Dust en-route to Jupiter and the Galilean satellites
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Spacecraft investigations during the last ten years have vastly improved our knowledge about dust in the Jovian system. All Galilean satellites, and probably all smaller satellites as well, are sources of dust in the Jovian system. In-situ measurements with the dust detectors on board the Ulysses and Galileo spacecraft have for the first time demonstrated the electromagnetic interaction of charged dust grains with the interplanetary magnetic field and with a planetary magnetosphere. Jupiter's magnetosphere acts as a giant mass-velocity spectrometer for charged 10-nanometer dust grains. These dust grains are released from Jupiter’s moon Io with typical rate of $\sim 1 \text{kg s}^{-1}$. The dust streams probe the plasma conditions in the Io plasma torus and can be used as a potential monitor of Io's volcanic plume activity. The other Galilean satellites are surrounded by tenuous impact-generated clouds of mostly sub-micrometer ejecta grains. Galileo measurements have demonstrated that impact-ejecta derived from hypervelocity impacts onto satellites are the major – if not the only – constituent of dusty planetary rings. We review the in-situ dust measurements at Jupiter and give an update of most recent results.

1. Introduction

Until the 1970s, when the Pioneer 10 and Pioneer 11 spacecraft passed by Jupiter, the exploration of the giant planet and its satellites was restricted to remote astronomical observations from the Earth. It was pure speculation whether dust would exist in the environment of Jupiter. Pioneer 10/11 were equipped with in-situ dust detectors which recorded several impacts when the spacecraft flew by Jupiter (22). Due to the relatively high detection threshold of the penetration detectors, however, only particles larger than several micrometers could be recognized.

The next spacecraft to visit Jupiter were Voyager 1 and Voyager 2. Although they did not carry dedicated dust detectors on board, they drastically changed our knowledge of dust in the Jovian system. Jupiter’s rings were discovered by remote sensing with Voyager 1, although earlier hints that this faint dusty ring might exist came from a dip in the density of charged particles measured near Pioneer 11’s closest approach to Jupiter (44), as well as from the impact events recorded by the Pioneer dust detectors. Typical grain sizes derived from the Voyager images were a few micrometers for the faint gossamer ring, whereas the main ring turned out to be composed of macroscopic rocky material. Another discovery by Voyager was tidally driven active volcanism on Io, Jupiter’s innermost Galilean moon. At the time it was speculated that small dust grains entrained in Io’s plumes may get accelerated away from Io by electromagnetic forces.
The next major step forward in the investigation of Jovian dust came from the Ulysses spacecraft which flew by the planet in 1992. Ulysses is equipped with a highly sensitive impact-ionization dust detector capable of measuring dust grains down to sizes of 0.1 $\mu$m (11). With Ulysses, periodic collimated streams of dust particles with up to 2000 impacts per day were discovered while the spacecraft was within 2 AU from the giant planet (16,2) (Fig. 1). The streams occurred at approximately monthly intervals ($28 \pm 3$ days) and their impact directions implied that the grains originated from the Jovian system. No periodic phenomenon for small dust grains in interplanetary space was known before.

Confirmation of the Jupiter dust streams came from the Galileo spacecraft which carries a twin of the Ulysses dust detector on board (10). Dust “storms” with up to 10,000 impacts per day were recorded while Galileo was within 0.5 AU from the planet. (1,31). Since December 1995, Galileo has been the first man-made spacecraft in orbit about a giant planet of our solar system. It explores Jupiter, its satellites and its huge magnetosphere. With the Galileo dust detector the dust streams seen in interplanetary space were also detected within the planet’s magnetosphere. The grains showed a strong electromagnetic interaction with the Jovian magnetic field (see Sect. 2).

In December 2000 the Cassini spacecraft flew by Jupiter on its way to Saturn and provided a unique opportunity for simultaneous two-spacecraft measurements of the Jovian dust streams. The Cassini cosmic dust analyser (10) measured the chemical composition of dust stream particles in-situ for the first time.

Apart from the Jovian dust streams, Galileo allowed for studies of impact-generated dust clouds surrounding the Galilean satellites (14) (Sect. 3), a tenuous dust ring in the region between the Galilean satellites (12,23) and further out from the satellites (27) as well as interplanetary and interstellar particles captured by the Jovian magnetosphere (6,5) (Sect. 4). The detection of most of the observed features was unexpected and their discovery has greatly expanded our knowledge about dust in the Jovian magnetosphere.

Comprehensive reviews of more than 10 years of dust measurements with Ulysses and Galileo focussing on Jovian dust as well as interplanetary and interstellar dust have also been given by Grün et al. (14) and Krüger et al. (32).
2. Jupiter dust streams

2.1. Electromagnetically interacting dust

The impact directions of the dust stream particles measured with Galileo and Ulysses in interplanetary space were close to the line-of-sight direction to Jupiter. The approach direction of most streams, however, deviated too much from the direction to Jupiter to be explained by gravitational forces alone. This deviation was correlated with the magnitude and the direction of the interplanetary magnetic field which implied that strong non-gravitational forces must have been acting on the grains. The observed 28 day period in the impact rate (Fig. 1) was most likely caused by changes in the tangential component of the solar wind magnetic field which periodically accelerated the particles towards and away from the ecliptic plane. Numerical simulations showed that only particles with velocities in excess of 200 km s\(^{-1}\) and radii in the range 5 nm \(\leq s \leq 15\) nm were compatible with the observations. Larger (smaller) grains did not interact enough (interacted too strongly) with the interplanetary magnetic field to explain the observed impact directions. This demonstrated that the solar wind magnetic field acts as a giant mass-velocity spectrometer for charged dust grains.

Strong electromagnetic interaction of dust grains was also found with the Galileo detector within the Jovian magnetosphere. Figure 2 shows an example of the impact rate measured with Galileo in the inner part of the magnetosphere. During this and most other times when Galileo collected data in this spatial region, the impact rate fluctuated with 5 and 10 h periodicities and the fluctuations typically exceeded 2 orders of magnitude. Furthermore, the impact directions of the grains and the measured charge rise times and charge amplitudes which were used to derive particle speeds and masses showed similar fluctuations. These fluctuations were correlated with the position of Galileo in the Jovian magnetic field (cf. bottom panel of Fig. 2). Due to a 9.6\(^{\circ}\) tilt of Jupiter’s magnetic axis with respect to the planet’s rotation axis the magnetic equator sweeps over the spacecraft in either up- or downward direction every 5 h.

In addition to the 5 and 10 h periods which are compatible with Jupiter’s rotation period, a modulation of the impact rate with Io’s orbital period (42 h) could also be recognized during some time intervals (e.g. Galileo orbits E4, G7 and C9) while at other times an Io modulation was missing (e.g. Galileo orbit G2, Fig. 2). A detailed frequency analysis of a two year dataset showed Io’s orbital frequency as a “carrier frequency” and primary source of the Jovian dust streams. Jupiter’s magnetic field frequency modulates Io’s frequency signal, giving rise to modulation sidelobe products seen around first order (10 h) and harmonic (5 h) Jupiter magnetic field frequencies. These modulation products confirm Io’s role as a primary source of the Jovian dust streams. Io as a source can best explain the time series analysis results showing Io’s orbit periodicity.

An Io source is also compatible with the deduced particle sizes of \(\sim 10\) nm: photometric observations of the Io plumes obtained with Voyager imply a size range of 5 to 15 nm, in agreement with numerical simulations. Recent Hubble Space Telescope (HST) observations constrained the grains to be smaller than 80 nm. Hence, given the ejection speeds of more than 200 km s\(^{-1}\), Io turned out to be a source for interplanetary and interstellar dust!
The suggested mechanism to eject dust grains from within the Jovian magnetosphere matched the size and velocity range of the observed stream particles by recognizing that these grains become positively charged in the Io plasma torus and can get accelerated by Jupiter’s corotational electric field \( \text{(20,21,13)} \). As grains traverse the various plasma regions in the torus, however, their charge will not remain constant. Dust grains escaping Io’s plumes first enter the cold plasma torus where they become negatively charged \( (\sim -3 \text{ V}) \). Grains that reach the outer hot regions of the torus change their sign of charge to positive \( (\sim +3 \text{ V}) \) because of secondary electron emission. Once positively charged, grains will be accelerated by the outward pointing corotational electric field. They will leave the Jovian system if their radii are between about 9 and 180 nm \( \text{(13)} \). Smaller grains remain tied to the magnetic field lines and gyrate around them like ions do, whereas bigger grains move on gravitationally bound orbits which are – depending on the particle size – more or less affected by the Lorentz force. Recent investigations showed that a higher secondary electron yield which leads to potentials of \(-5 \text{ V}\) in the cold torus and \(+5 \text{ V}\) elsewhere gives better agreement with the observations \( \text{(13)} \).

Since Io is located very close to Jupiter’s equatorial plane, the particles are to a first order approximation accelerated outward along this plane. Because of the 9.6° tilt of Jupiter’s magnetic field with respect to the planet’s rotation axis, however, the particles also experience a significant out-of-plane component of the Lorentz acceleration: particles continuously released from Io move away from Jupiter in a warped dust sheet which has been nick-named ‘Jupiter’s dusty ballerina skirt’ \( \text{(21)} \). A detector attached to a spacecraft moving in Jupiter’s equatorial plane detects an increased number of particles when this dust sheet sweeps over its position. The 5 and 10 h fluctuations in the dust impact rate as well as the impact directions of grains observed by Galileo \( \text{(13)} \) can be explained with this scenario of electromagnetically coupled dust grains. However, only grains within a narrow size range around 10 nm are in agreement with the observed features. Smaller and larger stream particles were not detected with the Galileo dust instrument.

The charge of a particle escaping from the Io torus strongly depends on variations in the
plasma density and temperature in space and time and thus is a function of Io’s position at the time of particle release. In fact, the position where a particle is released from the torus is correlated with Io’s position (Graps, priv. comm.). In addition, the torus shows a strong dawn-to-dusk asymmetry in the plasma conditions that influence the escape of the dust particles. Grain charges are more negative on the dawn side of the torus where a lower electron temperature leads to a reduced secondary electron production. Particles on the dawn side remain captured in the torus for longer times because of their lower positive charge. Six years of Galileo dust stream measurements clearly show a variation of the flux with Jovian local time: significantly higher dust fluxes were measured on the dawn and on the dusk sides than on the noon side of Jupiter (Krüger et al., in prep.) as predicted by numerical modelling (19). Thus, the Jovian dust streams serve as tracers of the plasma conditions in the Io torus.

The fly-by of the Cassini spacecraft at Jupiter in December 2000 provided a unique opportunity for a two-spacecraft time-of-flight measurement (Cassini-Galileo) of particles from one collimated stream from the Jovian dust streams. Particles in a stream were detected with Galileo as the spacecraft was inside the Jovian magnetosphere close to the orbit of Europa (about 12 R$_J$), and then particles in the same stream were detected by Cassini outside the magnetosphere (at 140 R$_J$). The Cassini data imply that particles of different sizes have different phases with respect to Jupiter’s rotation (Kempf et al., in prep.), a result which was also seen in earlier Galileo data (13). The comparison of the measurements from both dust instruments, however, is hampered by the higher detection sensitivity of the Cassini detector with respect to the Galileo detector. Both instruments have detected stream particles with different sizes and, hence, different phases. The analysis is ongoing and more detailed modelling to describe the phase relation of different-sized particles is in progress. The present analysis indicates particle speeds of about 400 km s$^{-1}$. This value is in agreement with speeds for 5 nm particles as derived from dynamical modelling and earlier studies of the Jovian dust stream dynamics (14).

The Cassini dust instrument is equipped with a time-of-flight mass spectrometer which measures the elemental composition of dust grains with a mass resolution $M/\Delta M \approx 100$. During Cassini’s approach to Jupiter impact spectra of a few hundred dust stream particles have been measured and their chemical composition reflects the chemistry found on Io. With the Cassini instrument the surface composition of a satellite other than our Moon has been measured directly.

2.2. Io as a source of dust in the Jovian system

How significant is Io as a source of cosmic dust? How does the amount of dust ejected compare with other dust sources in the solar system? With a simple calculation we can derive the total dust production rate of Io. Given the spread of Io dust along and away from Jupiter’s equatorial plane, we assume a cone-shaped emission pattern of dust originating at Jupiter. We assume a cone opening angle of $35^\circ$ and isotropic dust emission towards all jovigraphic longitudes. Although Galileo measurements were obtained only along the Jovian equatorial plane, this opening angle is justified by the Ulysses measurements. Ulysses measured the dust streams at $35^\circ$ jovigraphic latitude after Jupiter fly-by (cf. Fig. [1]). For a given impact rate $R$, particle density $\rho = 2$ g cm$^{-3}$, particle radius $a = 10$ nm, a detector sensitive area of $A = 0.02$ m$^2$ and a cone radius $r = 30$ R$_J$ the
Figure 3. Total dust production rate of Io assuming that the grains are ejected into a cone with 35° opening angle centered at Jupiter. Each vertical bar represents data from one Galileo orbit. The height of the bar shows the dust production rate derived from measurements between 10 to 30 R_J from Jupiter. The data have been corrected for a Jovian local time variation of the dust emission from the Io torus and for a long-term change of the dust instrument sensitivity (Krüger et al. in prep.). The labels of individual Galileo orbits are indicated at the top. No dust stream measurements were collected during Galileo orbits 5 and 13.

The Jovian dust stream measurements can serve as a monitor of Io’s volcanic plume activity. With Galileo imaging ten active plumes have been observed which is comparable with nine plumes seen by Voyager (35). At least tow types of plumes can be distinguished: large, faint ones, with short-lived or intermittent activity (Pele-type) or small, bright, long-lived ones (Promethens-type). The most powerful plume ever detected on Io, Pele, is the archetype of the first category and was observed to an altitude of more that 400 km (39). Pele is also the location of the most stable high-temperature hot-spot on Io and is probably related to an active lava lake. Plumes are normally related to hot spots but not vice versa. The Pele plume is known to be rich in S_2 gas as well as SO_2 (38). Although it has been suggested that the Pele plume may be a pure gas plume, plume observations can also be interpreted as due to very fine (≤ 80 nm) particulates (39).

It is of special interest to see whether variations in the dust production rate deduced...
from the dust stream measurements can be related to the activity of the Pele or other plumes on Io, or to the total thermal output of the satellite. A correlation with the activity of the Pele plume seems most promising because only the most powerful plumes are expected to accelerate the grains to sufficient altitudes so that they can finally escape from the satellite (25,24).

The dust production of Io for individual orbits of Galileo is shown in Fig. 3. Here, the vertical bars indicate the variation in the derived dust production rate if we vary the jovian-centric distance at which the dust flux is taken between 10 and 30 R$_J$ during one orbit. This reveals a strong variation in the dust production rate from orbit to orbit which is up to two orders of magnitude. If the plasma conditions in the Io torus and the Jovian magnetic field did not change too drastically from orbit to orbit, it reflects the variation of the activity of the Io plumes.

We have compared the dust production rate shown in Fig. 3 with the total thermal output of Io deduced from Galileo near-infrared measurements (Spencer, priv. comm.). Unfortunately, this did not give a clear picture. This negative result, however, is not too surprising because Io’s overall thermal output is not very well correlated with plume activity. The Pele plume was observed in July 1995, July 1996, December 1996 and possibly July 1997 (35). It was absent in June 1996, February 1997, June 1997 and July 1999. Although, the strong drop in the dust impact rate from December 1996 to February 1997 (E4 to E6 orbit) is consistent with these detections/non-detections, for other measurements it is not. Especially, the non-detection of the plume on 2 July 1999 is in contradiction with the large measured dust emission.

A correlation of the in-situ dust measurements with either Galileo or Earth-based imaging observations turns out to be very difficult because the imaging observations represent only sporadic glimpses. Many more observations would be needed to establish a firm link between the Galileo dust measurements and the activity of (an) individual plume(s) on Io. The picture is further complicated by the fact that the plume activity sometimes changes on timescales of days to weeks. Ideally, one would need imaging observations at exactly the same time as the dust measurements.

We have also estimated the Io dust production from the measurements of Galileo and Ulysses in interplanetary space out to 1 AU from Jupiter assuming again that the dust is uniformly distributed into a cone of 35°. This leads to unrealistically high dust production rates of more than 10$^7$ kg s$^{-1}$. It indicates that this simple picture cannot be extrapolated to interplanetary space and that the dust is not distributed uniformly to such large distances. Rather, the dust particle trajectories must undergo some focussing effect due to electromagnetic interaction with the interplanetary magnetic field.

Additional evidence for such a focussing effect came from Galileo measurements in 2000 when the spacecraft has left the Jovian magnetosphere for the first time since 1995. Measurements outside the magnetosphere at a distance of ~ 280 R$_J$ (0.13 AU) from Jupiter gave a surprisingly high impact rate of up to 10 impacts per minute (Fig. 4). This value was comparable with the rates detected both in interplanetary space (Fig. 1) and close to Jupiter during Galileo’s early orbital mission (Fig. 2).

In May and June 2000 (days 145 to 170), while Galileo was receding from Jupiter (from 10 to 170 R$_J$), the impact rate dropped by more than two orders of magnitude (from 0.05 to 0.0005 impacts per minute). This drop was close to the inverse square of the source
When Galileo was outside the magnetosphere, beyond \( \sim 200 \text{R}_J \) from Jupiter (after day 180), the impact rate increased by about four orders of magnitude. Between August and October 2000 (days 230 to 280), Galileo remained more or less stationary with respect to Jupiter and Io, and the impact rate remained remarkably constant for about two months with roughly 1 impact per minute. Assuming – as before – that dust particles get ejected into a 35° cone, this leads to a dust production of Io of \( \sim 100 \text{kg s}^{-1} \). It seems unlikely that such a high dust production is maintained over such a long time period. More likely is a focussing effect of the grains due to the boundary between the Jovian magnetosphere and the interaction with the interplanetary magnetic field. Interestingly, the impact directions measured with Galileo indicate that the grains approached the sensor from a direction very close to the ecliptic plane. Similarly high impact rates were also detected with the Cassini dust instrument (40) in September 2000 at \( \sim 0.3 \text{AU} \) from Jupiter when the spacecraft was approaching the planet (Kempf et al., in prep.).

Frequency analysis of the Galileo dust impact rates measured beyond \( \sim 250 \text{R}_J \) did not reveal 5 and 10 h periodicities as was seen within the magnetosphere. Instead, a strong peak at Io’s orbital period showed up in the frequency spectrum (A. Graps, priv. comm.), much stronger than seen close to Jupiter.

3. Dust-enshrouded satellites

Between December 1995 and January 2002 the Galileo spacecraft had a total of 31 targeted encounters with all four Galilean satellites. During many of these fly-bys the impact rate of dust grains showed a sharp peak within about half an hour centered on closest approach to the satellite (13, 29). This indicated the existence of dust concentrations in
Figure 5. Number density of dust as a function of altitude above the surface of Ganymede (data from 4 fly-bys), Europa (8 flybs) and Callisto (3 fly-bys). The altitude is shown in units of the satellite radius $R_{\text{sat}} = 1560, 2634, 2409$ km in the case of Europa, Ganymede and Callisto, respectively. Vertical error bars reflect statistical uncertainty due to the small number of impacts. The solid lines are least squares fits to the measured number densities.

the close vicinities of Europa, Ganymede and Callisto. No dust cloud could be measured close to Io because the spacecraft orientation prevented the detection of dust particles during all fly-bys at this satellite.

Analysis of the impact directions and impact speeds showed that the grains belonged to steady-state dust clouds surrounding the satellites (34,33). The measured radial density profiles of the dust clouds (Fig. 5) together with detailed modelling of the impact-ejection process implied that the particles had been kicked up by hypervelocity impacts of micrometeoroids onto the satellite’s surface (27). The projectiles were most likely interplanetary dust particles.

The measured mass distribution of the grains was consistent with such an ejection mechanism with grain sizes being mostly in the range $0.5 \mu m \leq s \leq 1.0 \mu m$. It implied that the particle dynamics was dominated by gravitational forces, whereas non-gravitational, especially electromagnetic forces were negligible. Most ejected grains follow ballistic trajectories and fall back to the surface within minutes after they have been released. Only a small fraction of the ejecta has sufficient energy to remain at high altitudes for several hours to a few days. Although they eventually strike the satellite’s surface, these short-lived but continuously replenished particles form a tenuous steady-state dust cloud which entirely envelopes the satellite. The total amount of debris contained in such a steady-state cloud is roughly 10 tons.

The optical thickness of the cloud is by far too low to be detectable with imaging techniques. Only a highly sensitive detector of the Galileo/Ulysses type could recognize a sufficient number of grains to detect these clouds. The low dust density is illustrated by the fact that only 35 cloud particles impacted the detector during 4 fly-bys at Ganymede.
A detailed analysis of the entire Galileo dataset for the three Galilean satellites is ongoing. One goal is to check for signatures of a leading-trailing asymmetry of the ejecta clouds, which can be expected from the orbital motion of the satellite with respect to the field of impactors (34).

The Galileo measurements are the first successful in-situ detection of satellite ejecta in the vicinity of a source moon. All celestial bodies without gaseous atmospheres (asteroids, planetary satellites of all sizes) should be surrounded by an ejecta dust cloud. Before Galileo, there were few attempts of direct in-situ detections of ejecta close to satellites — most notably, near the Moon (23). These experiments, however, did not lead to definite results.

4. Dusty Jovian rings

Apart from Io dust streams (Sect. 2) and circum-satellite ejecta-clouds (Sect. 3) the in-situ Galileo measurements have revealed additional populations of Jovian dust (Tab. 4): since the beginning of Galileo’s orbital tour about Jupiter the dust detector has measured more than 400 impacts of mostly micrometer-sized grains widely distributed in circum-jovian space. Although the highest fluxes of grains occurred in the region between Io’s and Callisto’s orbit (≈ 6 to 26 R_J from Jupiter, (13,29), Fig. 6) impacts were also detected out to 200 R_J and beyond. These grains form a tenuous dust ring around Jupiter with a number density of ≈ 2 \times 10^2 \text{ km}^{-3} \text{ at Europa’s orbit}. The spatial locations where these grains were detected, the impact directions and the charge signals imply that these are actually two populations: besides a population of particles on prograde orbits about Jupiter, another population on retrograde orbits must exist as well (12). The grains on retrograde orbits are most likely interplanetary or interstellar grains captured by the Jovian magnetosphere (35). Numerical models show that a tiny fraction of the impact debris
released from the surface of the satellites by hypervelocity impacts (Sect. 3) is ejected at speeds sufficient to escape from the satellites entirely (26) (an amount of 10 g sec\(^{-1}\) has been estimated to leave Ganymede). The ejected material goes into orbit about Jupiter and forms a tenuous ring of dust particles mostly on prograde orbits. This ring extends at least from Io’s orbit (5.9 R\(_J\) from Jupiter) out to Callisto’s orbit (26 R\(_J\)) but the dust detections indicate that it continues further out and further in (see below).

In the outer region of the Jovian system, between 50 and 300 R\(_J\), about 100 dust impacts were detected. Their orbits are compatible with prograde and retrograde jovicentric orbits with a wide range of inclinations (27). The number densities of \(\sim 10 \text{ km}^{-3}\) are more than an order of magnitude lower than those found in the region between the Galilean satellites but, on the other hand, by about an order of magnitude larger than the interplanetary background. Sources for these grains are Jupiter’s outer regular and irregular moons.

Indications for the existence of the ring can already be found in earlier measurements by the Pioneer 10/11 and Ulysses spacecraft: 12 meteoroid penetrations have been recorded with Pioneer within 45 R\(_J\) (Jupiter radius, R\(_J\) = 71,492 km) from Jupiter (22) and Ulysses has recorded 9 impacts of micrometer-sized dust grains in this spatial region. Two-third of the Ulysses impacts were detected at \(\sim 35^\circ\) jovigraphic latitude after Jupiter fly-by.

Between Io’s orbit at 5.9 R\(_J\) and the outer extension of the gossamer ring at about 3.1 R\(_J\), extremely little is presently known about the dust environment. Although Galileo has traversed part of this region during orbit insertion in December 1995, dust measurements were very patchy because the instrument had to be saved from the hazards of Jupiter’s radiation environment. However, a few probably micrometer-sized dust impacts were detected within Io’s orbit (12,30).

Still closer to Jupiter lies the region of Jupiter’s prominent ring system which consists of three components: the main ring, the halo and the tenuous gossamer rings. Here, the dust densities are so large that dust investigations have been performed with remote sensing techniques. The vertical extension and density profiles of the rings imply that a significant fraction if not all of the dust forming the rings is impact-ejecta derived from the inner moons Adrastea and Metis (in the case of the main ring), and Amalthea and Thebe (in the case of the gossamer rings (37)). These satellites orbit Jupiter inside the ring system. The motion of the dust grains in a certain size range contained in the gossamer ring is most probably dominated by the Poynting-Robertson drag force, indicating that the plasma density in this region is much lower than previously thought (3).

5. Conclusions and outlook

The Galileo dust measurements have drastically expanded our knowledge about dust in the Jupiter system. In fact, Jovian dust has been studied to at least a similar extent as cosmic (i.e. non-artificial) dust in the Earth environment. The properties of the various Jovian dust populations studied in-situ with Galileo are summarised in Tab. I.

All Galilean satellites are sources of dust in the Jovian system. The Galileo measurements have for the first time demonstrated the electromagnetic interaction of charged dust grains with a planetary magnetosphere. Jupiter’s magnetosphere acts as a giant mass-velocity spectrometer for charged dust grains in space. The Io dust streams can be used as a potential monitor of the activity of Io’s plume activity.
Table 1
Physical parameters of dust populations detected in-situ at Jupiter. Column 2 gives
typical particle sizes (radii) assuming spherical particles, col. 3 the mean measured impact
speeds, col. 4 lists the radial distance range where the particles have been detected, and
col. 5 gives derived particle number densities in space.

| Population           | Particle size | Impact speed | Jovicentric distance | Number density |
|----------------------|---------------|--------------|----------------------|----------------|
|                      | (µm)          | (km s\(^{-1}\)) |                      | (m\(^{-3}\))  |
| Stream particles     | ∼ 0.01\(^\ast\) | ≤ 400\(^\ast\) | 6 R\(_J\) – 2 AU     | 10\(^{-3}\) – 10\(^{-8}\) |
| Ejecta clouds        | 0.3 – 1       | 6 – 8        | ≤ 10 R\(_{sat}\)\(^\dagger\) | 10\(^{-4}\) – 10\(^{-5}\) |
| Ejecta ring          | 0.6 – 2       | ∼ 7          | 6 – 30 R\(_J\)       | 10\(^{-6}\) – 10\(^{-7}\) |
| Captured particles   | 0.5 – 1.5     | ∼ 20         | 6 – 20 R\(_J\)       | ∼ 10\(^{-7}\)     |
| Outskirts ring       | 1 – 2         | ∼ 5          | ≥ 50 R\(_J\)         | ∼ 10\(^{-8}\)     |

\(^\ast\): derived from dynamical modelling.
\(^\dagger\): altitude above satellite surface.

The Io dust stream particles probe the conditions in the Io plasma torus. Since in
a completely radially symmetric plasma and magnetic field configuration no 10 h period
should show up in the impact rate, only the 5 h period should be there. The prominent
modulation of the rate with the 10 h period points to variations in the acceleration mech-
anism of the grains correlated with Jovian local time which are presently not completely
understood.

In February 2004, Ulysses will approach Jupiter to 0.8 AU again. Additional dust
stream measurements with Ulysses in interplanetary space at high jovigraphic latitudes
and for varying Jovian local times will be beneficial to test our understanding of this new
phenomenon.

The Galileo measurements of impact-generated dust clouds surrounding the Galilean
satellites can be considered as unique natural impact experiments to study the dust ejec-
tion mechanism due to hypervelocity impacts onto celestial bodies without atmospheres.
They complement laboratory experiments in an astrophysically relevant environment. Al-
though far from being perfect impact experiments, the Galileo results offer two extremely
important improvements over laboratory experiments: 1) the projectile and target ma-
terials and projectile speeds are astrophysically relevant, and 2) the masses and speeds
of the ejecta particles can be determined in an important region of parameter space (mi-
crometre sizes and km s\(^{-1}\) impact speeds). This is especially important in view of the
Cassini mission. Cassini will start its exploration of the Saturnian system in 2004 and
will fly by several of Saturn’s satellites during its orbital tour about the giant planet. It
will provide a unique opportunity to study the dust environments of many of the small
Saturnian satellites.

Although considered to be the archetype of an ethereal dusty planetary ring, the Jovian
gossamer and main ring system has been relatively incompletely studied to date. The
in-situ measurements of ejecta grains escaping from the circum-satellite dust clouds and
images of Jupiter’s main and gossamer rings have demonstrated that impact-ejecta derived from hypervelocity impacts onto satellites is the major – if not the only – constituent of these dusty planetary rings. The details of the complex dynamics of grains over a large size range and under the various forces acting on the grains are as yet only poorly understood.

In November 2002 – during its final orbit about Jupiter – Galileo will traverse the gossamer ring system and fly by Amalthea (Fig. 7). Detailed in-situ studies of the dust grains in the gossamer rings will provide a better understanding of the forces dominating the grain dynamics in the rings (gravity, Lorentz force, plasma drag, Poynting-Robertson drag, radiation pressure). The relative importance of each force varies strongly with grain size and distance from the planet and leads to drastically different size distributions at different locations along the gossamer rings and in the main ring. Investigation of why the Poynting-Robertson drag dominates over the other forces will lead to a comprehensive picture of the grain dynamics in the gossamer ring, a neccessary step in deriving a full picture of the dust dynamics throughout the Jovian magnetosphere. In-situ studies of the ring material can provide valuable information about the surface properties of the source moons. Comparative studies of ejecta from the large Galilean moons and the smaller ones embedded in the gossamer rings will provide information about the ejection process over a large range in speed not accessible in the laboratory. Especially the close fly-by at Amalthea (< 300 km) will allow to test on a small moon the models for the impact-ejection process which have been developed for the much larger Galilean satellites.

In-situ dust measurements provide information about the physical properties of the dust environment not accessible with imaging techniques. Since all dusty planetary rings in our solar system are most likely dominated by impact-ejecta, studies of Jupiter’s gossamer ring provide valuable information not only about the mechanism feeding this ring system but also about the processes that govern planetary rings in general. Studies of the Jovian ring with Galileo and of the Saturnian ring with Cassini will lead to a vastly improved understanding of the formation and evolution of dusty planetary rings.

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