IN SITU MEASUREMENTS OF INTERSTELLAR DUST WITH THE ULYSSES AND GALILEO SPACEPROBES

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Abstract. Interstellar dust was first identified by the dust sensor onboard Ulysses after the Jupiter flyby in February 1992. These findings were confirmed by the Galileo experiment on its outbound orbit from Earth to Jupiter. Although modeling results show that interstellar dust is also present at the Earth orbit, a direct identification of interstellar grains from geometrical arguments is only possible outside of 2.5 AU. The flux of interstellar dust with masses greater than $6 \cdot 10^{-14} g$ is about $1 \cdot 10^{-4} m^{-2} s^{-1}$ at ecliptic latitudes and at heliocentric distances greater than $1AU$. The mean mass of the interstellar particles is $3 \cdot 10^{-13} g$. The flux arrives from a direction which is compatible with the influx direction of the interstellar neutral Helium of 252° longitude and 5.2° latitude but it may deviate from this direction by 15 – 20°.

1. Introduction

Interstellar dust in the heliosphere was first detected by Ulysses at a distance of 5 AU (Grün et al., 1993). Dust measurements with the Pioneer 10 and 11 spacecraft at distances between 3 and 18 AU (Humes, 1980) could not be explained with orbits typical for classical zodiacal dust, but the results are compatible with a randomly inclined population of dust on bound orbits. Interstellar meteors were detected using the AMOR radar in New Zealand (Taylor et al., 1996). This detection refers to grains with sizes greater than $40 \mu m$ and only very fast ($v_\infty \approx 100 kms^{-1}$) meteors were considered as of interstellar origin. These interstellar grains contribute with 1% to the impact of dust grains larger than $40 \mu m$ to the Earth atmosphere. A possible explanation of the failure to measure submicron–sized grains at the Earth orbit was given by (Jokipii et al., 1976).

The Ulysses and Galileo spacecraft were launched in October 1990 and 1989 respectively. Galileo performed gravity–assist flybys on Venus and two times on Earth before heading out for Jupiter. Ulysses was launched on a direct trajectory to Jupiter and used its gravity to propel the spacecraft to an elliptical orbit almost perpendicular to the ecliptic plane. The spacecraft carry two identical dust detectors capable of measuring the dust impact speed, mass and impact direction and possibly particle charge. The setup and calibration are described in detail in (Grün et al., 1992a) and (Grün et al., 1992b). The measurable speeds range from 2 kms^{-1} to 70 kms^{-1}, the

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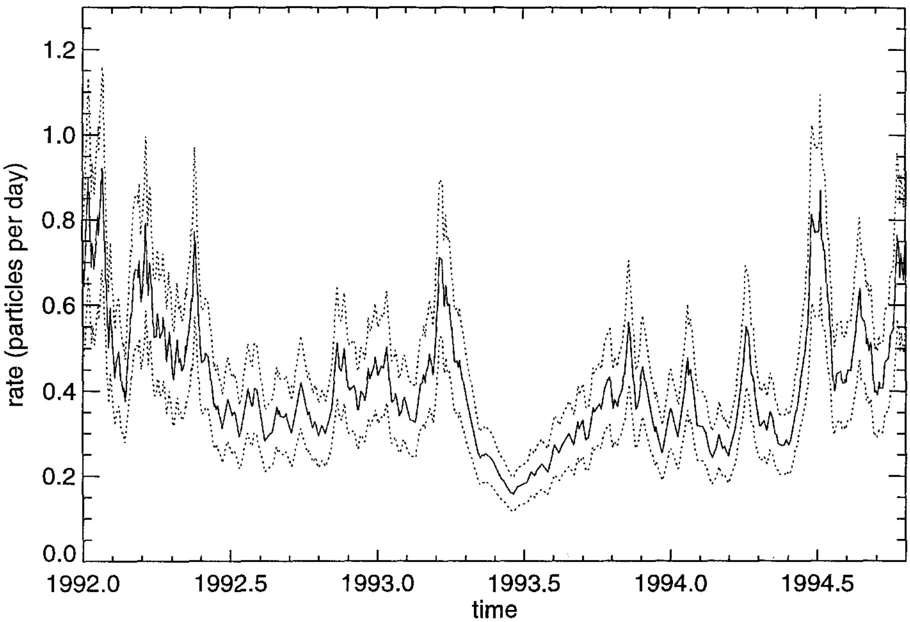

Figure 1. Ulysses flux rate. A sliding mean over 15 dust impacts was applied. The solid line shows the sliding impact rate, the broken lines denote the statistical 1σ–errors. Jovian stream particles, identified by their collimation in impact time and direction, were excluded from the displayed impact rate.

mass threshold is highly speed dependent and ranges from $10^{-15}g$ to $10^{-11}g$. The opening angle of the detector is 140°.

2. Ulysses measurements

In figure 1 we show the flux of dust particles observed by Ulysses during the first 2.8 years after Jupiter flyby. From this plots the Jupiter streams as described in (Grün et al., 1993) are excluded. The impact rate of the dust particles varies around its mean value of 0.45 day^{-1} with a small deviation of 0.16 day^{-1} over the complete range of heliocentric latitudes (nearly zero before Jupiter encounter in February 1992, then decreasing to $-80°$ while passing the Sun's south pole in October 1994, then increasing to $-55°$ in December 1994). This by itself suggests that measured dust population does not belong to the solar system. The zodiacal dust cloud in the inner solar system is on moderately inclined prograde orbits and extends only to 30° around the ecliptic plane. As (Grün et al., 1992c) show, the almost constant flux before and after the Jupiter flyby is a hint to retrograde orbits. Since almost all sources of zodiacal dust, namely asteroids and short period comets

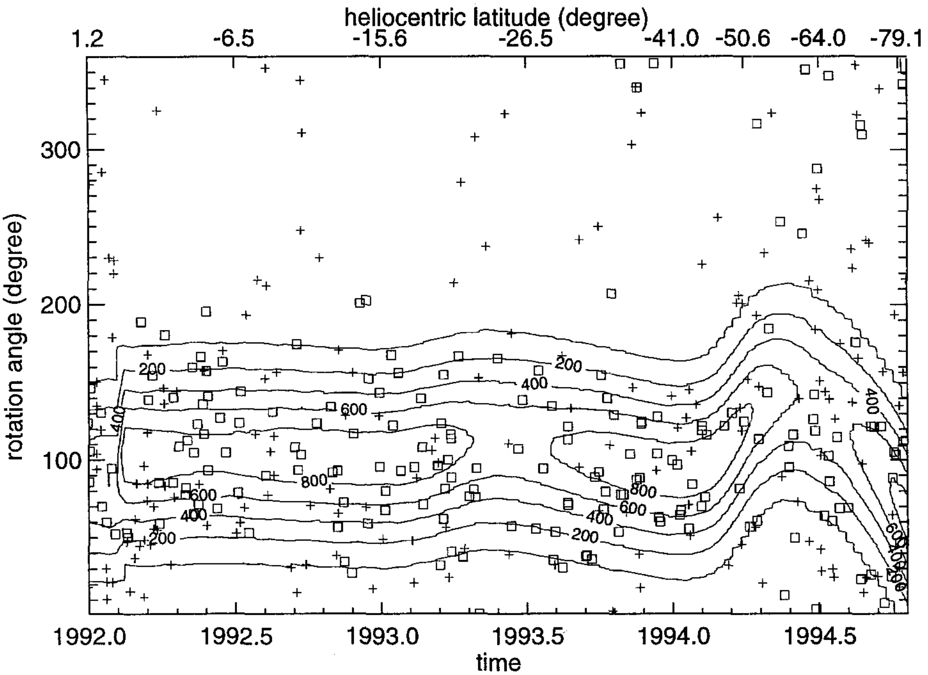

Figure 2. Impact direction of dust particles measured by Ulysses (For the definition of rotation angle see (Grün et al., 1993)). The contour lines give the differential geometrical sensitive area in cm^2 for impacts from a direction towards the upstream direction of the interstellar gas (Witte et al., 1993). The squares denote particles with signal amplitudes $> 1 \cdot 10^{-13} C$, plus signs denote impacts with smaller signal amplitudes. The contour lines included give the differential sensitive area in cm^2 for dust impacts from the flight direction of the neutral interstellar gas. The latitude of Ulysses in the heliocentric System is given at the top.

are on predominantly prograde, low inclined orbits, this is an additional reference to an interstellar origin.

Additional information on the dust particle origin can be collected from the impact directions. Figure 2 shows the sensor orientation and time for every impact, in comparison with the sensitive area of the detector for impacts from the upstream direction of interstellar gas. It can be seen that the direction of impacts of the fast dust particles (i.e. particles with high signal amplitude) is compatible with the direction of the gas. This becomes even more impressive by the fact that prograde dust on predominantly prograde orbits and low eccentricity should be sensed from rotation angles between 180° and 360°. The apparently worse fit at the highest latitudes may be explained by gravitational or electromagnetic deflection. Hamilton (pers. comm.) showed that this deflection may change the impact direction by up to 10°.

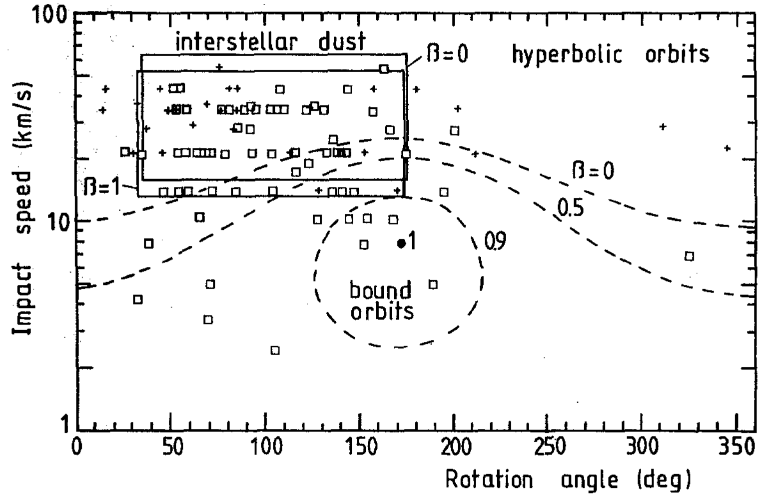

Figure 3. Measured impact speeds as a function of rotation angle for Ulysses data taken from one year after Jupiter flyby. The lines give the limits for particles on bound orbits for two different radiation pressure coefficients β. The boxes denote the opening cone around the interstellar direction of 140° and the 1σ uncertainty around the interstellar dust impact speed of $26kms^{-1}$ and $27.2kms^{-1}$. Interstellar dust impacts should lie within this box.

The measured impact speeds are also compatible with the assumption that the dust particles are predominantly on hyperbolic orbits. The limits for bound orbit speeds are given in figure 3. Taking into account that the measured speed is accurate within a factor 2, the plot clearly shows that the majority of the particles are on hyperbolic orbits entering the solar system.

3. Galileo measurements

We argued in the previous section that Ulysses detected interstellar dust after the Jupiter flyby. If this is true, interstellar particles should have been seen also 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. Therefore, both types are not distinguishable in the Ulysses data set on the basis of impact direction. 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 figures 4a and 4b, which give the impact directions of all dust impacts registered after the second Earth encounter. The good correlation between measured rotation angles and interstellar sensitive area can be seen in figure 4a. However,

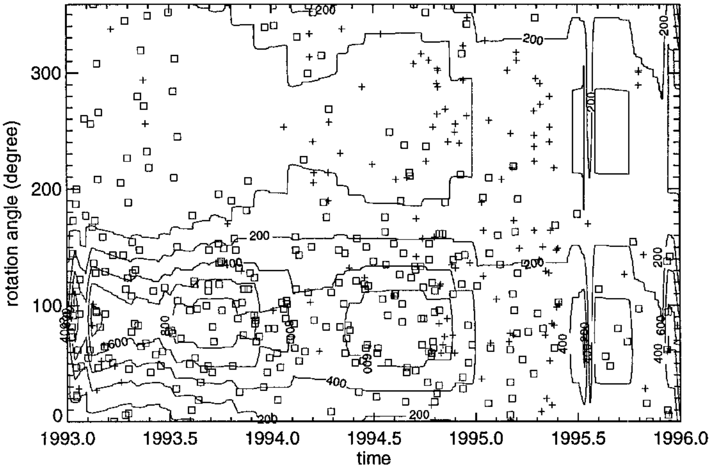

Figure 4a. Impact direction of dust particles versus time of Galileo. The contour lines give the differential geometrical area in cm^2 for impacts from the downstream direction of the interstellar gas. The squares denote particles with signal amplitudes $> 1 \cdot 10^{-13} C$, plus signs denote impacts with smaller signal amplitudes. Jupiter stream impacts have been excluded by their impact time as given in (Grün et al., 1996a). Note the almost empty space after 1995.0 caused by severe dead time due to Jupiter stream impacts.

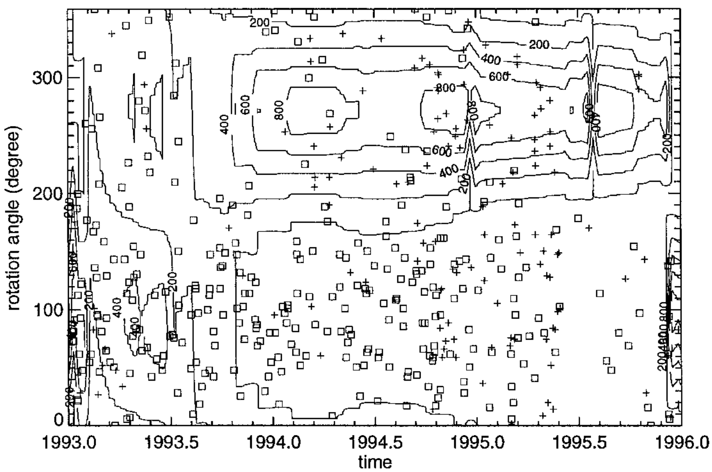

Figure 4b. The contour lines give the differential geometrical area in cm^2 for impacts of particles on prograde orbits with small inclinations.

in the Galileo case the geometry is more complicated than that of Ulysses.

Since Galileo moves in the prograde direction, for part of the orbit, from distances between 1 and $2.6 AU$, dust particles on prograde orbits with small inclinations are sensed from the same direction as the interstellar particles.

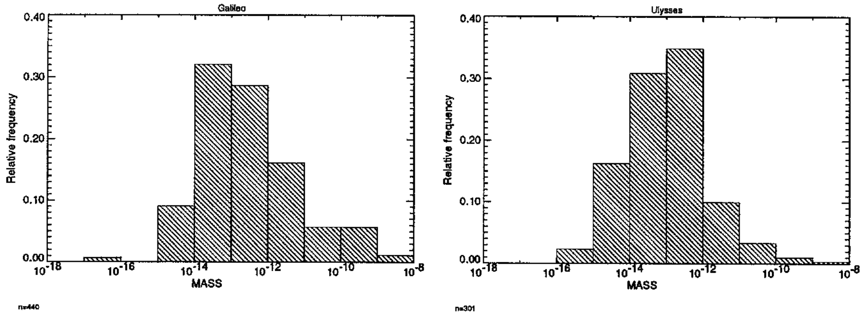

Figure 5. Mass distribution of the Galileo (left) and Ulysses (right) dust impacts. Selected are all impacts compatible with an interstellar impact direction. Jupiter stream particles have been excluded.

From directional arguments a clear identification of interstellar dust impacts is only possible outside the asteroid belt (fig. 4b).

The mass distribution of the identified interstellar particles is given in figure 5. The mass is given in g. Included are all particles with rotation angles compatible with the interstellar direction. To make the distributions comparable and to exclude contaminations of small Jupiter particles, only impacts with a signal amplitude (ion charge) greater than $1 \cdot 10^{-13} C$ are included. Before day 192 of 1994, Galileo was only sensitive to impacts above this threshold, other impacts were mostly overwritten by noise. See (Grün et al., 1995b) for a discussion of the Galileo effective threshold.

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 in the outer solar system. Galileo confirms this result. 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 increasing distance from the ecliptic plane and radial distance do not significantly influence the flux rate and the distribution of impact directions in agreement with the expected behaviour 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: Modeling shows (Grün et al., 1996b), that the data taken around the Ulysses ecliptic passage in March 1995 can be only explained by the assumption of interstellar dust contributing to the total flux by approximately 30% at the Earth orbit. Although a clear identification of interstellar dust from impact direction arguments can not be made inside $2.8AU$ the data don't contradict this assumption. (McDonnell et al., 1975) argue from Pioneer 8 and 9 measurements that the contribution of interstellar dust to the flux at terrestrial distances should be lower than 3%, a value derived from flux isotropy arguments. Further analysis of recent data is necessary to improve the reliability of this estimate.

Although the interstellar gas and dust directions are compatible, more analysis of the data is necessary to give the best fitting direction. Whether or not it deviates from the gas direction will allow important clues about the dust dynamic in the heliosphere and may give clues to the parameters of the surrounding local interstellar cloud itself.

The mass distribution of the measured interstellar dust particles indicate a dropoff at small masses that can not be explained by the sensor threshold. The dropoff value is at least one order of magnitude higher than the threshold. The dropoff indicates that smaller interstellar dust particles, known to exist in interstellar space, are kept out of the heliosphere by defocusing Lorentz forces. Modeling of these processes is underway (Grün et al., 1994). The mean mass of the distribution is $3 \cdot 10^{-13} g$. This is about a factor of 30 heavier than the mass expected from astronomical observations of the large scale interstellar dust component. Whereas astronomical measurements, however, are integrated over a large distance, our measurements are the first ever on the parameters of our local interstellar dust environment itself.

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