Aspects of the Mass Distribution of Interstellar Dust Grains in the Solar System from In-Situ Measurements

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Abstract

The in-situ detection of interstellar dust grains in the Solar System by the dust instruments on-board the Ulysses and Galileo spacecraft as well as the recent measurements of hyperbolic radar meteors give information on the properties of the interstellar solid particle population in the solar vicinity. Especially the distribution of grain masses is indicative of growth and destruction mechanisms that govern the grain evolution in the interstellar medium. The mass of an impacting dust grain is derived from its impact velocity and the amount of plasma generated by the impact. Because the initial velocity and the dynamics of interstellar particles in the Solar System are well known, we use an approximated theoretical instead of the measured impact velocity to derive the mass of interstellar grains from the Ulysses and Galileo in-situ data. The revised mass distributions are steeper and thus contain less large grains than the ones that use measured impact velocities, but large grains still contribute significantly to the overall mass of the detected grains. The flux of interstellar grains with masses \( > 10^{-14} \) kg is determined to be \( 1 \cdot 10^{-6} \) m\(^{-2}\) s\(^{-1}\). The comparison of radar data with the extrapolation of the Ulysses and Galileo mass distribution indicates that the very large \( (m > 10^{-10} \) kg) hyperbolic meteoroids detected by the radar are not kinematically related to the interstellar dust population detected by the spacecraft.
1. Introduction

The measurement of interstellar dust grains by the dust detectors on-board the Ulysses and Galileo spacecraft, allows us to determine the grain mass distribution of the local interstellar dust component. Impacts by interstellar dust grains were clearly identified first in the Ulysses data after Ulysses’ fly-by of Jupiter in February 1992 [Grün et al., 1994]. It was shown that they can be distinguished from interplanetary grains by their retrograde impact direction which also coincides with the direction from which interstellar neutral Helium atoms enter the Solar System [Baguhl et al., 1995]. A further indication that Ulysses did detect interstellar grains was the nearly constant rate and direction of impacts on the Ulysses detector after the spacecraft left the ecliptic plane and performed measurements at high latitudes [Baguhl et al., 1998]. Additionally, the measured impact velocities measured by Ulysses after Jupiter fly-by indicated, although subject to substantial uncertainties, that the dust velocities exceeded the local escape velocity, even if radiation pressure effects were neglected. The detection of interstellar dust grains by Ulysses were confirmed by measurements with the Galileo dust detector [Baguhl et al., 1997].

The mass distribution of dust grains in the galactic interstellar medium is an indicator for the grain growth and destruction processes inside the medium. It was recognized very early by Oort and van de Hulst [1946] that in cold environments the accretion of gas onto solid particles and their agglomeration increases the number of large particles and decreases the number of small ones. Grain destruction in hot environments has the opposite effect, since large particles are shattered into smaller ones and mass is removed from grains and returned to the gas phase by sputtering. The effect of a variable mass distribution can be observed by analyzing the wavelength dependence of the extinction of starlight along different lines of sight through the interstellar medium (for a review see Mathis, [1990]). Since the shape of the extinction curve is sensitive to the mass distribution of dust grains that cause the extinction, the mass distribution can be determined, in part, by fitting the wavelength dependence of extinction [Mathis et al., 1977; Kim et al., 1991; Li and Greenberg, 1997]. These models of the mass distribution and composition of interstellar dust are constrained by the total amount of refractory elements available in the medium to form dust grains, that is, the mass in refractory elements locked up in the dust plus the mass in refractory elements in the gas phase should not exceed the cosmic abundances of the elements. Consequently, models of interstellar dust based on fits to the extinction curve do not contain large amounts of big grains, because the large mass of refractory elements contributed by the large dust grains would contradict cosmic abundance considerations [Landgraf and Grün, 1998]. For example, the mass distribution of the Mathis et al. [1977] model is cut off at grain radii of 0.25 μm (1.6 × 10^{-16} kg assuming a grain mass density of ρₐ = 2.5 × 10^{3} kg m^{-3}). In contradiction to this suggested cut-off, most of the grains detected by Ulysses and Galileo have higher masses. Assuming that the mass contained in the interstellar dust grains measured with Ulysses and Galileo in the Solar System represents the value of the dust mass density in the local interstellar cloud (LIC), and comparing it with the mass contained in the gas phase of the LIC, it was found [Frisch et al., 1999] that the mass of refractory elements found in the LIC exceeds cosmic abundance limits.

For each impact onto the dust detectors, the Ulysses and Galileo dust instruments measure the velocity, mass, and direction of an impacting grain [Grün et al., 1992]. Since the detectors are mounted at angles of 95° (Ulysses) and 60° (Galileo) with respect to the spin-axes of the spacecraft, the impact direction is given by the detector pointing (rotation angle) at the time of impact with an accuracy of ±70° (field of view). The signal rise time is a measure for the impact velocity and the mass of the impacting grain is then derived from the impact velocity and the signal amplitude. By calibrating the instruments on the ground [Grün et al., 1993] it was found that the derived mass depends strongly on the impact velocity (see below). Earlier determinations of the mass distribution of interstellar dust grains detected by Ulysses and Galileo [Grün et al., 1994; Baguhl et al., 1996] used the masses derived from the measured impact velocity, which can only be determined with an uncertainty of a factor of 2, resulting in an uncertainty of the derived mass of a factor of 10 [Grün et al., 1993]. It was argued [Landgraf, 1998] that the mass of the dust grains can be determined with a higher accuracy if the impact velocity was determined from theoretical considerations.

In this work, we determine the mass distribution of interstellar dust grains detected by Ulysses and Galileo by using impact velocities calculated from simple dynamical models. The resulting mass distribution should be more reliable, provided that the...
Figure 1. Rotation-angle-vs-time plot of impacts detected with the Galileo dust instrument. Crosses represent impacts of particles that approached from the prograde direction. Impacts that we identify as of interstellar origin (total number: 268) are shown as squares. The solid line gives the rotation angle at which the maximum sensitive area is exposed to the interstellar upstream direction (as defined by the stream direction of neutral Helium [Witte et al., 1993]). The dotted contour contains the directions and times when the upstream direction was in the field of view of the instrument or the angle between the expected relative dust velocity vector and the instrument pointing vector was less than 80°. The time of the fly-by of the asteroid Ida is indicated by the dashed vertical line.
approximated impact velocities deviate by less than a factor of 2 from the true values. To visualize the contribution of different grain sizes to the number, cross section and total mass of dust grains in the LIC, we use “moments” of the differential mass distribution. The $i$-th moment of the differential logarithmic distribution $n(m) \, d \log m$ is given by $m^i \cdot n(m) \, d \log m$. In section 3 we describe the procedure of the mass determination and the models used to calculate the impact velocity, section 4 describes the resulting mass distributions and their moments. In section 5 we compare the Ulysses and Galileo measurements with the measurements of recently discovered [Taylor et al., 1996] interstellar radar meteors.

2. Dataset of Interstellar Dust Impacts on Ulysses and Galileo Instruments

For our analysis we use Galileo dust data collected between September 1993 (after fly-by of Asteroid Ida) and July 1995 (prior to probe release operations). The Ulysses dataset we use contains impacts measured between February 1992 (after Jupiter fly-by) and February 1999 (latest data). Since the dust datasets collected by Ulysses and Galileo contain impacts by interplanetary as well as interstellar grains, we have to find selection criteria that allow us to define datasets, that contain a negligible amount of other than interstellar impacts.

Both, Ulysses and Galileo have detected dust particles that had been ejected from the Jovian system in streams [Grün et al., 1993]. These streams can easily be identified in the datasets, because they occur within a short period of time. Impacts of stream particles have been removed from both datasets by rejecting impacts that occur in a time interval that is associated with a stream event.

Interstellar particles approach Ulysses and Galileo from a direction that is opposite to the direction expected for classic interplanetary grains, that is grains on prograde, circular orbits. Therefore, we preliminarily define interstellar datasets by selecting every impact that was measured at a rotation angle of the sensor for which the interstellar upstream direction was within the field of view of the detector. We allow for a $10^\circ$ margin, because interstellar grains do not move on perfectly straight lines. Since the sensor has a field of view of $\pm 70^\circ$, we expect no particles on prograde circular orbits to be present in the so defined datasets. We now remove impacts from the preliminary datasets for which an other than interstellar origin has been suggested. For Galileo, no interplanetary source has been suggested for impacts from the retrograde direction measured outside the asteroid belt. We therefore use the dataset of 268 impacts shown in figure 2 for our further analysis.

When Ulysses crossed the ecliptic at a heliocentric distance of 1.3 AU in March 1995, the directions of interstellar and prograde interplanetary grains were not as clearly separated as it was the case during the rest of Ulysses’ orbit. We therefore exclude all measurements when Ulysses was between $-60^\circ$ and $+60^\circ$ ecliptic latitude around perihelion. Over the Sun’s poles, Ulysses detected very small particles that have been interpreted [Hamilton et al., 1996] as fragments of interplanetary particles ejected from the inner Solar System by electromagnetic effects. To remove these particles from the Ulysses dataset, we require that the measured amplitude of the ion charge signal, which increases with impact velocity and the mass of the impactor, is more than one order of magnitude above the detection threshold. The described criteria are identical to the criteria used by Landgraf [1998], but here they are applied to a more recent dataset. After removing possible interplanetary impacts from the dataset as described above, we use the dataset of 444 impacts shown in figure 3 for our analysis.

By changing the numerical values of the parameters we use to select the datasets (directional margin, charge signal amplitude cut-off) we estimate the relative uncertainty in the number of interstellar particles to be smaller than 20%, on a 90% confidence level.

3. Theoretical Impact Velocities and Derived Mass

The change of velocity of an interstellar grain in the Solar System can easily be determined by taking into account the acceleration due to solar gravity and radiation pressure. For sub-micron grains the strength of radiation pressure, expressed as the ratio of magnitudes of radiation pressure to gravity $\beta$, can be in the same order ($\beta \approx 1$) or even larger ($\beta > 1$) as the strength of gravity. In this work we use two simple models to determine the velocity of the grains:

1. The radiation pressure force and gravity have exactly the same magnitude and opposite directions ($\beta = 1$). Therefore, the grains move on straight lines with their initial velocity and direction. In this case the impact velocity is sim-
Figure 2. Rotation-angle-vs-time plot of impacts detected with the Ulysses dust instrument. Crosses represent impacts of particles that approached from the prograde direction. As described in the text, impacts around perihelion ecliptic crossing (diamonds) and small amplitude impacts above the poles (stars) have been removed from the dataset of interstellar impacts. Impacts that we identify as of interstellar origin (total number: 444) are shown as squares. The solid line gives the rotation angle at which the maximum sensitive area was exposed to the interstellar upstream direction (as defined by the stream direction of neutral Helium \cite{Witte_1993}). The dotted contour contains the directions and times when the upstream direction was in the field of view of the instrument or the angle between the expected relative dust velocity vector and the instrument pointing vector was less than 80°. The times of the Jupiter fly-by, and the perihelion and aphelion ecliptic crossings are indicated by dashed vertical lines.
ply given by the difference of the grain velocity at infinity and the spacecraft velocity.

2. The ratio $\beta$ of radiation pressure force to gravity is given by the grain size. The velocity $v_{\text{ECL}}$ of the dust grain in the inertial (heliocentric, ecliptic) frame is changed by the acceleration ($\beta < 1$) or deceleration ($\beta > 1$) along its trajectory according to

$$v_{\text{ECL}} = \sqrt{v_\infty^2 + \frac{2\gamma(1-\beta)M_\odot}{r_{\text{hc}}}}, \quad (1)$$

where $\gamma$ is the gravitational coupling constant, $M_\odot$ the mass of the Sun, and $r_{\text{hc}}$ the heliocentric distance at which the grain was detected.

For the calculation of the heliocentric grain velocity as described in the second model, we have to determine the value of $\beta$ for each individual grain. To determine $\beta$ we use Mie-calculations \cite{Gustafson,1994} for compact spherical grains made of astronomical silicates with bulk densities of $2.5 \cdot 10^3$ kg m$^{-3}$, which give $\beta$ as a function of grain radius (see figure 3).

![Figure 3](image-url)  

**Figure 3.** The ratio $\beta$ of magnitudes of radiation pressure force to gravity as a function of grain radius $a$ as given by Gustafson [1994]. The optical properties of Astronomical Silicates, a spherical shape and a bulk density of $2.5 \cdot 10^3$ kg m$^{-3}$ have been assumed.

Because the size $a$ of a grain is not measured independently by the Ulysses and Galileo dust detectors, it has to be derived from the measured mass $m_{\text{meas}}$, i.e. the mass derived from the measured impact velocity, by $a = \sqrt{3m_{\text{meas}}/(4\pi\rho a)}$. Using the grain radius $a$, we can determine $\beta$ which gives us the dust velocity $v_{\text{ECL}}$ from equation (1). Once the dust velocity in the inertial heliocentric frame is established, the impact velocity $v_i$ is calculated as the magnitude of the velocity relative to the spacecraft. The mass is then given by

$$m[g] = 1.7 \cdot 10^{-5} \cdot Q_I[C] \cdot (v_i[\text{km s}^{-1}])^{-3.5}, \quad (2)$$

as described by Grün et al. [1995], where $Q_I$ is the amplitude of the measured ion charge signal. From this mass we determine a new grain size which gives a new $\beta$, and so forth. This iterative process gives us the value of $\beta$ and the mass of a particle in a self-consistent way. A disadvantage of this second model is its dependence on not well known properties of presumably complex dust grains. Therefore, we rely on the first (constant velocity) model for grains for which $\beta = 1$ is a good approximation. It was found that the constant-velocity model is a good approximation for the majority of the impacts detected by Ulysses and Galileo, because the Mie-calculations give a mean value of $\beta$ for all particles measured in-situ is $\beta = 1.02$, and for 90% of the detections $\beta$ deviates by less than 0.6 from unity \cite{Landgraf,1998}. But since we are interested in the large mass end of the distribution, where $\beta = 1$ is not a good approximation, we apply both methods to the datasets collected by Ulysses and Galileo, and compare the results.

For both models described above, we assume an initial velocity of 26 km s$^{-1}$ and an upstream direction of 259° heliocentric longitude and 8° heliocentric latitude. This initial velocity vector is: (a) compatible with the heliocentric speeds \cite{Grün et al.,1994} and direction of motion \cite{Baguhl et al.,1994} of the grains detected by Ulysses, (b) close to the asymptotic velocity vector of interstellar neutral Helium atoms detected by the Ulysses/GAS experiment \cite{Witte et al.,1993}, and (c) compatible with the relative velocity of the Sun with respect to the LIC \cite{Lallement and Bertin,1992}. We neglect the Lorentz-force exerted on the grains by interaction with the solar wind magnetic field \cite{Landgraf,1999}. This is a good approximation as long as the direction of motion is not strongly changed by the Lorentz-force, which is true for particles with masses larger than $10^{-17}$ kg, since their Larmor-radii are in the order of 500 AU \cite{Grün et al.,1994}, much larger than the length of their path through the domain of the solar wind.

4. Mass Distributions

We determine the grain mass distributions and their moments of the datasets described in section 3.
Figure 4. Histograms of the mass of the interstellar grains detected by Galileo (left panel) and Ulysses (right panel). The masses have been derived from the measured impact velocities.

Figure 5. Histograms of the mass of the interstellar grains detected by Galileo (left panel) and Ulysses (right panel). The masses have been derived from the straight-line ($\beta = 1$) model.
Figure 6. Histograms of the mass of the interstellar grains detected by Galileo (left panel) and Ulysses (right panel). The masses have been derived from the self consistent model of accelerated (decelerated) grains with $\beta < 1$ ($\beta > 1$).

The histograms of the distributions of grain masses that have been derived from the measured impact velocities are shown in figure 4 (compare Grün et al. [1993], Grün et al. [1995], Baguhl et al. [1996], Landgraf and Grün [1998]). The distributions cover a mass interval from $10^{-18}$ kg (which is the detection threshold of grains impacting with 20 km s$^{-1}$) to $10^{-12}$ kg and peak at $10^{-16}$ kg. From modeling the extinction of starlight [Mathis et al., 1977], the number of grains per mass interval is expected to increase steeply for smaller masses. In contradiction to this expectation, the in-situ measurements indicate a deficiency of grains in the lower mass region between $10^{-18}$ kg and $10^{-16}$ kg. This deficiency has been interpreted as being due to the electro-magnetic interaction of the grains with the solar wind magnetic field [Grün et al., 1994; Landgraf, 1999]. The upper limit of the grain mass range is determined by the limited size of the Ulysses and Galileo. Since large grains are much less abundant than small ones, no statistically significant number of particles with masses larger than $10^{-12}$ kg was detected. The distribution of masses determined by assuming a constant dust velocity of 26 km s$^{-1}$ and straight trajectories (first model described in section 3, $\beta = 1$) are shown in figure 4. Comparing these histograms with the distributions shown in figure 4, we find that the number of particles with small masses ($m < 10^{-16}$ kg) is increased and the number of particles with large masses ($m > 10^{-16}$ kg) is decreased when we derive the grain masses from the constant-velocity model instead from measured impact velocities. This is because the measured impact velocities of large grains are systematically lower than assumed impact velocity of interstellar particles at the location of the measurement. This can have two possible explanations: (a) The datasets contain unidentified interplanetary (bound) grains that impact the detector with a velocity lower than the assumed hyperbolic velocity, and (b) the measurements of velocities of fast and big grains deviate systematically from the true value to lower values. Such a systematic deviation can occur if recombinations take place in the plasma cloud that is generated by the impact, if the plasma density is high enough. In figure 6 we show the resulting histogram of masses derived from impact velocities that have been calculated taking into account the acceleration ($\beta < 1$) or deceleration ($\beta > 1$) of grains by the combined forces of solar gravity and radiation pressure. The resulting distribution is similar to the result obtained by neglecting the acceleration, but the number of grains with large masses is further reduced, because we used more realistically higher impact velocities (see equation (2)) were used to derive the grain mass.

As mentioned in the introduction and discussed in Frisch et al. [1999], the existence of interstellar grains with masses much larger than $10^{-16}$ kg is an important result of the in-situ dust measurements of Ulysses and Galileo. These large grains are not expected to contribute significantly to the total optical cross section of the interstellar dust population and can thus be difficult to observe. In the following we
Figure 7. Moments of the differential mass distribution of interstellar grains measured by Ulysses and Galileo in the Solar System. The panels show the number (left), cross section (middle), and mass (right) per logarithmic mass interval and unit volume.

calculate the contribution of grains of different masses to the concentration, cross section per unit volume, and total mass density of the interstellar dust population. Here we use the masses that we have derived from calculated impact velocities, taking into account acceleration by solar gravity and radiation pressure. To gain better statistics, we combine the Ulysses and Galileo measurements. Since both detectors had different exposure times to the interstellar upstream direction, we calculate number of impacts per logarithmic mass interval and unit volume for both datasets, and combine them by calculating the geometric average. The resulting differential number density mass distribution $n(m) \, d\log m$ is shown in the left panel of figure 7. The number density is dominated by grains with masses between $10^{-17}$ kg and $10^{-15}$ kg, as expected from the histograms of the Ulysses and Galileo data.

The cross-section-mass distribution is given by

$$
\sigma(m) \cdot n(m) \, d\log m = \pi a^2(m) n(m) \, d\log m \\
= \pi \left( \frac{3m}{4\pi \rho_d} \right)^2 n(m) \, d\log m.
$$

The resulting distribution of the combined Ulysses and Galileo data is shown in the middle panel of figure 7. In the in-situ data, the grain masses between $10^{-21}$ kg and $10^{-16}$ kg, that are believed to cause the extinction of starlight, do not contribute dominantly to the cross section. The reason is that their number is depleted in the Solar System by their interaction with the solar wind (see description of the histograms, figure 4). Therefore, Ulysses and Galileo did not detect abundantly the grains that cause the extinction of starlight.

The contribution of grains of different masses to the overall mass density of interstellar dust can be represented by the distribution of mass density per logarithmic mass interval $m \cdot n(m) \, d\log m$ (see right panel of figure 7). For the total mass density, the biggest particles measured become important. Calculating the total mass density from the Ulysses and Galileo in-situ data by integrating over the differential mass-density-mass distribution, we get the result $6.2 \cdot 10^{-24}$ kg m$^{-3}$.

From the value for the total mass density of in-situ detected dust grains we can extrapolate the gas-to-dust mass ratio in the LIC, which gives us information about the amount of refractory elements in the local interstellar environment. Adopting a Hydrogen density of $n_H = 3 \cdot 10^5$ m$^{-3}$ and a Helium density of $n_{He} = 3 \cdot 10^4$ m$^{-3}$ given by Frisch et al. [1999], and using the total mass density of interstellar grains detected by Ulysses and Galileo, the gas-to-dust mass ratio in the LIC is 113. This figure lies within the $1\sigma$-range of the value reported by Frisch et al. [1999] of $94^{+46}_{-38}$. As can be seen from the right panel in figure 7, the mass contribution of a given mass interval increases monotonically with mass. Therefore, the given total mass density is a lower estimate of the true value, because the upper mass limit of the integration is defined by the largest impact detected. Since the total number of large particles is low (left panel of figure 7), the upper limit of the mass integration de-
pends strongly on the sensitive area of the instrument and the accumulated time of measurements. To estimate the total mass density of grains in the LIC more realistically, we need information about the number of grains larger than the largest grain detected by Ulysses and Galileo. This data can be provided by the measurement of hyperbolic radar meteors described in section 5.

As described above, the mass we derive for big interstellar grains depends significantly on the impact velocity we assume. This effect can be seen in figures 8 and 9 that show the cumulative-flux-mass distribution of interstellar grains detected by Galileo and Ulysses, respectively.

For both datasets, the flux of large grains from the interstellar direction is overestimated when using the measured impact velocity to derive a mass. As mentioned above, this can be due to either misidentification of interplanetary grains or to systematic deviation of the measured impact velocity to lower values. Since the flux of large grains from the interstellar direction measured by Galileo is higher than the value derived from the Ulysses data, and Galileo operated in the ecliptic plane, where interplanetary grains on highly eccentric orbits could enter the detector from the retrograde direction, we conclude that the Galileo dataset contains a component of large interplanetary grains. Since a predominantly retrograde population of interplanetary grains is not believed to exist in the Solar System, and large impacts detected by Ulysses outside the ecliptic plane came from the retrograde direction (which coincides with the interstellar upstream direction), we conclude that the Ulysses dataset does not contain a significant contamination by an interplanetary component, and that the flux of interstellar grains of masses above \(10^{-14}\) kg is in the order of \(10^{-6}\) m\(^{-2}\) s\(^{-1}\).

Modeling of the interaction of small interstellar grains with the solar wind magnetic field [Landgraf, 1999] suggests that the mass distribution changes with time. One result of the modeling is that small grains (with radii of \(\approx 0.2\) μm) are depleted after mid 1996 because of the diverting configuration of the solar wind magnetic field. The analysis of the mass distribution of grains detected by Ulysses before and after April 1996 indicates such a depletion as shown in figure 10. The ratio of the number of particles with masses lower than \(10^{-16}\) kg to the number of particles with masses larger than \(10^{-16}\) kg was \(1.2 \pm 0.18\) before, and \(0.7 \pm 0.25\) after April 1996 when using calculated impact velocities to determine grain masses (when using measured impact velocities, the corresponding numbers are: \(0.88 \pm 0.14\) before, and \(0.66 \pm 0.24\) after April 1996). Unfortunately, the change in the ratio is not statistically significant and more data is needed to prove or disprove the suggested time dependence of the mass distribution.

5. Large Grain Masses and the Flux of Large Interstellar Dust Grains Detected as Radar Meteors

The existence of large (\(m > 10^{-15}\) kg) interstellar grains is a possible explanation for the observation that the grain population in the interstellar...
medium is replenished faster than by condensation in stellar outflows only [Jones et al., 1994]. It is argued [Grün and Landgraf, 1999] that large grains have long lifetimes in the interstellar medium and provide a source for smaller grains which can then be observed in extinction. Since the Ulysses and Galileo measurements provide limited statistics of the number of large grains, we compare detections of interstellar radar meteors with Ulysses and Galileo data to determine how and if the mass distribution of interstellar dust grains detected by the spacecraft can be extrapolated to higher masses.

Since the measurements by AMOR [Baggaley, 1999] allow the determination of the impact trajectory and velocity of meteoroids in the Earth’s atmosphere, hyperbolic meteoroids can be identified. It is then possible to determine the flux of large \( m > 3 \times 10^{-10} \) kg interstellar meteors for various source directions. It was found that the flux exhibits an ecliptic north-south asymmetry. The flux from the northern ecliptic hemisphere (including the upstream direction of grains detected by Ulysses and Galileo) was reported to be lower than \( 3 \times 10^{-10} \) m\(^{-2}\) s\(^{-1}\), whereas a flux of \( 1.8 \times 10^{-8} \) m\(^{-2}\) s\(^{-1}\) was reported from the southern ecliptic hemisphere. A discrete source direction of large interstellar grains could be identified for which a flux of \( 2 \times 10^{-9} \) m\(^{-2}\) s\(^{-1}\) was determined [Baggaley, 1999].

The comparison of the large-grain-flux derived from the radar measurements with the extrapolation of the Ulysses and Galileo results is shown in figure 11. We extrapolate the cumulative Ulysses and Galileo mass distribution by fitting a power-law function to the distribution of masses larger than \( 5 \times 10^{-16} \) kg, where the distribution is not affected by electromagnetic effects. The exponent of the resulting fit function is \(-1.1 \pm 0.1\). From the extrapolation of the Ulysses and Galileo mass distribution, we expect a flux of less than \( 10^{-10} \) m\(^{-2}\) s\(^{-1}\) for grains with masses larger than \( 3 \times 10^{-10} \) kg. This is compatible with the upper limit given for interstellar radar meteors coming from the same direction as the Ulysses and Galileo particles. The flux of interstellar radar meteors from the southern ecliptic hemisphere as well as from the discrete source is one or two orders of magnitude larger than the value expected from the extrapolation of the Ulysses and Galileo measurements.

6. Conclusion

We have derived a mass distribution of interstellar grains from the in-situ data gathered by the Ulysses and Galileo dust detectors using the assumption that interstellar grains impact the detectors with velocities that are given by their initial velocity of 26 km s\(^{-1}\) at large heliocentric distances, the acceleration by solar gravity and radiation pressure, and the motion of the spacecraft. As a result we find that the number of large particles decreases and the number of intermediate-size particles increases when deriving masses from calculated instead of measured impact velocities. However, we find that the values derived for

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**Figure 10.** Histograms (relative abundance) of the mass of interstellar grains detected by Ulysses before (left) and after (right) April 1996. The masses have been derived from the self consistent model of accelerated (decelerated) grains with \( \beta < 1 \) \( (\beta > 1) \). The later mass distribution contains less small \( (m < 10^{-16} \text{ kg}) \) grains.
total mass density and the gas-to-dust mass ratio in the LIC do not change significantly from the values reported by Frisch et al. [1999].

In the Ulysses data we find an indication that the mass distribution of interstellar grains is time-variable, as predicted by model calculations [Landgraf, 1999]. Long-term measurements are needed to assess the significance of this variability.

Grün and Landgraf [1999] suggest that the interstellar mass distribution in the LIC consists of two parts: Grain masses below $10^{-16}$ kg are distributed approximately like the dust component that causes extinction in the diffuse interstellar medium [Mathis et al., 1977]. At $10^{-16}$ kg a transition to a steeper mass distribution is suggested such that the large grain component still contains a significant amount of mass, but the contribution of each mass decade does not increase further for increasing grain mass. We determine the slope of the logarithmic cumulative in-situ flux-mass distribution to be $-1.1$. This figure is close to the slope of $-1.0$, for which each mass decade contributes the same amount to the total mass. Unfortunately, the shape of the measured mass distribution below $10^{-16}$ kg is strongly affected by heliospheric filtration [Landgraf, 1999] and can therefore not be compared directly to the expected mass distribution. In summary we find that the in-situ measurements support the interpretation of an extended mass distribution as described by Grün and Landgraf [1999].

Radar data collected by the AMOR facility in New Zealand indicates that there is a large reservoir of mass in big interstellar grains in the solar vicinity. Because these large grains couple to the gas phase of the interstellar medium on length scales much larger than the size of the LIC [Morfill and Grün, 1979], these big grains are not believed to be related to the grain population detected by Ulysses and Galileo, which enters the Solar System from the same direction as Helium atoms that originate from the gas phase of the LIC. The radar measurements indicate that the majority of radar meteors arrives from the southern ecliptic hemisphere. If they were accompanied by a large number of smaller grains, Ulysses and Galileo would have detected them, which is not the case. Since collisional evolution of large dust grains into smaller ones is believed to be an effective process in the diffuse interstellar medium [Jones et al., 1996], one can speculate that the grains detected by AMOR have been accompanied by smaller grains, but the small grains have been stopped on its way to the Solar System by an interstellar cloud.

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