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Penetration of the heliosphere by the interstellar dust stream during solar maximum

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[1] We analyze the Ulysses in situ measurements of interstellar dust in the solar system with respect to the temporal variation of the flux density. The data set that is used covers the time from after Ulysses' fly-by of Jupiter up to the most recent data taken end of November 2002. The decrease in interstellar dust flux observed in 1996 can be explained by the interaction of the small, electrostatically charged grains with the solar wind magnetic field during the solar minimum with the polarity prevailing since 1991, as was reported earlier. Now with the new data, taken especially between 2000 and the end of 2002, we find that the amplitude of the decrease and the timing of the rebound with the 2000/2001 solar maximum is such that grains with relatively high charge to mass ratio of 1.33 C kg^{-1} and effective radii of 0.2 μm cannot account for the observed profile, as was concluded earlier. The simulation of the interaction of charged dust grains with the solar wind magnetic field shows that the best fit to the observations is achieved when the interstellar dust stream is dominated by grains with a charge to mass ratio of 0.59 C kg^{-1} and a radiation pressure efficiency factor of $\beta = 1.1$, which corresponds to an effective radius of 0.3 μm. We predict that the cumulative interstellar dust flux measured by Ulysses will level off at a constant value greater than 1×10^{-4} m^{-2} s^{-1} until the end of 2004. *INDEX TERMS:* 2134 Interplanetary Physics: Interplanetary magnetic fields; 2162 Interplanetary Physics: Solar cycle variations (7536); 2164 Interplanetary Physics: Solar wind plasma; 6015 Planetology: Comets and Small Bodies: Dust; 7524 Solar Physics, Astrophysics, and Astronomy: Magnetic fields; *KEYWORDS:* dust, interstellar, Ulysses, heliosphere, solar maximum, dynamics

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1. Introduction

[2] Our immediate galactic neighborhood consists of a number of warm diffuse clouds embedded in the hot medium of the local bubble [*Holzer*, 1989]. Currently, the Sun moves through one of the warm clouds, the Local Interstellar Cloud (LIC) [*Lallement and Bertin*, 1992; *Frisch*, 2000]). Despite the relative motion between the Sun and the LIC, only a fraction of the gas and dust in the LIC reaches the space between the planets. The reason is the filtering effect of the solar wind plasma. This radially expanding solar wind plasma consists of charged particles immersed in a magnetic field [*Parker*, 1958]. The ionized component of the local galactic gas is deflected by the solar wind magnetic field [*Morfill et al.*, 1985], as well as a large part of the energetic particle spectrum [*Kota and Jokipii*, 1995], and galactic interstellar dust grains with sizes below 0.1 μm [*Linde and Gombosi*, 2000]. Larger dust grains [*Grün et al.*, 1993; *Baggaley*, 2000] as well as neutral gas atoms [*Witte et al.*, 1993] penetrate the heliopause and the solar wind plasma and can thus be detected by spacecraft in interplanetary space. Modeling [*Landgraf*, 2000] shows that how deep the interstellar dust stream can penetrate into the solar system depends on the solar cycle.

[3] The presence of interstellar dust in the solar system has a profound impact on the chemical evolution of the planets, because on long time scales the accretion of cosmic dust changes the chemical composition of planetary surfaces [*Flynn*, 1991] or atmospheres [*McNeil et al.*, 1996; *Moses et al.*, 2000]. Planets can either accrete interstellar dust directly or interplanetary dust that was produced by collisions of interstellar dust with large interplanetary grains [*Yamamoto and Mukai*, 1998]. Interstellar dust can also be captured into closed orbits around the Sun [*Jackson*, 2001].

[4] Here we report the observation of the variation of the galactic interstellar dust measured by the dust instrument on board the Ulysses spacecraft. An increasing number of interstellar grains has been detected since beginning of

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2000. According to our model calculations, the increase of interstellar dust in the solar system marks the beginning of large-scale disturbances of the solar wind magnetic field polarity during solar maximum. With the current solar maximum the solar wind magnetic field will change its polarity. The new polarity of the solar wind magnetic field will cause the number of interstellar dust grains in the solar system to steadily increase until the next solar maximum [*Landgraf*, 2000].

[5] The dust detector on board the Ulysses spacecraft is ideally suited to monitor the interstellar dust stream because the spacecraft circles the Sun on an elliptical orbit that is inclined at 79° with respect to the ecliptic plane. Its perihelion is at 1.3 AU, and the aphelion is at 5.4 AU. Ulysses carries an impact ionisation dust detector [*Grün et al.*, 1992a, 1992b] which measures the plasma cloud released on impact of cosmic dust grains onto its sensitive target. The plasma cloud is separated by an electrostatic field, and the charge signals are measured at the electrodes. A detection is confirmed by multiple coincidence of three independent charge signals. Masses and impact speeds of the impactors are determined from the measured amplitudes and rise times of the impact charge signals [*Grün et al.*, 1995]. In addition to the mass and speed of the impacting grains the coarse impact direction can be determined from the time of the impact, since the dust detector has a limited circular field of view of 140° (full angle) that scans directions perpendicular to the spacecraft's spin axis as the spacecraft rotates. During each scan the detector's bore-sight approaches the direction towards the ecliptic north pole. The rotation angle is defined as the angle between the closest direction to the ecliptic north pole and the instantaneous direction of the detector at the time of the impact. During most of Ulysses' orbit a rotation angle around 270° represents prograde, and a rotation angle around 90° retrograde impacts.

[6] The existence of interstellar dust grains in the Ulysses data was established by observing the dust impact direction, impact speed, and the dependence of the dust impact rate as a function of the ecliptic latitude of the spacecraft [*Grün et al.*, 1993]. It was found that interstellar dust arrives from the same direction as interstellar neutral gas atoms [*Witte et al.*, 1993], which for the aphelion side of Ulysses' orbit is the opposite (retrograde) direction as the arrival direction (prograde) of dust from interplanetary sources like short period comets or asteroids. In addition the impact speeds of dust grains from the retrograde direction were greater than the local solar system escape speed, even when radiation pressure effects are neglected. The observation that the impact rate of small dust grains did not decrease steeply after Ulysses left the ecliptic plane [*Baguhl et al.*, 1996], where most interplanetary sources are concentrated, shows that the impacts detected by Ulysses are in fact dominated by interstellar grains [*Krüger et al.*, 1999].

[7] Ulysses monitors the stream of interstellar dust grains through the Solar System since it left the ecliptic plane in February 1992. It was found that the solar wind filtration causes a deficiency of detected interstellar grains with sizes below 0.2 μm [*Grün et al.*, 1994]. The electromagnetic interaction of the dust grains with the solar wind magnetic field is caused by the electrostatic charging of the grains by the ambient plasma and solar UV photons to a constant surface potential of approximately $+5V$ [*Mukai*, 1981]. An additional filtration by solar radiation pressure that deflects grains with sizes of 0.4 μm was found to be effective at solar distances less than 4 AU [*Landgraf et al.*, 1999a]. Given the predicted variability of the heliospheric filtration with the solar cycle [*Landgraf*, 2000], the monitoring of the temporal variation of the interstellar dust flux was given special attention. In mid 1996 a decrease of the cumulative interstellar dust flux density from initially 1.5×10^{-4} m^{-2} s^{-1} to 0.5×10^{-4} m^{-2} s^{-1} was observed [*Landgraf et al.*, 1999b] (see Figure 2) that was attributed to the increased filtering of small grains by the solar wind during solar minimum conditions [*Landgraf*, 2000; *Landgraf et al.*, 2000]. It was expected that the interstellar dust flux will stay low until about 2005 when the polarity of the solar wind magnetic field of the new solar cycle will focus the interstellar dust stream to lower heliographic latitudes. Already since early 2000, however, Ulysses has detected interstellar dust flux levels above 10^{-4} m^{-2} s^{-1} again. This behavior of the interstellar dust stream can give us information about the dynamic interaction of interstellar dust with the heliospheric environment and thus about the dynamic parameters like radiation pressure efficiency and the charge to mass ratio of the dust grains. Here we present the data analysis and interpretation of the observed phenomena.

2. Measuring the Interstellar Dust Flux With Ulysses

[8] The first step in measuring the interstellar dust flux in the solar system is to identify the impactors of interstellar origin. Ulysses' unique, highly inclined interplanetary trajectory mostly avoids the ecliptic plane, where the dust population is dominated by grains from asteroids, short-period comets, as well as the Kuiper belt. Therefore it can be expected that most detections of the Ulysses dust instrument are of interstellar origin anyway. Other probably less prolific dust sources, however, can contribute to the impacts detected by the Ulysses dust detector. Mainly grains from Oort cloud comets like 1P/Halley are likely to orbit the Sun on highly inclined orbits. Due to their large semimajor axis and thus high orbital energy, most grains in the size range below 10 μm will not stay on bound orbits after their release from the comet. As the size distribution of cometary grains decreases steeply with size [*Mazets et al.*, 1986], the spatial density of interplanetary dust grains on highly inclined orbits is believed to be low.

[9] In order to eliminate possible contamination by interplanetary grains, we selected a subset of the Ulysses data set according to the following criteria: (1) The rotation angle for the impact must be available. (2) The rotation angle at the time of the impact was such that the interstellar upstream direction as defined by the stream direction of neutral gas atoms was in the field of view of the detector, plus a 10° margin in order to account for angular deflection of the grain on its way through the heliosphere. (3) The impact must not have occurred during the arrival of a Jupiter dust stream [*Grün et al.*, 1993]. Figure 1 shows the selected set of impacts. Besides interstellar impacts, events caused by Jupiter stream particles can also be seen in early 1992. Prograde impacts (rotation angles around 270°) are seen throughout the mission, but impacts from a direction of 100° rotation angle dominate the data set. Around the

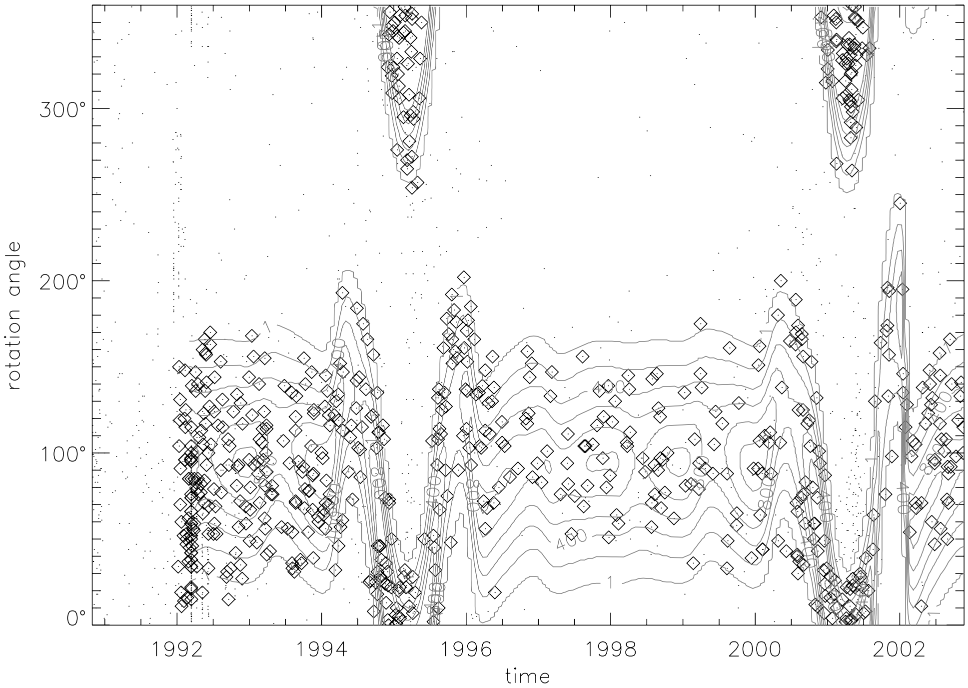

Figure 1. Overview of all impacts recorded by the Ulysses dust detector between early 1992 and the end of 2002. The impacts are marked in the rotation angle over time diagram. Dot symbols represent impacts that are not considered interstellar. The impacts that are shown as diamond symbols make up the subset of interstellar impactors. The underlying contours indicate the sensitive area [cm^2] of the detector for grains approaching on straight trajectories from the interstellar stream direction.

perihelion passages in March 1995 and May 2001 the approach direction of interstellar and prograde interplanetary grains was identical. Because we cannot clearly identify interstellar impacts in these periods, we disregard the measurements between the south and north polar passes.

[10] In order to determine the interstellar dust flux from the number of impacts counted in a given time interval, we have to take into account the sensitive detector area averaged over one rotation of the spacecraft. The flux is then given by the number of impacts divided by the area-time product. The sensitive area is calculated for an assumed monodirectional stream of grains from the interstellar upstream direction as defined by the stream direction of neutral gas atoms. We have divided the periods before the first perihelion passage into 3, and the period between the perihelion passages into 4 time intervals. The short period after the second perihelion passage we define as one single time interval. The flux of interstellar dust so determined is shown in Figure 2. After Ulysses' Jupiter fly-by in February 1992 and before 1997 the interstellar dust flux was nearly constant between 1×10^{-4} and 2×10^{-4} m^{-2} s^{-1}. In early 1997 it decreased by almost a factor of 3 to 5×10^{-5} m^{-2} s^{-1}. In early 2000 the flux returned to values around 1×10^{-4} m^{-2} s^{-1}, which it maintained up to end of November 2002 when the most recent data were taken.

3. Modeling the Heliospheric Interaction of Interstellar Dust

[11] What is the cause of the temporal variation of the interstellar dust flux as seen in Figure 2? Generally, there are three possible explanations: (1) a spatial variation of the dust concentration in the heliosphere that translates into temporal variation as the spacecraft moves through, (2) a variation of the dust concentration in the interstellar medium, and (3) a variation in the efficiency of the filtration mechanisms at the heliopause and within the heliosphere. The spatial variation of the interstellar dust distribution in heliosphere as indicated by possibility 1 and the dependence of the measurement on the spacecraft location must be considered when simulating the measurements [*Landgraf*, 2000]. If the flux variation was solely due to the spatial distribution, however, the flux value must be periodic with Ulysses' orbital period of 6.2 years. This is not the case, as the flux measured early 1993 was 1.5×10^{-4} m^{-2} s^{-1} and in mid-1999 it was 5×10^{-5} m^{-2} s^{-1}. A variation of the interstellar dust concentration as suggested by explanation 2 is considered unlikely as the local interstellar medium is assumed homogeneous on a spatial scale of a few parsec [*Holzer*, 1989]. More recent results [*Price et al.*, 2001] from UV absorption measurements along lines of sight toward nearby stars indicate, however, that local inhomogeneities on scales of 10 AU are present in the interstellar gas phase. Here we assume that the flux variation measured by Ulysses can be explained by possibility 3, an efficiency change of the filtration mechanisms. If an acceptable fit can be achieved under this assumption, we can conclude that the dust phase of the LIC is homogeneous on scales of a few 10 AU, as the Sun traveled 50 AU relative to the LIC in the period from the end of 1992 to the end of 2002. The filtration in the heliopause region will not have a strong effect on the detected dust grains because the dust grains

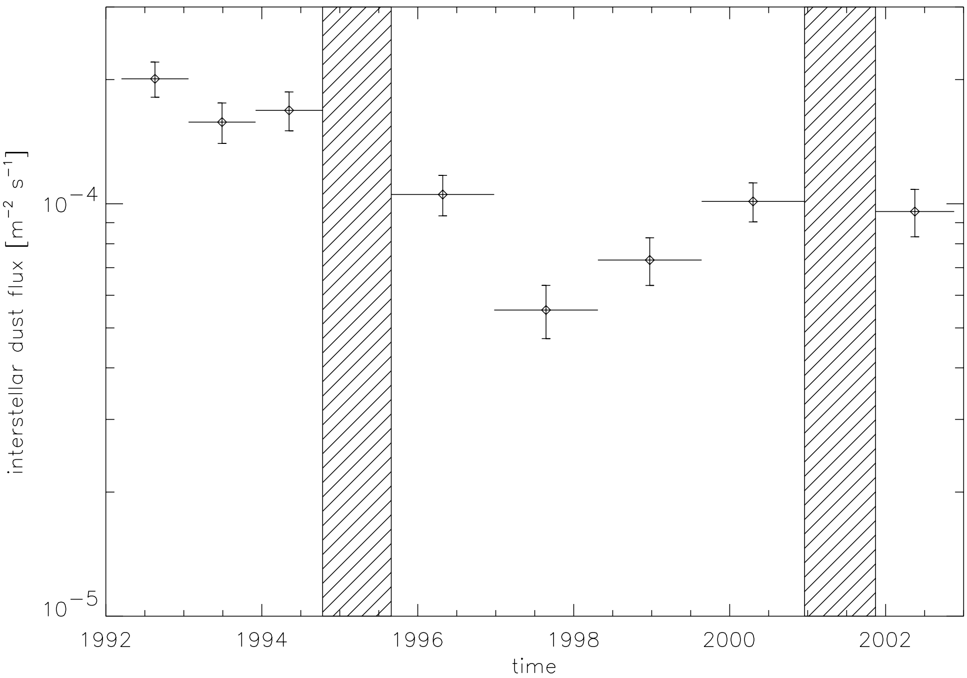

Figure 2. Interstellar dust flux as measured by the dust detector on board the Ulysses spacecraft. The horizontal lines indicate the length of the time intervals, and the vertical bars of the data points represent the 1σ uncertainty due to small-number statistics. The dashed regions in 1995 and 2001 show the periods of Ulysses' perihelion passage, where the distinction of interstellar dust from interplanetary impacts is difficult.

that can be detected by the Ulysses detector are typically larger than 0.2 μm in diameter, and thus their charge to mass ratio is too small for the heliopause to have a significant effect [*Linde and Gombosi*, 2000].

[12] In order to determine the influence of the varying solar wind magnetic field on the interstellar dust flux, a model of the heliospheric interaction of interstellar grains was constructed [*Landgraf*, 2000]. In this model the grains are assumed to be spherical with their charge to mass ratio q/m and radiation pressure coefficient β depending solely on the grain radius s. We have modeled the dynamics of four different grain sizes: s = 0.1, 0.2, 0.3, and 0.4 μm. The values of q/m and β, as well as their mass m and charge q are listed in Table 1.

[13] The equation of motion of the grains in the heliosphere is then given by [*Landgraf*, 2000]:

$$\ddot{\vec{x}} + (1-\beta)\frac{GM_\odot}{|\vec{x}|^3}\vec{x} - \frac{q}{m}\left(\left(\dot{\vec{x}} - \vec{v}_{\rm sw}\right)\times\vec{B}_{\rm P}\right) = 0, \qquad (1)$$

where $G = 6.6732 \times 10^{-11}$ m^3 kg^{-1} s^{-2} is the gravitational constant, $M_\odot = 1.989 \times 10^{30}$ kg is the solar mass, $\vec{v}_{\rm sw}$ is the solar wind velocity, and $\vec{B}_{\rm P}$ is the solar wind magnetic field. The solar wind speed vector is assumed radial with a magnitude of 400 km s^{-1}. We use this value representative of the low-speed solar wind despite Ulysses' encounter of solar wind with speeds up to 800 km s^{-1}. A change in $v_{\rm sw}$ does not affect our results because the azimuthal component $B_{\phi,0}$ of $\vec{B}_{\rm P}$, which dominates the interaction with the dust grains, is proportional to $1/v_{\rm sw}$, so that the acceleration due to the electromagnetic interaction in equation (1) is independent of $v_{\rm sw}$. For each location in the solar system given by its heliographic coordinates ($r_{\rm hg}$, $\lambda_{\rm hg}$, $\beta_{\rm hg}$), the spherical components of $\vec{B}_{\rm P}$ can be written as:

$$B_r = \pm B_{r,0}\left(\frac{r_0}{r_{\rm hg}}\right)^2$$
$$B_\phi = \pm B_{\phi,0}\frac{r_0}{r_{\rm hg}}\cos\beta_{\rm hg} \qquad (2)$$
$$B_\theta = 0,$$

where $B_{r,0} = B_{\phi,0}$ = 3 nT are the radial and azimuthal field strength at r_0 = 1 AU in the low-speed solar wind [*Gustafson*, 1994].

[14] We have simulated the stream of interstellar dust through the solar system by solving the equation of motion (1) numerically. Between 10^6 and 10^7 Monte-Carlo runs of simulated particles were performed for each grain size, in which the initial position was uniformly distributed

Table 1. Parameters of Spherical Interstellar Dust Grains of Various Sizes[a]

Radius s, μm	β	$\frac{q}{m}$, C kg^{-1}	Mass m, kg	Charge q, C
0.4	0.90	0.332	6.7×10^{-16}	2.2×10^{-16}
0.3	1.1	0.590	2.8×10^{-16}	1.7×10^{-16}
0.2	1.4	1.33	8.4×10^{-17}	1.1×10^{-16}
0.1	1.2	5.31	1.0×10^{-17}	5.3×10^{-17}

[a]The mass is determined by assuming the grains to be homogeneous spheres with a density of 2.5 g cm^{-3}. The radiation pressure parameter β is taken from Mie calculations for spheres made of astronomical silicates [*Gustafson*, 1994; *Draine and Lee*, 1984], and the charge is calculated for a sphere with a surface potential of U = +5 V.

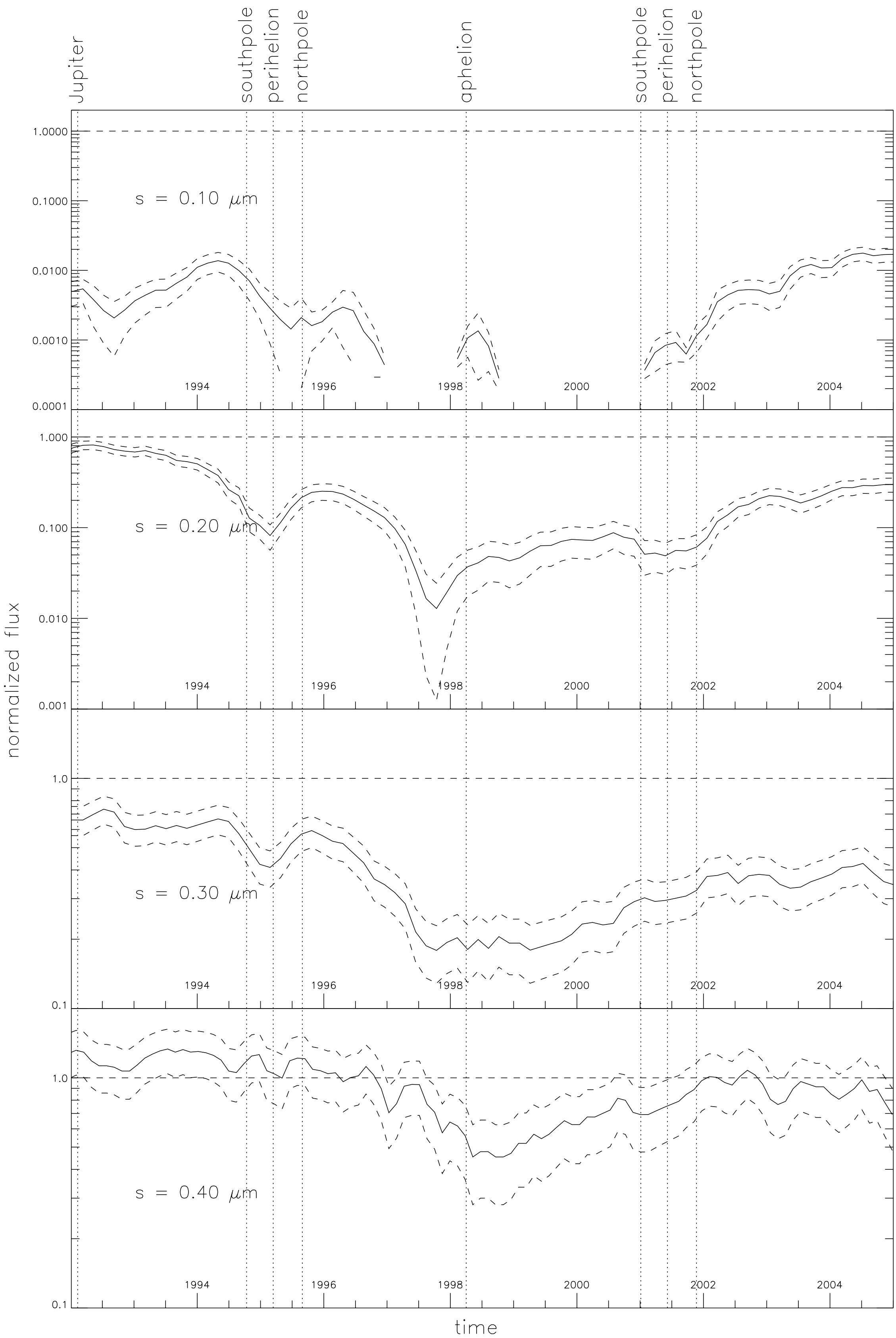

Figure 3. Predicted temporal variation of the flux (solid lines) of interstellar dust arriving at the Ulysses spacecraft for four different grain radii. The dashed lines around the flux prediction curves indicate the 1σ uncertainty due to small number statistics of the Monte-Carlo simulation. The vertical dotted lines mark the milestones along Ulysses' orbit. The flux is normalized to its value at large distances from the Sun.

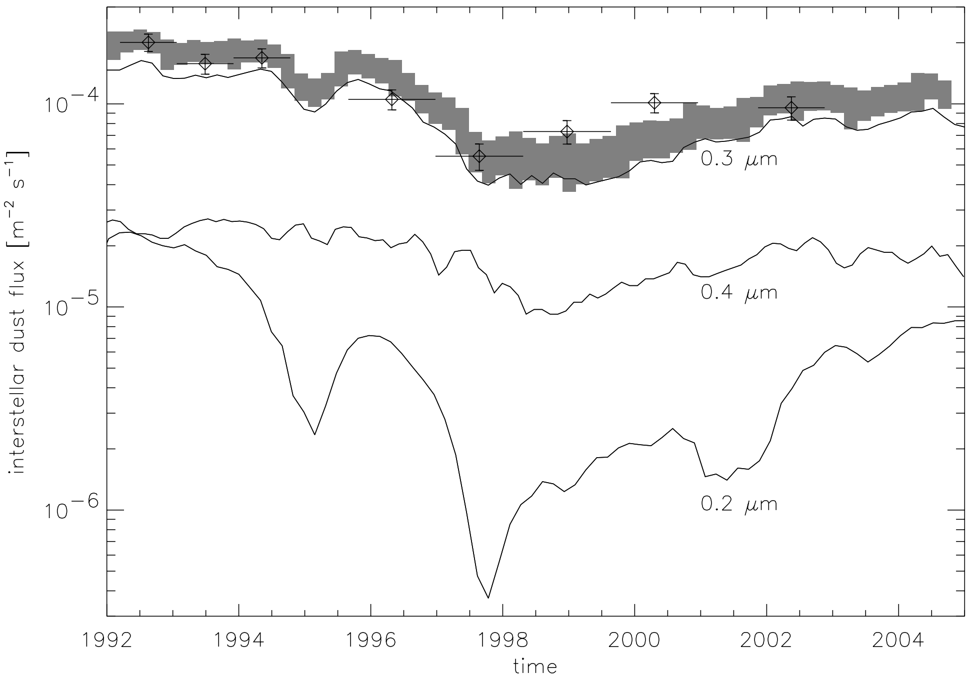

Figure 4. Fit of simulated to measured flux. The fit parameters are the relative contribution of grains of sizes between 0.1 and 0.4 μm (The 0.1 μm curve is not shown, because it did not contribute to the fit). The flux measurements by Ulysses are shown as in Figure 2. The solid lines show the flux profiles of the simulated grains of various sizes, scaled with their best-fit relative contributions. The shaded region indicates the best-fit total predicted flux, with its vertical extent giving the 1σ uncertainty.

in a volume 100 × 100 × 1 AU at a distance of 100 AU from the Sun. The initial velocity was set to 25.2 km s^{-1}, the value that was measured for the velocity of neutral interstellar Helium atoms [*Witte et al.*, 1996] relative to the Sun before they are influenced by the Sun's gravity field. It is thus assumed that the dust grains are in rest with respect to the neutral gas phase in the LIC. In order to take the interstellar flux at the spacecraft, we calculated the average inertial flux of simulated grains in a three-dimensional Cartesian grid with cubic cell size between 1 and 8 AU^3. Figure 3 shows the predicted flux at the location and in the frame of reference of the spacecraft, normalized to the initial flux, for various grain sizes. As expected, the simulation shows that the filtration is most efficient for the smallest grains (s = 0.1 μm). Between 1992 and 2005 their flux never reaches more than 2% of its value at infinity. In the second half of the last solar cycle between 1997 and 2001 these small grains are even completely removed from the part of the solar system inside 5 AU. Only around aphelion was Ulysses in the right location to detect them. Already the next bigger grains (s = 0.2 μm) are much less affected by the solar wind magnetic field. Their flux is close to its value in the interstellar medium at the beginning of the last solar cycle. The strong decrease in flux by one order of magnitude around Ulysses' perihelion is caused by the strong effect of radiation pressure on grains of this size. The simulation predicts the maximum suppression of the flux at Ulysses by two orders of magnitude just before the first aphelion in 1998. Grains with sizes of 0.3 and 0.4 μm follow the same trend as the 0.2 μm grains but exhibit much less variation due to their smaller charge to mass ratios.

[15] The comparison of the measured variation of the interstellar dust flux at Ulysses with the results of the Monte-Carlo simulation allows us to find the grains size and thus the combination of q/m and β that is dominant in the interstellar dust stream. On order to take into account a range of grain sizes, we fit the data against a linear combination of the flux profiles shown in Figure 3, with the relative contribution of the various grain sizes as fit parameters. Figure 4 shows the best fit of the simulated flux profiles to the Ulysses data. The fit results in a dominant contribution from 0.3 μm grains with some minor contribution from 0.4 μm grains. The contribution from 0.1 and 0.2 μm grains is not needed to achieve the fit. The fitted flux profile successfully represents the qualitative features of the measurement: The almost constant flux between 1992 and 1996, the decrease in 1997, and the rebound until 2002. Also the relatively low value of the normalized χ^2 of 0.1 (or not normalized χ^2_8 = 0.9 for 8 degrees of freedom) shows the good agreement of prediction and measurement. In the period between 1998 and 2000, however, the measured values are systematically higher, indicating an earlier rebound of the dust flux than predicted.

4. Conclusion

[16] We have analyzed the flux of dust from the LIC as measured in situ by the dust detector on board the Ulysses spacecraft. The variation of this flux gives us information about the interaction of the dust grains with the solar wind magnetic field, and thus about their dynamical parameters, i.e., the charge to mass ratio q/m and the radiation pressure

efficiency β. We simulated the dynamics of the grains and the measurement geometry using a Monte-Carlo method, in which more than ten million passages of dust grains through the solar system were recreated. From the predicted flux profiles we were able to determine the relative contribution of grains with different dynamical parameters to the dust stream employing a fit of a linear combination of the profiles to the Ulysses data. The simulation confirmed that the flux of grains with radii of 0.1 and 0.2 μm is highly variable and strongly filtered by the interaction with the solar wind magnetic field. Because this highly variable behavior over orders of magnitude is not reflected in the data, we consider it highly unlikely that these small grains are present in the parts of the solar system accessible to Ulysses. The sensitivity of the Ulysses dust detector is sufficient to record impacts by 0.1 μm grains at velocities around 20 km s^{-1}. Because small interstellar grains are observed in the diffuse interstellar medium astronomically [*Mathis*, 1990], there must be a physical mechanism that removes these grains from the solar system. This mechanism we find to be electromagnetic filtration we have analyzed in this work. According to the simulation the flux of 0.1 μm grains at the location of Ulysses never exceeds 2%, and is most of the time lower than 0.1% of its value in the interstellar medium (see Figure 3). From the canonical grain size distribution in the diffuse interstellar medium [*Mathis et al.*, 1977] it is expected that 0.1 μm grains are only 50 times more abundant than 0.3 μm grains. Thus despite their initially higher number, interstellar grains with radii of 0.2 μm are not abundant in the part of the Solar System inside 5 AU.

[17] Grains with radii of 0.2 μm (q/m = 1.33 C kg^{-1}; β = 1.4), however, should be present in the Ulysses data, especially between 1992 and 1994. The fact that their profile does not fit the data indicates that there is a filtration mechanism other than electromagnetic interaction that removes grains with intermediate charge to mass ratios from inside 5 AU. In our opinion the most plausible explanation for this other filtering mechanism is the effect of solar radiation pressure, because the relative strength of radiation pressure β is maximum for grains with effective diameter of 0.4 μm (B. Å. S. Gustafson et al., Forces on dust in interplanetary space, unpublished manuscript, 1996). If this is the case, β must have a peak value of 1.9 for these grains [*Landgraf et al.*, 1999a].

[18] According to the best fit, the dominant contribution comes from grains which in the simulation have radii of 0.3 μm with a minor contribution from grains with radii of 0.4 μm. We cannot, however, conclude that the interstellar dust stream is dominated by spherical grains with an effective radius of 0.3 μm. Our analyses merely shows that the typical grain in the interstellar dust stream has a charge to mass ratio of q/m = 0.59 C kg^{-1} and a radiation pressure efficiency of β = 1.1. The observation that we are able to fit the flux variation assuming a constant dust concentration in the LIC lets us conclude that the dust phase of the LIC is homogeneously distributed over length scales of 50 AU, the distance inside the LIC traveled by the Sun between the end of 1992 and the end of 2002, the period when the data was taken. Given the best-fit flux profile shown in Figure 4, we predict that the flux of interstellar dust will level off at a constant value just above 1×10^{-4} m^{-2} s^{-1} until the end of 2004.

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