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Science, New Series, Volume 274, Issue 5286 (Oct. 18, 1996), 399-401.

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About a hundred dust impacts per day were detected during the first week in December 1995 by Galileo during its approach to Jupiter. These impacts were caused by submicrometer-sized particles that were just above the detection limit. After the closest approach to Io on 7 December, impacts of these small particles ceased. This effect is expected for dust grains emitted from Io that exit the field of view of the instrument after the flyby. The impact rate of bigger micrometer-sized dust grains continued to increase toward Jupiter. These dust particles are in orbit about Jupiter or are interplanetary grains that are gravitationally concentrated near Jupiter.

The Galileo dust detector system (DDS) (*1*), like its twin aboard Ulysses (*2*), is an impact ionization detector that measures the plasma cloud released upon impact of submicrometer- and micrometer-sized dust particles onto the detector. Only dust grains within the field of view (FOV, Fig. 1) are sampled. From each impact three independent measurements of the impact-created ionization cloud were used to derive the mass and impact speed of the particle (*3*). From the coincidence time of the three charge signals a classification was derived, with class 3 being dust impacts and class 0 being noise events. Depending on the noise rate of the charge measurements on the individual channels, classes 1 and 2 can be considered true dust impacts or spurious noise events. Because of the expected increase of the high energy (megaelectron volts) electron flux near Jupiter the detection thresholds of the channels were increased, and the high voltage on the channeltron detector was lowered at a distance of 15 R_J (Jupiter radius, R_J = 71,492 km), which resulted in a reduction of the sensitivity of the detector by about a factor of 6. Here we consider class 3 events and those class 2 events that were at least a factor of 20 above the detection threshold and that were not affected by noise. From 1 to 6 December 1995 DDS data were received on Earth about once a day in the form of memory-read-outs (MROs) (*4*). On 28 December an MRO with data from Io and Jupiter flybys was received. From 7 December 15:21 UT to 18:25 UT, around the time of Galileo's closest approach (CA) to Io (17:45 UT), DDS data were collected and recorded on Galileo's tape recorder. Another 2 hours of DDS data were recorded shortly after CA to Jupiter (21:53 UT). Because of the short duration of the recorded periods only a few class 3 impacts were contained in the data from the tape recorder. In early December 1995 while Galileo was already inside the jovian magnetosphere, DDS recorded small dust impacts (impact charges from 10^{-14} C to 10^{-12} C) at a mean rate of about 150 events per day (Fig. 2A). On 6 December, at a distance of 15 R_J, after the sensitivity of the sensor was reduced, the recorded impact rate dropped to only about 10% of the previous impact rate. During the 36-hour period of reduced sensitivity 19 dust impacts were recorded up to the CA to Io in the lowest amplitude ranges and none thereafter. In view of the decreased sensitivity, this leads to an almost constant rate of recorded small dust particles up to the CA to Io. Seven dust impacts with large signal amplitudes (impact charges from 10^{-12} C to 10^{-8} C) were observed only close to Jupiter (Fig 2B). Most of them were recorded in the period from just before the CA to Io until the CA to Jupiter, where the high voltages of the instrument were shut off in order to save it from hazards associated with insertion of Galileo into Jupiter orbit.

DDS also measured impact directions (Fig. 3A). Although the uncertainty of a

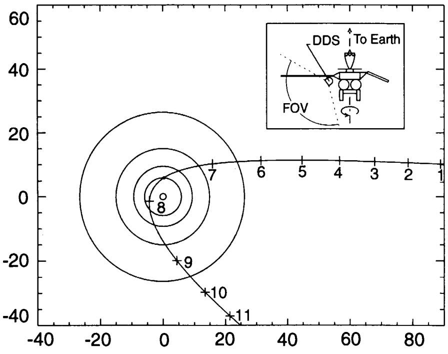

Fig. 1. Galileo's trajectory and dust sensing geometry projected onto Jupiter's equatorial plane. Crosses on Galileo's trajectory mark the positions on 0 UT 1 to 11 December 1995. Jupiter and the orbits of Io, Europa, Ganymede, and Callisto are shown. In the inset the Galileo spacecraft is sketched at the orientation it was in during most of the time: the antenna (top) points toward Earth and the dust detector (DDS) faces the anti-Earth hemisphere. Galileo spins around the spacecraft-Earth line while the DDS-axis and the field of view (FOV) scans a cone with 110° opening angle.

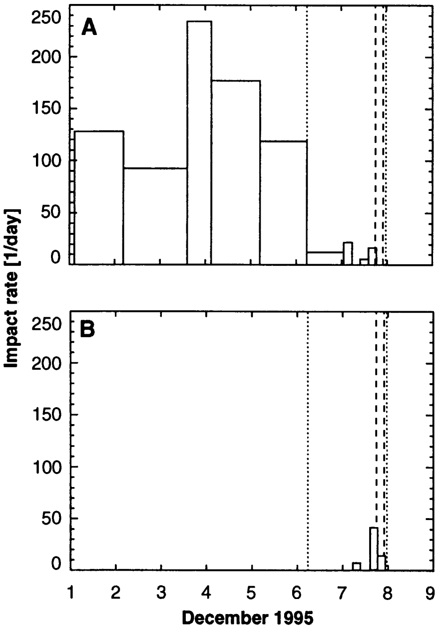

Fig. 2. Dust impact rates. Times of CA to Io and then Jupiter are indicated by dashed lines, while times when the detector's sensitivity was reduced are indicated by dotted lines. (**A**) Impacts of submicrometer-sized particles that generated impact charges from 10^{-14} to 10^{-12} C (class 3 impact events). (**B**) Impacts of micron-sized grains with impact charges $>10^{-12}$ C (class 2 and 3 events).

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single impact direction is ±70°, the average direction of a stream of dust particles is much better defined. During Galileo's approach to Jupiter impact directions of submicrometer-sized grains were concentrated between 180° and 360°. Near Galileo's CA to Io the range of impact directions widened, and dust grains even arrived from the opposite direction. The amplitudes of the impact charges showed significant variations during the approach to Jupiter (Fig. 3B). Galileo observed at least two different sizes of dust particles: small submicrometer-sized particles during the approach to Jupiter all the way up to the CA to Io and bigger micrometer-sized dust grains just inside a distance of about 10 R_J.

Collimated streams of submicrometer-sized dust detected by the Ulysses dust detector came from a source in the jovian system (*5*). Galileo also detected dust streams in interplanetary space on its approach to Jupiter (*6*) and confirmed the jovian source. Horanyi *et al.* (*7*) and Hamilton and Burns (*8*) showed that strong electromagnetic forces, acting on positively charged submicrometer-sized dust near Jupiter, actually overcome the planet's gravity and eject small debris into interplanetary space with high velocities. These studies proposed different sources for the jovian dust: Volcanic eruptions on Io (*7*) and collisions in Jupiter's Gossamer ring (*8*). Hamilton (*9*) recently argued that negatively charged submicrometer-sized dust released from Io may be temporarily stored in a broad ring extending inside Io's orbit. Analysis of the interplanetary trajectories of Ulysses dust stream particles by Zook *et al.* (*10*) suggest that they traveled at speeds of several hundreds of kilometers per second and that particle sizes were about 10 nm. These speeds and sizes are consistent with both models if the tiny grains start to accelerate outward from about the distance of Io.

The flux of submicrometer-sized grains did not increase dramatically, as would be expected for a near-Jupiter source that ejects particles in all directions. Instead, the rate of detected submicrometer-sized grains remained roughly constant up to the CA to Io (Fig. 2). Galileo's approach was nearly along the jovian equatorial plane, a region that may be partially shielded from a near-Jupiter dust source by the dense plasma of the Io torus. Alternatively, because escaping dust particles are accelerated by the magnetic field, they are slower and harder to detect close to their source region: only the largest of the emitted particles exceed the detection threshold of DDS.

The detection of small particles near Io CA is also significant. Within the 4-hour time interval before the CA to Io, three small dust impacts were detected (one within a minute before CA), whereas none were seen in the following 4-hour interval (up to the CA to Jupiter at 4 R_J). At an average impact rate of three impacts per 4-hour interval there is a 5% chance that an impact was missed within the second 4-hour time interval. The lack of particles capable of producing class 3 signals inside Io's orbit is probably real. In summary, these data do not yet rule out any of the possible sources, but point toward Io as the probable source of the dust streams.

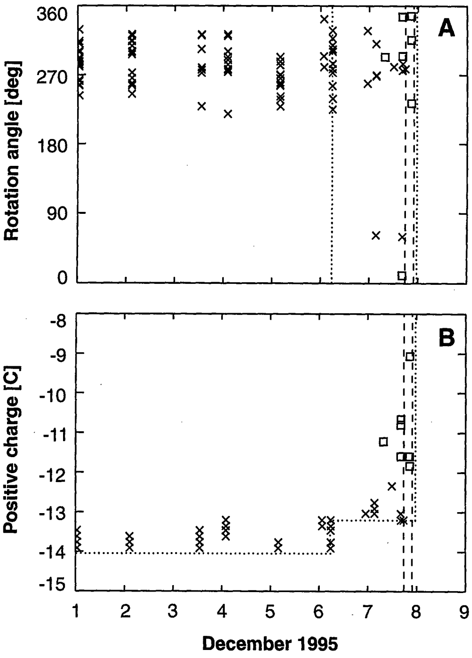

Fig. 3. Impact parameters of recorded dust particles (class 3 and large class 2 impacts). The information displayed is derived from completely transmitted data in MROs up to 28 December; that is, only complete information on impacts that occurred shortly before the read-out is displayed. The symbols indicate the magnitude of the impact charge recorded (crosses: $<10^{-12}$ C, squares: $\geq 10^{-12}$ C). On 7 December, closest approaches to Io and Jupiter are indicated by dashed lines. Changes of the detection threshold are marked by dotted lines. (**A**) Sensor direction at time of impact. At rotation angle 0° the sensor axis points closest to the ecliptic north direction, at 90° the sensor points closest to the direction of Jupiter's motion around the sun. The direction to Io is at about 270° during approach and shifts by 180° after the flyby. (**B**) Impact charges. The positive charge released by high-velocity impacts was measured to be proportional to $mv^{3.5}$ (m is particle mass, v is its impact speed) from calibration experiments (*4*). The DDS classifies the positive charge released by each impact into 1 of 48 discrete logarithmically spaced levels that cover a range of six orders of magnitude of charge. The dotted staircase line at the bottom of the figure indicates the charge detection threshold.

In addition to Galileo's jovian dust measurements, there is also data from dust detectors aboard Ulysses, Pioneer 10, and Pioneer 11. Each of these sensed $\sim$5 to 10 dust grains with sizes of 1 to 10 μm (*3*, *11*). There are three general sources for micrometer-sized dust around Jupiter: (i) gravitationally focused interstellar dust (ii) focused interplanetary dust, and (iii) bound jovian dust. Humes *et al.* (*11*) analyzed the Pioneer data and concluded the jovian dust detections could be explained by focused interplanetary dust. The results of Ulysses and Galileo, however, suggest that interstellar dust (about 0.4 μm in radius) dominates the flux of grains beyond $\sim$3 AU (astronomical units). It is possible, though, that interplanetary dust dominates near Jupiter because it is more strongly focused than interstellar dust because interplanetary dust travels slower than Jupiter. Furthermore, three of the Ulysses (CA to Jupiter at 6.3 R_J) near-Jupiter particles come from directions incompatible with the interstellar direction, which suggests that this dust had an interplanetary or jovian source. Finally, the near-Jupiter detection rates for Ulysses and Galileo are too large to be easily explained by focused interstellar dust.

Potential jovian sources for large dust grains near Io's orbit include (i) the outer prograde and retrograde satellites, (ii) the four Galilean satellites, and (iii) the jovian ring. Micrometer-sized dust from distant outer satellites is rapidly perturbed onto highly eccentric and inclined orbits that penetrate the inner jovian system (*12*). This source forms a diffuse but extended pancake-shaped halo of dust around Jupiter. Impacts of interplanetary or interstellar dust onto the Galilean satellites themselves will release small amounts of micrometer-sized dust that will remain in orbit for tens to hundreds of years. Gravitational interactions with the parent satellite and radiation forces can perturb dust onto moderately eccentric and inclined orbits. Finally, dust in the jovian Gossamer ring may be dragged outwards by plasma drag, but it should be reabsorbed by Io within about 10 years of encountering that satellite.

REFERENCES AND NOTES

1. E. Grün *et al.*, *Space Sci. Rev.* **60**, 317 (1992). The Galileo dust detector had a sensitive area of 0.1 m^2 and a 140°-wide conical FOV. It was mounted on the spinning section of the Galileo spacecraft at an angle of 55° with respect to the positive spin axis (opposite to the antenna direction which pointed toward Earth). Only dust particles with relative velocity vectors within the FOV of the detector could

be measured. The impact direction was determined by the spin position (or rotation angle) of the spacecraft at the time of impact. This sensor mounting direction constrained the directions from which dust grains could be sensed. This limitation varied with spacecraft rotation angle and with spacecraft location along its trajectory. During Galileo's approach to Jupiter dust particles impacting the DDS from the inner jovian system (that is, from inside the position of Galileo) could be detected when the detector was facing Jupiter; at a spin position half a rotation later DDS was facing away from Jupiter and these particles could not enter the detector. Shortly after Galileo's CA to Jupiter, Jupiter and the inner jovian system was in the Earth-facing hemisphere as seen from Galileo, and no dust grains emanating from that region could reach the dust detector.

2. E. Grün *et. al.*, *Astron. Astrophys. Suppl.* **92**, 411 (1992).
3. E. Grün *et al.*, *Science* **257**, 1550 (1992).
4. Each event detected by DDS was recorded in two ways [see also E. Grün *et al.*, *Space Sci.* **43**, 941 (1995)]: (i) it was counted in 1 out of 24 accumulators according to its class and signal amplitude; and (ii) the complete information (all signal amplitudes, event time, sensor direction and other supplementary data) was stored in an instrument data frame (IDF). Up to 40 new IDFs were stored in DDS memory that were either continuously read out at high rate to the tape recorder or all 40 IDFs were read out at once in a memory-read-out (MRO). Each MRO contained a complete set of event counters. From these data impact rates were calculated. In addition to the counter information each MRO contained 16 IDFs of class 3 impacts and 24 IDFs of lower class events. The event time information that was included in an IDF had a time resolution of 4 hours. Depending on the impact rate and the time between two consecutive MROs the complete information of only a fraction of the impacts that were detected by DDS was received on Earth. DDS data that were stored on Galileo's tape recorder contained highly time resolved information: a complete set of DDS data was recorded about once a minute.
5. E. Grün *et al.*, *Nature* **362**, 428 (1993).
6. E. Grün *et al.*, *ibid.* **381**, 395 (1996).
7. M. Horanyi, G. E. Morfill, E. Grün, *ibid.* **363**, 144 (1993); *J. Geophys. Res.* **98**, 21245 (1993).
8. D. P. Hamilton and J. A. Burns, *Nature* **364**, 695 (1993).
9. D. P. Hamilton, *Div. Planet. Sci. Abstr.*, in press.
10. H. A. Zook *et al.*, in *Physics, Chemistry, and Dynamics of Interplanetary Dust*, B. A. S. Gustafson and M. S. Hanner, Eds. [ASP Conference Series (1996)], vol. 104, pp. 23–25; H. A. Zook *et al.*, *Science*, in press.
11. D. H. Humes, J. M. Alvarez, R. L. O'Neal, W. H. Kinard, *J. Geophys. Res.* **79**, 3677 (1974).
12. D. P. Hamilton and J. A. Burns, *Icarus* **96**, 43 (1992).

13. We thank the project, operations, and data system teams from the Jet Propulsion Laboratory for their roles in the successful flight of Galileo to and around Jupiter and the recovery of high-quality data. This work was supported by DARA.

4 September 1996; accepted 24 September 1996

Electron Beams and Ion Composition Measured at Io and in Its Torus

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Intense, magnetic field–aligned, bidirectional, energetic (>15 kiloelectron volts) electron beams were discovered by the Galileo energetic particles detector during the flyby of Io. These beams can carry sufficient energy flux into Jupiter's atmosphere to produce a visible aurora at the footprint of the magnetic flux tube connecting Io to Jupiter. Composition measurements through the torus showed that the spatial distributions of protons, oxygen, and sulfur are different, with sulfur being the dominant energetic (>~10 kiloelectron volts per nucleon) ion at closest approach.

On 7 December 1995, the Galileo spacecraft flew through Io's plasma torus on a trajectory that included a close flyby of the moon at an altitude of 890 km [0.5 R_{Io} (Io radii)]. Measurements made by Galileo's energetic particles detector (EPD) (*1*) were recorded on the tape recorder and transmitted to Earth in June 1996. Here we present the spatial dependence of charged particle intensities through the torus passage and observations of the particle pitch angle distributions at Io.

The correspondence of Galileo and Voyager 1 (*2*) total ion intensities (Fig. 1A) is quite good given the time and spatial differences between the observations. Voyager 1 passed by Io at a distance of nearly 22,000 km (~11 R_{Io}) about 17 years ago. An important new aspect of the EPD composition data is that although all species decrease in intensity as Io is approached from higher jovian altitudes, the proton (P) and oxygen (O) intensities increase at altitudes below the orbit of Io whereas sulfur (S) intensities continue to decrease. At either a given fixed energy or energy per nucleon, S ions have the largest intensities at Io closest approach. At higher energies, O and S intensities display a mild decrease inward of Io, whereas P intensities again increase, as inferred from the total ion intensity plot. This behavior may reflect gyroperiod effects through the spatially varying density of the torus, gyroradius dependencies in the transport properties of the observed ions, and possible differences in charge exchange and Coulomb losses as the ions are transported through the Io torus, or a combination of these effects.

Localized high-energy particle intensity decreases (Fig. 1A) occur within several Io radii of Io closest approach but are most noticeable in the higher energy (greater than a few hundred kiloelectron volts) electron channels. The effect of the much closer Galileo flyby (compared with Voyager) is evidenced by a more than two-order-of-magnitude decrease in the electron fluxes. At lower energies, the electron intensities display a markedly different behavior (Fig. 1B), with a number of sharp spikes seen. The spikes are presumed to continue through the instrumental mode change period that yielded the large decrease in count rates nestled within the observed spike structure (*3*). The region where the spikes were observed was centered near Io closest approach (Fig. 1C).

Expanding the region of closest approach reveals that S ions surprisingly show a broad field-aligned maximum that contains a small decrease of intensities in the most field-aligned directions throughout the entire Io flyby (Fig. 2). As Galileo approaches Io, intensities of ions with pitch angles close to 90° steadily decrease and cause the increasing anisotropy (Fig. 2). Given the observed orientation of the magnetic field (*4*), this is qualitatively consistent with the expected pitch angle dependence of energetic S ions that can come closest to Io and be lost to its surface or atmosphere; that is, S ions at a 90° pitch angle are most likely to be lost as compared with ions with field-aligned pitch angles.

As the spacecraft approaches Io, the electron distributions gradually evolve (Fig. 2) from a trapped-like distribution with maximum fluxes at a 90° pitch angle to a distribution with peaks appearing between 0° and 90° and between 90° and 180° (butterfly distributions). Near closest approach the electron distribution suddenly (within one spacecraft spin, ~20 s) changes to an intense, bidirectional field-aligned beam,

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