Dust Measurements at High Ecliptic Latitudes

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Along Ulysses' path from Jupiter to the south ecliptic pole, the onboard dust detector measured a dust impact rate which varied slowly from 0.2 to 0.5 impacts per day. The dominant component of the dust flux arrived from an ecliptic latitude and longitude of 10°±10° and 280°±30° which indicates an interstellar origin. An additional flux of small particles, which do not come from the interstellar direction and are unlikely to be zodiacal dust grains, appeared south of -45° latitude. One plausible explanation is that these particles are beta-meteoroids accelerated away from the Sun by radiation pressure and electromagnetic forces.

The objective of the Ulysses dust detector is to measure impact directions, velocities, and masses of dust in the solar system. In this paper we report on results from the orbital arc traversed between March 1992 and September 1994, covering latitudes from 0 to -79° and heliocentric ranges from 5.4 to 2.2 AU. For earlier results see (1,2,3). The Ulysses dust detector (4) is a multi-coincidence, impact-ionization sensor with 1000 cm^2 of area sensitive to incoming submicrometer- to micrometer-sized dust particles (5). Measurements by a twin dust detector on the Galileo spacecraft (6) serve as an in-ecliptic base line for the dust measurements of Ulysses. The only previous dust measurements in the outer solar system were performed near the ecliptic by the Pioneer 10 and 11 spacecraft (7). The Pioneer results predict about five impacts with masses $> 10^{-9}$ for Ulysses during the three years that it spent outside 3 AU. During this time, Ulysses recorded three particles with masses larger than 10^{-9} g and seven which exceeded 10^{-10} g. These results are consistent with the Pioneer findings.

Between March 1992 and September 1994, Ulysses recorded the impacts of 826 dust particles. These particle impacts were separated from a large number of noise events and classified by the process described in (5). Many of these impacts occurred within nine months of the Jupiter flyby during dust streams that are believed to emanate from that planet's magnetosphere (3,5). In this work, we concentrate on the large-scale distribution of dust in the heliosphere and thus disregard all dust impacts detected within two days of each Jupiter dust stream. Jupiter dust streams, interesting in their own right, are discussed elsewhere (5). Of the remaining 352 particles, 33 have invalid directional information (8) due to an instrumental deficiency which was corrected by a reprogramming command sent to Ulysses on May 6, 1993.

The pointing of the dust sensor boresight for each of the 319 remaining impacts is given in Fig. 1A. The most striking feature of the figure is the concentration of impacts to rotation angles near 90°. Because of the 140° opening angle of the dust detector, such a concentration is consistent with particles arriving from a single direction. Interstellar helium, for example, arrives from 253.5° ± 2.5° ecliptic longitude and 5.6° ± 2.5° ecliptic latitude at a speed of 25.2 ± 1 km/s, as determined by the Ulysses neutral gas experiment (10,11). Fig. 1B shows the directions from which interstellar dust particles are expected to arrive assuming that they are coupled to interstellar helium; the contours are well correlated to the data displayed in Fig. 1A. The contour levels are determined by the fact that the instrument's sensitivity falls off as the angle between the boresight and the impact directions increases (9,4). Variations of the sensitive area with time are due to the orbital motion of Ulysses and to changes in the orientation of its spin axis.

Most of the large dust impacts come from directions consistent with the interstellar direction (rotation angles near 90°). In contrast, interplanetary dust orbiting the Sun along the usual prograde orbits should come from the opposite direction with rotation angles near 270°. This difference, which greatly simplifies the identification of possible sources, is a consequence of Ulysses' unique out-of-ecliptic orbit.

In Fig. 2 we compare the measured impact directions of the particles to the distribution expected for a mono-directional stream from the interstellar gas direction. Most particles fall into the interstellar dust band as can also be seen in Fig. 1. Particles with the smallest masses (plus signs in Fig. 1A) are distributed more uniformly over all rotation angles and account for most of the deviations from the interstellar direction. These particles were either not predominantly of interstellar origin or were highly influenced by electromagnetic scattering processes within the solar system. Ignoring these small particles, we find that the width of the measured distribution for the more massive particles in Fig. 2 is still somewhat larger than expected for a theoretical mono-directional distribution. Part of the reason for this discrepancy may be due to different perturbations suffered by gas and dust inside our solar system. In addition, the coupling between interstellar dust and gas may not complete (4). The extent of any coupling depends on the morphology of the local interstellar cloud which is poorly known and currently in dispute (12,13). Our measurements indicate that (i) the mean direction of the interstellar dust particles may be offset from the direction of the interstellar gas and (ii) interstellar dust particles probably have a slight spread in their incoming directions.

To strengthen our assertion that the directions from which interstellar dust and gas come may differ, we plot the impact rate of all particles compatible with the interstellar direction in Fig. 3A. Because Ulysses' antenna tracks the Earth, the spacecraft's sensitivity to particles from a particular direction changes with roughly a one-year period. The main variation in the measured impact rate appears to be roughly in phase with the theoretical expectation, but is about a factor of two larger. We attempted to improve the match by varying our assumptions for the direction and speed of the dust particles. We investigated two different speeds, 10 km/s and 30 km/s, as well as a range of upstream latitudes and longitudes. In all of our simulations, particles with the lower speeds were incapable of matching the impact rate in Fig. 3A. During the early part of the orbit when Ulysses was near the ecliptic plane, we find that the distribution in rotation angles is dominated by the latitude of the interstellar upstream direction. Later, as Ulysses rose out of the ecliptic, the longitude dominates. A good fit, therefore, depends on both these parameters. The overall variation of impact rate with rotation angle was best fit by a longitude of 280°, a latitude of 10°, and a speed of 30 km/s.

For longitudes in a 60° range centered on 280° longitude, the predicted and measured impact rate variations were in phase, although the amplitudes did not always match. We therefore take ± 30° as the uncertainty of our determined longitude. Variations of more than 10° in latitude caused significant departures and hence we adopt this value as a rough measure of the latitude uncertainty. The measured values for interstellar Helium differ from our results, but lie within the error bars (10).

The Ulysses data shows that interstellar particles penetrate the solar system to at least 2.2 AU which allows us to constrain their composition. If interstellar dust grains were made predominantly of H_2O ice or other volatiles, they would sublime well before reaching 2.2 AU. Indeed, sublimation could start as far as 5 AU from the Sun, in obvious contradiction to our measurements. The grains sensed by Ulysses must therefore have been composed primarily of nonvolatile materials. Some of the pick-up ions measured by the SWICS experiment onboard Ulysses (17) seem to be of interstellar origin. A possible source is sublimation of dust grains in the inner solar system. These pickup ions were observed over Ulysses' entire out-of-ecliptic path and support our findings of a nonvanishing interstellar dust component even at heliocentric distances of 2.2 AU. Barring electromagnetic deflection, interstellar dust grains might even be able to reach Earth's orbit. Results obtained by Pioneer 8 indicate a maximum 3% contribution of unbound dust to the total flux near 1 AU (14), but recent measurements by the *Munich dust counter* in the Earth-Moon system (15) give some indication for an enhanced flux of particles from the interstellar upstream direction (16).

During most of the trajectory, few particles arrived from outside the interstellar band, but the rate increased abruptly in early 1994 at a radial distance of 3.7 AU from the Sun and an ecliptic latitude of about -45° (Fig. 3b). These particles were, on average, smaller than the interstellar component as can be seen in Figs. 1 and 2.

Three possible sources for the origin of the non-interstellar dust population are: (i) long-period comets with randomly inclined and highly elliptical orbits, (ii) interstellar matter and (iii) the zodiacal dust cloud. The first possibility is difficult to reconcile with the onset of the new population at 3.7 AU and -45° ecliptic latitude (Fig. 3B). If long-period comets were the dominant source, one would expect to see a relatively uniform contribution all along the Ulysses orbit, for example at 4.5 AU and -28° latitude in Fig. 1A where significantly fewer impacts were detected.

The second possibility is also problematic. Dust that enters the sensor with rotation angles near 270° needs to come from a direction at least 90° from the upstream direction that accounts so well for most of our data. One possibility is a second interstellar population. As with the long period comets, however, we would expect to see such a population all along the Ulysses orbit. Gravitational deflection of interstellar grains is capable of changing impact directions, but by the time that these grains intersect the orbit of Ulysses, they are deflected by only about 10° from straight line trajectories. A small fraction of interstellar dust grains (approx. 1%), however, travel on indirect orbits around the Sun and are deflected by about 90° before finally meeting Ulysses. Even if all of these particles survived their 0.33AU approach to the Sun, their flux is too small to easily account for our observations. Finally submicrometer particles are electromagnetically influenced. We find that the primary effect of electromagnetic forces is to exclude small particles from the inner solar system which explains why Ulysses' interstellar population consists of grains larger than the interstellar norm (see e.g. 18). Our numerical simulations also indicate that interstellar particles are not strongly deflected from the upstream direction.

We favor the third possibility: interplanetary particles originating in the inner zodiacal cloud. Submicrometer particles are a natural product of collisions between zodiacal dust particles, which are found from 3 AU inward to within a few radii of the Sun. These submicrometer grains are electromagnetically dominated and depart the solar system along trajectories that, during the current phase of the solar cycle, reach high latitudes (19). Our numerical investigations indicate that even particles started on circular zero-inclination orbits are capable of reaching the high latitudes traversed by Ulysses. Furthermore, it is difficult for these particles to reach Ulysses when the spacecraft was farther from the Sun and at lower heliocentric latitudes; by the time they reach Ulysses' distance, particles originating in the zodiacal cloud have typically risen well out of the ecliptic plane.

One of the major goals of the Ulysses dust experiment is the investigation of the latitudinal distribution of dust particles in the zodiacal cloud. Up to now, this goal has remained elusive since Ulysses' out-of-ecliptic path was first too far from the Sun and then too far from the ecliptic to see strong indications of an interplanetary flux. During Ulysses' descent beneath the ecliptic plane, we have improved our understanding of the interstellar flux penetrating the solar system and identified a population of tiny particles at high latitudes. These results will assist us in characterizing the interplanetary population during Ulysses' rapid return to the ecliptic in March 1995.

Figure captions

Fig 1: (A) Dust particle impact directions. The rotation angle given denotes the orientation of the dust sensor boresight about the spacecraft spin axis at the time of each impact. A value of zero occurs when the dust sensor points closest to ecliptic north (3). After removal of the jovian stream particles, the remaining grains are separated into two mass ranges: plus signs denote particles with masses $< 6 \cdot 10^{-14}$ g and squares denote more massive particles. (B) Sensitivity of the instrument to the interstellar flux assumed to originate from 253.5° ecliptic longitude and 5.6° ecliptic latitude. The contour lines denote lines of constant sensitivity (in cm^2 of effective area) with the broken line indicating the maximum.

Fig 2: Number of detections versus rotation angles recorded over the entire 2.5 year period excluding Jupiter stream particles. This figure shows the number of impacts per 10° rotation angle interval for large particles (white histogram) and for small particles with masses $< 6 \cdot 10^{-14}$ g (cross-hatched histogram). Error bars are calculated for the sum of small and large particles assuming an $\sqrt{n}$ statistical error. The solid line indicates the distribution expected for particles arriving from the assumed upstream interstellar direction. It is derived by integrating Fig. 1B over time. The slight asymmetry of the curve about its peak is due to slow changes in the orientation of the spacecraft's spin axis.

Fig 3: (A) The impact rates for interstellar grains (thick line). Interstellar grains are identified as non-stream particles compatible with the interstellar direction (Fig. 1B). The rates were calculated using a sliding average over 25 particles; statistical errors are indicated by the hatched region surrounding the impact-rate curve. The dotted line shows the average impact rate of 0.25 impact/day and the thin solid line indicates the sensitivity, averaged over a full spacecraft rotation, to particles arriving from the interstellar direction. The sensitivity curve was normalized so that its average agrees with the mean impact rate derived from the data. We suspect that the first six months of this data are contaminated by small Jupiter particles which were not identified with streams. (B) Impact rate versus time for particles whose rotation angles are inconsistent with the interstellar direction.

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