THE FLUX OF INTERSTELLAR DUST OBSERVED BY ULYSSES AND GALILEO

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Abstract. Interstellar dust detected by the dust sensor onboard Ulysses was first identified after the Jupiter flyby when the spacecraft's trajectory changed dramatically (Grün et al., 1994). Here we report on two years of Ulysses post-Jupiter data covering the range of ecliptic latitudes from 0° to -54° and distances from 5.4 to 3.2 AU. We find that, over this time period, the flux of interstellar dust particles with a mean mass of $3 \cdot 10^{-13}$ g stays nearly constant at about $1 \cdot 10^{-4}$ m^{-2} s^{-1} $(\pi$ sr$)^{-1}$ with both ecliptic latitude and heliocentric distance.

Also presented are 20 months of measurements from the identical dust sensor onboard the Galileo spacecraft which moved along an in-ecliptic orbit from 1.0 to 4.2 AU. From the impact direction and speeds of the measured dust particles we conclude that Galileo almost certainly sensed interstellar dust outside 2.8 AU; interstellar particles may also account for part of the flux seen between 1 and 2.8 AU.

Key words: Interstellar dust – Ulysses dust measurements – Galileo dust measurements

1. Introduction

There is clear evidence that the distribution of dust in the outer solar system is quite different from the zodiacal population which dominates within a few AU of the Sun. The first dust measurements in the outer solar system were performed by the Pioneer 10 and 11 spacecraft (Humes, 1980). At a distance of 3 AU, these probes found impact rates about a factor of three lower than those observed at 1 AU. Curiously, between 3 AU and 18 AU, the impact rates stayed roughly constant despite the fact that the spacecraft reached ecliptic latitudes of 15°. Humes (1980) concluded that the observations are inconsistent with the low-eccentricity low-inclination orbits typically assumed for zodiacal dust particles. On the contrary, the observations seemed to imply a population of dust particles on randomly-inclined highly-eccentric orbits.

Grün et al. (1992a) argued that beyond about 3 AU the Ulysses dust detector also measured a non-zodiacal dust population. From the flux ratio before and after Jupiter flyby, Grün et al. (1992b) concluded that the back-

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ground dust flux was on retrograde trajectories. Based on the analysis of a year of Ulysses data covering the ecliptic latitude range from 0° to -16°, Grün et al. (1993 and 1994) concluded that the trajectories and impact speeds could best be explained by dust particles on hyperbolic orbits penetrating the solar system from the upstream direction of the local interstellar wind (Witte et al., 1993).

Divine (1993) developed an empirical model of the interplanetary dust cloud using impact rates observed by Pioneers 10 and 11 as well as early data from Galileo and Ulysses. Although Divine's model lacks an interstellar population, it does contain a component with randomized inclinations that, to some extent, mimics the behavior of interstellar particles. In this paper we compare data from the later phases of the Galileo and Ulysses missions with predictions from both Divine's interplanetary model and a simple model of interstellar dust.

2. Ulysses measurements from 0° to -54°

In Fig. 1 we show the flux of dust particles observed by Ulysses during the first two years after Jupiter flyby. Except for three of the latitude intervals, the flux shows no strong trend, remaining roughly constant over a large range of latitudes. Assuming that the flux is constant, we obtain a mean dust flux of $1 \cdot 10^{-4}$ m^{-2} s^{-1} $(\pi$ sr$)^{-1}$ with a mean mass of $3 \cdot 10^{-13}$ g. Divine's model, by contrast, shows a gradual rise in the flux due to increases in both the spatial density of dust particles and in typical impact velocities as Ulysses moves inward. The data is marginally compatible with Divine's model, but also consistent with a flux of interstellar grains.

In particular, the interstellar flux is expected to be nearly constant over the timespan shown in Fig. 1. Deflection and focusing by solar gravity should cause the flux to increase by only about 10% over the Ulysses orbit from 5.4 AU to 3.2 AU. Unfortunately, these variations are too small to be easily detected in the data. In addition, the importance of sublimation of interstellar dust, which leads to a diminishing interstellar flux with decreasing radial distance, is difficult to assess. This effect depends on particle sizes and on material properties.

A better test of the predicted flux rates will occur as Ulysses continues to descend beneath the ecliptic. At extreme southern latitudes, the spatial density of Divine's interplanetary population is primarily latitude dependent and eventually drops to levels five times lower than at -45°. In the absence of sublimation, the interstellar dust flux should continue to increase to a value about 20% larger at maximum southern latitude than at -45° .

The predictions of the two models can be tested more stringently by combining the information contained in measured impact directions and speeds. This has been performed by Grün et al. (1994) for impact data until

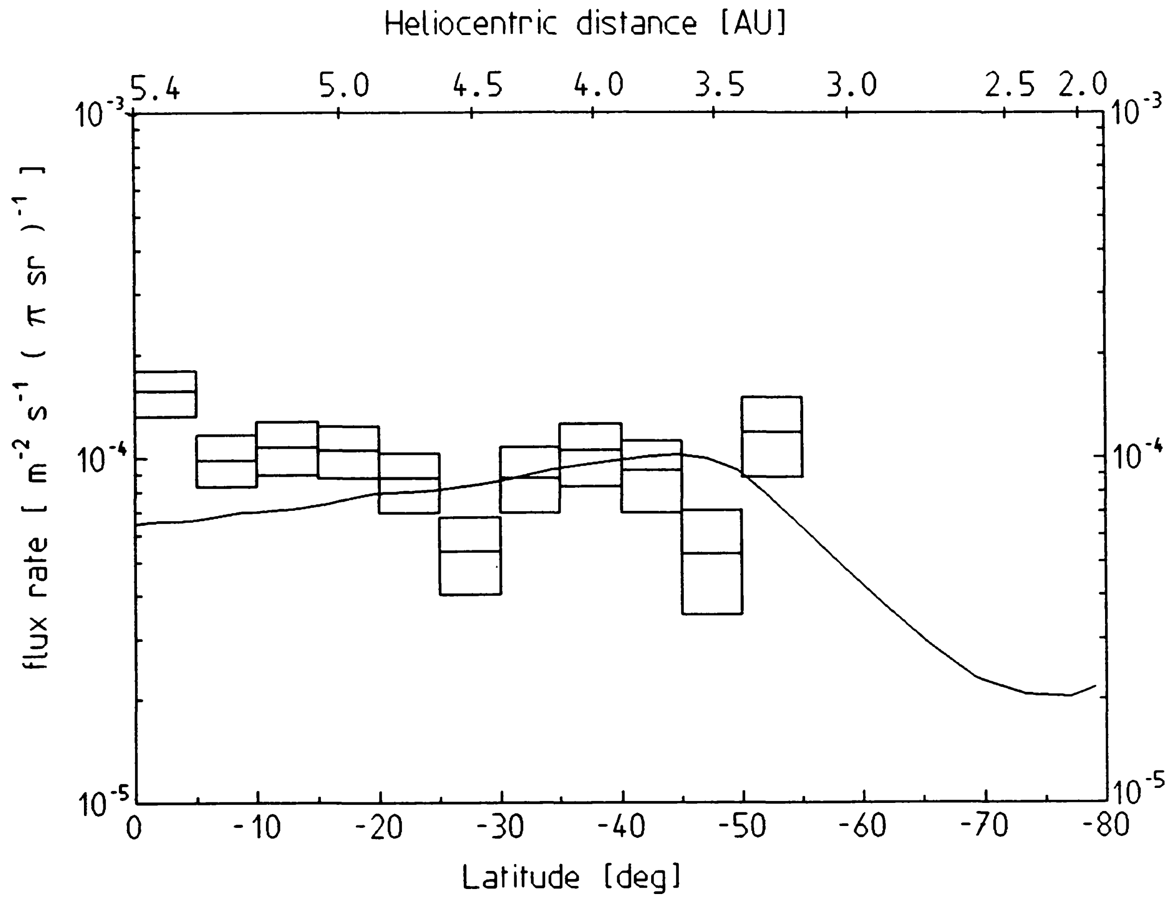

Fig. 1. Ulysses flux rate as a function of ecliptic latitude and heliocentric distance. The boxes represent the flux of particles with a mean mass of $3 \cdot 10^{-13}$ g measured after Jupiter flyby in 5° intervals of latitude and their heights correspond to statistical errors. Jovian stream particles, identified by their collimation in impact time and direction, were excluded from the displayed impact rate. The solid line is the flux predicted by Divine's model over the same time period.

the end of 1992 (ecliptic latitude from 0° to -16°). In Fig. 2 we show the impact directions of dust particles measured between 1 March 1992 and 24 April 1994 versus ecliptic latitude.

If bound orbits dominate the flux, then Ulysses, sweeping rapidly through a cloud of randomly-inclined orbits, should see impacts strongly concentrated near the spacecraft apex direction. Over the time period shown in Fig. 2, this direction is visible to the dust detector between rotation angles of 150° and 180°. Such a concentration is not seen in the figure; instead, the impact directions concentrate strongly towards the interstellar direction (near 90° - see Fig. 2). The measured impact speeds are also compatible with the assumption that the dust particles are predominantly interstellar in origin. These results indicate that Divine (1993)'s model requires the addition of an interstellar dust population.

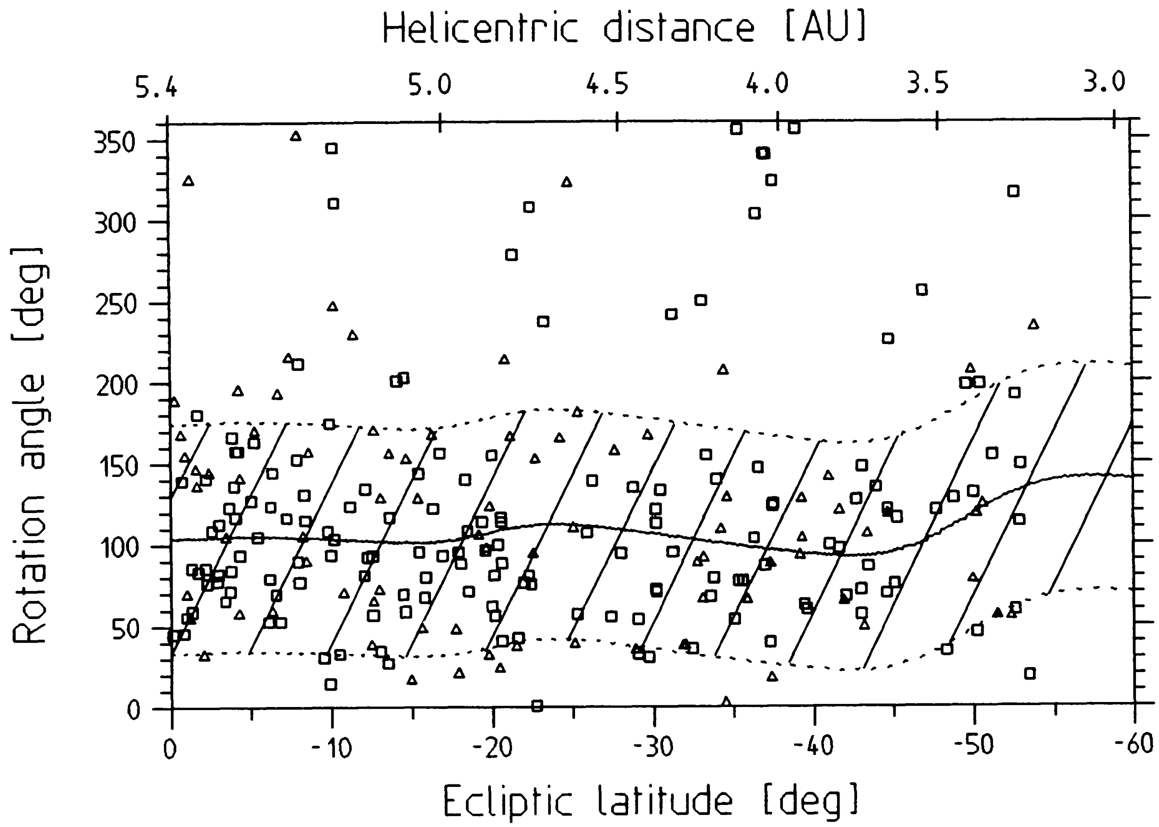

Fig. 2. Impact direction of dust particles versus the ecliptic latitude of Ulysses (For the definition of rotation angle see Grün et al. (1993)). The solid line gives the direction towards the upstream direction of the interstellar gas and the broken lines indicates the limits of the sensor's field of view for this direction. The squares denote particles with impact speeds compatible with an interstellar origin (v > 15 km/s, within the 1σ-error of the speed determination), triangles denote slower speeds.

3. Galileo dust measurements from 1 to 4.2 AU

We argued in the last section that Ulysses is currently seeing interstellar dust. If this is true, interstellar particles should also have been seen by Ulysses before the Jupiter encounter as well as by Galileo enroute to Jupiter. In the former case, Ulysses' highly eccentric orbit caused the impact directions of classical interplanetary and interstellar dust particles to largely overlap. In contrast, interstellar particles can be distinguished from dust on low-eccentricity low-inclination orbits over a large part of Galileo's orbit. This can be seen in Fig. 3, which gives the impact directions of all dust impacts registered after the second Earth encounter. The shaded region in Fig. 3 represents the arrival directions of interstellar particles. Nearly all impacts outside a distance of 2.6 AU have impact directions compatible with an interstellar origin. But between 1.0 and 2.8 AU, the direction is also consistent with that expected for low-eccentricity and low-inclination particles.

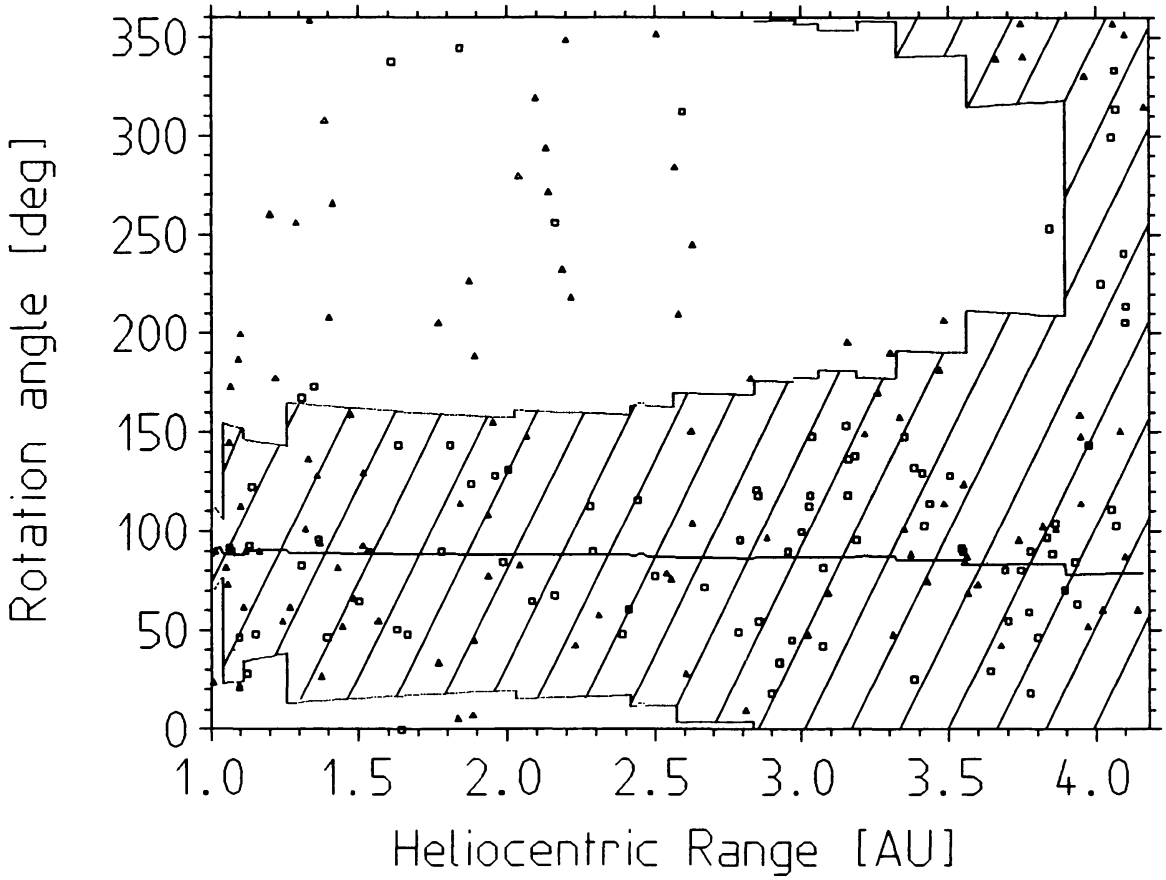

Fig. 3. Impact direction of dust particles versus the heliocentric range of Galileo. The solid line gives the direction towards the upstream direction of the interstellar gas and the dotted lines limit the sensor's field of view for this direction. Squares denote fast particles with impact speeds > 15 km/s, triangles represent slower particles.

Outside of 2.8 AU, however, particles on such orbits should come from near a rotation angle of 270° (see Fig. 3), clearly incompatible with the data. Although a distribution of bound orbits with large eccentricities and inclinations cannot be immediately ruled out, the distribution of impacts is more naturally explained with interstellar trajectories.

4. Discussion

From the data presented, it can be seen that dust of interstellar origin is the best explanation for the majority of the dust flux measured by Ulysses after the Jupiter flyby. Galileo too, appears to have sensed interstellar dust. Although speed measurements in both cases indicate hyperbolic velocities for the impacting particles, the best argument for an interstellar origin are the impact directions of the dust particles. For Ulysses, the combined effects of decreasing ecliptic latitude and radial distance do not significantly influence the flux rate and distribution of impact directions in agreement with the expected behavior of interstellar particles. Whereas during the in-ecliptic leg of the Ulysses orbit no distinction between interstellar and bound orbits can be derived from the impact directions, the out-of-ecliptic leg and the Galileo measurements show that interstellar dust is definitely present in the ecliptic plane outside about 2.8 AU. The situation within 2.8 AU is more complicated, but it is possible that interstellar dust may be present inward to 1 AU. Nevertheless, the contribution of interstellar dust to the flux at terrestrial distances should be lower than 3%, a value derived by McDonnell and Berg (1975) from flux isotropy arguments. Further analysis of recent data is necessary to improve the reliability of this estimate.

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