DUST MEASUREMENTS IN THE OUTER SOLAR SYSTEM

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Abstract. In-situ measurements of micrometeoroids provide information on the spatial distribution of interplanetary dust and its dynamical properties. Pioneers 10 and 11, Galileo and Ulysses spaceprobes took measurements of interplanetary dust from 0.7 to 18 AU distance from the sun. Distinctly different populations of dust particles exist in the inner and outer solar system. In the inner solar system, out to about 3 AU, zodiacal dust particles are recognized by their scattered light, their thermal emission and by in-situ detection from spaceprobes. These particles orbit the sun on low inclination ($i \leq 30°$) and moderate eccentricity ($e \leq 0.6$) orbits. Their spatial density falls off with approximately the inverse of the solar distance. Dust particles on high inclination or even retrograde trajectories dominate the dust population outside about 3 AU. The dust detector onboard the Ulysses spaceprobe identified interstellar dust sweeping through the outer solar system on hyperbolic trajectories. Within about 2 AU from Jupiter Ulysses discovered periodic streams of dust particles originating from within the jovian system.

1. Introduction

The classical conception of interplanetary dust is derived from the interpretation of zodiacal light observations. Zodiacal light can be observed from non-polluted areas on the Earth with the naked eye. It appears as a diffuse glow in the west after twilight and in the east before dawn. It is symmetric with respect to the ecliptic and is wedge shaped with its widest and brightest parts near the Sun. For centuries it has been accepted wisdom that zodiacal light is caused by the reflection of sunlight from myriad interplanetary dust particles which are concentrated in the ecliptic plane. This concentration in the ecliptic plane is direct evidence for dust particles on low-inclination ($\leq 30°$) orbits (cf. Leinert and Grün, 1990) which contribute to the zodiacal brightness. The size distribution of interplanetary dust at 1 AU has been determined from lunar micro-craters and spacecraft data (Grün et al., 1985). From these observations it has been concluded that maximum scattering cross-section lies in the size range from 10 to 100 μm and hence it is this size range which contributes most to the zodiacal light.

It has been suggested by ground-based observations that the concentration of interplanetary dust particles is highest near the sun and decreases with heliocentric distance. Space probe measurements of the zodiacal light brightness from 0.3 AU (Leinert et al., 1981) to 3 AU (Toller and Weinberg, 1985) and beyond found that the intensity I of zodiacal light falls off with heliocentric distance r as $I \sim r^{-\gamma}$, with $\gamma = 2$ to 2.5. Beyond about 3 AU zodiacal light was no longer observable above the background light. Dumont and Levasseur-Regourd (1988) and Levasseur-Regourd et al. (1991) conclude from these and ground-based observations that there is a

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radial variation of the optical dust properties (scattering function, polarization and albedo) and hence the radial variation of the spatial dust density is approximately proportional to the inverse of the solar distance.

Besides a small increase in the visible brightness of zodiacal light in the antisunward direction (Gegenschein), which is caused by the scattering characteristics of small dielectric particles there is little evidence from observations in the visible wavelength range for dust outside the Earth orbit.

Because of the generally low albedo of interplanetary dust (Hanner, 1980) most of the energy from insolation is absorbed and re-emitted as thermal radiation at infrared wavelengths. Observations by e.g. the IRAS satellite (Hauser et al., 1984) show that maximum thermal emission from dust at the distance of the asteroid belt occurs in the 10 to 20 μm wavelength range. However, modelling of the interplanetary dust populations by Divine (1993) and by Staubach et al. (1993) show that both optical and thermal zodiacal light emissions can be explained to a large extent by a single "core" population of dust particles on low-inclination orbits which are concentrated towards the sun.

Recently Dubin and Soberman (1991) published a "Cosmoid"-hypothesis by which meteoroids flare up due to sublimation and disintegration into many smaller grains. This hypothesis was introduced in order to explain some (previously considered spurious) observations of the optical dust detector (AMD) on Pioneers 10 and 11. These ideas will not be discussed here because acceptance of them would invalidate the large body of experience gained from previous observations and analyses of interplanetary dust - the authors fail to substantiate these consequences.

In the following two chapters we will separate the discussion of in-situ dust measurements and interpretations inside and outside 3 AU because at about this distance there seems to be a significant transition of dust populations. In the fourth chapter the newly discovered dust emissions from the jovian system are discussed and in the fifth chapter evidence for interstellar dust in the solar system is presented.

2. Dust Inside 3 AU

Complementary to ground-based are in-situ observations by dust impact detectors on board interplanetary spaceprobes. In-situ measurements of interplanetary dust have been performed in the heliocentric distance range from 0.3 AU out to 18 AU (for a complete review see Leinert and Grün, 1990). We will start the discussion on the most recent results from the dust measurements on board the Galileo spacecraft (Grün et al., 1992a).

The Galileo spacecraft was launched in October 1989 on its trajectory to Jupiter. Before the Galileo spacecraft will reach Jupiter it has to perform a six year journey through the solar system. Figure 1 shows the Galileo trajectory through the inner solar system. A Venus swing-by took place in February 1990 and the spacecraft flew by the Earth in December 1990 for the first time. Until end of 1992 Galileo repeatedly traversed interplanetary space between 0.7 and 2.26 AU and had fly-bys of the asteroid Gaspra and the Earth for a second time.

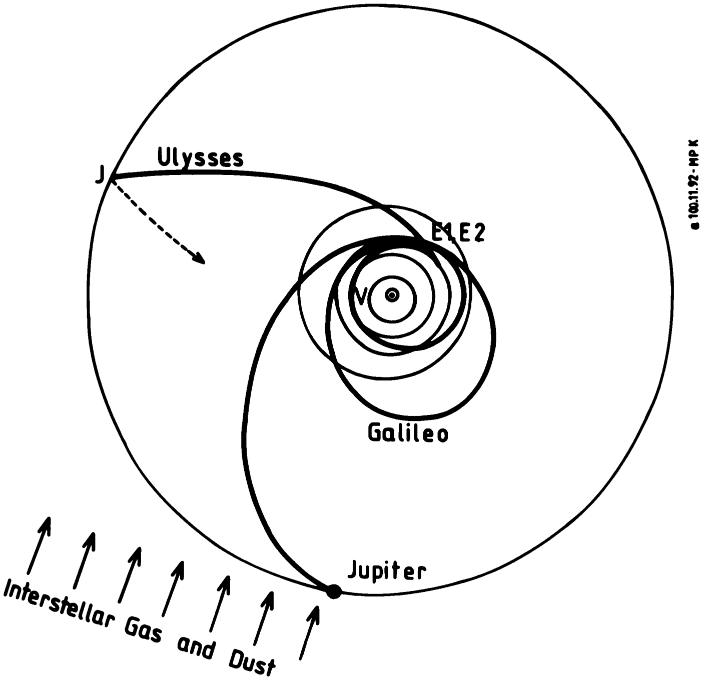

Fig. 1. Orbits of the Galileo and Ulysses spaceprobes through the solar system. The orbits of Mercury, Venus, Earth, Mars and Jupiter are indicated by thin lines. The dot at the end of the Galileo trajectory indicates that Galileo will become a satellite of Jupiter after swing-bys of Venus (V), and Earth (E1 and E2). The Ulysses trajectory was deflected by Jupiter out of the ecliptic plane onto a 80°-inclination orbit (dashed line). The inflow direction of interstellar gas and dust is shown for comparison.

The Galileo dust detector is a multi-coincidence impact ionization detector (Grün et al., 1992b). Masses and impact speeds of dust particles are determined from the measured amplitudes and rise-times of the positive and negative impact charge signals. The mass sensitivity threshold is $4 \cdot 10^{-15}$ g at 20 km/s and $6 \cdot 10^{-16}$ g at 40 km/s impact speed, as deduced from laboratory impact calibrations with carbon, silicate and iron dust particles (Göller and Grün, 1989). The accuracy of the speed determination is a factor of 2 and that of the mass determination is a factor of 10 in the calibrated range (Grün et al., 1992c).

The dust detector instrument is mounted on the spinning section of the spacecraft. During the initial phase of the mission the spin vector points away from the Sun. The viewing direction of the dust detector forms an angle of 55 degrees with respect to the spin vector. In December 1989 the dust detector was switched on for the first time, when Galileo was at a distance of 0.88 AU from the Sun. Figure 2 shows the measured dust flux during the initial Galileo mission phase. At the same heliocentric distance the impact rates were lower by a factor of ten when the spacecraft moved towards the Sun compared to the rates measured when it moved away from the Sun. After both Earth fly-bys the impact rate increased by about an order of magnitude. The general decrease of the flux with heliocentric distance is due to the decrease of the dust population with increasing distance from the sun. During the Gaspra fly-by no enhancement above the average count rate was observed.

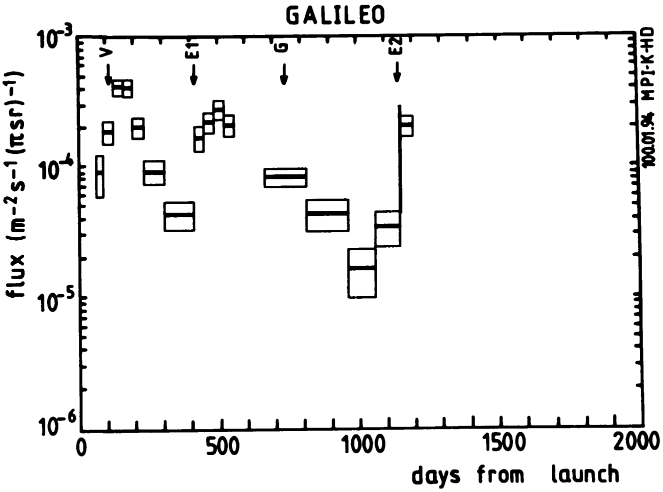

Fig. 2. Cumulative flux of dust particles recorded by the Galileo dust detector from launch (October 1989) until the end of 1992. The fluxes refer to a flat plate sensor (effective solid angle π sr) and to a positive impact charge of $\geq 10^{-13}$ C which corresponds to an effective mass threshold of $5 \cdot 10^{-14}$ g (for an assumed impact speed of 20 km/s). Each box represents the time interval over which the flux was averaged and the 1-σ uncertainty of this flux. Fly-bys of Venus (V), Earth (E1 and E2) and the asteroid Gaspra (G) are indicated.

The different fluxes observed by Galileo inbound and outbound at the same heliocentric distance R inside the asteroid belt are explained by the model of Divine (1993) as dust populations which show up differently under the different observation conditions along the Galileo trajectory (Fig. 3). In the Divine model a dust population is described by distributions of the particle mass, perihelion distance, eccentricity and inclination. Five distinct populations are required to match most interplanetary meteoroid data ranging from 10^{-18} to 1 g in mass and 0.1 to 20 AU in heliocentric distance. Inside about 3 AU the most important population to match both the Galileo data and the zodiacal light observations is the "core" population. The radial concentration of the core population falls off as $r^{-1.3}$ and the orbits have low inclinations ($i \leq 30°$) and moderate eccentricities (≤ 0.6). Among the other populations only the "inclined" population (small particles, with orbit inclinations of up to 60° and low eccentricities) contributes significantly to the Galileo flux at about Venus' distance. Outside about 3 AU distance the "halo" population becomes dominant.

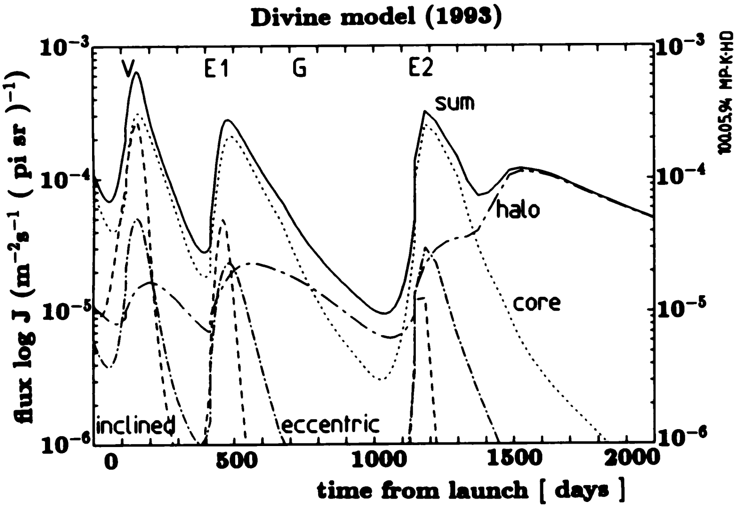

Fig. 3. Divine (1993) model of the Galileo flux (cf. Fig. 2) from launch until Jupiter arrival. Contributions to the flux from 5 different dust populations are shown separately as well as the sum of all. The model calculations take into account the orbit of Galileo, the detector geometry and sensitivity.

3. Dust Outside 3 AU : Early Measurements

The first spacecraft which passed through the asteroid belt and went beyond it were the Pioneer 10 and 11 probes (Fig. 4). Both spacecraft carried several detectors which measured different aspects of interplanetary dust. Only the meteoroid penetration detectors recorded significant concentrations of meteoroids outside 3 AU (Humes, 1980). These detectors are simple but highly reliable detectors which record the puncture of a pressurized cell by a meteoroid impact. Each detector

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consists of 234 individual detectors assembled in two independent data channels. On Pioneer 10 one channel malfunctioned early in the mission leaving only 108 pressurized cells available.

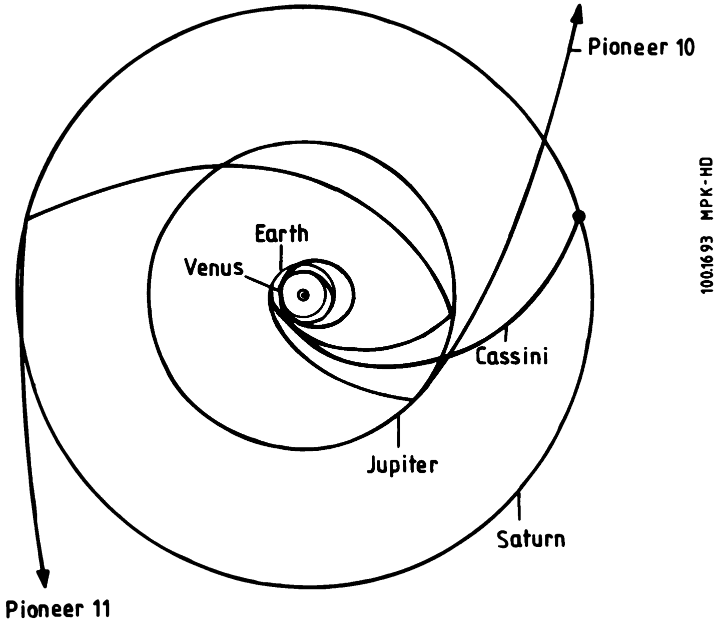

Fig. 4. Orbits of the Pioneer 10, 11 and Cassini spaceprobes projected onto the ecliptic plane. The orbits of some planets are shown as thin lines. The Pioneers 10 and 11 (launches in 1972 and 1973) had fly-bys of Jupiter (P10 and P11) and Saturn (P11) before they obtained solar system-escape-trajectories. After launch in 1997 the Cassini spaceprobe will fly-by Venus, Earth and Jupiter before becoming a satellite of Saturn.

From launch out to about 3 AU the impact flux decreased by about one order of magnitude and stayed constant for the remainder of the interplanetary tour (Fig. 5). No sign of the asteroid belt is recognized in the data. Out to 18 AU Pioneer 10 recorded 87 penetrations and Pioneer 11 recorded 87 penetrations past Saturn's fly-by. During fly-bys of the planets Jupiter and Saturn one to two orders of magnitudes increased impact fluxes were observed, mainly due to dust populations orbiting the planets. Pioneer 11 crossed three times the region between 3.7 and 4.9 AU at different impact configurations with respect to the meteoroid population (outbound, and after Jupiter fly-by inbound and outbound again).

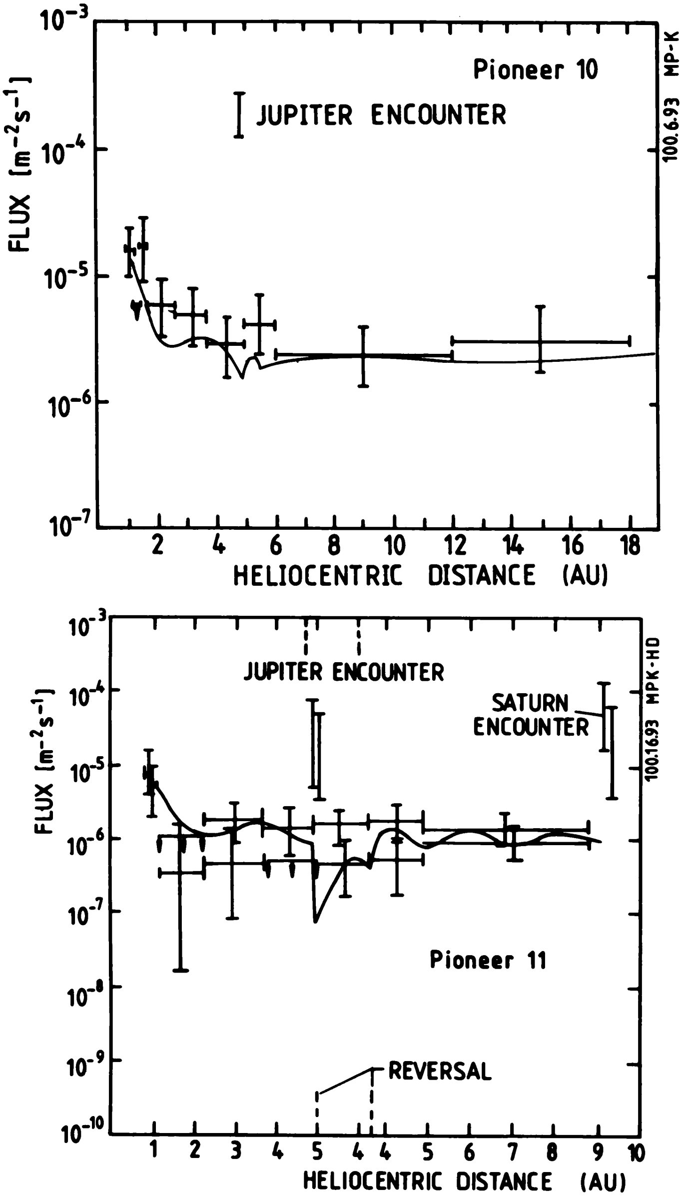

Fig. 5. Meteoroid fluxes recorded by the Pioneer 10 and 11 penetration detectors (after Humes, 1980). The threshold sensitivities of the Pioneer 10 and 11 instruments are $8 \cdot 10^{-10}$ and $6 \cdot 10^{-9}$ g, respectively, at an assumed impact speed of 20 km/s. The instruments were mounted on the back of the antenna dish which always pointed towards Earth. The solid line corresponds to the expected impact flux from a population of meteoroids on randomly inclined bound orbits of high eccentricities and with constant spatial density. Upper panel Pioneer 10 fluxes. Lower panel Pioneer 11 fluxes, two channels.

Extensive model calculations by Humes (1980) showed that the spatial density of $6 \cdot 10^{-9}$ to $8 \cdot 10^{-10}$ g meteoroids is essentially constant out to 18 AU. The multiple flux measurements with Pioneer 11 inside Jupiter's orbit allowed Humes to compare them with different inclination- and eccentricity-distributions of solar system dust. He found that the Pioneer 11 data obtained between 4 and 5 AU are best explained by meteoroids being in randomly inclined orbits of high eccentricity.

Recently Divine (1993) modelled the Pioneer 10 and 11 data by his "halo" population which has similar orbit characteristics as Humes' population except that the eccentricities needed only to reach moderate values (≤ 0.6). The impact rates recorded by Ulysses on its trajectory out to Jupiter are represented by the core and halo populations as well. However, additional information on these meteoroid populations is obtained from Ulysses data by the determination of impact direction, speed and particle mass.

4. Jupiter Dust Streams

The Ulysses and the Galileo dust detectors have a mass sensitivity 10^5 times higher than the Pioneer 10 and 11 penetration detectors. From 8 days prior to closest approach (CA) to Jupiter until 2 days after CA the Ulysses dust instrument sensitivity was reduced for reasons of instrument safety. The trajectory of Ulysses and the geometry of dust detection is explained in Fig. 6. The spacecraft spins around an axis which, along with the high gain antenna, points towards Earth. The dust detector onboard has a 140° conical field-of-view (FOV), and is mounted almost at right angle with respect to the Ulysses spin axis. The spin averaged sensitive area of the dust detector to a mono-directional stream of dust grains is ≤ 0.02 m^2; the maximum occurs when the center of the detector FOV passes through the stream during spacecraft rotation.

The impact rate observed by Ulysses (Fig. 7) of all particles (Baguhl et al., 1993) was low (about one impact per 2 days) for most of the time, although a statistically significant peak of big particles did occur at the time of Jupiter encounter (Grün et al., 1992d). For most of 1991 when Ulysses was inside 4 AU from the sun the impact rate of small particles was also low. However, within a few months of Jupiter fly-by, several bursts, in the impact rate were observed, which occurred with a remarkable periodicity of 28 ± 3 days around Jupiter fly-by (Grün et al., 1993a). No periodic dust phenomena in interplanetary space have been known before for such small grains.

The directions of sensor pointing at times when impacts were detected are shown in Fig. 8. Small particles ($m \leq 2.5 \cdot 10^{-14}$ g) appear mostly in well collimated streams of short duration. Most streams arrive from directions which include the direction to Jupiter (rotation angle 265° before CA and 53° post CA). Five characteristics of the streams, taken as a whole can be explained only if we assume a jovian origin; no interplanetary or interstellar source is capable of causing them :

1. Narrow, collimated streams must have a nearby source, otherwise they should be dispersed in space and time.
2. The streams are concentrated near Jupiter and the strongest stream was detected closest to it.

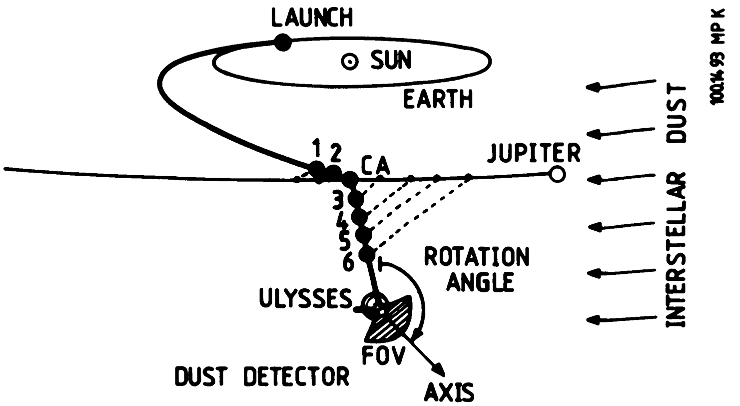

Fig. 6. Ulysses trajectory and geometry of dust detections. Oblique view from above the ecliptic plane also showing the sun and the orbits of Earth and Jupiter (in the foreground). Dots along the trajectory refer to positions of Ulysses at which major dust streams were detected - dotted lines point to Jupiter's positions. The rotation angle of the sensor axis at the time of a dust impact is measured from the ecliptic north direction. Arrows indicate the flow of interstellar dust (c.f. Grün et al., 1993a).

3. The streams are wider further away from Jupiter.

4. The streams before Jupiter CA approach Ulysses from directions almost opposite to the streams after CA; however, all streams radiate from close to the line-of- sight direction to Jupiter.

5. The observed periodicity strongly suggests that all streams derived from a single source and tends to rule out fortuitous cometary or asteroidal origins of individual streams.

Several mechanisms have been suggested which may explain the observed streams. Horanyi et al. (1993) show that small positively charged grains are accelerated and ejected by Jupiter's magnetosphere. Electromagnetic forces oppose and dominate jovian gravity. It is assumed that if Io is the source of the dust grains (Johnson et al., 1980, Morfill et al., 1980) its location in geographic and geomagnetic coordinates determines the exit direction of the escaping particles and provides a possible explanation of the observed periodicities.

An alternate source (Jupiter's gossamer ring) for the dust particles is discussed by Hamilton and Burns (1993). The periodicity of about 28 days is then caused by the modulation of the dust trajectories by the interplanetary magnetic field. Further analyses of Ulysses dust, magnetic field and solar wind data may give the clue to the correct mechanism. In addition, more data will become available when the Galileo spaceprobe reaches Jupiter in 1995.

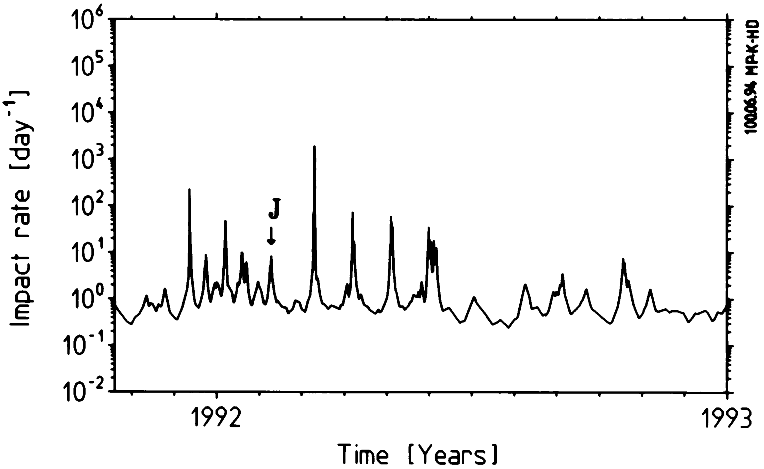

Fig. 7. Impact rate detected by the Ulysses dust detector from Oct. 1991 until end of 1992. Jupiter closest approach (J) occurred on Feb. 8, 1992. Running average continuously include 5 impacts.

5. Interstellar Dust

The Ulysses spaceprobe observed several aspects of interstellar material in the solar system. Besides ions of interstellar origin being picked-up by the solar wind (Geiss et al., 1993) the flow of interstellar helium through the solar system has been directly measured (Witte et al., 1993). The speed of the interstellar gas was 26 km/s outside the gravitational influence of the sun. It arrives from the direction : ecliptic longitude $l = 252°$ and latitude $b = 2.5°$. Grün et al. (1993a) identified a significant flux of interstellar grains at the distance of Jupiter. In a more recent paper (Grün et al., 1993b) a detailed analysis of the extended Ulysses data set (Baguhl et al., 1993) is given.

Dust particles emitted from the jovian system are identified by their smaller masses ($m \leq 2.5 \cdot 10^{-14}$ g) and their narrow bunching both in time and impact direction. The proof for the interstellar origin of some of the bigger particles outside the stream periods came from considerations of the impact direction and speed. Grün et al. (1993b) demonstrated that after the Jupiter flyby of Ulysses possible interstellar dust can be easily distinguished from interplanetary dust (generally on prograde orbits) by their retrograde trajectories. The authors identified those particles as of interstellar origin which had speeds above the maximum speed possible for particles on bound orbits.

The maximum speed which interplanetary dust can have on bound orbits varies with the impact direction from which dust is detected. Fig. 9 shows all dust particles

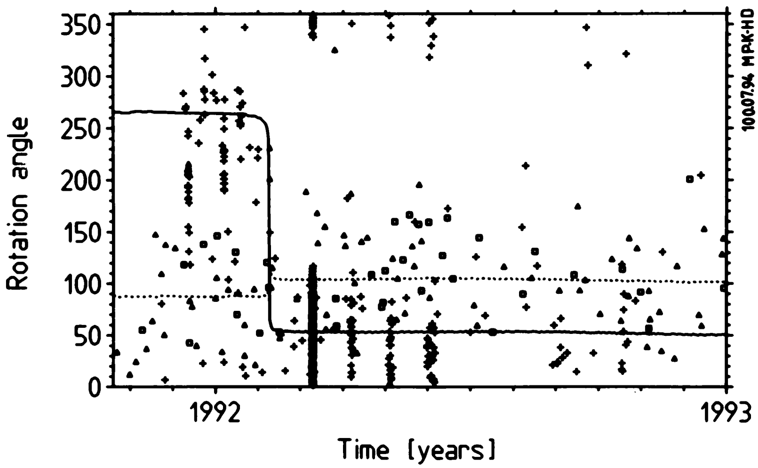

Fig. 8. Dust impact times versus spacecraft rotation angle observed by Ulysses. Only those impacts are shown (about 80% of all) for which correct masses and rotation angles were determined. The rotation angle is taken to be 0° when the dust sensor axis points closest to the north ecliptic pole. At rotation angle 90° the detector axis points parallel to the ecliptic plane in the direction of planetary motion. Impacts are marked according to their masses and impact speeds : squares : $m \geq 2.5 \cdot 10^{-14}$ g, $v \geq 26$ km/s, triangles : $m \geq 2.5 \cdot 10^{-14}$ g, $v < 26$ km/s, and crosses : $m < 2.5 \cdot 10^{-14}$ g, $v \geq 26$ km/s. The solid line indicates the direction to Jupiter. The arrival direction of interstellar dust (assumed to coincide in direction and speed with interstellar gas) is shown by the dashed line.

detected in the time interval from shortly after Jupiter flyby (day 43 of 1992) until end of 1992. During this time interval the radiant and impact speed of interstellar gas stayed almost constant. The radiant of interstellar gas and dust occurs at rotation angle 103°, that of Jovian dust on straight trajectories is at 50°.

Radiation pressure reduces the effect of solar gravity. The ratio $\beta = F_{rad}/F_{grav}$ (c.f. Burns et al. 1979) is independent of solar distance r and depends only on the size, density and the optical properties of a dust grain. The maximum heliocentric speed v_{max} of a particle on a bound orbit is

$$v_{max}(\beta) = \sqrt{2(1-\beta)\frac{\mu}{r}} \qquad (1)$$

where $\mu = G\, M_{\odot}$, with gravitational constant G and solar mass $M_{\odot}$. The spacecraft speed ($v_{Uls} = 8.2$ km/s) has to be vectorially added in order to obtain the relative speed between spacecraft and dust particle. Fig.9 shows the limiting speeds between bound and unbound orbits (dashed lines) for different β-values. Speeds of particles on bound orbits are reduced for increasing β-values until at $\beta > 1$ no bound orbits exist. Assuming intermediate β-values for micron sized grains detected by Ulysses we conclude that about 80% of all big particles are on unbound orbits and hence may be of interstellar origin. Interstellar grains arriving at the solar system with a speed of 26 km/s will gain additional speed from the solar gravitational field (corresponding to the escape speed, 18 km/s at the distance of Jupiter), which is again reduced by radiation pressure. The resulting impact speed at Ulysses is $v_{is} \approx \sqrt{26^2 + (1-\beta)18^2 + 8.2^2}$, v_{is} varies from 32.6 to 27.2 km/s for β equal 0 and 1, respectively. In Fig. 9 we show the 1-σ uncertainty range (factor 2) for both cases.

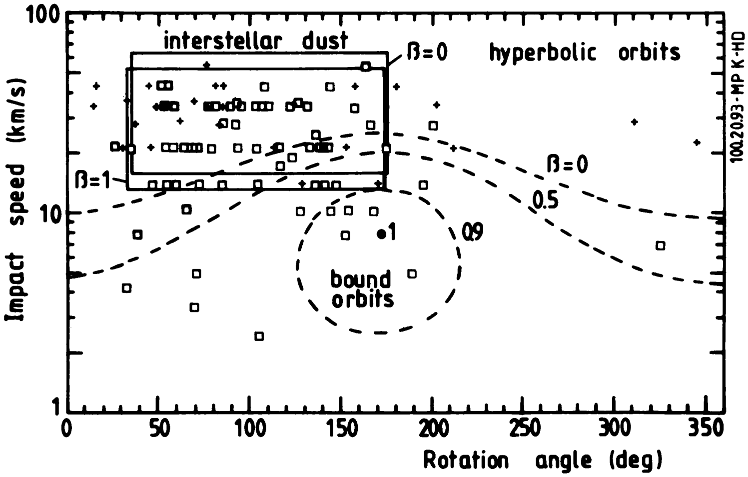

Fig. 9. Rotation angle vs impact speed of particles detected by Ulysses after Jupiter fly-by (impacts occurring during Jupiter streams are excluded). Impacts are marked according to their masses : squares : $m \geq 2.5 \cdot 10^{-14}$ g, and crosses : $m < 2.5 \cdot 10^{-14}$ g. The speed and rotation angle ranges for interstellar dust grains are shown by the boxes (both for β-values 0 and 1). The broken lines show the bound/unbound orbit limit for different β-values.

Grün et al. (1993b) identified dust grains with masses above $2.5 \cdot 10^{-14}$ g and impact speeds above 14 km/s as interstellar grains. 73 of these grains with an average mass of $3.2 \cdot 10^{-13}$ g have been recorded during the post Jupiter non-stream periods until end of 1992, which amounts to 278.4 days. Taking into account an effective sensitive area of 0.02 m^2 for the Ulysses detector an interstellar dust flux of $1.5 \cdot 10^{-4}$ m^{-2} s^{-1} and a mass flux of $5 \cdot 10^{-17}$ g m^{-2} s^{-1} is obtained.

The constant flux of 10^{-9} and 10^{-8} g particles out to 18 AU observed by Pioneers 10 and 11 could also be explained quite naturally by the assumption that the Pioneer detectors recorded impacts of 10 μm-sized interstellar grains. A consequence of this assumption, however, is that the flux of the big interstellar particles detected by the Pioneers had to arrive from the hemisphere opposite to the interstellar gas flow through the heliosphere.

The discovery of micron-sized and perhaps bigger interstellar grains will have some profound impact on our understanding of the interstellar medium : (1) because of the weak coupling of big grains to interstellar gas and fields they may provide information on their distant sources, (2) a significant mass fraction may hide in these optically invisible grains, the cosmochemical significance of which has to be explored (cf. Geiss et al., 1993) and (3) processes have to be found in which these grains can form in abundance. Chemical analyses of these particles will be attempted in the future by the Cosmic Dust Analyzer on the Cassini spacecraft.

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