Discovery of jovian dust streams and interstellar grains by the Ulysses spacecraft

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On 8 February 1992, the Ulysses spacecraft flew by Jupiter at a distance of 5.4 AU from the Sun. During the encounter, the spacecraft was deflected into a new orbit, inclined at about 80° to the ecliptic plane, which will ultimately lead Ulysses over the polar regions of the Sun[1]. Within 1 AU from Jupiter, the onboard dust detector[2] recorded periodic bursts of submicrometre dust particles, with durations ranging from several hours to two days, and occurring at approximately monthly intervals (28 ± 3 days). These particles arrived at Ulysses in collimated streams radiating from close to the line-of-sight direction to Jupiter, suggesting a jovian origin for the periodic bursts. Ulysses also detected a flux of micrometre-sized dust particles moving in high-velocity ($\geq$26 km s^{-1}) retrograde orbits (opposite to the motion of the planets); we identify these grains as being of interstellar origin.

TABLE 1 Dust burst characteristics

Days from CA	−57.7	−32.1	31.4	59.8	86.9	117.4
Date (yr/d)	91/346	92/7	92/71	92/99	92/126	92/157
Duration (h)	4.7	6.0	25.0	43.4	19.8	16.3
Number of particles	3	4	124	7	4	4
Mass range ($\times 10^{-15}$ g)	3–6	0.1–7	1–90	2–9	5–20	3–4
Mean mass ($\times 10^{-15}$ g)	4	3	9	4	9	4
Speed range (km s^{-1})	28–37	27–56	28–44	28–44	20–37	28–37
Mean speed (km s^{-1})	31	37	42	33	29	30
Mean rotation angle	201°	211°	51°	54°	44°	32°
Distance to Sun (AU)	4.93	5.14	5.40	5.39	5.38	5.36
Distance to Jupiter (R_J)	995	562	553	1025	1480	1980

The time corresponds to the centre of the burst. Closest approach (CA) to Jupiter occurred on 92/39.5. The definition of stream particles and hence the number of members is somewhat arbitrary, but here it refers only to small (mass $\leq 5\times10^{-14}$ g) and collimated (±70° from mean rotation angle) particles. Jupiter radius R_J=71,400 km.

The Ulysses dust detector is a multi-coincidence impact ionization detector[2] with a sensitivity 10^5 times higher than any dust detector previously flown in the outer Solar System. Masses and impact speeds of dust particles are determined from the measured amplitudes and rise-times of the impact charge signals. We restrict our analysis here to reliably identified[3] impact events (that is for small impact events, triple coincidence is required). The mass sensitivity threshold is 4×10^{-15} g at 20 km s^{-1} and 6×10^{-16} g at 40 km s^{-1} impact speed, as deduced from laboratory impact calibrations with carbon, silicate and iron dust particles[4]. The accuracy of the speed determination is a factor of two and that of the mass determination is a factor of 10 in the calibrated range[5]. From 8 days before closest approach (CA) to Jupiter until 2 days after, the instrument sensitivity was reduced by ground command by about a factor of two. For 17 hours each side of CA this sensitivity was further reduced by a factor of more than 10, for reasons of instrument safety. The trajectory of Ulysses and the geometry of dust detection is explained in Fig. 1.

The impact rate observed by Ulysses (Fig. 2) of big particles was low (~0.3 impacts per day) for most of the time, although a statistically significant peak of big particles did occur at the time of Jupiter encounter[6]. For most of 1991, when Ulysses was <4 AU from the Sun, the impact rate of small particles was also low. Within a few months of Jupiter fly-by, however, six bursts

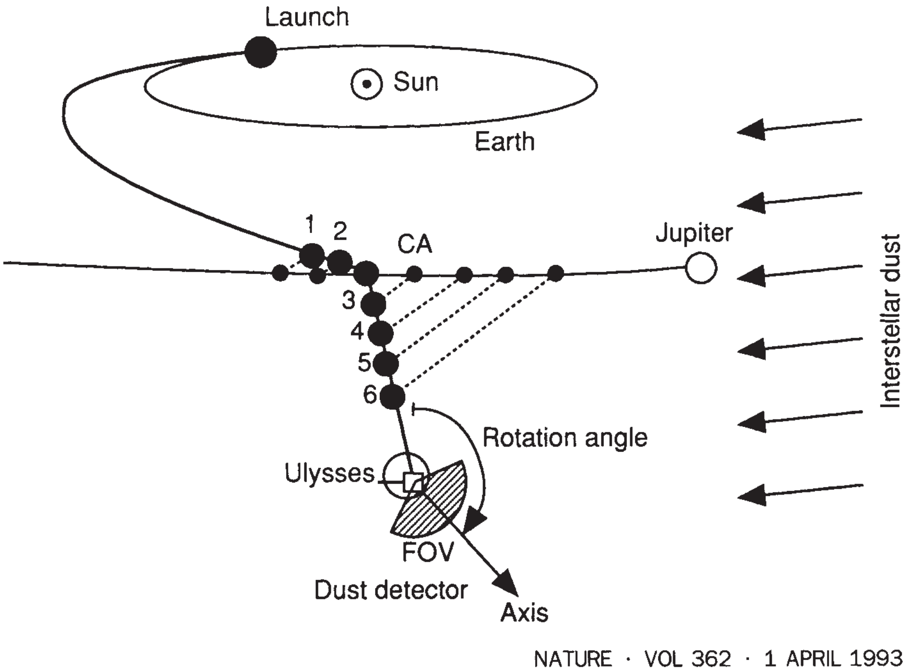

FIG. 1 Ulysses trajectory and geometry of dust detection—oblique view from above the ecliptic plane also showing the Sun and the orbits of Earth and Jupiter (in the foreground). Arrows indicate the flow of interstellar dust. The trajectory of Ulysses[1] after Jupiter closest approach (CA) is deflected into an orbit inclined at 80° to the ecliptic going south. Numbers along the trajectory refer to positions of Ulysses at which dust streams were detected—dotted lines point to Jupiter. Two hundred days after CA, Ulysses had reached a distance of 1.6 AU from Jupiter and an ecliptic latitude of −9°. The spacecraft spins around an axis which, along with the high-gain antenna, points towards Earth. The dust detector onboard has a 140° conical field-of-view (FOV), and is mounted almost at a right angle (85°) to the Ulysses spin axis. Radiant directions from which it can sense impacts therefore include the plane perpendicular to the spacecraft-Earth line. The rotation angle of the sensor axis at the time of a dust impact is measured from the ecliptic north direction. The spin-averaged sensitive area[2] of the dust detector to a mono-directional stream of dust grains is $\leq$0.02 m^2; the maximum occurs when the centre of the detector FOV passes through the stream during spacecraft rotation.

in the impact rate were observed, which occurred with a remarkable periodicity of 28 ± 3 days (Table 1). Although only three or four impacts in a single burst may seem debatable, the periodicity of their occurrence enormously increases their statistical significance. No periodic dust phenomena in interplanetary space have been known before for such small grains.

Figure 3 shows the direction that the sensor was pointing during impacts. Small particles (mass $\leq 5\times10^{-14}$ g) appear mostly in well collimated streams of short duration: a collimated stream, whose radiant passes through the detector field-of-view (FOV) once each spacecraft rotation, will be sensed over a range of a maximum of 140°. In Fig. 3*b* we show the same data as in Fig. 3*a*, only this time we have marked the larger particles according to their impact speed. No particles with impact speeds above 26 km s^{-1} (which represents the maximum possible vectorial sum of the Ulysses post-Jupiter heliocentric velocity of 8 km s^{-1} and the escape velocity of 18 km s^{-1} from the solar system at 5.4 AU) can move on bound orbits about the Sun. Therefore, all particles with impact speeds >26 km s^{-1} move on hyperbolic trajectories through the Solar System. Even particles with lower impact speeds can be on hyperbolic orbits if they arrive from northerly directions or if radiation pressure reduces their solar attraction.

Jovian dust streams. In our opinion the following four characteristics of the dust streams, taken as a whole, can be explained only if we assume a jovian origin: (1) narrow, collimated streams must have a nearby source, otherwise they should be dispersed in space and time; (2) the streams are concentrated near Jupiter and the strongest stream was detected closest to it; (3) the first two streams before Jupiter CA approach Ulysses from directions almost opposite to the streams after CA. All streams, however, radiate from close to the line-of-sight direction to Jupiter. (4) The observed periodicity strongly suggests that all streams are derived from a single source and tends to rule out fortuitous cometary or asteroidal origins of individual streams.

The first three dust streams occurred when the plasma instrument[7] and the magnetometer[8] on Ulysses recorded 'corotating interaction regions' (ref. 9) in the solar wind and interplanetary magnetic field (IMF). These events were associated with intense magnetic fields (up to 5 nT) and high solar wind speeds (up to 600 km s^{-1}). Under these conditions the speed gained by the Lorentz force on a 0.1-μm-sized (or smaller) charged[10] dust particle can be up to several kilometres per second per day. Particles in the first two streams arrived from about 50° south of the direction to Jupiter. The azimuthal component of the IMF at this time had maximum values in the direction opposite to planetary motion, which gave rise to a strong northward acceleration. The polarity and strength of the local IMF seem to be sufficient to bend the trajectories of the small stream particles enough for them to be detected from the direction indicated.

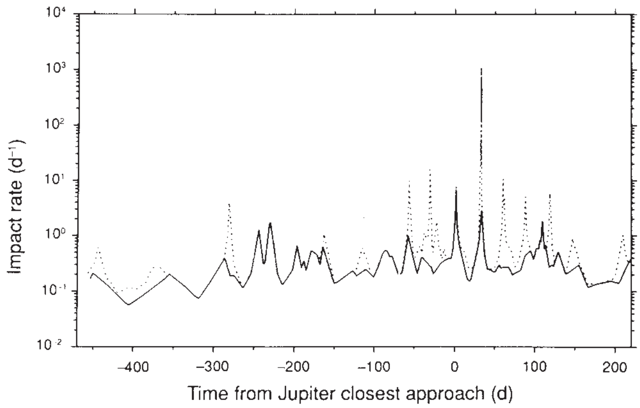

FIG. 2 Impact rate (from the Ulysses dust detector) from October 1990 to July 1992. Jupiter closest approach (CA) occurred on 8 February 1992. Solid line: impacts of big particles (mass $>5\times10^{-14}$ g); broken line: all recorded impacts. Running average is over four impacts.

Assuming that the observed streams originate from within the jovian system we still need to identify the source and ejection mechanism, and explain the periodicity. Any of the dusty regions (main ring, halo and the gossamer ring)[11,12] could be the source of the observed particles. Also, the volcanoes on Io have been suggested[13,14] as a source of submicrometre grains. Grains from any of these sources are exposed to the jovian magnetospheric plasma and will collect electrostatic charge. Their motions may then be dominated by electromagnetic forces that can overcome gravity and possibly lead to ejection. If particles originate from the dusty regions of Jupiter, one could argue for a sheet of continuously ejected dust similar in morphology to the interplanetary current sheet. The modulation of this dusty sheet could be due to a combination of the tilted nature of the jovian magnetic field and the solar wind. The modulation by the solar wind might manifest itself by Lorentz forces on the grains as they travel outside the magnetosphere—in this case the streams would correlate with the azimuthal component of the IMF—or also by the changing morphology of the jovian magnetosphere itself due to changes in the solar wind ram pressure. We note the similarity of the periods of dust streams with that of long-wave radio emissions from Jupiter, which were detected by the Voyager spacecraft and which are related to the solar wind magnetic sector structure[15]. If the source is Io, the dust sheet would probably reduce to rays or fans and there will be an additional modulation due to the orbital motion of Io[16].

More modelling of the detailed dust emission mechanism and the subsequent accelerations needs to be done. Future measurements by the Galileo dust detector[5], however, will provide new information on this new population of dust when Galileo reaches Jupiter late in 1995.

Interstellar dust. All planets and asteroids, and most short-period comets, as well as most interplanetary dust particles, orbit the Sun in the prograde sense (counterclockwise). With the spinning Ulysses spacecraft we are able to distinguish pro- and retrograde orbits. After Jupiter fly-by the spacecraft velocity component parallel to the ecliptic plane was small (~1.5 km s^{-1}) and hence dust particles in prograde orbits appear well separated in rotation angle (180° to 360°) from particles in retrograde (0° to 180°) motion. Before the encounter with Jupiter, this separation is less clear. Big particles (mass $>5\times10^{-14}$ g) display a non-uniform distribution in rotation angle (Fig. 3): most impacts are compatible with retrograde motion. This conclusion was already indicated by the ratio of impact rates before and after Jupiter fly-by[6].

The only class of objects in the Solar System which has high orbital inclinations and retrograde orbits are comets. Even long-period comets, which show a nearly random inclination distribution, do not match the observed dust particle distribution. Most of the dust released from these comets should be observable in the inner Solar System as well. Earlier measurements[17] by Galileo and Ulysses show that significant amounts of high-inclination dust do not occur in the inner Solar System[18].

A straightforward explanation for many of the retrograde orbits is that they are interstellar grains sweeping through the Solar System. This is because the upstream direction of interstellar dust (assumed to coincide with the flow of interstellar helium which has been directly measured by Ulysses[19]) is located at ecliptic longitude $l = 252°$ and latitude $b = 2.5°$, whereas Ulysses is currently at an almost right angle ($l = 157°$) as seen from the Sun. Because of this configuration, interstellar dust particles, which directly reach the position of Ulysses, appear to have retrograde orbits (see Fig. 1).

The speed of interstellar grains should be high and comparable to the speed of interstellar gas, which is 26 km s^{-1} (ref. 19) outside the gravitational influence of the Sun. The speed of the particles should also be reflected in the apparent direction (rotation angle) from which these particles arrive at the detector.

Because the spacecraft (apex) velocity vector changes by 80° in rotation angle at Jupiter (see Fig. 3) the relative impact velocities should shift accordingly. The mean rotation angle of slow ($<26\ \mathrm{km\ s^{-1}}$) particles shifts by about 50° at Jupiter, whereas the shift for fast particles (excluding stream particles) is only 20°. These shifts are in agreement with the measured speeds and give credibility to these measurements.

The masses of the fast particles range from 10^{-15} to 5×10^{-12} g, except for the time around Jupiter CA when even bigger particles were observed. The flux of those particles compatible with interstellar dust, both in rotation angle and speed, is $8\times10^{-5}\ \mathrm{m^{-2}\ s^{-1}}$; if we take a mean particle mass to be 8×10^{-13} g, the mass flux becomes $6\times10^{-17}\ \mathrm{g\ m^{-2}\ s^{-1}}$. This value compares to $2\times10^{-17}\ \mathrm{g\ m^{-2}\ s^{-1}}$ for an estimate[2] of interstellar dust in the vicinity of the Solar System. This latter value is lower than the observed one, especially if one considers that the particles observed by Ulysses are bigger than the typical interstellar particles (mass $<10^{-14}$ g) which dominate the extinction of starlight.

McDonnell and Berg[20] estimated that at 1 AU from the Sun the upper limit flux of interstellar particles did not exceed $3\times10^{-5}\ \mathrm{m^{-2}\ s^{-1}}$ for grains with a mass of 10^{-13} g. It has been suggested[21,22] that both radiation pressure and electromagnetic interactions with the IMF may reduce the flux of interstellar grains in the inner Solar System. Ulysses dust observations indicate that in fact only the biggest interstellar particles are able to penetrate relatively deep into the Solar System (5 AU from the Sun) during the present magnetic field configuration[23]. The probable identification of individual interstellar grains is of interest because it suggests that *in situ* analysis of such grains may be possible. Chemical analysis of these particles will be attempted in the future by the Cosmic Dust Analyzer on the Cassini spacecraft. □

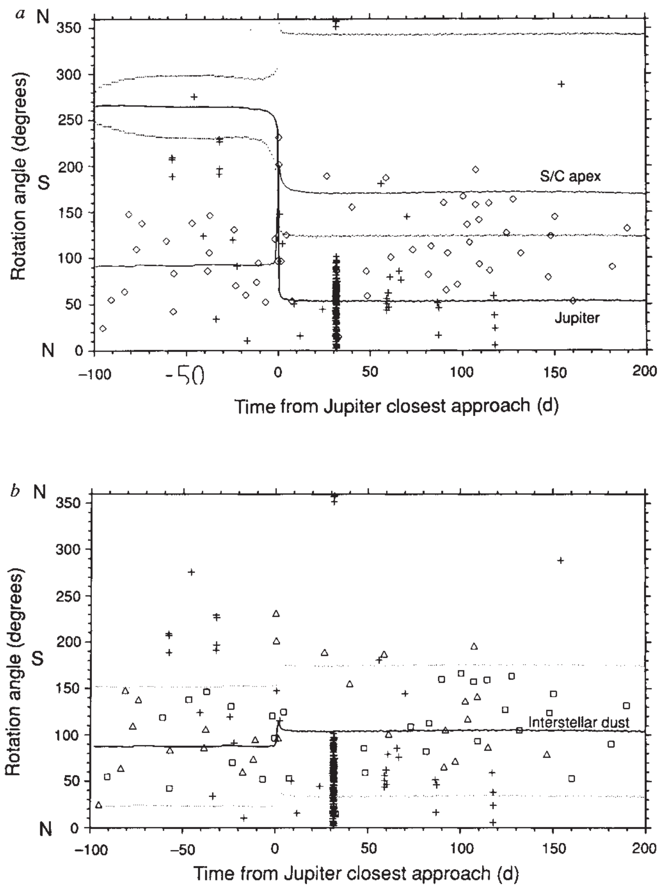

FIG. 3 Dust impacts versus spacecraft rotation angle and days from Jupiter closest approach (CA). Thirty-four out of 240 impacts are not shown because no correct rotation angle could be determined. The rotation angle is taken to be 0° when the dust sensor axis points closest to the north ecliptic pole. At rotation angle 90° the detector axis points parallel to the ecliptic plane in the direction of planetary motion, at 180° it points closest to the south ecliptic pole and so on. *a*, Impacts are marked according to their masses: diamonds: mass $>5\times10^{-14}$ g, crosses: mass $\leq5\times10^{-14}$ g. The dotted lines on each side of the thick line labelled 'Jupiter' give the range of rotation angles when Jupiter is in the field-of-view (FOV) of the detector. The direction of spacecraft motion (S/C apex) is given by the thin line. Before Jupiter CA the detector pointed in the direction of spacecraft motion (S/C apex) at rotation angle ~90°. After the fly-by the spacecraft went almost due south resulting in a new apex direction at rotation angle ~170°. Impact directions of interplanetary dust particles, moving on low eccentricity and low inclination orbits, should follow this trend. *b*, Same data as in *a*, but marked according to the impact speeds. Small particles (crosses) all have impact speeds above $26\ \mathrm{km\ s^{-1}}$. Impact speeds of bigger particles are identified by two different symbols: squares, $v\geq26\ \mathrm{km\ s^{-1}}$; triangles, $v<26\ \mathrm{km\ s^{-1}}$. The arrival direction of interstellar dust (assumed to coincide in direction and speed with interstellar gas[19]) is shown by the solid line, and the limits of detector FOV for interstellar grains are given by the dotted lines.

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Time–distance helioseismology

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THE application of seismology to the study of the solar interior[1,2] (helioseismology) has advanced almost solely by the prediction and measurement of the Sun's frequencies of free oscillation, or normal modes. Direct measurement of the travel times and distances of individual acoustic waves—the predominant approach in terrestrial seismology[3]—would appear to be more difficult in view of the number and stochastic nature of solar seismic sources. Here, however, we show that it is possible to extract time–distance information from temporal cross-correlations of the intensity fluctuations on the solar surface. This approach opens the way for seismic studies of local solar phenomena, such as subsurface inhomogeneities near sunspots, and should help to refine global models of the internal velocity stratification in the Sun.