

Dust in Interplanetary Space and in the Local Galactic Environment

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Abstract.

The solar system is a natural laboratory, accessible by a variety of methods, for studying the astrophysics of dust. Astronomical measurements mostly at visible and infrared wavelengths, yield the large-scale distribution of dust and its average composition. Examining natural surfaces deployed to the space environment, and assessing those surfaces' micro-crater distributions, reveals the size distribution of dust. Meteor observations and their corresponding measurements provide orbital information of dust grains and their genetic interrelation to the larger bodies in our solar system: comets and asteroids. From analyses of meteorites and interplanetary dust particles collected in the stratosphere, we have a comprehensive understanding of the isotopic, elemental, and mineralogical composition of this primordial material. Finally, in situ dust analysis via dust detectors located in interplanetary space, the most versatile

method, have been providing data to determine the dust particles' mass, speed, trajectory, and chemical composition.

An assortment of dust exhibiting a variety of dynamical processes has been identified in interplanetary space. In Jupiter's proximity, intense streams have been observed of nanometer-sized ash particles, which are emitted from the volcanoes of Jupiter's moon Io. These particles are accelerated by the powerful Jovian magnetic field to speeds of several 100 km/s, and are propelled further into interplanetary and interstellar space by the solar wind magnetic field. In interplanetary space, concentrations of collisional debris in the asteroid belt have been identified by infrared observations. The Poynting-Robertson effect drags these particles in towards the Earth and the Sun, where they sublimate. If the giant planets did not block their inward drift, a similar fate is expected for the dust assortment that is generated by collisions in the Kuiper belt. Another dust population is the mostly sub-micron-sized dust from comets, released while the comets traverse the inner parts of our solar system. These comet particles are shed from the comet's coma and consequently, quickly driven out of the solar system by radiation pressure forces. Larger particles form trails along the orbit of the parent comet, which result in a meteor storm as the Earth crosses the trail. Furthermore, the dust of comet trails can disperse via planetary perturbations into the background zodiacal cloud. Last, but not least, an important dust population identified by in situ dust instruments is the micron-sized interstellar grains flowing through the planetary system with the interstellar gas flow being part of the local interstellar cloud. This cloud is at the edge of the local bubble of hot tenuous gas which was excavated by supernova explosions in the near-by Scorpius-Centaurus and Orion Associations.

These dust populations are the target of future dust observatory missions in space. Such a dust observatory satellite carries a dust telescope, which is a combination of a dust trajectory sensor together with an analyzer for the particles' chemical composition. With accurate dust trajectory measurements, we can identify its place of origin: for example, comets, asteroids, or interstellar space. From the particles' bulk properties and their chemical composition, we can infer properties of the environments out of which the particles were formed, and in which they were subsequently altered.

1. Introduction

Interplanetary dust is sometimes considered a nuisance to modern astronomical observations because the zodiacal dust cloud obscures and covers more distant and fainter objects, especially at infrared wavelengths from 5 to 50 μm . In its favor, the zodiacal dust cloud is the dust cloud closest to us and most accessible to a wide range of observations. Studies of our zodiacal cloud have led to a greater understanding of solar system dust phenomena, and this understanding further acts as a model for dusty phenomena elsewhere.

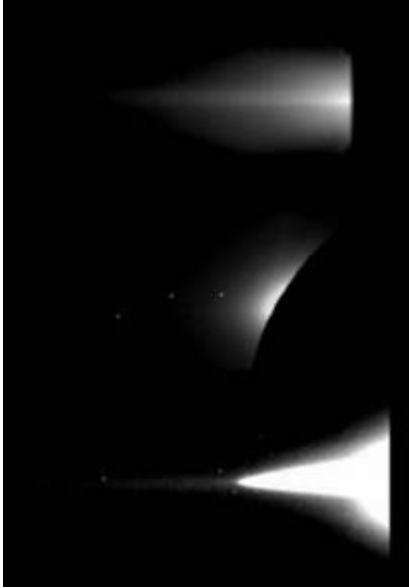


Figure 1. Dust disks. Top: Edge-on view of the dust disk around the star Beta Pictoris (HST image, radial extent of the disk ca. 1000 AU). This disk is a model for the suspected Kuiper belt dust ring of our solar system. Middle: Inner zodiacal dust cloud, partially obscured by the moon. The planets shown are Mercury, Mars, and Saturn (NASA Clementine image, ca. 3 AU radial extent). Bottom: Jupiter dust ring. Outside the bright central ring there is the faint gossamer ring that derives from the Jovian satellites Amalthea and Thebe (NASA Galileo image, ca. 0.03 AU radial extent).

A hierarchy of dust disks exists in the solar system, some directly observable and some that are suspected on the basis of circumstantial evidence. Outside of Neptune's orbit, more than six hundred bodies, which have diameters larger than 100 km, out of an estimated 70,000 objects, have been identified in the Edgeworth Kuiper belt. Mutual collisions among these and, probably more numerous smaller bodies, plus erosion by interstellar grains, generate dust at a rate between 0.3 (Yamamoto & Mukai, 1998) and 50 tons per second (Landgraf et al., 2002), resulting in the outer Kuiper dust disk. This disk, which is about one thousand times more tenuous in number density than the β Pictoris dust disk (Fig. 1a), has not yet been identified by optical or infrared methods. However, in situ instruments on board the Pioneer 10 (Humes, 1980) and Voyager (Gurnett et al., 1997) spacecraft recorded hints of the Kuiper disk (Landgraf et al., 2002).

In the region of the asteroid belt, the zodiacal cloud is accessible to both optical and infrared observations, as well as to in situ measurements, which provide information on both its structure and its dynamics. Collection of meteorites and dust from deep-sea sediments, polar ice and the stratosphere provides dust grains with which we can study the chemical, isotopic, and mineralogical composition of interplanetary and interstellar matter.

All giant planets have extended satellite systems and genetically linked dust disks. Dust is generated on satellites by impacts of interplanetary projectiles (Krüger et al. 1999) and consequently, form dust rings. Early spacecraft missions (Pioneer 10 and 11 and Voyagers 1 and 2) provided a cursory look at the miniature planetary systems around the outer giant planets. Follow-up missions (Galileo and Cassini) have allowed us to study the detailed interactions between the dust and its environment over long time scales.

The populations of dust in our solar system each have sources, sinks and consequently limited lifetimes. The evolution of the particles are determined

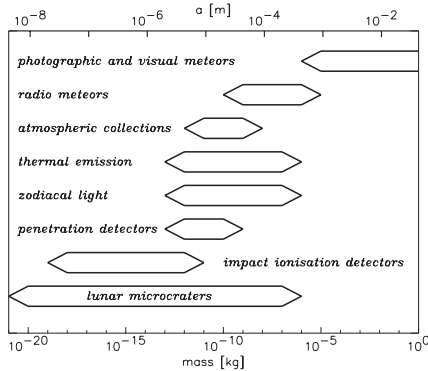


Figure 2. Methods for dust detection and analysis in interplanetary space, distinguished by the size or mass range of particles that can be studied.

by mutual collisions and the dominant forces: gravity, radiation pressure, and electromagnetism, with data from the radiation, fields and particle environments providing supporting information.

This paper is organized as follows. In Sect. 2., we discuss observational methods for obtaining interplanetary dust measurements in a variety of locations. In Sect. 3., we present a modern picture of our understanding of the zodiacal dust cloud, and in Sect. 4., we describe an exotic type of tiny dust grain, that is ejected by Jupiter's strong magnetic field into interplanetary space. In Sect. 5., we describe recent findings about interstellar grains passing through our planetary system. The current knowledge about dust in our galactic environment is described in Sect. 6., and finally, we discuss some future observations which open a new window on interplanetary and interstellar dust.

2. Observation Methods

We have a number of different methods available to study interplanetary dust (Fig. 2). The earliest methods were ground-based optical zodiacal light observations. One goal of zodiacal dust cloud measurements is to learn about its large-scale spatial distribution. However, from the vantage point of the Earth one cannot derive uniquely the spatial density of the dust cloud because the angular scattering function and the spatial density distribution are convolved together in the brightness integral over the line of sight. Spacecraft moving radially through the zodiacal cloud are less encumbered because observations at a constant elongation angle will reflect directly the radial spatial density distribution, assuming that the angular scattering function does not change with heliocentric distance. Photometers carried on the early Helios and Pioneer (10 and 11) spacecraft measured light intensities at different solar distances. The converted densities disclosed a radial dependence, which was slightly steeper than the inverse distance dependence. The measurements suggested that the visible zodiacal dust cloud is lens-shaped with an axial ratio of about 1:7, and that it extends out to about 3 AU (Leinert and Grün, 1990).

Other factors affecting the light-scattering function are the dust particles' morphological shape and composition. Consequently, the observed zodiacal

brightness is a mean value, averaged over all dust particle sizes, compositions and shapes, along the line-of-sight. Fortunately, interpretation of thermal infrared observations of the zodiacal cloud does not have the ambiguity of the material-dependent scattering function but, instead, relies only on the radial temperature profile, which can be determined from the spectral energy distribution (e.g. Leinert et al., 2002).

The size distribution of interplanetary dust particles is expressed through the lunar microcrater record. The distribution of microcraters on lunar rocks ranges from 20 nm to millimeters in diameter (Grün et al., 1985). Laboratory simulations of high velocity impacts corresponding to the above particle sizes on lunar-like materials have been performed in order to calibrate crater sizes with projectile sizes and impact speeds.

From the meteoroid size distribution, it is possible to determine which particles are most effective in forward-scattering the sunlight that produces the zodiacal light. It has been found that the main contribution comes from particles which increase in concentration towards the ecliptic plane, ranging from 10 to 100 μm in radius. For this reason, the dust manifested by the zodiacal light must be considered as only a subset of the full interplanetary dust cloud. The total mass of the zodiacal cloud inside the Earth's orbit corresponds to the mass of a single object (comet or asteroid) of about 20 km in diameter.

Visible meteors appear in our sky when cm-sized meteoroids enter the Earth's atmosphere at a speed larger than 10 km/s. Here, a luminous train of several km in length caused by ionized atmospheric gas follows the meteoroid. Furthermore, the train of ionized gas scatters radar signals, inviting dust measurements at other than optical wavelengths. A typical incident meteoroid may start to ablate at about 115 km above the Earth's surface, and then evaporating completely after falling further to approximately 85 km in height (Ceplecha et al., 1998). Geometrical triangulation of the meteor train by ground stations (consisting of several cameras or radar stations) provides highly-accurate pre-atmospheric orbits for those meteoroids.

After reaching the Earth's surface, objects of mass larger than about ten kilograms, denoted meteorites, provide a direct source of information about extraterrestrial material. Bigger objects than this, however, (even meter-sized meteoroids) may not reach the Earth's surface, hinting at the paucity of, and probably biased sampling of meteorites in our collections. For example, the Tunguska event of 1908 was triggered by an object of mass several ten thousand tons, which disintegrated about 10 km above the ground in Siberia.

There is another "window" in addition to the "meteorite-window", through which extraterrestrial material reaches the Earth's surface in a more-or-less undisturbed state. Small interplanetary dust particles of a few to 50 μm in diameter are decelerated with little friction in the tenuous atmosphere above 100 km in height. Such particles experience very little heating and float through the atmosphere to become accessible to collection and scientific examination (cf. review by Hoppe, this volume).

As a complement to ground-based and astronomical dust observations, we have in situ measurements by dust impact detectors on interplanetary spacecraft. Two types of impact detectors have been mainly used for interplanetary dust studies: penetration detectors, where the micrometeoroid must penetrate



Figure 3. Cosmic Dust Analyzer on Cassini. The detector has a sensitive area of 0.1 m^2 and is based on the impact ionization effect: A dust particle which enters the detector and hit the gold target at speed above 1 km/s will produce an impact crater and free electrons and ions are generated. These ions and electrons are separated in an electric field within the detector and collected by electrodes. The strength and the wave form of the signal are measures of the mass and speed of the impacting particle. A combination of an impact ionization detector with a mass spectrometer gives the chemical composition of the produced ions.

25 to $50 \text{ }\mu\text{m}$ thick metal films, with detection thresholds of 10^{-9} g , and impact ionization detectors, which detect the charge released upon impact with thresholds of 10^{-16} g for a typical impact speed of 20 km/s . With these detection methods, micrometeoroids have been identified in interplanetary space at distances from 0.3 AU to 18 AU from the Sun.

Fig. 3 shows a photograph of the Cosmic Dust Analyzer (Srama et al., 2003) which is a detector of the impact ionization type, presently carried on the Cassini spacecraft. This detector measures the mass, speed, flight direction, electrical charge, and composition of individual dust particles. To calibrate space dust detectors, electrostatic dust accelerators (ground-based) provide micron and submicron-sized projectiles at impact speeds of up to about 100 km/s .

3. The Zodiacal Dust

During the formation of our planetary system, 4.6 billion years ago, the dust particles were immersed in the gas disk around the Sun that dampened their relative velocities and allowed for agglomeration. The planetary embryos were formed, most of which merged further into the major planets, with the rest being left undeveloped as the minor bodies — comets and asteroids. In the planets, the pristine materials were altered by chemical reactions launched from their depths by the high pressure due to self-gravity, and on their surfaces due to their atmospheres and the solar radiation. Minor bodies ($< 100 \text{ km}$ radius) are believed to preserve the composition of the early Solar system largely unmodified.

Since then, in the absence of gas, the destruction processes gained dominance over the agglomeration processes, and the pristine materials were spawned

from the minor bodies. Comets yield gas and dust as they approach the Sun. Asteroids that are whittled down when smaller objects collide with them, subsequently release surface material, including dust particles.

Of the minor bodies, comets are the most obvious sources of dust in our present-day solar system. Dusty tails of particularly bright comets can sometimes be observed with the naked eye (e.g. comet Hale-Bopp). Millimeter-sized and larger ejecta particles are distributed via velocity dispersions along the parent body's orbits. The distribution of semi-major axes of the ejecta particles leads to differences in the orbital periods and mean anomalies. ISO observations of comet 2P/Encke have provided evidence that the millimeter and larger-sized cometary particles span large spatial regions along the comet's orbit, forming cometary trails (Reach et al. 2000). If the Earth crosses such a trail, large dust grains, with sizes up to one centimeter, generate spectacular meteor storms, e.g. the Leonid meteor storm of debris from comet 55P/Tempel-Tuttle. The dust densities in the Leonid stream near its maximum are sufficient to be observed in space with modern optical instruments (Nakamura et al. 2000).

In addition to cometary dust, a significant fraction of meteors and dust grains in the zodiacal cloud must have been produced in the asteroid belt. The abundance of asteroids suggests that dust may be produced by mutual collisions and by impacts of interplanetary meteoroids. This idea is well-supported by IRAS infrared observations of dust corresponding to asteroids of several prominent families (Sykes 1990). Infrared images display a nested set of broad, diffuse bands which extend from the region occupied by the asteroid families.

Although missions to these objects are exciting, a pickup of the material from comets, asteroids and probably from Kuiper belt objects is possible with a bit of improvisation nearly everywhere in the solar system (cf. Sect. 7.). Meteoroids and dust released from these bodies experience a number of perturbations which affect their subsequent dynamics and orbital trajectories. Distant planetary perturbations and orbital resonances with the planets randomize the longitudes of nodes and perihelia of the particle orbits. Strong perturbing forces from the close encounters with planets modify all of the elements, including the semimajor axis a , eccentricity e and inclination i (see e.g. Cremonese et al. 1997). In particular, most of the comets cross or approach the orbit of Jupiter, so do the dust particles emitted by them. The particles encounter Jupiter frequently and the gravity of the giant planet sends the particle into another orbit. Only Tisserand parameter $T = 1/a + 2\sqrt{a(1-e^2)}\cos i$, is preserved intact, and the phase volume is constant along the trajectory. After several encounters, the meteoroid stream is spread into a wide distribution (Dikarev & Grün 2002)

$$f(a, e, i) \propto N(a, e, i) n_6(T) \sqrt{ae} \sin i. \quad (1)$$

Here $n_6(T)$ is the phase density of particles in Cartesian variables, which is constant along the trajectory specified by $T = \text{const}$ (the other orbital parameters are mixed), and $N(a, e, i)$ is the integral of the indicator function of the torus crossing by the orbit over all orbit orientations.

The solar radiation pressure force includes a component called the Poynting-Robertson effect, which pulls the dust toward the Sun (Wyatt & Whipple 1950). Inside of the region of encounters with Jupiter, however, larger effects dominate the particle orbits. The Poynting-Robertson drag only weakly disturbs the Tisserand parameter because the radiation pressure strength is small with respect

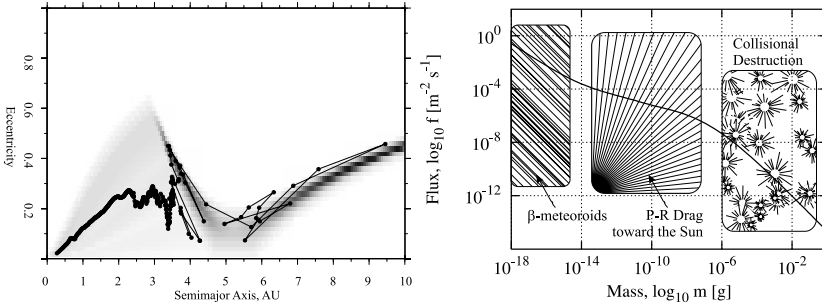


Figure 4. Left: the orbital distributions of dust grains ejected by comets of Jupiter family and having the Tisserand parameter $T = 2.96$ (encounter speed with Jupiter $U = 0.2$ Jovian orbital speeds). A numerically simulated trajectory is overplotted. Right: the mass distribution of interplanetary dust at 1 AU with the dynamical regimes labelled.

to the effect of the close encounters on the micrometer and larger-sized particles. Consequently, the small dust grains follow the routes of the larger particles in the encounter region, yet their trajectories leak through the encounter region's inner boundary where they form a distribution of Gor'kavyy et al. (1997). The combined distributions are shown in Fig. 4 (left) along with a numerically simulated trajectory through the orbital space.

Meteoroids with a sufficient cross-sectional area are likely to collide with another meteoroid or a smaller dust grain and fragment. These mutual collisions control the mass distribution of the particles. If one assumes the dust production rate in the form of a power law $n^+(m)dm \propto m^{-\delta}dm$, then laboratory experiments have shown the slope δ is near $-5/3$ (Ishimoto 2000). The collision rate is roughly proportional to the meteoroid cross-sectional area, i.e., $\lambda_c^- \propto m^{2/3}$. Their ratio $n^+/\lambda_c^- \propto m^{-7/3}$ gives the equilibrium mass distribution of the meteoroids.

Wherever dominant, e.g. outside the encounter region, the Poynting-Robertson drag forces the particles to spiral in toward the Sun at a rate $\lambda_{pr}^- \propto m^{-1/3}$. When this rate is above the collision rate, i.e. for particles sizes less than $\approx 100 \mu\text{m}$, the equilibrium mass distribution is given by $n^+/\lambda_{pr}^- \propto m^{-4/3}$ (Fig. 4, right).

Some of the meteoroid collision fragments are small enough that Solar gravity is counterbalanced by Solar radiation pressure. The unusually weak combined force plus the rapid motion inherited from the parent meteoroids makes the orbits of the fragments (called β -meteoroids) hyperbolic. They leave the solar system swiftly. The mass distribution of these small particles is close to that of the collisional ejecta n^+ since their short lifetimes are not influenced by their cross-section area nor by the size-dependent strength of the Poynting-Robertson effect. In addition, close encounters with planets can modify the orbit of a me-

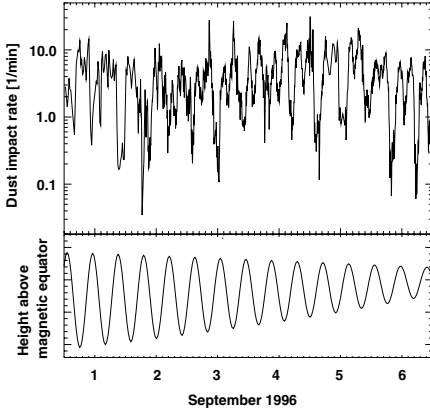


Figure 5. Phase relation between Galileo's position in Jupiter's magnetic field (here Galileo's distance from the magnetic equatorial plane, Z) and observed impact rate during part of Galileo's G2 orbit about Jupiter in 1996. A dipole tilted at 9.6° with respect to Jupiter's rotation axis pointing toward $\lambda_{\text{III}} = 202^\circ$ has been adopted for the magnetic field. From (Grün et al. 1998).

teoroid or a dust grain into a hyperbolic orbit, sending the information on the composition of the Solar system into interstellar space.

4. Jovian Dust Streams: Electromagnetically Interacting Dust

In 1992, when the *Ulysses* spacecraft flew by Jupiter, the dust detector instrument on board recorded several periodic bursts of submicrometer dust particle impacts with durations ranging from several hours to two days and occurring at approximately monthly intervals (28 ± 3 days, Grün et al. (1993)). The dust streams were observed within 2 AU from Jupiter, and the particles arrived at *Ulysses* in collimated streams radiating from close to the line of sight to Jupiter, suggesting a jovian origin. The Galileo dust detector, which is identical with *Ulysses*' dust instrument, confirmed the dust streams and has continuously observed them in the jovian system since December 1995 (Grün et al. 1996, 1998; Krüger et al. 2003b).

From the Galileo dust measurements, strong electromagnetic interaction of the charged dust grains within the jovian magnetosphere became evident. Figure 5 shows an example of impact rates measured while Galileo was in the inner part of the magnetosphere. During this time, the rate fluctuated with 5 and 10 hr periods and the fluctuations reached up to two orders of magnitude. These fluctuations are correlated with the position of Galileo in the jovian magnetic field (lower panel in Fig. 5). Due to a 9.6° tilt of Jupiter's magnetic axis with respect to the planet's rotation axis, the magnetic equator sweeps over the spacecraft in an either up- or downward direction every 5 hr, shaping the fluctuations in the measured impact parameters. With the Galileo dust detector, the electromagnetic interaction of charged dust particles with a planetary magnetosphere could be demonstrated for the first time.

Immediately after the dust streams were seen originating from within the jovian system, the source of those particles became the leading question. Even though indirect support for an Io source via detailed modeling existed, direct support of an Io source remained elusive until a frequency analysis of Galileo dust data collected within Jupiter's magnetosphere (Fig. 6) showed several char-

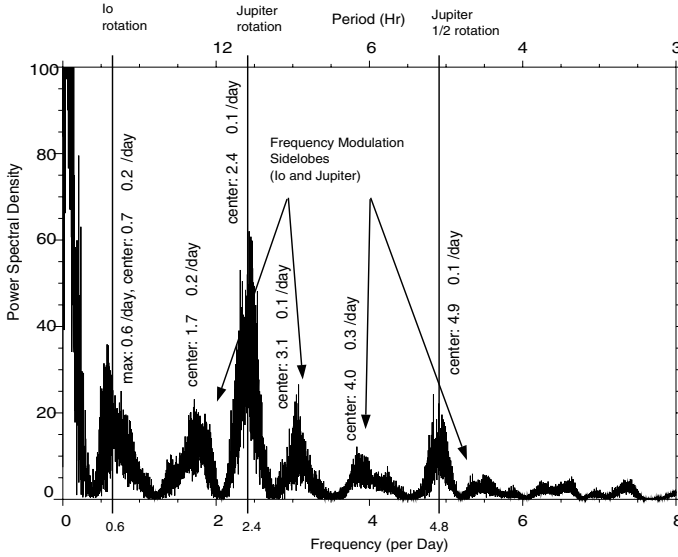


Figure 6. A Scargle-Lomb periodogram for two years of Galileo dust data (1996 and 1997). A carrier source (Io) is modulated by Jupiter’s magnetic field frequency which leads to “modulation product” peaks at 13.9 and 7.7 h. There are additional frequencies: a half period of Jupiter’s magnetic field (4.9 h), Io as a single source (41.9 h), and a low-frequency oscillation trend due to the spacecraft orbital geometry. From (Graps et al. 2000)

acteristic signatures. The impact rate transformed into frequency space showed the frequency of Io’s orbital period (~ 42 hr), illustrating that Io can act as a point source for the dust streams, and amplitude modulations of Io’s orbital period and Jupiter’s rotation period confirmed the connection between the Io dust and Jupiter’s magnetic field (Graps et al. 2000). The origin of the dust from Io is thought to be condensation in the expanding volcanic plumes on Io.

Dust stream speeds derived from the *Ulysses* measurements are greater than 200 km s^{-1} and particle radii derived in the same study are about 10 nm (Zook et al. 1996). The high dust stream speeds are due to their acceleration by Jupiter’s corotating electric field (Horányi et al. 1993). Charging processes are important and Lorentz forces dominate for these tiny particles. After the grains are released from Io, they eventually acquire a positive charge of $\approx +5 \text{ V}$ in Io’s plasma torus. The charging mechanism most influential is secondary electron emission in the hot plasma torus. Modeling has provided information of the range of particles that can escape from that location in Jupiter’s magnetosphere. Dust stream particles with radii approximately 9 to 180 nm can be ejected from the jovian system (Grün et al. 1998), but not smaller and larger grains. Smaller

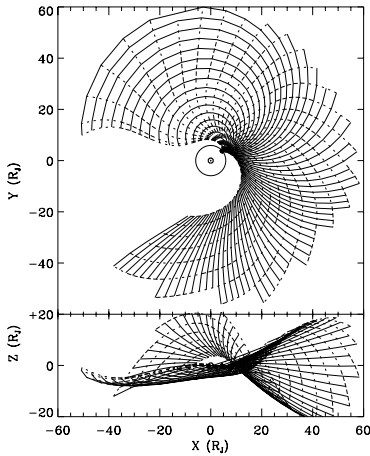


Figure 7. Jupiter’s “dusty ballerina skirt” formed by Jupiter stream particles moving away from the planet in a warped dust sheet. Jupiter is in the center and the particles are released from a point source at Io’s distance (Io’s orbit is shown as a circle). The dust sheet is defined by synchrotrons (solid lines, positions of dust particles released at the same time) and syndynes (dashed lines, positions of dust particles which have the same charge-to-mass ratio, q/m). Particle trajectories have been followed only out to $50 R_J$ which causes the ragged outer edge of the dust sheet. In steady state the dust sheet extends to much larger distances. The configuration of the dust sheet depends strongly on the phase of the magnetic field. From (Grün et al. 1998).

grains remain tied to the jovian magnetic field while larger grains move on gravitationally bound orbits.

To a first order approximation, particles which are released from a source close to Jupiter’s equatorial plane (e.g. Io or the gossamer ring), are accelerated along this same plane. The 9.6° tilt of Jupiter’s magnetic field w.r.t. the planet’s rotation axis, however, causes the particles to experience a significant out-of-plane component of the Lorentz acceleration. The result is that particles continuously released from Io move away from Jupiter in a warped dust sheet which we sometimes call “Jupiter’s dusty ballerina skirt” (Horányi et al. 1993), illustrated in Fig. 7. Particles are separated according to their charge-to-mass ratio (corresponding to their size) and the time of generation.

One additional facet of the Galileo dust streams measurements since 1996 is that they can act as a monitor of Io’s volcanic activity. About 10 g s^{-1} to 10 kg s^{-1} of dust are continuously released from Io. This is less than 1% of the total plasma mass ejected from Io into the torus. Large area surface changes due to volcanic eruptions on Io detected on Galileo images (Geissler et al. 2003) occurred during time intervals when strong dust emission was detected with the Galileo dust instrument (Krüger et al. 2003a).

As a dust source, Io can now be considered as a minor source of interplanetary dust. Io’s dust is a trivial source, however, compared to the dust generated from comets or main belt asteroids (Whipple 1987).

5. Interstellar Dust

After its fly-by of Jupiter, the dust detector on board the Ulysses spacecraft, which has a highly inclined orbit with respect to the ecliptic plane, detected impacts predominantly from a direction that was opposite from the expected impact direction of interplanetary dust grains. Interplanetary dust usually travels on low-inclination and low-eccentricity orbits. It was found that, on average, the impact velocities exceeded the local solar system escape velocity, even if radiation pressure effects were neglected (Grün et al. 1994a). Subsequent analysis showed that the motion of the interstellar grains through the solar system was parallel to the flow of neutral interstellar hydrogen and helium gas, both traveling with a speed of 26 km/s. The interstellar dust flow persisted at higher latitudes above the ecliptic plane, even over the poles of the Sun, whereas interplanetary dust was strongly depleted away from the ecliptic plane.

Measurements in the ecliptic plane by Galileo confirmed that, outside about 3 AU, the interstellar dust flux exceeds the flux of micron-sized interplanetary grains. Recent work by Altobelli, et al. (2003) further demonstrates the ubiquity of interstellar dust in the solar system. Both Cassini and Galileo dust detectors have recorded interstellar grains at distances as close as 0.7 AU from the Sun. These interstellar grains observed by the spacecraft detectors range from 10^{-18} kg to above 10^{-13} kg. If the mass distribution of these interstellar dust particles measured in situ is compared with the interstellar dust mass distribution derived with astronomical techniques, we find that the in situ mass distribution overlaps only with the largest masses as observed by remote sensing. Newer measurements of interstellar dust, those measurements sensitive to larger (10^{-10} kg) particle masses, and identified by their hyperbolic speeds, have recently added to our knowledge (Baggaley, 2000, Meisel et al., 2002). The flow direction of these larger particles varies over a much wider angular range than that of small grains observed by Ulysses and Galileo.

Since Ulysses left the ecliptic plane in February 1992, it has monitored the stream of interstellar dust grains through the solar system at higher latitudes. Results from the last decade of study have shown that the solar wind filtration causes a deficiency of detected interstellar grains with sizes below $0.2 \mu\text{m}$ (Grün et al. 1994). An additional filtration by solar radiation pressure, that deflects grains with sizes of $0.4 \mu\text{m}$, was found to be effective at solar distances below 4 AU (Landgraf et al. 1999a). In addition to studies of the distribution of grain masses, the instrument monitors the flux density of the interstellar dust particles. In mid 1996, a decrease of the interstellar dust flux density from initially $1.5 \times 10^{-4} \text{ m}^{-2} \text{ s}^{-1}$ to $0.5 \times 10^{-4} \text{ m}^{-2} \text{ s}^{-1}$ was observed (Landgraf et al. (1999b), see figure 8), that was attributed to the increased filtering of small grains by the solar wind magnetic field during solar minimum conditions (Landgraf 2000; Landgraf et al. 2000). Since early 2000, Ulysses has detected interstellar dust flux levels above $10^{-4} \text{ m}^{-2} \text{ s}^{-1}$ again.

According to a Monte-Carlo simulation of the grain dynamics in the heliosphere (Landgraf et al. 2003), the dominant contribution comes from grains which, in the simulation, have radii of $0.3 \mu\text{m}$ with a minor contribution from grains with radii of $0.4 \mu\text{m}$ (see figure 8). We cannot, however, conclude that the interstellar dust stream is dominated by *spherical* grains with an effective radius of $0.3 \mu\text{m}$. Our analysis merely shows that the typical grain in the in-

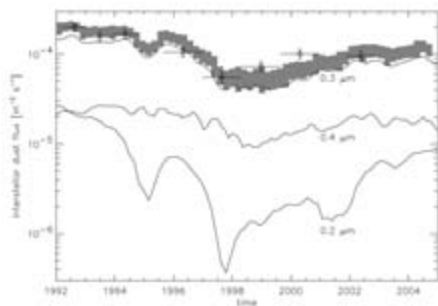


Figure 8. Fit of simulated to measured flux. The fit parameters are the relative contributions of grains of sizes between 0.1 and 0.4 μm (the 0.1 μm curve is not shown, because it did not contribute to the fit). The solid lines show the flux profiles of the simulated grains of various sizes, scaled with their best-fit relative contributions. The shaded region indicates the best-fit total predicted flux, with its vertical extent giving the 1σ uncertainty.

terstellar dust stream has a charge to mass ratio of $q/m = 0.59 \text{ C kg}^{-1}$ and a radiation pressure efficiency of $\beta = 1.1$. The observations that we are able to fit the flux variation assuming a constant dust concentration in the Local Interstellar Cloud (LIC) leads us to conclude that the dust phase of the LIC is homogeneously distributed over length scales of 50 AU, which is the distance inside the LIC travelled by the Sun between end-1992 and end-2002, the period when the data was taken. Given the best-fit flux profile shown in figure 8, we predict that the flux of interstellar dust will level-off at a constant value just above $1 \times 10^{-4} \text{ m}^{-2} \text{ s}^{-1}$ until the end of 2004.

6. Dust in our Galactic Environment

The galactic environment of our own star on a larger scale is shown in Fig. 9. The Local Interstellar Cloud, LIC, is located at the edge of the local bubble which was excavated by supernova explosions in the neighboring star-forming regions of the Scorpius-Centaurus and Orion Associations. The nearby interstellar medium (within 3 pc of the Sun) is dominated by a shell of material, the LIC. What do we know from astronomical observations about the Local Interstellar Cloud? Observations of interstellar material (ISM) towards nearby stars and inside of the solar system, combined with radiative transfer models, give a self-consistent description of the Local Interstellar Cloud (LIC) around the Sun (Frisch 1998, 1999; Frisch & Slavin 2003). The main characteristics of the LIC are: atomic neutral hydrogen density $n(\text{H}^0) \sim 0.20 \text{ cm}^{-3}$, electron and ion density $n(e^-) \sim 0.10 \text{ cm}^{-3}$, temperature $\sim 6300 \text{ K}$, and a relative Sun-cloud velocity $\sim 26.3 \text{ km s}^{-1}$. The physical conditions in the LIC are those of the intercloud medium — warm, low density, partially ionized gas. The enhancement of refractory elements (such as Fe, Mg, Mn) in LIC gas, compared to cool interstellar clouds, points to the destruction of interstellar dust grains by interstellar shocks (velocity 100 to 200 km s^{-1}) (Frisch et al. 1999). Such shocks would reduce the heliosphere dimensions by a factor ~ 10 (Frisch 1999), and increase the penetration of interstellar dust grains to 1 AU. When the LIC gas mass (in-

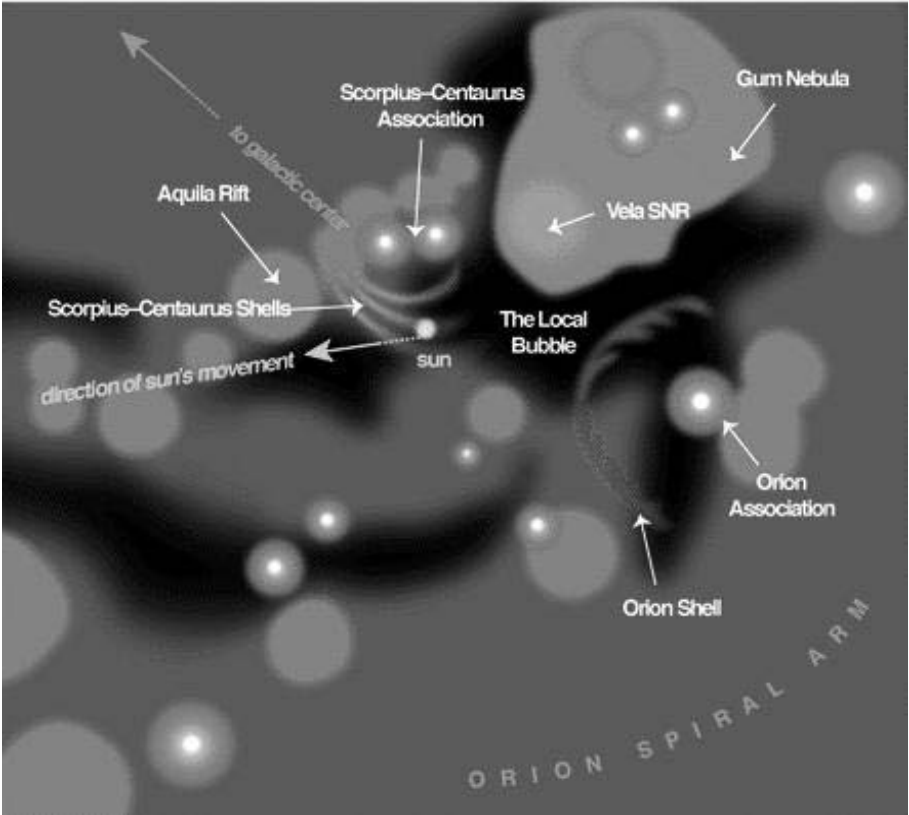


Figure 9. The galactic environment of the Sun. Top: The surroundings within 500 pc of the Sun contain gas clouds of various densities and temperatures (cold dense molecular clouds: light gray; star forming regions: shaded light gray circles). The Sun has been passing through a hot, very low-density region, the Local Bubble (black), for several million years, and it is now embedded in a shell of warm, partly ionized material (light gray) flowing from the Scorpius-Centaurus star-forming region.

cluding He) is compared to the interstellar dust mass observed by Ulysses and Galileo (Landgraf 2000), the limit $R_{g/d} < 120$ is found for the LIC gas-to-dust mass ratio at the Sun, since the smallest grains are prevented from entering the solar system.

The ISM within 10 pc of the Sun is highly inhomogeneous. Most of the mass of the nearby ISM is located in the galactic center hemisphere, where a cluster of cloudlets is seen flowing past the Sun at $\sim 28 \text{ km s}^{-1}$ from an upstream direction towards the Scorpius-Centaurus Association and six degrees from the galactic center (after converting to the Local Standard of Rest, Frisch et al. 2002). At least 5 distinct cloudlets are found within 5 pc of the Sun, with differing compositions and physical properties. Temperatures range from 5,400 K (towards α Cen) to 10,000 K (Blue Cloud towards ϵ CMa) and total densities from $>0.04 \text{ cm}^{-3}$ (Blue Cloud towards ϵ CMa) to possibly $>5 \text{ cm}^{-3}$ (G-cloud towards α Cen, Frisch 2003; Gry & Jenkins 2001). The gas-phase abundance of Fe, with respect to undepleted S, varies by $\sim 50\%$ within 3 pc of the Sun, evidently due to grain destruction processes (Frisch & Slavin 2003).

If the ISM is chemically homogeneous, elements absent from the gas phase must be depleted onto dust grains. This argument can be used to evaluate $R_{g/d}$ over the integrated LIC column, and $R_{g/d}$ can be compared with that of other nearby interstellar clouds. However, the required knowledge of the total chemical composition of the ISM is an elusive quantity that has not been reliably determined. The 40%–50% variation in Fe^+/S^+ and Si^+/S^+ for the two clouds towards ϵ CMa indicates different grain histories for two similar clouds within 3 parsecs of each other. If atoms not observed in the gas are concentrated in the dust, $R_{g/d}$ can be calculated from observations of interstellar absorption lines towards nearby stars. When evidence for 60%–70% subsolar abundances is included, $R_{g/d} \sim 600$ integrated over the diameter of the LIC (Frisch & Slavin 2003). This is a factor of >5 larger than the in situ value, indicating a relative concentration of interstellar dust at the Sun compared to the ~ 0.5 pc LIC cloud length towards ϵ CMa. The gas-to-dust mass ratio also varies over the nearest 3 pc, by $>30\%$. If ISM abundances are solar, the in situ and astronomical methods of determining $R_{g/d}$ are in better agreement, but interstellar absorption line data towards weakly reddened stars are unexplained. These differences are not yet understood. The chemical composition of interstellar dust grains observed within the solar system thus provides a window on the chemical composition and homogeneity of the ISM.

Interstellar gas and dust couple through collisional processes, and through coupling of ions and charged grains to the interstellar magnetic field. Over distance scales of 100–500 pc, gas-dust coupling is demonstrated through the correlation of starlight-reddening dust grains (measured as color excess $E(B-V)$) and interstellar hydrogen ($\text{N}(\text{H}^+) + 2\text{N}(\text{H}_2)$) (Bohlin et al. 1978). For the multcloud structure observed within 5 pc, gas-dust coupling is not proven. The collisional lifetimes for classical dust grains (radii $a \sim 0.2 \mu\text{m}$) in the LIC are $\sim 0.3 \times 10^6$ years, during which time the LIC will move ~ 5 pc through local space. The gyroradius is ~ 0.1 pc in a field of $3 \mu\text{G}$ (Grün & Landgraf 2000). The result will be magnetically captured dust grains that are collisionally destroyed over the lifetime of the cloud. Grün and Landgraf (2000) suggest that classical grains are replenished by the collisional destruction of larger dust grains. Alternatively,

silicate grain destruction peaks near shock column densities of $N(\text{H}) \sim 6 \times 10^{17} \text{ cm}^{-2}$ (Jones et al. 1994), allowing the breakdown of gas-dust coupling locally over $\sim 1 \text{ pc}$ length scales. Spikes of ^{10}Be in ice core samples ($\sim 3.3 \times 10^4$ and 6×10^4 years ago) provide evidence for recent interstellar shocks crossing the solar system, and may contribute to the inhomogeneous $R_{g/d}$ values found within 3 pc .

There are no direct observations of interstellar dust within 5 pc and outside of the solar system. The observations of very weak starlight polarization towards nearby stars ($< 40 \text{ pc}$) may originate from magnetically aligned dust grains close to the Solar system. The observed polarization strength is consistent with the average interstellar density of $\sim 0.1 \text{ cm}^{-3}$ over tens of parsecs in the upwind direction (Frisch 1990). The in situ grains have a size distribution consistent with these classical dust grains.

The Solar system passes currently through a shell of material which is located at the edge of the local bubble. It emerged from the interior of this bubble within the past 2×10^2 – 10^5 years (depending on cloud geometry). Since entering the cluster of clouds flowing from the Scorpius-Centaurus direction, the Sun has encountered a new interstellar cloud at least once per 10^4 years. It is clear that sampling of dust from our LIC would greatly help to understand the nature and processing of dust in various galactic environments, and cast new light on the chemical composition and homogeneity of the ISM.

7. A Future Dust Observatory

Based on the experience gained by previous in situ dust measurements in space, we propose a new approach to dust measurements, which we call "dust astronomy". Dust particles, like photons, are born at remote sites in space and time, and carry from there information that may not be accessible to direct investigation by other means. From knowledge of the dust particles' birthplace and their bulk properties, we can learn about the remote environment out of which the particles were formed.

The dynamics of dust particles is affected by gravitational, radiation, and magnetic fields. Dust trajectories trace out their gas, plasma, radiation, and dust environments. By accurate dust trajectory measurements, we can derive their place of origin: comets, asteroids, or interstellar space. From the particles' bulk properties and their chemical composition, we can infer properties of the environments out of which the particles were formed and in which they were subsequently altered. Therefore, our dust astronomy term encompasses and denotes both the trajectory determination and chemical analysis of the same dust particle. This is state-of-the-art technology: Recent developments of in situ dust detectors allow us to combine sensors of these capabilities into a single dust telescope, that is carried into space by a dust observatory satellite.

A dust telescope is a combination of a dust trajectory sensor together with an analyzer for the chemical composition of dust particles. Dust particles' trajectories are determined by the measurement of the electric signals that are induced when a charged grain flies through a position-sensitive electrode system. The objective of the trajectory sensor is to detect dust particles $> 0.2 \mu\text{m}$ radius and

to measure their trajectories with an accuracy of a few percent in angle and speed.

Sufficient mass resolution ($M/\Delta M > 100$), should be provided by the dust chemical analyzers in order to resolve ions with atomic mass number up to 100. The dust analyzer will use time-of-flight mass spectrometry of the plasma that is generated upon impact of the dust particle onto the target of a dust analyzer. Such high-resolution dust mass analyzers that provide chemical composition of dust particles have been flown on the Halley missions, and is currently flying on the Stardust mission. The impact area of the mass analyzer shall be at least 0.1 m^2 , in order to cope with the low fluxes expected in interplanetary space.

The first proposals of a dust observatory mission carrying a dust telescope are currently under discussion. An assessment study by the European Space Agency for the Cosmic DUNE (Cosmic DUSt Near Earth) mission demonstrated the feasibility of a dust observatory mission and has received high marks for its scientific prospects. In the following paragraphs we describe the mission objectives and requirements and the science operations scenario.

The scientific objectives of the Cosmic DUNE observatory are: (1) to allow the distinction between interstellar dust and interplanetary dust, (2) to measure the elemental and isotopic composition of impacting dust particles, and (3) to monitor the overall dust flux for various directions and masses over the duration of the mission.

A possible Cosmic DUNE's trajectory is an orbit about the libration points of the Sun-Earth system (Fig. 10). This trajectory exploits the effect of Earth's motion ($v_E \sim 30 \text{ km s}^{-1}$) on the local interstellar dust velocity ($v_{ISD} \sim 26 \text{ km s}^{-1}$) and flux. The interplanetary dust flux is constant throughout the year. In contrast to the interplanetary flux, the interstellar dust flux varies strongly during the year: during the Earth's upwind motion, the velocities add up to 56 km s^{-1} , and during the downwind motion, the relative velocity is a few km s^{-1} . When the dust telescope points into this interstellar dust flow direction during the spring months, the flux of interstellar grains is almost an order of magnitude larger than the flux of interplanetary grains. In particular, deviations of the flux direction of large interstellar grains from the nominal direction are important to characterize the coupling of the large galactic grains to the LIC, and/or larger cloud structures, and to identify potential sources of these particles. We estimate that a one m^2 -sized dust telescope will detect more than 1000 impacts of interstellar grains per year.

Despite the great advances made in the last years in the understanding of the heliospheric dust environment, there remain many important questions to be answered. Significant compositional information will be gained by in situ measurements, but even more can be learned if this dust is collected and brought to the laboratory, where the most advanced instrumentation can be used for its analysis. Sample return from Earth orbit is, of course, much easier than sample return from distant worlds. However, in order to separately collect interplanetary and interstellar dust in Earth orbit, a preceding detailed analysis of the various dust flow components by a dust telescope is necessary. In summary, the future of dust measurements in Earth orbit is seen to lie in two areas: (1) use of dust telescopes to separate and analyze dust populations of different origin,

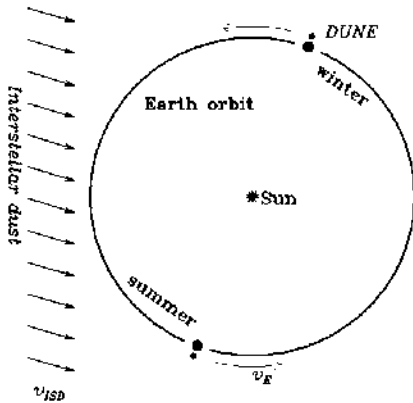


Figure 10. Cosmic DUNE mission scenario. Earth's orbit around the Sun ($v_E = 30$ km/s), and the direction of the interstellar gas and dust flow at speed $v_{ISD} = 26$ km/s are shown. Cosmic DUNE orbits the Earth at L2 (not to scale). Two positions of the Earth and the satellite are shown (top: late winter, and bottom: late summer). The corresponding fluxes of interstellar grains are about a factor 10 higher in winter than in summer.

and (2) collection and sample return of dust from various sources for in-depth analysis in the laboratories.

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