DETECTING DUST WITH ELECTRIC SENSORS IN PLANETARY RINGS, COMETS AND INTERPLANETARY SPACE

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Abstract

Dust particles have been detected *in situ* by radio and plasma wave instruments aboard several space probes in various environments. What is measured is the voltage induced on the electric antennas when a dust grain impacting the spacecraft at a high velocity is vaporised and ionised, thereby producing a plasma cloud which is partially recollected by the target. For these measurements, the effective detection area is much greater than that of conventional dust detectors. Furthermore, even if the particles do not impact the spacecraft, they may be detected by the transient voltage their electric charge induces on the electric antennas when they pass closer to them than the Debye length. This yields a still larger effective area for dust detection. Finally, we show that the recent breaking of thin dipole antennas by dust impacts aboard several spacecraft might have been foreseen from the values of the mean interplanetary dust flux at 1 A.U. and of the cross section of these antennas. It is consolatory - but not necessarily significant - that the observed life spans of these antennas provide rough estimates of the interplanetary flux of grains larger than a few 10^{-7} g which agree with current models.

Key words: dust; electric antennas; waves; planetary rings; interplanetary medium; comets.

1. INTRODUCTION

Dust grains are nearly as ubiquitous in the solar system as are plasmas. When a dust particle impacts a spacecraft at a high velocity, it is vaporised and ionised, and the resulting charge - which is much larger than that normally carried by the grain - induces a large voltage on the electric antennas, which can be detected by the onboard radio and plasma wave receivers. Even when a dust particle does not make an impact but passes near the electric antennas, its electric charge produces a transient electric potential which can be detected by a sensitive wave receiver. It is therefore not surprising that several radio and plasma wave instruments have performed *in situ* dust detection in diverse space environments. An extreme case of dust detection is the breaking of electric antennas by impacts of large dust particles, which happened recently on several spacecraft carrying fragile antennas.

We review briefly these measurements, which, albeit serendipitous, have produced interesting new data on dust particles in various environments.

2. IMPACT IONISATION

2.1. A Short Point of History

On November 13, 1980, the spacecraft Voyager 1 passed through Saturn's E ring - a faint dusty structure having a rather large radial extension and thickness (see Hamilton and Burns, 1994). The Voyager spacecraft did not carry conventional dust detectors, but they carried two wave instruments designed for measuring radio (Warwick et al., 1977) and plasma waves (Scarf and Gurnett, 1977). Both instruments recorded dust signals, but this was recognised much later because the plasma played a dirty trick: genuine dust signals were mixed with intense plasma waves, and that made them difficult to interpret. Nearly one year later, Voyager 2 passed through the outer part of Saturn's G ring - another faint ring containing a relatively large population of dust particles. On this occasion the plasma was silent, so that the electric signals were quickly recognised as produced by dust impacts (Warwick et al., 1982; Scarf et al., 1982). This serendipitous detection opened the way to a novel technique to measure dust using wave instruments.

2.2. How Does it Work?

When a dust particle impacts a solid target at a velocity greater than the sound speed in the materials - typically a few km/s - it undergoes a strong shock compression which vaporises and ionises it as well as a part of the target's material. All this material then expands into the low-pressure ambient medium, cooling and partially recombining (Drapatz and Michel, 1974). The residual charge of the expanding plasma cloud is recollected, and then detected by the antennas (Fig. 1). This phenomenon is basically the same as for classical impact ionisation detectors (see Fechtig et al.,1978) with, however, two important differences. Firstly, since it was not anticipated that the wave instruments would record dust, they were neither designed nor calibrated for this purpose. Secondly, this technique has the advantage of having a very large effective area for dust detection: roughly that of the spacecraft itself, or more precisely that part of the surface having a high yield for impact ionisation; in the case of Voyager, this was estimated to be about 1 m^2.

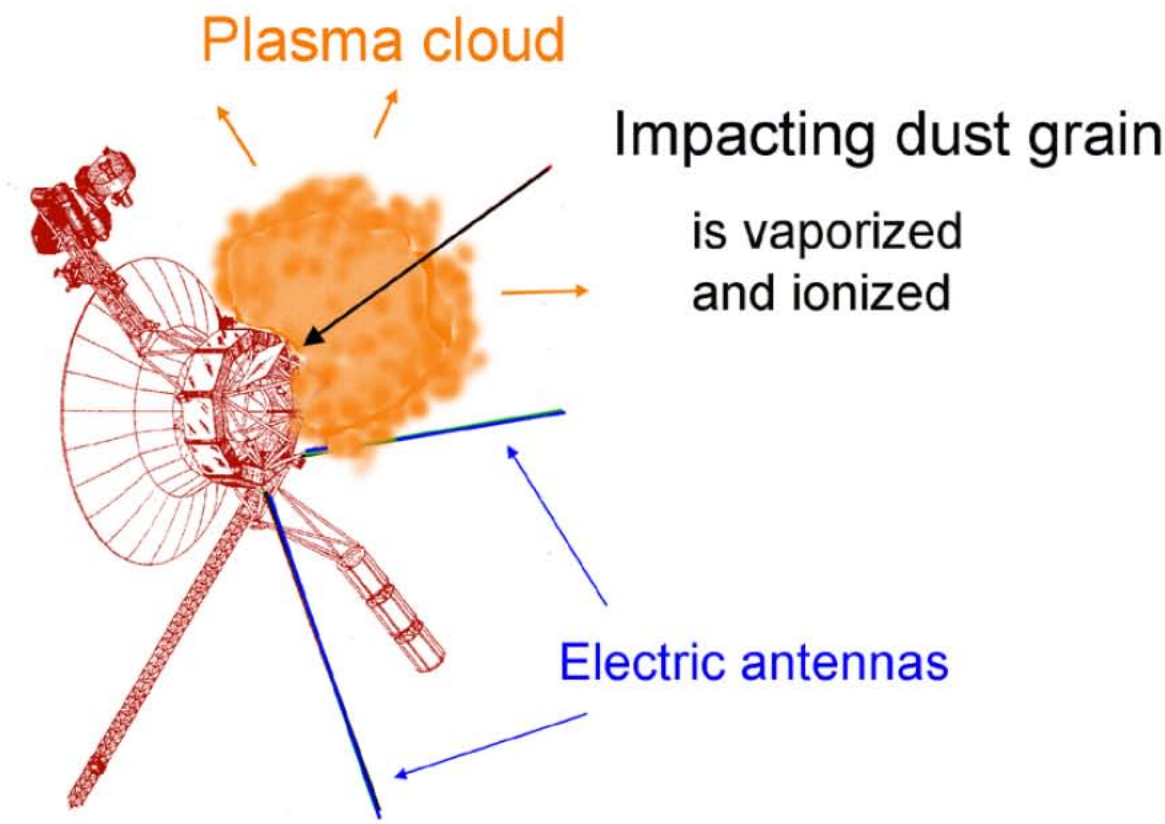

Figure 1. A dust grain impacting the spacecraft at a high speed is vaporised and ionised; this produces an expanding plasma cloud whose charge is partially recollected, thereby inducing a transient voltage on the electric antennas.

2.3. On Calibration and Design

Since the wave instruments on Voyager were not calibrated for dust detection, one had to rely on the calibration of conventional impact ionisation detectors in order to relate the charge Q recollected by the target to the grain mass m, given the nature of the materials and the relative velocity (see Göller and Grün, 1989).

Having evaluated the charge recollected by the spacecraft, one must then estimate the corresponding response of the wave receiver. This response depends on how the antennas are operated. On Voyager, the radio and plasma wave instruments use the same antennas but operate them differently. The radio instrument uses the antennas as monopoles, so that the receiver measures the voltage between one antenna arm and the spacecraft. In contrast, the plasma wave instrument is operated as a dipole, so that the receiver records the difference of potential between the antenna arms. As a consequence, it responds very weakly to dust impacts on the spacecraft and this response is unknown as it depends on subtle asymmetries of the system. This means that the *monopole* configuration used by the radio instrument is better adapted than the *dipole* one to detect dust impacts (see Meyer-Vernet et al., 1986b; Oberc, 1994). Since 1986 this fact has been taken into account in the analysis of the data of the plasma wave instrument (Gurnett et al. 1987, 1989; Tsintikidis et al. 1994, 1995), and the levels have been accordingly calibrated using those recorded by the radio instrument. In fact, Tsintikidis et al. (1994, 1995) have introduced a "mean" calibration of the plasma wave instrument based on observed radio spectra for several planetary encounters. Unfortunately, for unknown reasons, they have based their calibrations on incorrect levels of radio power spectra, offset from the published ones by roughly two orders of magnitude, which results in an offset in their deduced particle sizes (see the discussion by Meyer-Vernet et al., 1996).

2.4. Power Spectral Density

Since the Voyager radio instrument is operated in the monopole mode, the power spectral density can be evaluated in a straightforward way. When the residual charge Q (function of the grain mass) is recollected by the spacecraft, the recorded voltage $V(t)$ rises to a maximum amplitude given by

$$V_{max} \approx Q/C \tag{1}$$

C being the spacecraft capacitance, estimated from rheographic measurements (see Meyer-Vernet et al., 1996). Basically, the voltage rises with a time scale τ_r, and subsequently decays with a much longer time scale τ_d. The time τ_r can be evaluated from simple physical arguments (see Meyer-Vernet et al., 1986; Oberc, 1994), whereas the decay time is roughly equal to the time constant of the system. At frequencies $f \gg 1/2\pi\tau_r$, the Fourier transform is determined by the discontinuity of the derivative in the rising part, so that it is generically given by

$$\begin{aligned} |V(\omega)| &= V_{max}/\tau_r\omega^2 \\ &= Q/C\tau_r\omega^2 \end{aligned} \tag{2}$$

Finally, the total voltage power spectral density at high frequencies is

$$V^2 = 2\langle N\,|V(\omega)|^2\rangle \tag{3}$$

where N is the impact rate, the brackets stand for a mean over the dust mass distribution since Q is a function of the mass m, and the factor of two stems from the fact that the spectral density is defined only for positive frequencies. This yields a power spectrum varying as $1/\omega^4$ at high frequencies. At frequencies intermediate between the inverse decay time and the inverse rise time, the signal behaves as a step function, so that the power spectrum varies as $1/\omega^2$. This frequency range is therefore not suited for detecting dust because such a spectrum may be confused with genuine plasma signals which have often a similar spectral index (see Meyer-Vernet et al., 1989).

2.5. Some Observations

A power spectrum with spectral index equal to -4 at high frequencies was indeed observed by the radio instrument during the ring plane crossings of Saturn by Voyager 1 (Meyer-Vernet et al., 1996), and Voyager 2 (Aubier et al., 1983), and also when Voyager 2 crossed the ring planes of Uranus (Meyer-Vernet et al., 1986a) and Neptune (Pedersen et al., 1991) as shown on Fig. 2. Detailed results on the deduced particle concentrations and size can be found in these papers. Since the receiver had been carefully calibrated for radio measurements, the uncertainty comes mainly from the assumed relation between the charge Q and the particle mass.

As noted above, the analysis of the plasma wave instrument was not straightforward as it involved the unknown relation between the voltage recorded by the antenna and the charge Q. This instrument has, however, the additional capability of detecting wave forms, which enables it to detect individual impacts. Detailed results can be found in papers by Gurnett et al. (1983; 1987; 1991) and Tsintikidis et al. (1994; 1995). Interestingly, this instrument also detected dust particle impacts in the outer solar system (Gurnett et al., 1997).

The passage through Saturn's E ring gave the opportunity to compare the measurements performed by the radio and plasma wave instruments with those deduced from optical data. The analysis of the radio data on Voyager 1 (Meyer-Vernet et al., 1996) and of the optical data (Showalter et al, 1991) both yielded a narrow particle's size distribution centred at a radius of 1 μ-m (for icy particles), whereas the plasma wave instrument found a significantly larger particle's radius of about 5 μ-m (Tsintikidis et al., 1995) (for icy particles). For the other encounters, no comparison with optical data could be made. In Saturn's G ring, the grains detected by the radio and plasma wave instruments were too large to be observed by optical means (Showalter and Cuzzi, 1993; Throop and Esposito, 1998). For the other planets, the optical depths found by Meyer-Vernet et al. (1986) and Gurnett et al. (1987) near Uranus, and by Pedersen et al. (1991) and Gurnett et al. (1991) near Neptune were so small that they were not observed by optical instruments.

Dust grains have also been detected *in situ* with electric sensors in cometary environments. The first spacecraft to explore a comet was ISEE-3 - renamed ICE - which crossed the tail of comet Giacobini-Zinner in 1985. As in the case of Voyager, this probe did not carry conventional dust detectors, but the in board plasma wave instrument recorded dust impacts (Gurnett et al., 1986), whereas the radio instrument did not record dust, thereby setting an upper limit on the dust concentration and mass (Meyer-Vernet et al., 1986b). Giotto, which explored comet Halley in 1986 did not carry wave instruments, but the spacecraft Vega did, and the instruments APV-V and APV-N detected dust particles near comet Halley (Trotignon et al., 1987; Laasko et al., 1989; Oberc and Parzydlo, 1992; Oberc, 1993).

3. PASSING GRAINS

3.1. Individual flybys: The Radio Dust Analyser

Following previous work by Lesceux et al. (1987), Meuris et al. (1996) have proposed a novel technique to detect dust particles, which does not require the grains to impact the spacecraft and to have a high velocity. This technique is based on the transient voltage that the charge carried by the particle induces on an electric antenna when it passes close to it - in practice it has to pass closer than the Debye length of the ambient plasma. The grain's electric charge and velocity can be deduced from an analysis of this voltage. The main advantage of this technique is that it has a huge equivalent area for grain detection since both the antenna length and the Debye length are generally large. Since, however, the voltage induced is small and might be confused with genuine plasma wave effects, this method requires a very sensitive receiver and an elaborate analysis. The interesting prospects of this technique, which is a (free) by-product of plasma wave-form analysers, make it worth being tested.

3.2. Numerous flybys: Dust "Thermal" Noise

The above technique is well suited to a small concentration of large grains so that the receiver detects individual particle flybys. In the opposite case when the dust concentration is sufficiently high that numerous flybys are detected simultaneously, the wave receiver records a voltage power spectrum which is a superposition of the spectra produced by individual particle flybys near the antenna. Dust properties may be measured by analysing this spectrum. The principle is similar to the electron measurements performed routinely from plasma thermal noise spectroscopy in space (Meyer-Vernet et al., 1998b), but the calculation is easier because the dust particles generally move so slowly that the plasma temporal dispersion plays a negligible role. In the simple case where the dust particles have similar speeds (with random directions), the voltage power spectrum on a wire dipole antenna of half-length L is easily calculated in the high and low frequency limits (Meyer-Vernet et al., 1991):

$$V^2 \approx \frac{\sum_i 2n_i q_i^2 V^2}{3\epsilon_0^2 L\omega^3} \text{ for } \omega \gg V/(L, L_D) \tag{4}$$

$$V^2 \approx \frac{\sum_i n_i q_i^2 L^2}{3\pi\epsilon_0^2 V} \ln(V/\omega L) \text{ for } \omega \ll V/L \tag{5}$$

where the summation is over a population of dust grains of electric charge q_i and concentration n_i, and L_D is the Debye length of the ambient plasma.

Table 1. Life time T (years) and cross section S (m^2) of the antennas which were broken by dust impacts on the spacecraft ISEE-3, WIND and IMAGE, and deduced values of the flux F ($m^{-2}s^{-1}$) of dust particles capable of breaking them. The corresponding values for Ulysses are indicated in the last row.

Spacecraft	T (years)	S (m^2)	F(m^{-2}s $^{-1}$)
ISEE-3	1.	0.07	4.6×10^{-7}
WIND	5.7	0.04	1.5×10^{-7}
IMAGE	0.54	0.4	1.5×10^{-7}
Ulysses	> 10.5	0.2	$<1.5 \times 10^{-8}$

4. DESTRUCTIVE IMPACTS

4.1. The thin wire antennas on ISEE-3, WIND and IMAGE

On October 3, 2000, the IMAGE spacecraft, orbiting the earth with perigee and apogee altitudes of 1000 km and 7 earth radii respectively (Gibson et al., 2000) lost a part of an antenna. The culprit was most probably an impact of a relatively large dust particle. On August 3, 2000, a similar event occurred on the WIND spacecraft (Harten and Clark, 1995), which was then in the magnetosphere at a distance of 5.3 earth radii. Since its launch, WIND's orbit has evolved in a complicated way through periodic encounters with the moon, between the interplanetary medium and the magnetosphere, where it approaches the earth up to about 5 earth's radii. Another documented antenna breaking occurred on ISEE-3 (Ogilvie et al., 1978) on August 1, 1979 when the spacecraft was in the interplanetary medium on a halo orbit around the L1 Lagrange point. The spacecraft ISEE-3 spent most of its life in the interplanetary medium except for an exploration of the distant geotail during the year 1983 (Tsurutani and Rosenvinge (1984), and a brief passage through the tail of comet Giacobini-Zinner in September 1985 (Rosenvinge et al. 1986) from which the antennas emerged intact.

These three spacecraft have one common property: they all carry very thin electric antennas, made of beryllium-copper wires of 0.2 mm radius. The question then arises of whether these events could have been foreseen, given the cross section of these antennas and the properties of dust particles along the spacecraft orbits.

The broken wire on ISEE-3 belongs to the long dipole made of a pair of 45-m wires used by the radio instrument (Knoll et al., 1978) and mounted in the spacecraft spin plane; note that the plasma wave instrument uses another similar (orthogonal) dipole (Scarf et al., 1978). The broken antenna on WIND belongs to the long dipole made of a pair of 50-m wires used by the radio and plasma wave instrument (Bougeret et al., 1995) and lying in the spacecraft spin plane. Finally, the wire recently broken on IMAGE was a piece of one of the two orthogonal dipoles, each made of a pair of 250-m wires lying in the spacecraft spin plane, used by the radio plasma imager instrument (Reinisch et al., 2000). The other antennas mounted on these spacecraft were much less fragile.

Table 1 indicates for each spacecraft the cross-sections S of the antennas for dust impacts and the time T between launch and antenna breakage. Assuming that each breakage was produced by a single grain impact, each event yields a crude estimate of the flux of grains capable of breaking the antennas as $F \approx (ST)^{-1}$. The three values of the flux do not differ by more than about a factor of three, which suggests that the fluxes of these particles were rather similar along the orbits of these spacecraft.

Let us now try to estimate the minimum mass of the particles capable of breaking the antennas. In the absence of a realistic laboratory simulation, we will use measurements performed to calibrate penetration detectors (see Fechtig et al., 1978), which furnish penetration depths of dust particles impinging on metallic targets. To get a preliminary estimate, we use an empirical formula adapted from Fish and Summers (1965), with a target density of 8 g cm^{-3} (since the wires are made of Be-Cu) and assume a dust particle density of 2.5 g cm^{-3}(Grun et al., 1985). This gives the penetration depth

$$D(\mathrm{cm}) \quad \approx \quad 0.4 \times m(\mathrm{g})^{0.35} V(\mathrm{km/s})^{0.87} \tag{6}$$

as a function of the grain mass m (in g) and impact velocity V (in km/s). In the spirit of this preliminary estimate, we assume a mean impact velocity of 20 km/s, and suppose that a wire is broken when the penetration depth is roughly equal to 3/4 its diameter, i.e. when $D \approx 0.03$ cm. With these parameters, the minimum particle mass capable of breaking the antennas is from Eq.6: $m \approx 3 \times 10^{-7}$g. With the assumed particle density of 2.5 g cm^{-3} this corresponds to a particle radius of about 30 μ-m.

The breaking events thus furnish three independent estimates of the flux of particles larger than this mass along the spacecraft trajectories (Table 1). On Figure 3 we have superimposed these values on the interplanetary dust flux model at 1 A.U. of Grün et al.(1985). The agreement is rather surprising, given the roughness of our estimate and the wide range of particle densities and velocities; if this agreement did not occur by chance, it suggests that the flux of particles larger than a few 10^{-7} g encountered by WIND and IMAGE along their orbits were rather similar to the one in the interplanetary medium. Anyway, given the (happily) small number of events, we are not in a position to perform any meaningful statistics.

4.2. The Ulysses thin strip antenna

The alert reader might ask why the (thin) dipole antenna lying in the spin plane of Ulysses (Wenzel, 1992) is still working properly, more than ten years after launch. The answer is that this antenna is not as fragile as the ones mentioned above. It is made of a pair of 35-m Be-Cu strips, 5 mm wide and 0.04 mm thick (Stone et al., 1992). This relatively large width enables the antenna to survive when a dust particle perforates the tape. A breakage is expected to occur when one (or several) impact makes a hole of size equal to a large fraction of the strip's width. To obtain an order-of-magnitude estimate, we use laboratory simulations serving to calibrate dust measurements from crater sizes, which are reported by Fechtig et al. (1978), for a relative velocity of 20 km/s. Assuming that a destructive impact requires a hole's diameter equal to 3/4 the tape's width, we find that breaking the antenna requires a minimum mass of about 10^{-4}g. This value should be taken with a pinch of salt owing to the crudeness of our estimate. Note that it is several orders of magnitude larger than the saturation limit of the dust detector on Ulysses (Grün et al., 1992). The life span of at least 10.5 years for this antenna, with a cross-section of about 0.2 m^2, yields an upper limit of $1.5 \times 10^{-8} m^{-2} s^{-1}$ for the cumulative dust flux above 10^{-4} g. This value is much above the interplanetary dust model at 1 A.U. Furthermore, Ulysses travels most of the time out of the ecliptic, at heliocentric distances between 1.3 and 5.4 A.U. Hence, one may expect without undue optimism that its dipole antenna has still a long life expectancy.

5. CONCLUDING REMARKS

When implemented adequately, electric sensors may be a useful complement to conventional dust detectors in space, since they generally have a much larger effective area for dust detection, and are (free) by-products of wave instruments in space. The major cause of uncertainty stems from the absence of adequate calibration for dust impacts, due to the serendipitous character of the detection events performed till now. Anyway, interesting results have been obtained, especially in the rings of outer planets where these measurements are the main *in situ* ones ever obtained. Finally - and rather ironically, the wire dipole antennas on board ISEE-3, WIND and IMAGE have served as effective dust detectors, albeit rather expensive ones. It is worth noting that our preliminary estimate suggests that doubling the diameter of these wires would have increased by nearly an order of magnitude the mass of the particles capable of breaking them (from Eq. 6), which would have presumably increased their life span by nearly a factor of five (From Fig. 3). On future missions, thin dipole antennas should preferably be either slightly thicker or of the type used on Ulysses, which is both resistant to impacts and effective in terms of scientific results (see for example MacDowall et al, 1996; Meyer-Vernet et al., 1998b).

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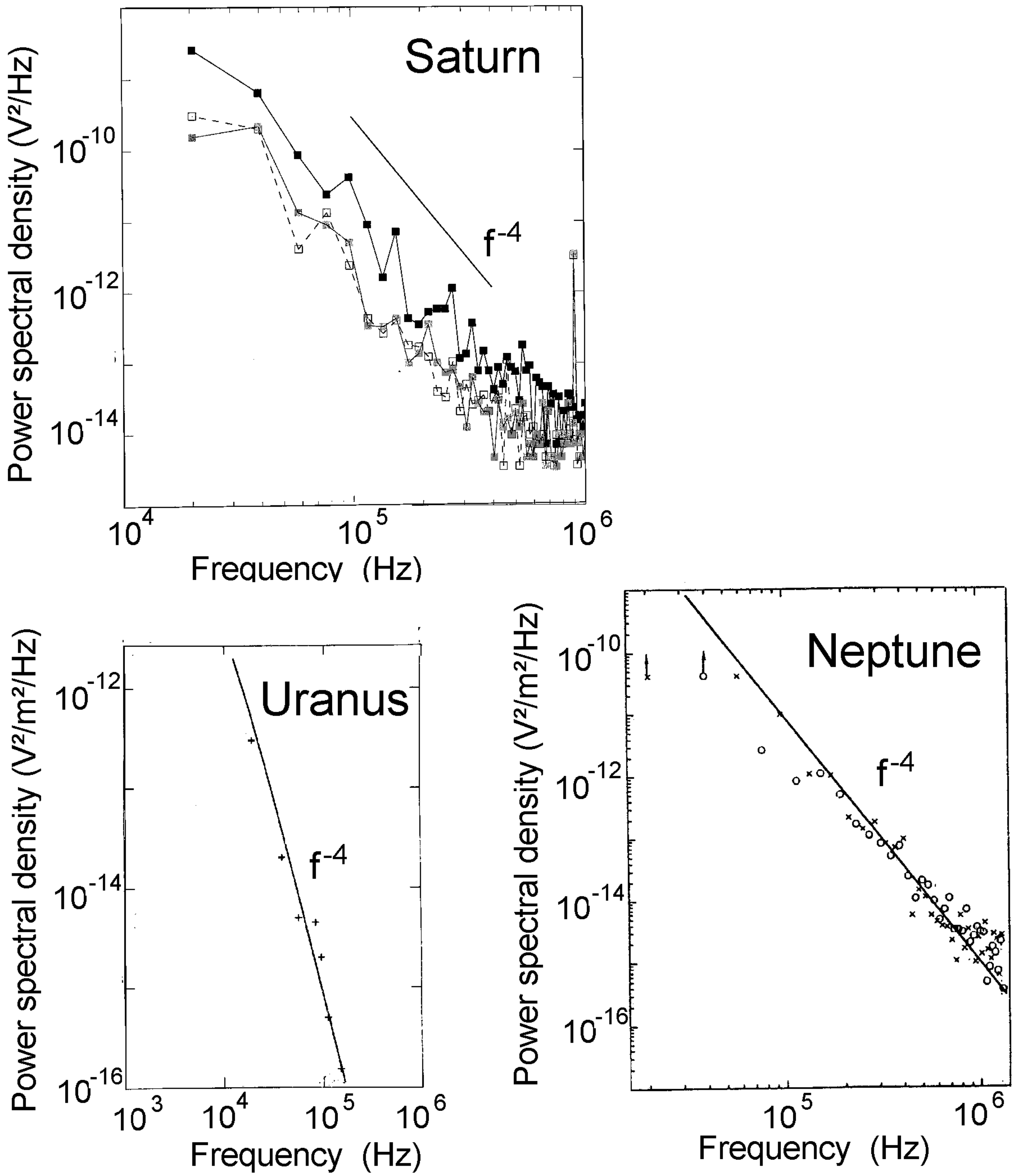

Figure 2. Voltage or field power spectra recorded by the radio instrument when Voyager 2 crossed the ring planes of Saturn, Uranus and Neptune (adapted from Meyer-Vernet et al., 1998a; Meyer-Vernet et al., 1986; Pedersen et al., 1991 respectively). A f^{-4} spectrum is shown for comparison.

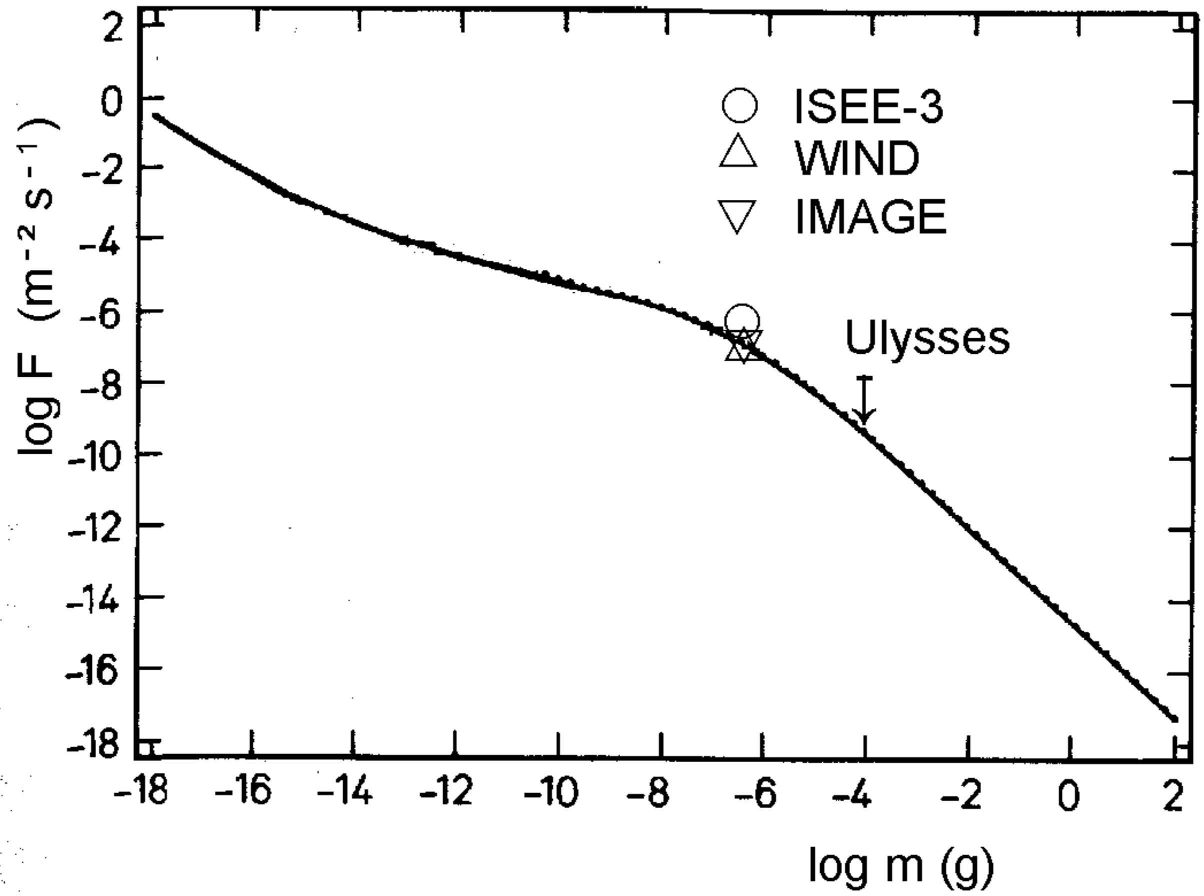

Figure 3. Cumulative flux of dust particles estimated from the antenna breaking events on ISEE-3, WIND, and IMAGE (symbols ○, △, and ▽, respectively), superimposed on the cumulative dust flux model at 1 A.U. adapted from Grün et al. (1985). The arrow indicates the upper limit estimated from the present life span of Ulysses (although the dust model may not be adapted for the trajectory of that spacecraft).