 3) of Grün et al. (1985) which includes lunar microcrater data and in situ measurements from Earth satellites and spaceprobes at 1 AU distance from the sun. The core population matches the data over a wide mass range from 10^{-13} to 10^{-5} g. The asteroidal population represents bigger meteoroids at 1 AU. Smaller particles are represented by the eccentric population.

According to Grün et al. (1985) the mass range responsible for most of the scattered zodiacal light is from 10^{-8} to 10^{-5} g. The radial concentration of zodiacal particles has been reported to depend on $r^{-1.3}$ (Leinert et al., 1981) which is well represented by the core population. The $r^{-1.3}$ dependence is extended only to 2 AU (Divine, 1993). Fig. 4 shows the elongation dependence of the zodia-



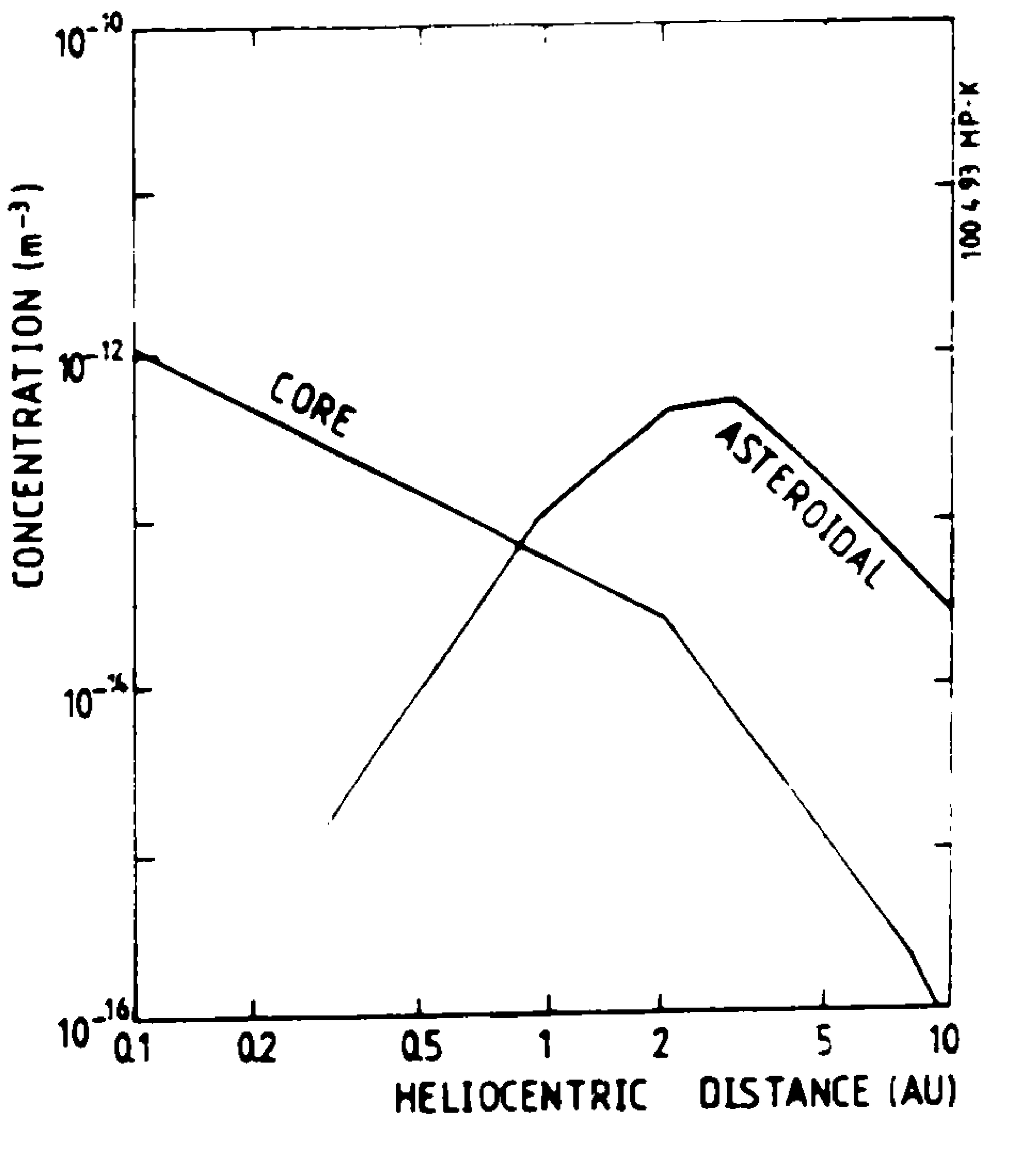


Figure 2. Spatial mass density of Radar meteor particles. 2a. Harvard Radar Meteor Survey (λ=heliocentric latitude) (Southworth and Sekanina, 1973) and 2b. model densities (10^{-4} g).

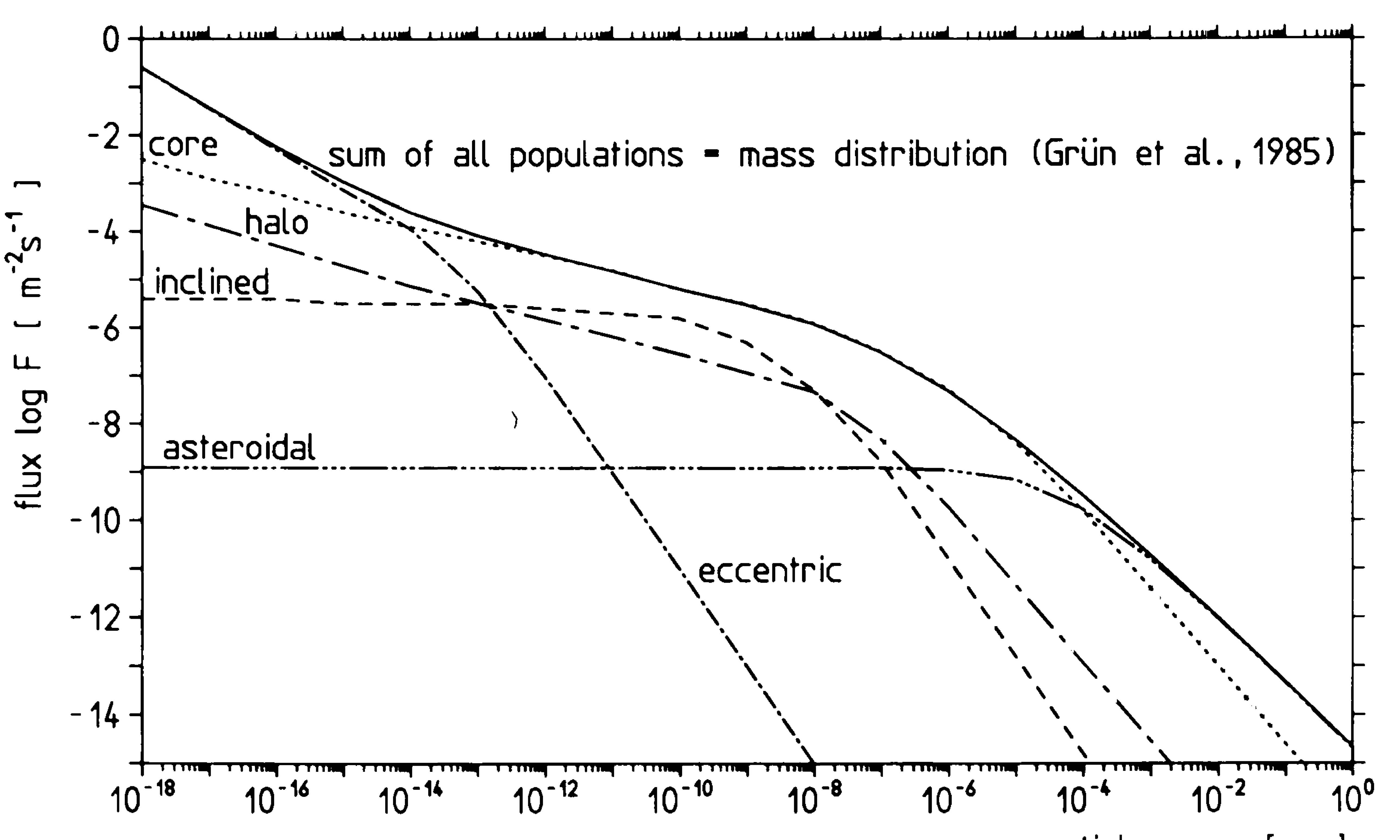


Figure 3. Cumulative mass distribution of meteorids at 1 AU (Grün et al. 1985) and representation by model populations (Staubach et al., 1993).

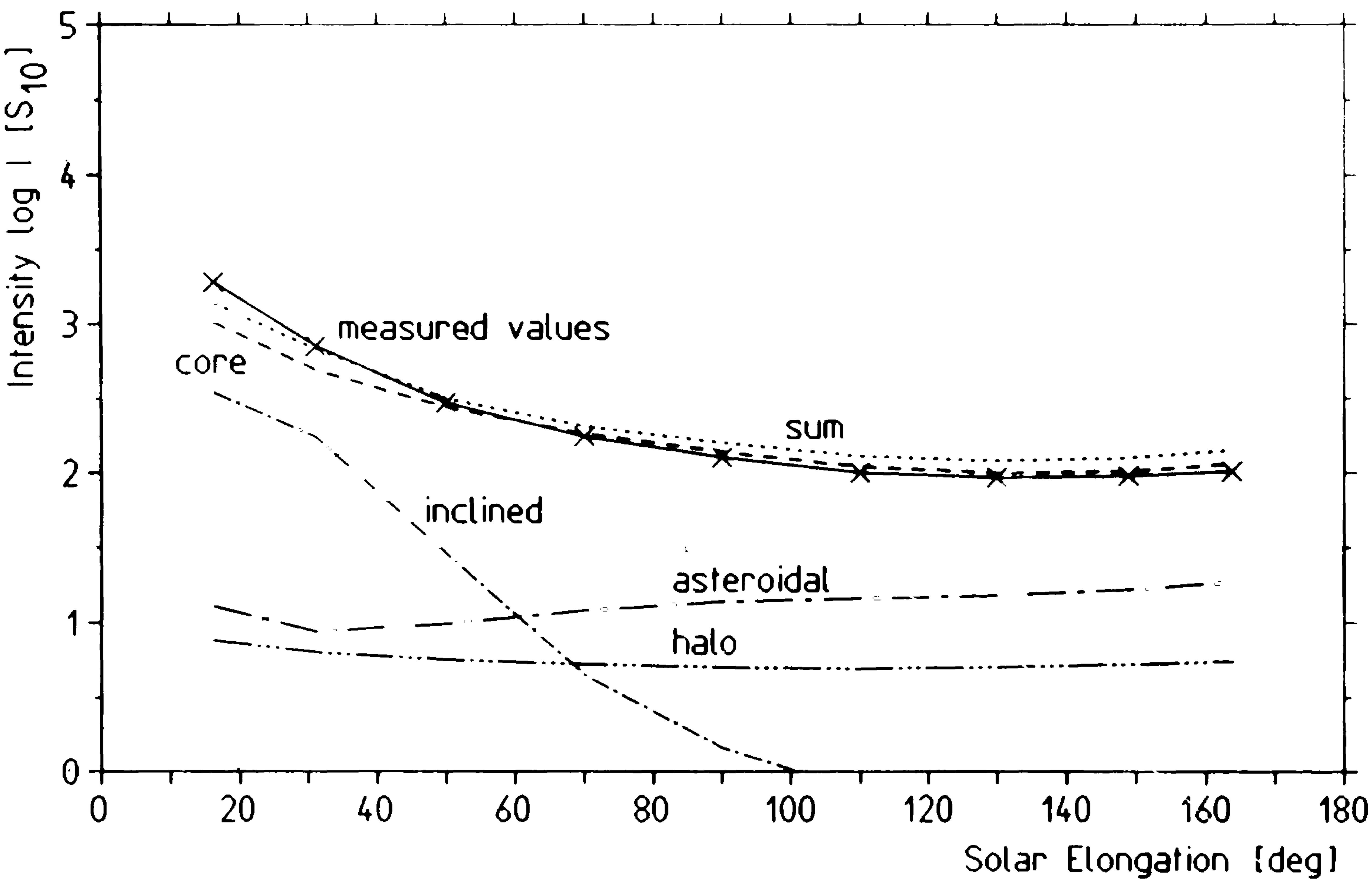


Figure 4. Zodiacal light intensity at 1 AU as function of solar elongation. Measurements by Leinert et al. (1981, crosses) and contributions by the model populations to the lines of sight (Staubach et al., 1993)

cal light intensity and the corresponding contributions by the model populations.

During its first three years the Galileo spacecraft traversed interplanetary space from 0.7 to 2.6 AU and had encounters with Venus, the Earth and the asteroid Gaspra. Initial in situ data from the Galileo dust detector are complete for meteoroid masses $> 10^{-12}$ g (Grün et al., 1992). Fig. 5 shows the observed impact rate and the contribution of the model populations to that data. Most of the data is qualitatively represented by the core population. Only at small heliocentric distances the eccentric population contributes significantly, whereas, at large heliocentric distances the halo population becomes dominant.

The inclined population has been introduced in order to explain some differnces in the count rates of the ecliptic and south sensors of the Helios spacecraft. In addition a more isotropic component of the zodiacal light at small solar distances supports such a population. Although it describes the count rates of small meteoroids quite well, an obvious deficiency of Divine's eccentric population is that it is unable to describe the directional flux of small beta meteoroids. Berg and Grün (1973) and Zook and Berg (1975) demonstrate with Pioneer 8 and 9 data that these particles represent a stream of small particles leaving the solar system on hyperbolic orbits due to the effect of radiation pressure. Recent measurements by the HITEN satellite (Svedham, 1995) support these observations.

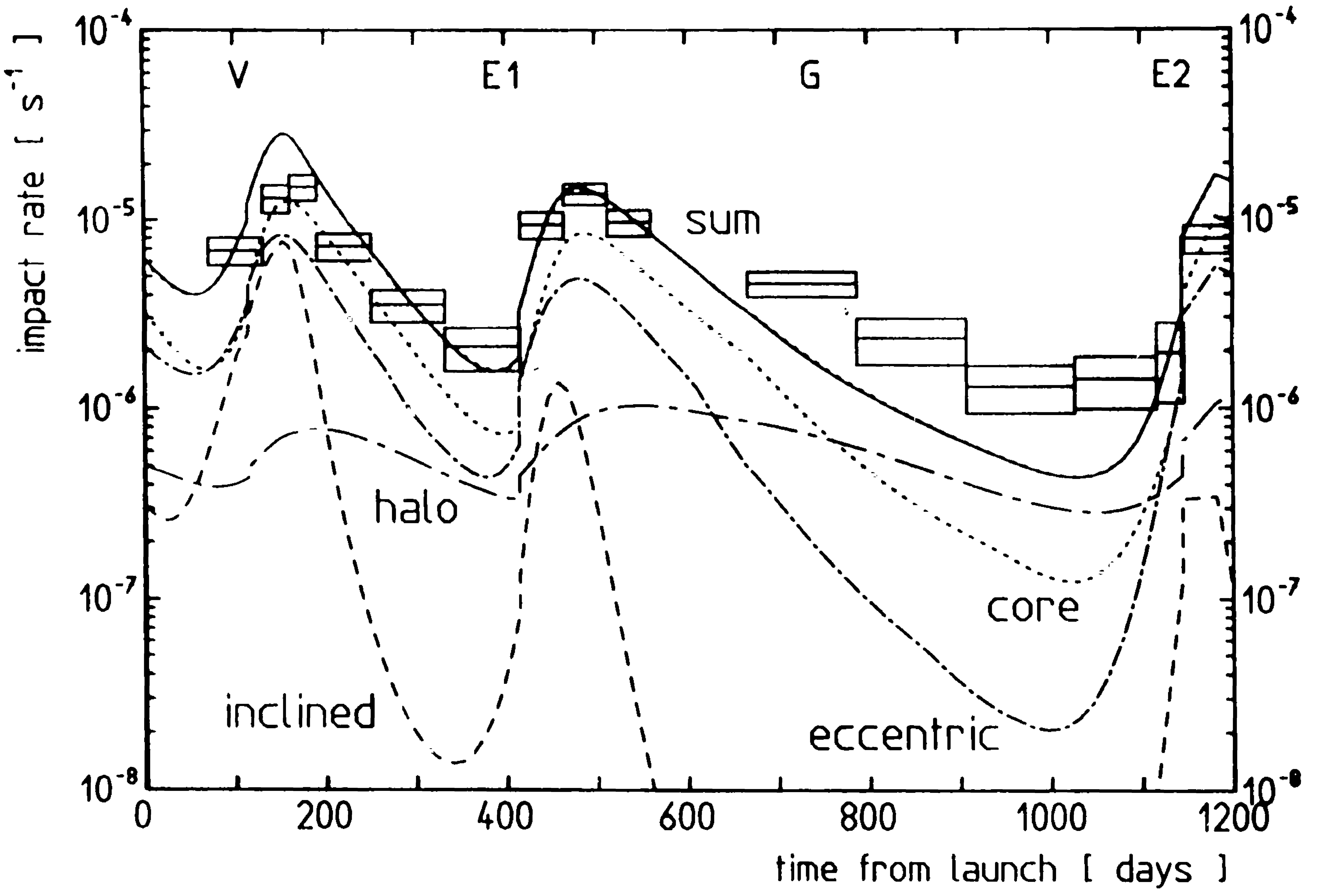
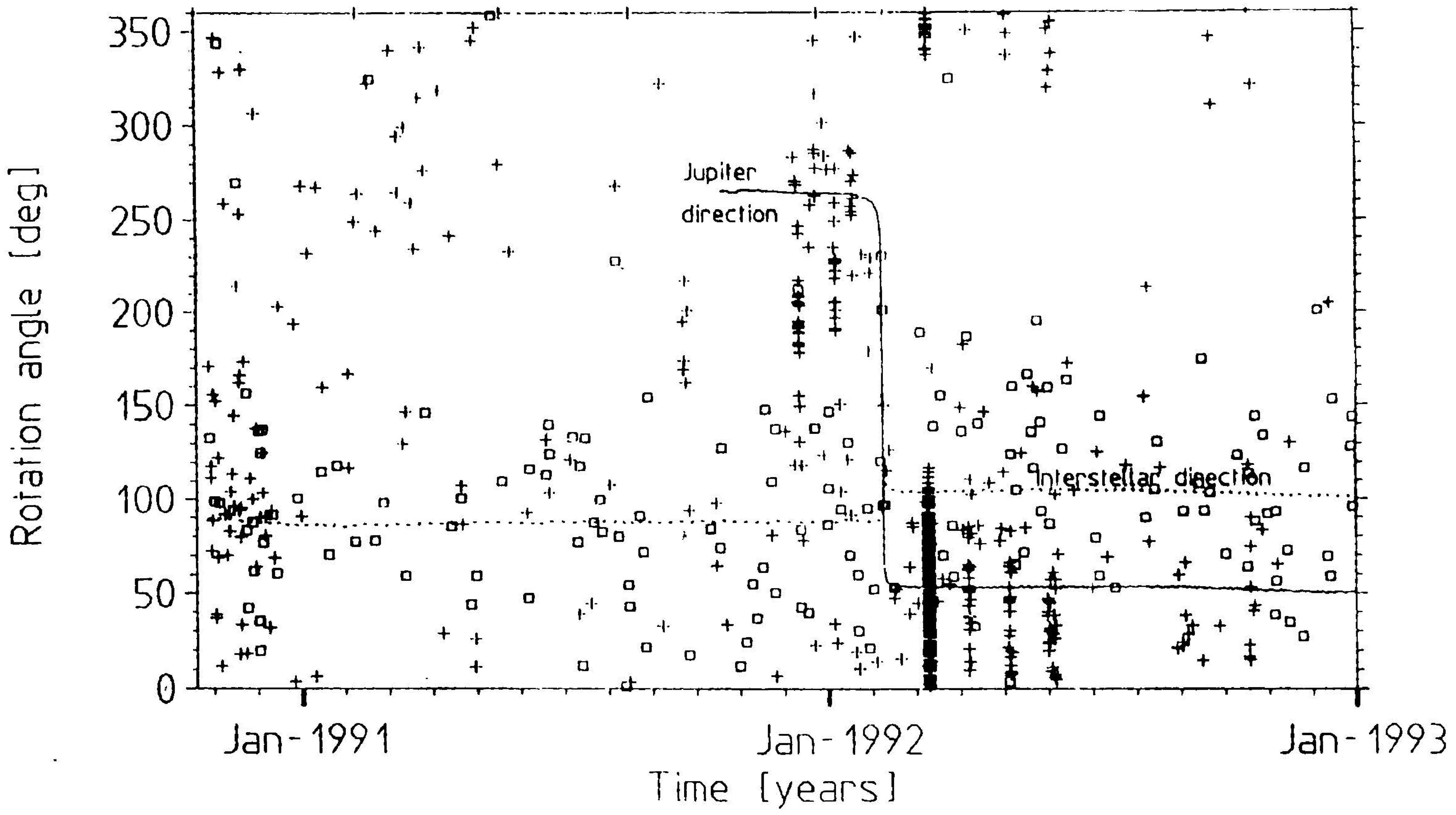


Figure 5. Impact rate of 10^{-12} g particles onto the Galileo dust detector during its first three years of operation (encounters with Venus, V, Earth, E, and Gaspra, G, are indicated). The contributions of the model distributions are shown.

4. New Developments

An extension of Divine's original model is the inclusion of additional observational parameters into the model like impact direction and impact speed. A first step in this direction was already done by Divine himself by including the directionality of Helios event data. This method has been further developed by one of the authors (P.S.) and is applied to Galileo and Ulysses data.

Fig. 6a shows the traditional representation of the directional information of Ulysses dust data. The first part of the orbit was in the ecliptic plane, after Jupiter fly-by in February 1992 the spacecraft moved in an orbit almost perpendicular (80^o) to the ecliptic plane. In September 1994 it flew below the solar south pole, in March 95 it crossed the ecliptic plane, and in August 95 it flew over the north pole. Within a year around Jupiter closest approach Ulysses discovered streams of small dust particles which arrived from approximately the jovian direction (Grün et al., 1993). Since this dust population is a localized phenomenon (it has only been observed within 2 AU from Jupiter), we will not further consider it here. Another new population of dust was recognized after Jupiter fly-by when the majority of particles impacted at rotation angles around 90^o (prograde interplanetary dust particles should have rotation angles of 270^o). This retrograde population of dust was identified as interstellar dust passing through the planetary system (Grün et al., 1994).



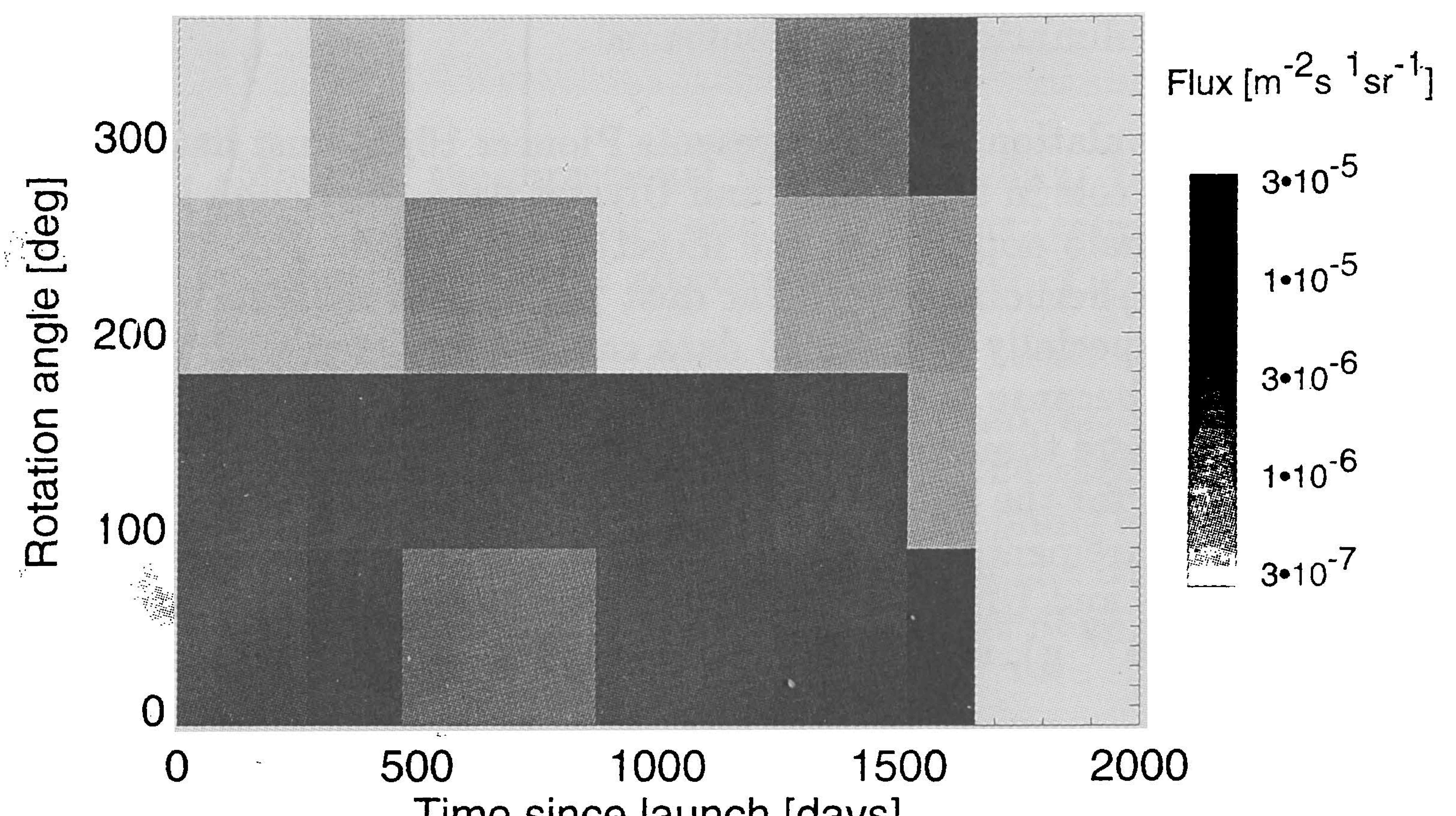


Figure 6. Ulysses dust impact data. 6a. For each impact which is represented by symbols indicating two mass ranges (□: m > 6· 10^{-14} g, +: m < 6· 10^{-14} g) the impact time and the sensor direction (rotation angle) is given. The Ulysses sensor scans with 140° field-of-view in a plane roughly perpendicular to the spin axis (which points to the Earth). Rotation angle is defined in the scan plane counting from the direction closest to the North-direction in a right-handed sense around the spacecraft spin axis. 6b. Binned big impacts (m > 6· 10^{-14} g): the flux in each bin is represented by a grey scale.

In order to compare this directional data with the dust model a new representation had to be found. All Ulysses dust data (m > 6 10^{-14} g) are binned into 6 time intervals, 4 rotation angle intervals and 3 speed intervals (which are ignored in the following discussion) and a smoothing routine is employed. A finer resolution in parameter space is not practical because of the poor statistics. Fig. 6b shows the projection of the data onto the time-rotation angle plane, with the flux represented by a grey scale.

Ulysses observations obviously require the inclusion of an interstellar dust population in the model. These particles pass on hyperbolic orbits through the solar system, arriving from 257^o ecliptic longitude and 3^o latitude at speed of about 26 km/s. For these 10^{-13} g-particles radiation pressure cannot be neglected, which reduces the effect of solar gravity. Ulysses data from mid 1991 to the end of 1994 is ideally suited to characterize this new population, because in this time period interstellar dust dominates the data, except for the small particles in the Jupiter streams and another small particle population over the solar poles, which both can easily be separated. The flux of interstellar particles is $1.5 \cdot 10^{-4}$ m^{-2} s^{-1}; no reduction of the interstellar dust flux in the inner solar system due to sublimation can be confirmed.

The halo population, which represents Pioneer 10/11 dust data seems not to play a significant role in the Galileo and Ulysses data. Although both fluxes can be fitted by the halo population, the directionality of the flux can not! On the other hand the hyperbolic interstellar dust population matches well these data sets. However, especially Pioneer 10 data can not be fitted with the interstellar dust population because the flux observed by that spacecraft arrived from the opposite hemisphere than the interstellar dust seen by Ulysses. Therefore, there remains the need for the halo population in order to explain the Pioneer 10 and perhaps 11 measurements. That the halo population does not prominently show up in the Galileo and Ulysses data may be due to the poor statistics of the big particles (m > 10^{-9} g), to which the halo population must be restricted.

The mass range of the dust particles detected by Galileo and Ulysses immediately shows that radiation pressure and for the smallest particles even electromagnetic interactions affect the dynamics of these particles. In order to include at least radiation pressure effects, the purely gravitational core population was cut off at masses below 10^{-10} g and three new populations were added at smaller masses: at 10^{-12} - 10^{-10} g a population with radiation pressure constant $\beta = 0.3$ (β is the ratio between radiation pressure and gravitational force), at $5 \cdot 10^{-15}$ - 10^{-12} g a population with radiation pressure constant $\beta = 0.8$, and below $5 \cdot 10^{-15}$ g a population with radiation pressure constant $\beta = 0.3$. Especially, the Galileo data from the first 4 years of operation (where the influence of interstellar dust is considered small) were iterated with solely the three new small particle populations, the truncated core population and the interstellar population (defined by the Ulysses data) and a satisfactory fit has been found (Fig. 7). The eccentric, inclined and halo populations needed not be included.

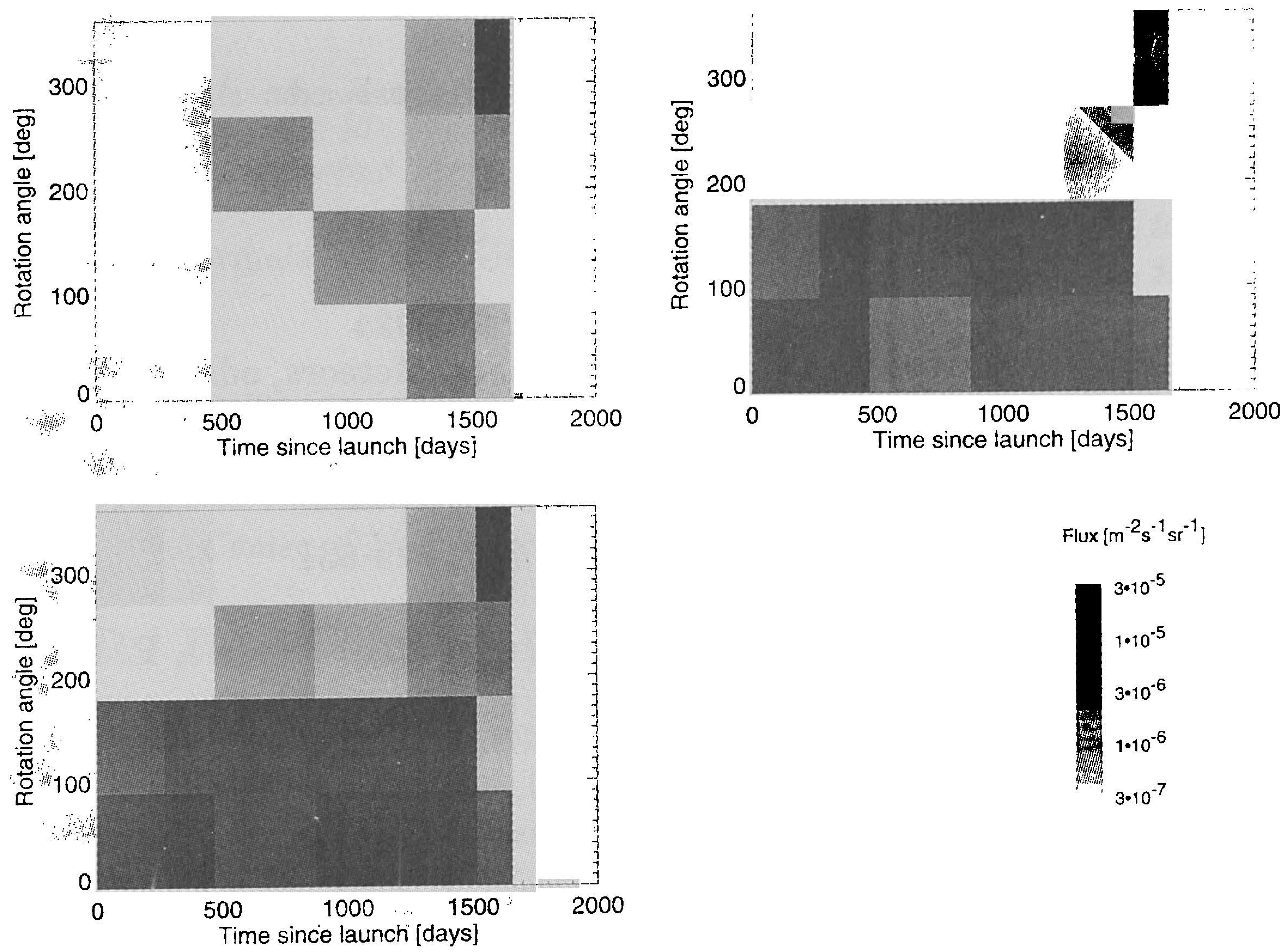


Figure 7. Model of the directional Ulysses dust flux. 7a interstellar dust population, 7b interplanetary dust populations (capped core, and three β populations), 7c sum of all contributions (cf. Fig. 6b).

Recently the Harvard radio meteor analysis has been reappraised by Taylor (1995). Taylor showed that the previous analysis of the speed data was erroneous which led to too low eccentricities of the corresponding orbits. Because of the strong influence of this data set on the definition of the core and asteroidal populations a redefinition of these populations has to be done as soon as better analyses become available.

In summary, Divine's original five populations describe well the data sets he used. The inclusion of directional information on small particle fluxes requires the introduction of new populations affected by radiation pressure and on hyperbolic orbits. New radar meteor data also requires a redefinition of the original dust populations. A comprehensive set of populations which matches all new data is not yet available.

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