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Dust measurements in the Jovian magnetosphere

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Abstract

Dust measurements have been obtained with the dust detector onboard the Galileo spacecraft inside a distance of about $60 R_J$ from Jupiter (Jupiter radius, $R_J = 71,492\,\mathrm{km}$) during two periods of about 8 days around Galileo's closest approaches to Ganymede on 27 June and on 6 Sept 1996. The impact rate of submicrometer-sized particles fluctuated by a factor of several hundred with a period of about 10 hours, implying that their trajectories are strongly affected by the interaction with the Jovian magnetic field. Concentrations of small dust impacts were detected at the times of Ganymede closest approaches that could be secondary ejecta particles generated upon impact of other particles onto Ganymede's surface. Micrometer-sized dust particles, which could be on bound orbits about Jupiter, are concentrated in the inner Jovian system inside about $20 R_J$ from Jupiter.

1. Introduction

The Galileo Dust Detector System (DDS), like its twin onboard Ulysses, is a multi-coincidence impact ionization detector [*Grün et al.,* 1992a; 1995] which measures submicrometer- and micrometer-sized dust particles.

During Galileo's 6 years' journey to Jupiter DDS has measured dust in interplanetary space and detected several dust streams within 2 AU of Jupiter originating from the Jovian system [*Grün et al.,* 1996a]. After Galileo's arrival at Jupiter DDS detected dust during the flyby of Io on 7 Dec 1995 [*Grün et al.,* 1996b]. Now in a highly elliptical orbit around Jupiter, Galileo performs close flybys of Jupiter's Galilean satellites. Here we present dust measurements obtained during two periods of about 8 days around flybys of Ganymede which occurred on 27 June and 6 Sept 1996.

Galileo is a dual-spinning spacecraft with an antenna that points antiparallel to the positive spin axis (PSA). During most of the orbital tour around Jupiter the antenna points towards Earth. The Dust Detector System is mounted on the spinning section of the spacecraft and the sensor axis is offset by an angle of 55° from the PSA (Fig. 1). DDS has a 140° wide field of view. Dust particles that arrive from within 15° of the PSA (anit-Earth direction) can be sensed at all rotation angles, while those that arrive at angles from 15 to 125° from the PSA can only be sensed over a limited range of rotation angles.

For each dust impact onto the detector three independent signals of the impact-created plasma cloud are measured [*Grün et al.,* 1995]. and the three charge signals are used to classify each impact. Throughout this paper we consider only the class 3 of highly reliable dust impacts.

During both Ganymede flybys DDS data were usually read-out every 7 or 21 minutes and transmitted to Earth. During the first Ganymede flyby data were obtained from 23 June to 1 July 1996. For the second flyby continuous data were obtained from 31 August to 9 September 1996. In both periods during which we have obtained data, Galileo was inside about $60 R_J$ from Jupiter (Jupiter radius, $R_J = 71,492\,\mathrm{km}$).

The readout interval determines the maximum dust impact rate which can be measured with DDS. At rates below 30 or 10 impacts per minute all impacts were recorded and transmitted to Earth. The complete information on each impact was received on the ground when the impact rate was below one impact per either 7 or 21 minutes.

During the first Ganymede flyby DDS was operated in the same mode as in interplanetary space [*Grün et al.,* 1996a]. In this mode high noise rates were recorded inside about $15 R_J$ distance from Jupiter that prevented the detection of dust impacts around the time of perijove. For the second flyby the event definition status which initiates a measurements cycle was changed inside $18 R_J$ in order to avoid dead-time problems and to reduce the noise sensitivity. The sensitivity for class 3 dust impacts, however, was not affected by this change.

2. Data from the Ganymede Flybys

During the first Ganymede flyby we have obtained DDS data for a period of about 8 days (day of year 175.7 to 183.4) centered around Ganymede closest approach (CA) on 27 June 1996. The impact rate of our smallest class 3 dust events (ion collector charge $Q_I < 10^{-13}\,\mathrm{C}$) is shown in the upper panel of Fig. 2. During the 4 day interval before Ganymede CA we have detected high impact rates of up to several impacts per minute. The impact rate shows a strong fluctuation by 2 orders of magnitude with 3 clear maxima and a period of about 10 hours. During the same period the average impact rate dropped to about 0.01 imp/min half a day before CA and later increased again. During the closest approach itself a strong sharp spike of about 1 imp/min occurred, which lasted only about 5 min. About six hours after CA the rate of class 0 noise events saturated. This prevented the recording of dust impacts from day 179.5 to 181.0, and the recording of class 3 impacts ceased almost completely during this period. From day 181 to 183, when the noise rate was low again, no small dust impacts were detected.

The impact direction of the dust particles has been derived from the sensor orientation at the time of the particle impact (Fig. 2, lower panel). The impact direction of a single particle is only known to lie somewhere within the 140° wide sensitive solid angle cone of DDS. During Galileo's approach to Ganymede the impact direction (rotation angle) of the dust particles was concentrated between 200° and 340°. Half a day before Ganymede CA the impact direction shifted by 180° and dust particles approached from the opposite direction. Particles detected at CA itself came from the opposite direction again, namely from between 240° and 310°. The vast majority of the particles were small submicrometer-sized dust particles that just exceeded the detection threshold (ion collector charge $Q_I \geq 10^{-14}$ C). Two bigger ones ($Q_I \sim 10^{-13}$ C) were detected at the time of Ganymede CA and one even bigger particle ($Q_I \sim 10^{-11}$ C) 4.5 days later (day 183).

In the upper panel of Fig. 3 we present the DDS data for a period of 9 days around Galileo's second Ganymede flyby on 6 Sept 1996. The maximum dust impact rate was higher than during the first flyby, reaching 10 imp/min about 3.5 days before Ganymede CA. The 10 hour periodicity is also evident before CA. Again, a minimum in impact rate occurred half a day before CA, and the small dust impacts ceased another half a day after CA. This time, no dead-time problems occurred in the inner Jovian system and the cessation (day 251.5) in impact rate is real. Finally, a strong peak also occurred around Ganymede CA, but this time about 20 min before the closest approach itself.

The impact direction of small dust particles (Fig. 3, lower panel) shifted again from a range of 200° to 340° to a range between 10° and 140° about half a day before CA. Three small particles approached from about 270° during CA. Again, the majority of particles were small dust particles just above the detection threshold. During the second flyby, however, more big particles (ion collector charges $10^{-13}\,\mathrm{C} \lesssim Q_I \lesssim 10^{-11}\,\mathrm{C}$) were detected because of the changed operational mode. During both Ganymede flybys such big particles have been seen mostly within about $20 R_J$ from Jupiter (cf. Fig. 1).

3. Discussion

Within the Jovian system at least three different types of dust particles have been identified by the Galileo dust detector: 1. Small dust particles with high and variable impact rates throughout the Jovian system during Galileo's approach to Jupiter. 2. a concentration of small dust impacts at the times of Ganymede closest approach, and 3. big dust particles concentrated in the inner Jovian system.

The first kind of dust particles is the continuation of the dust streams observed in interplanetary space out to 2 AU from Jupiter. Both observations show the same characteristics in terms of impact magnitude and impact direction and there is a smooth transition of the impact rate from interplanetary space to within the Jovian system [*Grün et al.,* 1996b]. We will call these particles dust stream particles. Since the time resolution of the measurements presented here is much higher than that of the measurements in interplanetary space, new phenomena became observable. Most striking is the time variability of the impact rate. Preliminary Fourier analysis shows the strongest power at frequencies corresponding to periods of 9.6 and 4.9 hours ±5%. These periods correspond roughly to the full (10.0 h) and half value of Jupiter's rotation period as seen by Galileo during the times when the highest impact rates were detected. A longer period of about 37 hours ±10% seems to be indicated by the Fourier analysis but more data will be needed to confirm this period. Furthermore, the dust impact rate is correlated with Galileo's position in the Jovian magnetic field, but there is a phase shift between both Ganymede flybys. Both the 5 and 10 hour periodicity and the correlation with Galileo's position in the magnetic field, are clear evidence for dust particles whose trajectories are dominated by electromagnetic interactions with the Jovian magnetic field. The time variability is caused by the deflection of dust particles out of the equatorial plane (where the source region is assumed to be located: Io, the Io torus, or the Gossamer ring) by Jupiter's inclined magnetic field. Such deflection had been confirmed by Ulysses' finding of dust streams at 45° above Jupiter's equatorial plane [*Baguhl et al.,* 1993]. The vanishing impact rate after perijove is an effect of geometry: expected dust trajectories are outside the FOV of the detector.

The observed impacts in interplanetary space have been explained as streams of tiny particles electromagnetically ejected from the Jovian system [*Horányi et al.,* 1993] and [*Hamilton and Burns,* 1993]. Modeling of the dust trajectories shows that the impact directions observed in interplanetary space are strongly correlated with the interplanetary magnetic field [*Zook et al.,* 1996]. From this it was concluded that particles range around 10 nm in radius and have speeds in excess of 200 km/s which is outside the calibrated mass and velocity ranges of DDS. Unfortunately, charges on the dust grains cannot be reliably measured, and we have to rely on theoretical considerations (see accompanying paper by [*Horanyi et al.,* 1997], this issue).

There are several additional features of the small dust particle observations that modeling must explain: The change of impact direction by 180° near Ganymede's orbit (Fig. 2 and 3). Because of the detection geometry this may be due to a change of Galileo's position relative to the source region (cf. inset in Fig.1): before days 178.5 and 250.3, respectively, the sensor could only detect particles approaching Galileo from the direction of the spacecraft motion, whereas particles recorded later reached the sensor from the direction against the spacecraft motion. Similarly, after perijove passage the dust stream may have gone out of view of the sensor leading to the observed termination of small dust impacts (day 181 after the noise rate went down and day 251.5). The drop of the impact rate between 20 and $15R_J$ (day 178.5 and 250.3) is not easily understood as the effect of Galileo passing in front of the source region. From the anti-Earth direction the detection sensitivity is only reduced by about 25% while the impact rate decreases by about a factor of 10. Alternatively, the drop in impact rate could be due to shielding of the source by Ganymede during the flybys.

There is no clear correlation of the impact rate with any satellite position, which indicates that the source region is probably extended (e.g. Io torus or Gossamer ring). There are several indications that variation in the source strength or the conditions during passage from the source to the spacecraft modify the impact rate by orders of magnitude within days. The observed impact rate during the first Ganymede flyby which showed a strong maximum 2 days before CA had this characteristic. Another hint is that the impact rate showed no obvious $1/r^2$-dependence with distance from the assumed source region within the inner Jovian system.

The second category of particles, which contains only a handful of impacts but which occurred within a few minutes of Ganymede CA, has the signature of dust released from Ganymede: the impact rate is strongly peaked at Ganymede CA and the impact directions are compatible with a Ganymede source (note that only particles arriving from about 270° can be explained by a Ganymede source, whereas 90° is not compatible with Ganymede). These particles could be secondary ejecta particles that are generated upon impact of other particles onto the surface of Ganymede. The sizes of ejecta particles could be in the range from 10 to several 100 nm radius with impact speeds from 30 to 400 km/s. These ranges depend on whether we apply our empirical calibration [*Grün et al.,* 1995] or we accept that these particles are outside the range of our calibrations, just like the dust stream particles. Since ejecta particles have been recorded very close to their probable source a lower impact speed and a larger dust size is suggested.

Big particle impacts behave quite differently than dust stream particles: their impact rate peaks near perijove where the change of rotation angle occurs. Such a population of particles has also been observed by previous spacecraft carrying dust detectors through the Jovian system: Pioneers 10 and 11, [*Humes,* 1980], and Ulysses, [*Grün et al.,* 1992b]. The six impacts on days 250 to 252 with rotation angles of about 270° are compatible with particles orbiting on prograde or retrograde orbits, whereas the impacts on days 183 and 253 with rotation angles of 90° can best be explained by highly inclined or even retrograde orbits. Therefore, beside a population of particles orbiting Jupiter on prograde orbits which could be ejecta from the inner Jovian satellites there has to be a population on highly inclined or retrograde orbits [*Zook and Su,* 1982]. Another possibility is dust left-over from the break-up of comet Shoemaker-Levy 9 in 1992 [*Horányi,* 1994]. Further study is needed to test these hypotheses with Galileo data.

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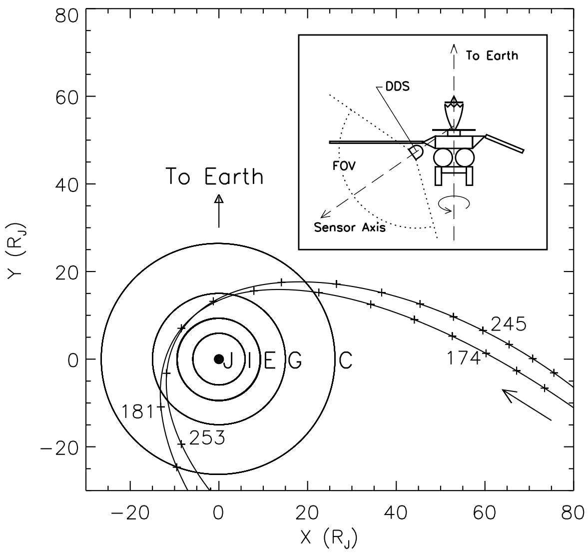

Figure 1. Galileo's trajectories during both Ganymede flybys projected onto Jupiter's (J) equatorial plane (Jupiter radius, $R_J = 71,492\,km$). The orbits of the Galilean satellites are shown: Io (I), Europa(E), Ganymede (G), and Callisto (C). Dates are marked by crosses (numbers give day of year) on Galileo's paths through the Jovian system. The inset shows the spacecraft orientation: the antenna (top) points towards Earth, and the dust detector (DDS) faces the anti-Earth hemisphere. During one spin rotation of the spacecraft the sensor axis scans a cone with 110° opening angle. The dust detector itself has 140° field of view (FOV).

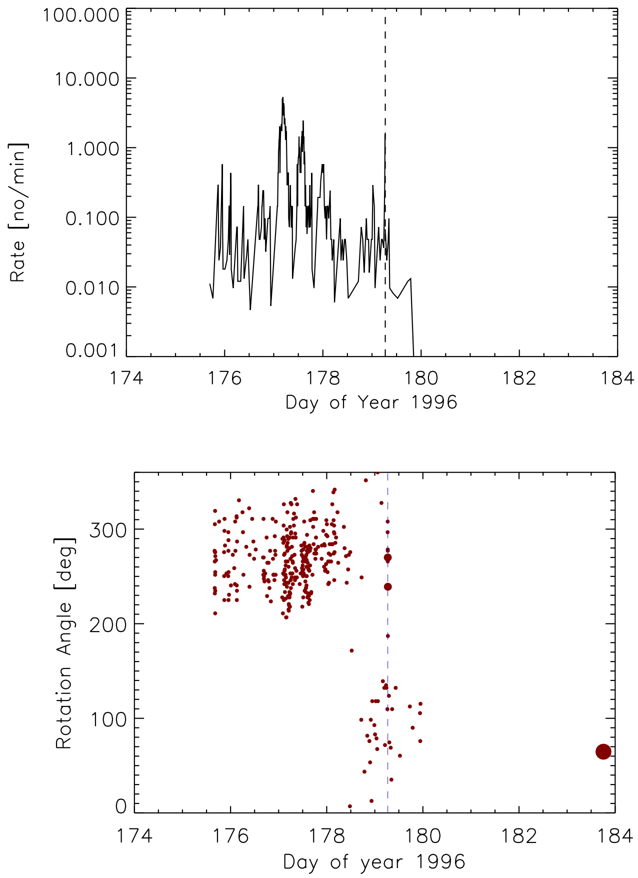

Figure 2. Dust data obtained during the first Ganymede flyby (27 June 1996). Closest approach (CA) to Ganymede is indicated by a dashed line. Upper panel: impact rate of small dust particles (ion collector charge $Q_I < 10^{-13}$ C). Shortly after CA high noise rate caused deadtime which significantly reduced the number of recorded impacts. Note the ten hour periodicity in the impact rate. Lower panel: sensor direction at time of dust particle impact for those impacts for which complete information was available on the ground. The symbol sizes indicate the different impact charges (smallest symbols: $Q_I < 10^{-13}$ C; for the larger dots the impact charges are $Q_I \sim 10^{-13}$ C and $\sim 10^{-11}$ C, respectively.) At 0° the sensor points close to the ecliptic North direction, at 90° and 270° the sensor points close to Jupiter's equatorial plane.

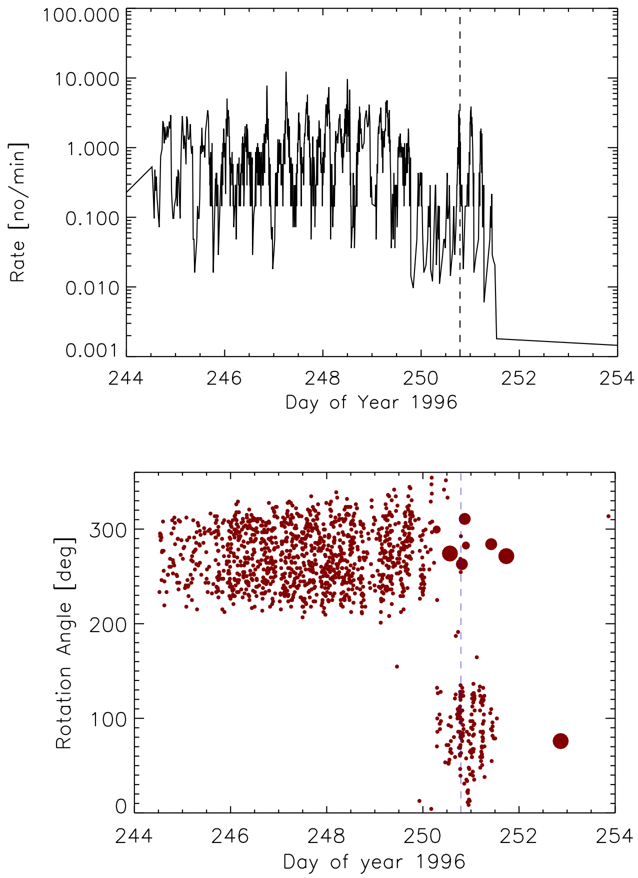

Figure 3. Same as Fig. 2, but for the second Ganymede flyby on 6 Sept 1996. Due to a different instrument configuration, deadtime did not affect the recording of dust impacts in the inner Jovian system. The reduced impact rate about one day after Ganymede CA is real. The symbol sizes in the lower panel represent 4 orders of magnitude of impact charge.