DUST MEASUREMENTS DURING ULYSSES' 2^{ND} JUPITER ENCOUNTER

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ABSTRACT

In 2004 the Ulysses spacecraft had its second flyby at Jupiter at 0.8 AU from the planet. 28 dust streams emanating from the jovian system were identified over a 26-month period while the spacecraft was within 4 AU of the planet, and the dust instrument was operating, scanning jovigraphic latitudes from $+75°$ to $-25°$. From late 2002 until mid 2005, jovian dust stream particles dominated the overall impact rate, reaching a maximum of about 2000 per day in mid 2004. The dust stream data imply strong coupling of the grains to the interplanetary magnetic field. Ulysses also continuously monitored the interstellar dust stream in the heliosphere.

1. INTRODUCTION

The Ulysses spacecraft was launched in October 1990. A swing-by manoeuvre at Jupiter in February 1992 rotated the orbital plane 79° relative to the ecliptic plane (with a six-year orbital period and aphelion distance at 5.4 AU). Subsequent aphelion passages occurred in April 1998 and June 2004.

In 1991/92 within 2 AU from Jupiter, the dust detector on board (1) discovered a total of 11 periodic, collimated burst-like streams of submicron dust particles. While the particles' approach directions were roughly along the line-of-sight to Jupiter – suggesting a jovian origin – most streams deviated somewhat from this direction implying that strong non-gravitational forces must have been acting on the grains (2). Such forces are also required for dust to escape the jovian system. An approximately monthly (28 ± 3 days) periodicity of the streams implied strong particle interaction with the interplanetary magnetic field (3, IMF). Particle sizes derived from numerical simulations were about 10 nm and the particle speeds exceeded $200\,\mathrm{km\,s^{-1}}$ (4). From Galileo and Cassini dust measurements Io could be identified as the source for the majority of the grains (5; 6), and the streams served as a monitor of Io's volcanic plume activity (7).

In February 2004 – about 12 years after its initial flyby – Ulysses approached Jupiter a second time and had a closest approach distance of 0.8 AU. Because the spacecraft's orbital trajectory is almost perpendicular to the ecliptic plane, the dust streams could be measured over a large range in jovigraphic latitude β_J from the planet's north polar region down to just below the jovian equator ($75° > \beta_\mathrm{J} > -25°$; Fig. 1). This geometry provided unique conditions for jovian dust streams measurements beyond the jovian equatorial plane, and these data nicely supplement the Ulysses stream measurements of 1991/92 obtained with $-35° \leq \beta_\mathrm{J} \leq 0°$.

Another important discovery made with the Ulysses dust detector were interstellar dust grains sweeping through the solar system (2). The grains, which originated from the Local Interstellar Cloud (LIC), were identified by their impact direction and impact speeds, the latter being compatible with particles moving on hyperbolic heliocentric trajectories. The impact directions were – within the measurement accuracy – coincident with the upstream direction of the interstellar helium flow.

For Ulysses, the best conditions for detection of interstellar impactors are in the outer solar system beyond 3 AU and at high ecliptic latitudes and far away from Jupiter where impact rates of jovian stream particles or interplanetary grains are comparatively small. The dust dynamics is grain size-dependent and strongly affected by the interaction with the IMF and by solar radiation pressure. Ulysses has continuously monitored the interstellar dust flux in the heliosphere since 1992.

2. DUST MEASUREMENTS 2002 – 2006

2.1. Dust impact rates

Previous analysis has shown that – for stream particles – the charges Q_I generated during dust impact onto the target and subsequently measured at the ion collector grid of the instrument were generally below $10^{-13}\,\mathrm{C}$ (9, note that

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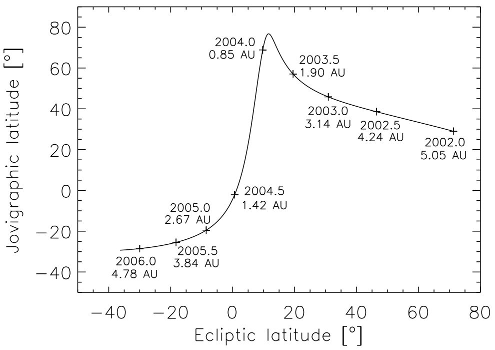

Figure 1. Ulysses' jovigraphic latitude β_J vs. ecliptic latitude β_{ecl} for 2002 to 2005. Distance from Jupiter r_J is indicated for selected times (reprinted from (8), with permission from Elsevier).

Q_I does not measure the charge carried by the dust particle itself). Q_I is the most suitable parameter for a general impact classification compared to the other charge signals because it is less affected by noise. By far, the majority of particles identified in the 2002 to 2006 Ulysses data set are below this threshold.

In the top panel of Fig. 2 we show the dust impact rate measured by Ulysses in the 2002 to 2006 interval. In this panel we show only impacts with impact charges $Q_I \leq 10^{-13}$ C which – in the time interval considered here – are dominated by jovian stream particles. The strongest dust streams appear as individual spikes. In November 2002, when the spacecraft was still at $r_J \simeq 3.4$ AU distance from Jupiter, it detected its first dust stream after 1992. Unfortunately, on 1 December 2002, while this very distant stream was still ongoing, the dust instrument was switched off for power saving on board the spacecraft. The instrument was not switched on again until six months later when Ulysses had already moved to within 2 AU of Jupiter, causing a significant loss of potential dust stream detections. The instrument was also switched off for three other much shorter intervals, as indicated by the shaded areas in Fig. 2. A total of 28 streams were identified between November 2002 and August 2005 (8).

In summer 2004, when Ulysses was close to Jupiter's equatorial plane, a particularly strong dust burst occurred with rates above 2000 per day, containing many more impacts than all of the other streams combined. This burst was the strongest dust emission measured from 2002 to 2005 and the second largest dust stream flux seen in interplanetary space. It was exceeded only by the fluxes measured by Galileo during approach to Jupiter in 1995. In the 2002 to 2005 interval, the dust impact rate varied by more than 4 orders of magnitude and in 2004/05 the streams were continuously detected from $r_J \simeq 0.8$ AU out to 4 AU, beating Ulysses' previous 2 AU record of 1991/92. During 10 of the identified 28 streams, the impact rates exceeded 100 per day.

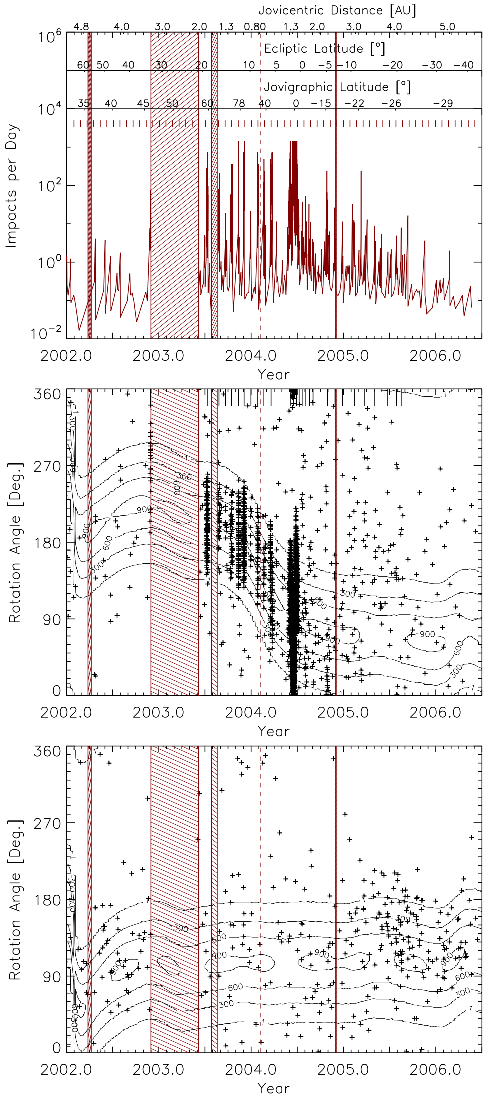

Figure 2. Ulysses dust measurements 2002–2006. A vertical dashed line shows Jupiter closest approach on 5 Feb. 2004, four shaded areas indicate periods when the dust detector was switched off. *Top panel:* Impact rate (impact charges $Q_I \leq 10^{-13}$ C). No smoothing was applied to the data. Distance r_J from Jupiter, ecliptic latitude β_{ecl}, and jovigraphic latitude β_J are shown at the top. Short vertical dashes indicate the solar rotation period. *Middle panel:* Impact direction (i.e. spacecraft rotation angle at dust particle impact; ecliptic north is at 0°; $Q_I \leq 10^{-13}$ C). Each cross indicates an individual impact. Contour lines show the effective sensor area for particles approaching from the line-of-sight direction to Jupiter, vertical dashes at the top indicate the dust streams. *Bottom panel:* Same as above but for $Q_I \geq 10^{-13}$ C. Here, contour lines show the effective sensor area for grains approaching from the upstream direction of interstellar helium.

Note that between October 2003 and June 2004, Ulysses' jovicentric distance r_J changed only relatively little between 0.8 and 1.3 AU, while the latitude β_J varied over almost the entire northern jovian hemisphere ($0° \lesssim \beta_J \lesssim +75°$). Ulysses thus scanned over a large latitude range with only little variation in jovicentric distance. In particular, the strong burst detected in summer 2004 occurred close to the jovian equator at about 1.3 AU, while near Jupiter closest approach at 0.8 AU, when the spacecraft was at $\beta_J \sim +50°$, the rates were about an order of magnitude lower (Fig. 2). Dust fluxes are higher closer to the planet, consistent with the expectation that closer to the source the flux should increase. For simple particle dispersion in space, the flux should drop with the inverse square of the distance from the source if the source strength remains constant. Ignoring the measurements obtained at low latitudes during the dust burst in mid 2004, the data are grossly consistent with this expectation, while close to the jovian equator, the fluxes are enhanced by 1-2 orders of magnitude (8). It implies that systematic and stochastic changes by orders of magnitude revealed within the jovian magnetosphere (7) mostly smear out in interplanetary space far away from the planet.

2.2. Impact directions

Ulysses is a spin-stabilised spacecraft with an antenna that usually points towards Earth. The dust sensor has a 140° wide field-of-view and is mounted nearly at right angles (85°) to the antenna pointing direction (negative spacecraft spin axis). Due to this mounting geometry, the sensor is most sensitive to particles approaching from the plane perpendicular to the spacecraft-Earth direction (1). The impact direction of dust grains is measured by the rotation angle which is the sensor viewing direction at the time of a dust impact. During one spacecraft spin revolution the rotation angle scans through a complete circle of 360°. It is measured in a right-handed system and 0° rotation angle is defined to be the direction closest to ecliptic north.

In the middle panel of Fig. 2 contour lines indicate the effective dust sensor area for particles approaching the spacecraft from the line-of-sight direction to Jupiter. Given that the grain speeds exceed the spacecraft speed by far ($\geq 200\,\mathrm{km\,s^{-1}}$; 4), grains approaching on straight trajectories from a source in the Jupiter system should arrive from close to the line-of-sight direction to the planet, while the directions of particles interacting with the IMF can differ significantly (4).

Many dust streams are easily recognised as vertical bands lying approximately in the line-of-sight direction to Jupiter. A few streams, however, strongly deviate from this direction. This is particularly evident for the stream measured at $r_J \simeq 3.4$ AU in November 2002 right before the switch-off of the instrument and for the burst detected in mid 2004. For most streams, the measured rotation angle ranges over more than 100°, consistent with the wide field-of-view of the dust sensor and the favorable spacecraft orientation for stream detection during this time.

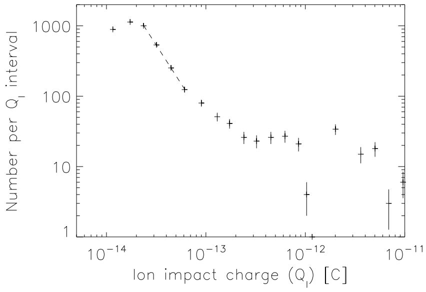

Figure 3. Charge distribution of impacts measured from 2002 to 2006. The gap at $Q_I \approx 10^{-12}$ C is due to an instrumental artefact. The dashed line is a power law fit dominated by jovian stream particles (number $N \sim Q_I^{-2.2}$).

The bottom panel of Fig. 2 shows impacts with larger impact charges $Q_I \geq 10^{-13}$ C. The most obvious difference as compared to the middle panel is the absence of the striping caused by jovian dust stream impactors. Impacts shown in this panel are dominated by interstellar grains and the approach directions of most particles are consistent with the upstream direction of the interstellar helium flow. Beginning in mid 2005, the impact direction seems to be shifted significantly from the helium flow. The reason for this shift remains mysterious and will be investigated in the future. Whether it is connected to a secondary stream of interstellar neutral atoms shifted from the main neutral gas flow (10) is presently unclear.

2.3. Impact charge distribution

The second and third panel of Fig. 2, which separate impacts based on impact charges (Q_I) implies that a reasonable separation between jovian dust stream particles and interstellar impactors can be obtained. In order to better define this boundary between the two dust populations, we show in Fig. 3 the charge distribution for all impacts detected in the 2002 to 2006 interval, with $Q_I \leq 10^{-11}$ C.

It is evident in Fig. 3 that at $Q_I \approx 2 \cdot 10^{-13}$ C the impact charge distribution flattens. The distribution for particles with $2 \cdot 10^{-14}\,\mathrm{C} < Q_I < 8 \cdot 10^{-14}$ C follows a power law with index -2.2, confirming results from Galileo measurements within the jovian magnetosphere (11). The distribution flattens below $2 \cdot 10^{-14}$ C, indicating that the sensitivity threshold of the instrument may not be sharp.

3. DISCUSSION

The short vertical dashes in Fig. 2 indicate the solar rotation period, and a closer inspection of the impact rate reveals that the dust streams fluctuate with this period. Frequency analysis of the dust and IMF data, both measured with Ulysses, show strong peaks at 26 days (8), closely matching the solar rotation cycle. This indicates that the solar rotation period dominates the fluctuations in the dust impact rate. At the jovian equatorial plane the periodicity switched to about 13 days, consistent with theoretical considerations (3). Comparison with the magnetic field measurements showed that the grain impact directions fluctuated with the orientation of the magnetic field vector due to the Lorentz force acting on the grains.

Galileo dust measurements obtained within the jovian magnetosphere monitored the dust emission of Io's volcanic plumes from 1996 to 2002 (7). Elevated dust fluxes could be correlated with plume sightings and surface changes on Io. Assuming homogeneous dust ejection from the Io torus towards all jovian longitudes and towards latitudes of $\pm 35^\circ$, the derived average dust emission rate was $0.1\text{-}1\,\mathrm{kg\,s^{-1}}$. Compared with $\sim 10^3\,\mathrm{kg\,s^{-1}}$ of plasma ejected from Io into the torus, the dust amounts to only 0.01-0.1% of the total mass released. While being a major dust source for the jovian system itself, Io is a minor source of interplanetary dust compared with comets and main belt asteroids ($\sim 10^4\,\mathrm{kg\,s^{-1}}$).

Estimates of Io's dust emission from the Ulysses measurements obtained in May/June 2004 at $r_\mathrm{J} \simeq 1.3\,\mathrm{AU}$ – using the same assumptions – give unrealistically high dust production rates exceeding $10^7\mathrm{kg\,s^{-1}}$. It clearly shows that this simple picture cannot be extrapolated into interplanetary space. From numerical simulations one expects particles to be transported to latitudes of $\pm 25^\circ$ rather homogeneously (12; 13) while the measurements imply a much stronger concentration towards Jupiter's equatorial plane. On the other hand, groundbased observations showed strong volcanic activity on Io on 29 May 2004 (F. Marchis, priv. comm.), coincident with the beginning of the strong dust burst measured with Ulysses. Thus, the dust burst may indeed – at least partially – be connected with a sharp increase in Io's dust emission.

Similar to the Ulysses findings for the jovian dust streams, Cassini measured strong fluctuations in the impact directions of saturnian stream particles (14). During a time interval when the directionality of the streams could be analysed, the authors identified three streams with impact rates exceeding 100 per day. For these streams, the grain impact directions deviated by about 90° from the line-of-sight direction to Saturn.

An additional – possibly important – phenomenon is corotating interaction regions (CIRs) which are compressed, high-speed solar wind regions characterised by enhanced IMF strength. The Lorentz force can be 5-10 times larger at these times, leading to i) stronger deviations from the Jupiter direction; ii) accelerated grains and enhanced detectability and iii) perhaps even destruction of larger grains and stream formation. The occurrence of the dust streams at Jupiter and Saturn is correlated with such events (2; 14) which is confirmed by the Ulysses 2002 to 2005 measurements (15). Perhaps CIRs compress the planet's magnetosphere enough to trigger a dust escape mechanism. In any case, CIRs bear further investigation as they appear to play a key role in forming or deflecting dust streams.

Ulysses monitored the interstellar dust flux between 3 and 5 AU. Dust measurements between 0.3 and 3 AU in the ecliptic plane exist also from Helios, Galileo and Cassini. This data shows evidence for distance-dependent alteration of the interstellar dust stream caused by radiation pressure, gravitional focussing and electromagnetic interaction with the time-varying IMF (16).

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