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Ulysses Dust Measurements Near Jupiter

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Submicrometer- to micrometer-sized particles were recorded by the Ulysses dust detector within 40 days of the Jupiter flyby. Nine impacts were recorded within 50 Jupiter radii with most of them recorded after closest approach. Three of these impacts are consistent with particles on prograde orbits around Jupiter and the rest are believed to have resulted from gravitationally focused interplanetary dust. From the ratio of the impact rate before the Jupiter flyby to the impact rate after the Jupiter flyby it is concluded that interplanetary dust particles at the distance of Jupiter move on mostly retrograde orbits. On 10 March 1992, Ulysses passed through an intense dust stream. The dust detector recorded 126 impacts within 26 hours. The stream particles were moving on highly inclined and apparently hyperbolic orbits with perihelion distances of >5 astronomical units. Interplanetary dust is lost rather quickly from the solar system through collisions and other mechanisms and must be almost continuously replenished to maintain observed abundances. Dust flux measurements, therefore, give evidence of the recent rates of production from sources such as comets, asteroids, and moons, as well as the possible presence of interstellar grains.

Ulysses carried a new type of dust detector through the Jovian system. The instrument (hereafter called "DUST") is sensitive to submicrometer- to multimicrometer-sized dust particles. DUST has performed flawlessly at close to its maximum sensitivity since launch. Two results obtained by the sensor include the unexpected detection of meteoroid streams in the outer solar system as well as a relative lack of small dust in the region near Jupiter traversed by Ulysses. Before Ulysses our knowledge about the existence of dust in space near Jupiter was based on two types of observations:

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1) Pioneer 10 recorded ten meteoroid penetrations (*1*) and Pioneer 11 recorded five (*2*) during 5-day periods when these two spacecraft flew by Jupiter. Corresponding sensitive areas were: Pioneer 10, 0.13 m^2 and Pioneer 11, 0.5 m^2. The minimum masses that could be sensed at an impact velocity of 20 km/s (comparable to the velocities of impact to be expected during much of the Jovian flyby) were 8×10^{-10} g for Pioneer 10 and 6×10^{-9} g for Pioneer 11.

2) When Voyager 1 flew by Jupiter (*3*), it photographically recorded a relatively bright dust ring between about 1.72 and 1.81 Jovian radii (1 R_J = 71,400 km). Later a tenuous outer extension of that ring was discovered in the photography (*4*) that extended out to about the orbit of Thebe at 3.1 R_J.

The DUST sensor has a 140° conical field of view and is mounted to point nearly perpendicular (85°) to the spacecraft spin axis. The direction of an impact is determined from the spacecraft spin angle at the moment of impact. DUST is a multicoincidence impact-ionization detector (*5*) that senses the ionized plasma generated when a dust particle impacts with high speed upon a hemispherical gold target with a sensitive area of 0.1 m^2. The plasma charges are separated, and three signals can be derived for every impact: a negative charge pulse, a positive ion charge pulse, and a channeltron charge pulse that is derived from part of the positive ions. Through empirical calibration both the particle mass and speed can be derived from the signal amplitudes and rise times (*6*).

There is some noise in the lowest amplitude events. Therefore, we only report on noise-free events that, for those we call "small" events, correspond to an impact mass of about 10^{-14} g at an impact velocity of about 15 km/s. When we better understand which very low amplitude events are truly noise, a lower mass threshold can be established. This will permit publication of higher fluxes. During the Ulysses Jupiter flyby [see (*7*) for trajectory characteristics], the experiment was set to a configuration that balanced instrument safety against sensitivity to dust impacts. To avoid enhanced noise (*8*), the instrument was switched to a reduced sensitivity (threshold mass of about 10^{-13} g to record only "large" impacts) 16 hours before closest approach. At 16 hours after closest approach the instrument was set back to high sensitivity. These precautions resulted in an absence of noise events during the Jupiter flyby. As impact velocities are uncertain to about a factor of 2, impact masses are uncertain by about a factor of 10.

During the first 80 days of 1992 (see Fig. 1A) impact rates from both large and small events display two different modes: one is a slowly varying background mode, and the other is a mode of short-term peaks. We call a sequence of dust impacts a peak if the count rate averaged over three impacts is at least a factor of 10 above the background. There were two peaks of large impacts: one at the beginning of the year consisting of three impacts and one around day 39 consisting of nine impacts. In addition, two peaks of small impacts were recorded: one on day 7 (four impacts) and the other a very pronounced peak during days 70 and 71 consisting of 126 impacts.

The peak centered near day 39 corresponds to the flux near the closest approach to Jupiter, at about the time of equatorial plane crossing. Because of the reduced sensitivity of the instrument, only large impacts could be recorded there. Inside 50 R_J only two impacts occurred on the approach leg while seven occurred on the outgoing leg of the flyby trajectory. The full significance of this is still being investigated.

The spin angles of the dust detector at the times of impact (Fig. 1B) were scattered over nearly the full range of possible values. However, the impacts during peak times, except for the ones near Jupiter, display limited ranges of spin angles. This result indicates that particles composing a peak in the impact rate arrived on similar trajectories and we consider them members of a "dust stream."

Starting at 9:00 hours on 10 March 1992, Ulysses encountered an intense dust stream at a distance to the sun of 5.4 astronomical units (AU) and a distance to Jupiter of about 540 R_J or 0.26 AU. The nonstream background impact rate at that time was about 0.25 per day and increased by a factor of about 1000 within a few hours. The impact rate rose slowly during the first 10 hours of the stream (Fig. 2A) and then increased by a factor of 8 over the next 10 hours before dropping. After 26 hours the impact rate dropped to its initial value. The extension of the dust stream along the trajectory of Ulysses was about 800,000 km. A total of 126 particles were registered.

The similarity of rise times of the ion charge signals strongly suggests that the velocities of particles in the stream were all about the same, with an indicated velocity of 40 to 50 km/s (the uncertainty is about a factor of 2). The ion charge amplitude was quite low for all particles in the stream, indicating that particle masses did not exceed about 10^{-13} g. Although all particle masses were in the same small mass range, particle mass did slowly increase from the beginning to the end of the stream, as shown by the averaged impact ion charge depicted in Fig. 2B. At constant velocity, laboratory calibrations show that impact ion charge is proportional to particle mass.

The distribution of spin angles during the stream impacts is shown in Fig. 3. It is roughly symmetric about 345° (−15° in Fig. 3) and has a total width of about 125°. This angular distribution is consistent with a directional dust stream that passes almost completely across the full field of view of the sensor during spacecraft rotation. The stream direction is therefore determined to within a few degrees of uncertainty.

During the time of the dust stream, the plasma wave experiment on-board Ulysses (9) was subject to nonnominal signals that are interpreted as plasma generated from dust impacts on the spacecraft structure (*10*). Similar signals were observed by a plasma wave instrument during the Saturn ring plane crossing of the Voyager 2 space probe (*11*).

Because of the strong change in spacecraft trajectory at Jupiter, where the orbital inclination increases to 80° the dust detector's sensitivity to particles of a given orbit class changes accordingly. As shown in Fig. 4, the ratio of the theoretically modeled background flux before the Ulysses flyby to the background flux after the flyby is small for low orbital inclinations (i). At low inclinations, different orbital eccentricities cause significant effects. For retrograde orbits ($i \geq 90°$), the ratio can exceed unity and different eccentricities have little effect. For randomly inclined orbits the ratio is 0.4 to 0.6 depending on eccentricity as shown by the horizontal lines in Fig. 4.

The observed ratio of the background flux before the Ulysses flyby to the background flux after the flyby is nearly 2 with an uncertainty of a factor of 2. This high ratio points to a dust population with mostly retrograde orbits; highly inclined orbits had earlier been suggested from the Pioneer 11 data (2). Before day 39, most particles detected near the apex direction (dashed line in Fig. 1B) were almost certainly particles in heliocentric retrograde motion; the high Ulysses heliocentric radial velocity (about 14 km/s) before the Jupiter flyby made it difficult to sense particles in heliocentric prograde orbits, as their radiants would not fall within the sensor's field of view. After the Jupiter flyby, particles in retrograde orbits would generally be detected at spacecraft spin angles from 170° less than to 10° more than the spacecraft "apex direction." After day 44, all but one of the nonstream impacts, as well as the stream centroid, occurred in this retrograde range of directions (Fig. 1B). This result is totally consistent with, and supportive of, the theoretical modeling result.

Dust particles on highly inclined orbits

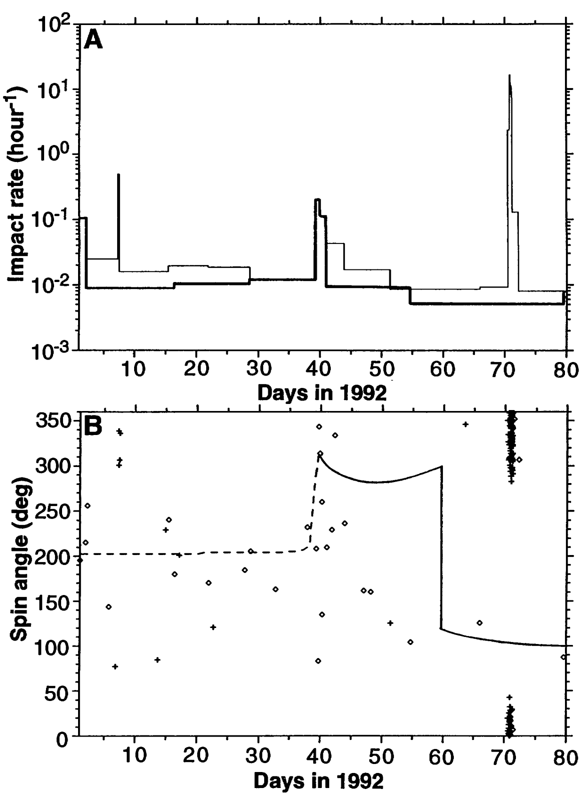

Fig. 1. Dust impacts recorded during the first 80 days of 1992. Jupiter closest approach occurred on day 39. (**A**) Impact rate. All impacts: (thin line, positive impact charge $IA \geq 10^{-14}$ C); large impacts: (thick line, $IA \geq 2 \times 10^{-13}$ C). The integration interval contains at least three impacts. (**B**) Spin angle at the time of impact [small impacts (crosses); large impacts (diamonds)]. The spin angle at which the dust sensor points closest to the direction of spacecraft motion (spacecraft apex) and where the spacecraft apex is also within the field of view of the dust sensor is shown by the solid line. The dashed line indicates the same direction but over a time interval during which the spacecraft apex never entered the field of view at any spin angle. The 80° shift in spacecraft apex on day 39 was caused by the Jupiter flyby; the shift of 180° on day 58 occurred because Ulysses went through solar opposition with Earth.

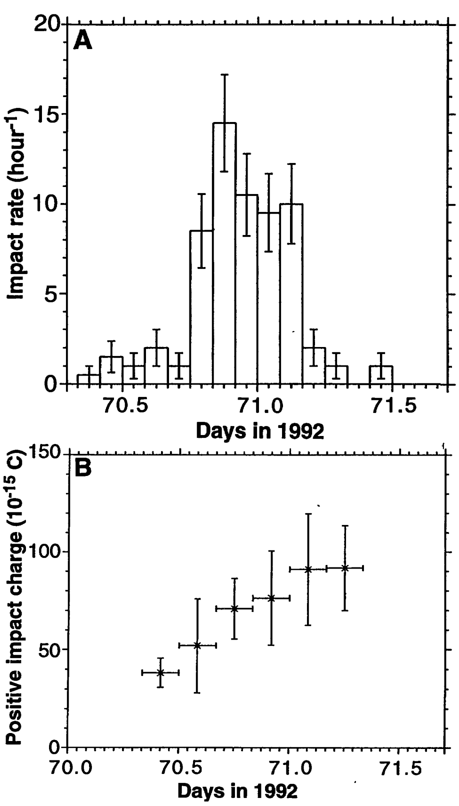

Fig. 2. Characteristics of the 10 March (day 70) dust stream as a function of time. (**A**) Impact rate. (**B**) Positive impact charge.

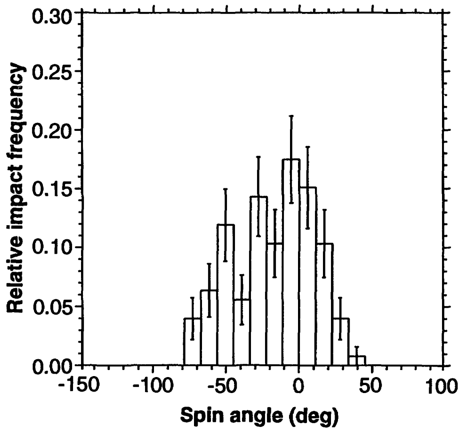

Fig. 3. Distribution of the spacecraft spin angle at the time of impacts of dust cloud particles on 10 March 1992.

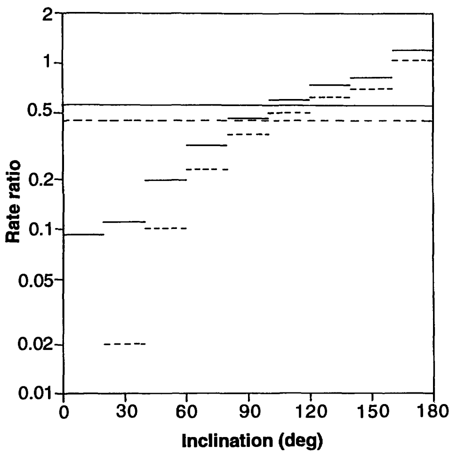

Fig. 4. Flux ratios (the flux before the Ulysses flyby to the flux after) are calculated for each of nine different 20° ranges of orbital inclination and are combined with two different orbital eccentricities [e = 0.1 (dashed line) and 0.9 (solid line)]. Also shown are flux ratios for the same two eccentricities combined with a random distribution of orbital inclinations.

are quite different from the population found by the Galileo and Ulysses detectors in the inner solar system (*12*): inside about 2 AU the observed fluxes are compatible with a population of interplanetary dust particles moving for the most part on low to moderately eccentric (e = 0.1 to 0.5) and low-inclination (i = 0° to 30°) orbits. Detailed modeling (*13*) confirms that different populations are needed, as one proceeds from 1 to 5 AU, to explain data from various space detectors and from ground-based observations.

An interesting analogy comes from a comparison with comets with large perihelion distances. Marsden (*14*) listed 28 parabolic or near-parabolic comets with perihelion distances outside 3.5 AU. Most parabolic comets have high and even retrograde inclinations. This similarity may reflect the possibility that parabolic comets are the parents of outer solar system dust detected by Ulysses.

Only three of the dust grain impacts that occurred during the Jupiter flyby are consistent with dust grains in prograde Jovian orbits. The rest can be attributed to a gravitationally enhanced flux of interplanetary meteoroids. Detailed modeling has not yet been done, but calculations indicate that the measured "gravitational enhancement" of the meteoroid flux is consistent with our Jupiter flux modeling for the time before and after the Jupiter flyby.

Surprisingly, we saw only three meteoroid impacts that could be attributed to Jupiter-orbiting particles during Jupiter closest approach. First, even with the reduced sensitivity of the Ulysses dust detector during the Jupiter flyby, the instrument was still sensitive to meteoroids four orders of magnitude smaller in mass than the meteoroids detected with the Pioneer 10 meteoroid sensor. The fact that Ulysses had a trajectory inclined 142° to the Jovian equator would increase impact velocities with prograde dust particles and hence result in a higher count rate. However, this flux increase was possibly counterbalanced by the fact that Ulysses did not spend much time near the Jovian equator.

It may be, for example, that submicrometer particles do not drift outward from their sources at the inner moons but drift inward instead under a gyrophase drift mechanism (*15*); or they are eliminated by sputtering (*16*) or mutual collisions; or some other mechanism is operating. Additional clues might be provided by the Galileo spacecraft, carrying Ulysses's twin dust detector, when it arrives at Jupiter in December 1995.

Both the narrow collimation and the mass dispersion of the 10 March dust stream resembles closely what one would expect from a detector crossing the dust tail of a comet. The total extent of the dust cloud is determined by three effects: (i) the time and duration of dust emission from the parent, (ii) the emission speed, and (iii) the size distribution of the dust particles. We do not know anything about the time and duration of the dust emission event despite several attempts to find the parent object by astronomical means. No known comet was nearby. The column density of the dust stream was about 1 cm^{-2} along the Ulysses trajectory. This value translates into an optical depth of 10^{-9} if one assumes a typical particle cross section of 10^{-9} cm^2. The corresponding surface brightness will be too small to be detectable by ground-based astronomical means. However, if the parent object is still nearby and active, there might be some denser parts of the dust cloud that are detectable. Several observatories took Schmidt plates, around the time of the dust stream detection, of the corresponding region of sky, but no possible identification has been reported to us to date.

An argument against the comet connection is that the comet would appear to be traveling at an exceedingly high speed of about 50 km/s relative to Ulysses. The heliocentric speed is similarly high. At the distance of Ulysses, the escape speed from the solar system is only 18 km/s. Therefore, even with an uncertainty of a factor of 2 in the speed, hyperbolic orbits with orbital inclinations of 110° to 140° and perihelion distances >5 AU for the dust particles seem to be required. No comet on such an orbit has ever been observed.

At the time of out observation of the dust stream, both Jupiter and the upstream direction of interstellar gas (*17*) were in the field of view of the dust sensor, but no conclusions can be drawn from these data. No matter what the origin of the 10 March dust stream may be, this dust stream was unlike any event known before.

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