GEOPHYSICAL RESEARCH LETTERS, VOL. 13, NO. 7, PAGES 617-620, JULY 1986

VOYAGER 2 AT URANUS : GRAIN IMPACTS IN THE RING PLANE

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Abstract. During the Uranus ring plane crossing at 4.57 Uranus radii, the PRA instrument aboard Voyager 2 recorded a characteristic intense noise extending 10^4 km perpendicular to the ring plane. This is interpreted as due to impact ionization of dust grains striking the spacecraft. The noise level is smaller by a factor ~ 170 than the same kind of event recorded during Voyager 2 Saturn encounter just outside the G-ring. The results indicate a maximum concentration of about 10^{-9} cm^{-3} of grains larger than 1 μm with a scale height ~ 150 km across the ring plane. The distribution is asymmetrical, extending farther on the sunlit side. The inferred geometric optical depth is of order 10^{-8}.

Introduction

Voyager 2 crossed the Uranian ring plane at 17:15:30 spacecraft event time (SCET) on 24 January 1986. The spacecraft was at ~ 4.57 R_U. The Planetary Radio Astronomy (PRA) instrument detected an additional noise superposed on the Uranian low frequency radio emission [Warwick et al., 1986]. This noise occurred in the PRA-channels from 1.2 kHz up to 154.8 kHz. As in the case of Voyager 2's Saturnian ring plane crossing [Aubier et al., 1983], we interpret this event as due to grain impacts on the spacecraft. The interpretation developped in the present paper is improved and more detailed than in the case of Saturn, including recent studies of high-velocity grain impacts.

Observations

The PRA receiving system [Warwick et al., 1977] was designed to detect and identify planetary radio emissions and to determine their spectrum. It consists of a pair of 10 m orthogonal monopoles loaded against the conductive structure of the spacecraft, and connected to a high-sensitivity broadband sweeping receiver (1.2 kHz to 40.2 MHz). The basic mode allows to obtain dynamic spectra which are generated by 6 s scans dwelling 25 ms at each of the 198 steps.

The low frequency range (1.2 kHz to 1.3 MHz) is covered by 70 channels 1 kHz-wide each. Each channel detects the flux density alternatively in the left and right-hand circular polarization.

Figure 1 shows fixed frequency plots expressed in relative intensities. The ring plane event that we are studying in this paper is centered at 17:15:30 SCET and is most visible in the 20.4 and 39.6 kHz channels. We selected the data in the left-hand polarization, Uranian magnetospheric emission being right-handed at that time [Warwick et al., 1986]. Then we deduce the electric field power spectrum given in Figure 2 by plotting the peak value in each frequency channel. The lowest frequency for which a measurement has been possible in the PRA frequency range at ring plane crossing is 20.4 kHz. In the lowest channel (1.2 kHz) the noise saturates the receiver.

Noise due to grain impacts

The plasma observations near the ring plane [Bridge et al., 1986] yield an electron density n ~ 1 cm^{-3} and temperature T ~ 2 eV. Then it can be easily shown (e.g. Meyer-Vernet, 1983) that both the plasma thermal noise and the shot noise due to plasma particle impacts on the spacecraft or antennas are negligible.

Let us now calculate the noise due to grain impacts. When a small dust grain hits the spacecraft or antennas at a velocity v ~ 17 km/s (relative velocity between Voyager 2 and the grains), it is vaporized and ionized, as also a small part of the target's material. This produces an expanding plasma cloud, and a fraction of the released charge Q is recollected by the target, yielding a variation V(t) of its voltage. If the impacts are independent, this produces a noise with power spectrum

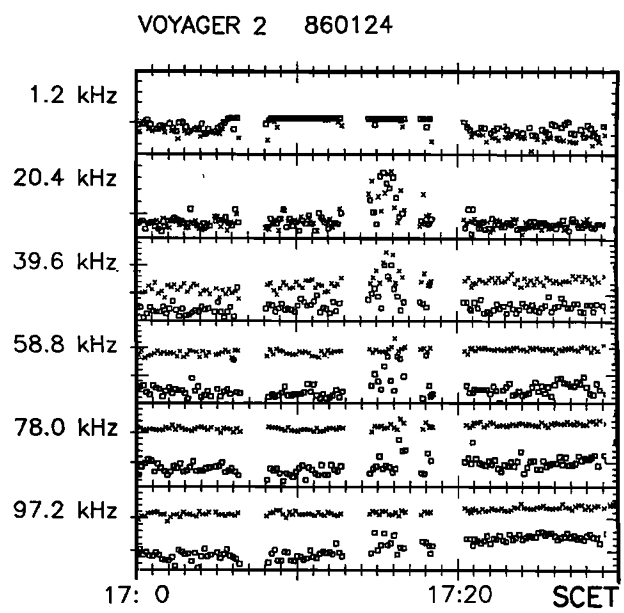

Fig. 1. Fixed frequency relative intensity plots of 6 PRA-channels as a function of time in a 30 minutes interval around the ring plane crossing. The symbols refer to different polarizations (squares: left-hand, crosses : right-hand). At frequencies higher than 20.4 kHz the signal is much more intense in right-hand polarization due to the proper emission of Uranus. The event attributed to dust impacts is near 17:15:30 SCET and most visible in the 20.4 and 39.6 channels.

Paper number 6L6163.
0094-8276/86/006L-6163$03.00

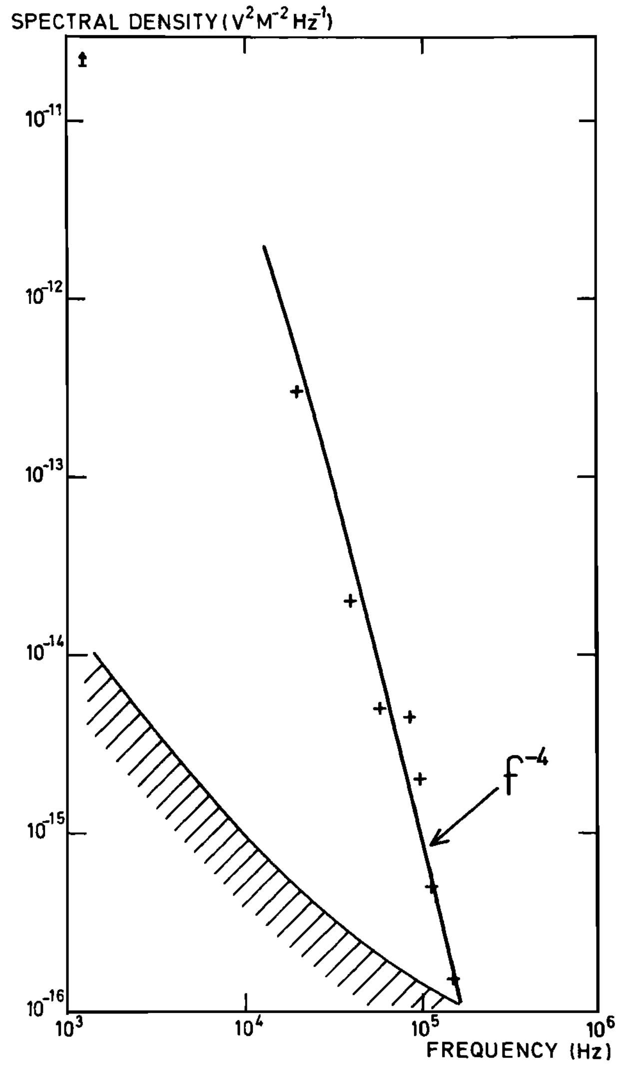

Fig. 2. Comparison between the electric field spectral density observed on left-hand polarization at ring plane crossing and the model of grain impacts (Eqs. 11 and 13). The arrow at 1.2 kHz indicates the channel saturation. The hatched area shows the minimum detectable level. The crosses represent the noise peak level in each frequency channel, between about 17:15 and 17:16 SCET.

$$V^2 = 2\ N \left| V\ (\omega) \right|^2 \tag{1}$$

where $V(\omega)$ is the Fourier transform of V(t) and N the impact rate ; (with non-identical impacts, Equation (1) is replaced by an integral).

The observation of that noise can be used to deduce parameters of the dust mass distribution. To achieve that, one must answer the following questions : i) what is the target ? ii) how does the charge Q depend on the impacting grain ? iii) what is the form of the induced voltage V(t) ?

The Target

The PRA receiver uses the antennas as monopoles which detect the voltage between each antenna and the spacecraft body. Therefore, the relevant target is the spacecraft conductive body, which receives most of the impacts since it has a much larger projected surface $S_\perp$ than the antennas, and which will recollect most of the charge released. The impact rate is related to the number of ambient grains per cm^3, n_G by $N = n_G\ v\ S_\perp$ i.e. (with $S_\perp \sim 2m^2$)

$$N = 3.4 \times 10^{10}\ n_G \quad s^{-1} \tag{2}$$

Note that the result would be different if the antennas were in a dipole configuration (Meyer-Vernet et al., 1986).

Released Charge Q as a Function of Grain Parameters

This problem, previously studied in the frame of in-situ detectors of interplanetary dust [Fechtig et al., 1978], has been recently reinvestigated for applications to cometary exploration. One obtains generally a relation of the form $Q = Q_o\ m^\alpha\ v^\beta$ where m is the impacting grain mass, $\beta \sim 3.5$, $0.6 < \alpha < 1$, and the factor Q_o depends on the grain and target material. The inequality $\alpha < 1$ reflects two main facts : i) electron-ion recombination is more effective for higher mass ; ii) the charge stemming from the target material itself is proportional to area rather than mass, yielding $\alpha \sim 2/3$ for this contribution [Kruger and Kissel, 1984]. Only for the smallest particles is α near 1.

As a conservative estimate, we take

$$Q \sim 5 \times 10^{-3}\ m^{0.8} \tag{3}$$

(Q in Coulomb, m in g) which is a factor 2 below an usual empirical relation for metallic targets [Fechtig et al., 1978]. For grains of radius $r = 1\ \mu m$, i.e. $m = \frac{4}{3} \times 10^{-12}$ g (assuming a density $\rho \sim 1\ g\ cm^{-3}$) Equation (3) yields $Q \sim m$, which is near recent measurements for aluminium targets, scaled to the proper velocity [Grün, 1984].

Induced Voltage V(t)

We calculate now the potential V(t) induced between the spacecraft and the monopole antennas when a grain of mass m impacts the spacecraft, releasing a charge Q which is subsequently recollected by the spacecraft. The rise time τ_r of V(t) depends on the dynamics of cloud expansion and charge recollection. The decay time τ_d depends on the currents flowing through both the receiver system and the plasma.

The decay time is easily calculated. The capacitance of the monopoles has been measured to be $C \sim 80$ pF [G. Daigne, private communication, 1986] and the input resistance is $R \sim 2 \times 10^7\ \Omega$.

It is easily shown that the parallel resistance due to the currents flowing between the spacecraft surface and the plasma is much larger than R ; thus, the main contribution to the decay time τ_d comes from R, and we get

$$\tau_d = RC = 1.6 \times 10^{-3}\ s \tag{4}$$

Thus, for frequencies $f \gg (2\pi\ \tau_d)^{-1} \sim 100$ Hz, the signal recovery can be neglected.

We now evaluate the signal rise time τ_r, which is related to the plasma cloud expansion, charge separation and recollection [Maasberg, 1984]. In a first approximation, the cloud expands radially, with a velocity $v_{ex} \sim v\ /\ [1+ (\rho/\rho_T)^{\frac{1}{2}}\ ]$ [Hornung and Drapatz, 1981] where ρ/ρ_T is the ratio of grain to target (Al) densities ; this yields $v_{ex} \sim 10$ km/s. There are several limits for τ_r : first it must be smaller than the time τ_1 taken by the cloud diameter to reach the spacecraft typical size D ~ 1 m, i.e.

$$\tau_r < \tau_1 \sim D/2v_{ex} \sim 5 \times 10^{-5} \text{ s} \quad (5)$$

Second, it must be smaller than the time τ_2 taken by the plasma density in the cloud, (which is $<3Q/(e\ 4\pi\ v_{ex}^3 t^3)$) to decrease to the ambient level n, i.e.

$$\tau_r < \tau_2 < (3Q/4\pi ne)^{1/3}/v_{ex} \approx 1.8\times10^{-4}\ r^{0.8} \text{ s} \quad (6)$$

where we have used (3) and r is the grain radius in µm. Finally, τ_r is probably not much smaller than the time τ_3 taken for the cloud radius (which increases as t) to be equal to its proper Debye length (which increases as $t^{3/2}$), since for $t<\tau_3$ the charge separation in the cloud is prevented, τ_3 satisfies

$$\tau_3 < 3Q/(4\pi\varepsilon_0\ T_c\ v_{ex}) \approx 10^{-5}\ r^{2.4} \text{ s} \quad (7)$$

where we have assumed an electron temperature in the cloud $T_c \sim 1$ eV [Hornung and Drapatz, 1981] and used (3).

A final constraint stems from the observations: the spectrum is near f^{-4} at frequencies $f > f_{min} \sim$ 20 kHz ; this means that the signal rise time is not negligible at these frequencies (otherwise the power spectrum would be near f^{-2}) ; thus $\tau_r > 1/(2\ \pi f_{min})$, i.e.

$$\tau_r > 8 \times 10^{-6} \text{ s} \quad (8)$$

The above constraints (and especially (5) and (8) which do not depend on the grain size), yield $\tau_r \sim 2 \times 10^{-5}$s , within a factor two. We approximate the rising part of the signal due to one impact as in Aubier et al., 1983

$$V(t) = H(t)\ (1 - e^{-t/\tau_r})\ Q/2\ C \quad (9)$$

where H(t) is the unit-step function.

Theoretical Spectrum

Inserting in (1) the Fourier transform of (9), we obtain the spectrum

$$V^2 = \frac{N\ Q^2}{2\ C^2\ \tau_r^2\ \omega^4}\ (1 + 1/\omega^2\tau_r^2)^{-1} \quad (10)$$

where $\omega = 2\pi$ f and f ≫100 Hz ; (for smaller frequencies the decay of the signal should be taken into account which changes V^2 by the factor $(1 + 1/\omega^2\ \tau_d^2)^{-1}$).

Equations (2), (3) and (10) yield the spectrum

$$V^2 = 10^{32} [n_G\ m^{1.6}]\ f^{-4} (1 + 6 \times 10^7 f^{-2})^{-1} \quad (11)$$

where n_G is the number (in cm^3) of grains of mass m (in g), the bracket stands for a mean over the grains, f is in Hz and V^2 in $V^2\ Hz^{-1}$. For a continuous grain mass distribution, one gets

$$[n_G\ m^{1.6}] = \int_{m_1}^{m_2} dm\ m^{1.6}\ \frac{dn_G}{dm} \quad (12)$$

where dn_G is the number of grains in the mass range from m to m+dm, and m_1 and m_2 are the minimum and maximum mass of detected grains. (Since the mass spectrum generally decreases for large m, m_2 is not the maximum mass of ambient grains but that of the largest grains that can impact the spacecraft in the finite measurement time).

Deducing grain parameters

Figure 2 shows the observed spectrum for the electric field V^2/L^2 (the antenna equivalent length is L~ 7m) ; the best fit to Equation (11) yields

$$[n_G\ m^{1.6}] \sim 0.5 \times 10^{-25} \quad (13)$$

Comparing with the Saturn ring plane crossing [Aubier et al., 1983] by Voyager 2 at 2.87 R_s, we find a noise smaller by a factor ~ 170. Thus, if others parameters were the same, the quantity $[n_G\ m^{1.6}]$ would be a factor 170 smaller for Uranus than for Saturn.

Deducing additional grain parameters from (12) and (13) requires further assumptions. We consider below two typical cases.

Unimodal Distribution

First, we assume that the grain distribution is largely dominated by r ~ 2 µm grains, as has been sometimes controversially argued in Saturn environment (cf. Burns et al., 1984). With $\rho \sim 1$ g cm^{-3}, i.e. m ~ 3 x 10^{-11} g, Equation (13) gives $n_G \sim 3 \times 10^{-9}$ cm^{-3} .

Power-law mass Distribution

Second, we consider a power-law mass spectrum

$$dn_G / dm = A\ m^{-p} \quad (14)$$

above some minimum mass (equivalently, as a function of the size $dn_G/dr \propto r^{-(3p-2)}$). For instance collisional ejecta have p ~ 1.8 [Grün et al., 1980], while small interplanetary particles have p ~ 1.3 to 1.5 for m < 10^{-10} g [McDonnell, 1978]. If p<2.6, Equation (12) is dominated by the largest particles and yields

$$[n_G . m^{1.6}] \sim A\ m_2^{2.6-p}/(2.6-p) \quad (15)$$

The mass m_2 of the largest impacting particles is deduced by noting that the observed spectrum (Figure 2) has been acquired during a time (removing the dead time) Δt ~ 0.17 s (7 times 0.025 s) : thus, the mean number of grains of mass above m_2 received during Δt must be smaller than one, i.e. (using (2))

$$3.4 \times 10^{10} \int_{m_2}^{\infty} dm\ \frac{dn_G}{dm} \sim 0.5/\Delta t \quad (16)$$

From (14) to (16) with p>1, we deduce that the largest detected mass is $m_2 \sim 3\times10^{-10}$ g (r = 4 µm grains), while the number of grains with m > m_2 in the ring plane is $\Delta n_G = 10^{-10} cm^{-3}$; this estimate does not depend on the value of the exponent p. On the other hand, the number of grains in the size range r > 1 µm is $\Delta n_G \sim 43(p-1) \times 10^{-10}$ cm^{-3}: for p ~ 1.5, this yields $\Delta n_G \sim 8 \times 10^{-10}$ cm^{-3} , i.e. (from (2)) 27 impacts per second on the spacecraft for grains larger than 1 µm. (This estimate is model dependent : taking $p \sim 1.8$ would give a value of Δn_G three times higher).

Finally, in the two cases considered (unimodal or power-law with $p = 1.5$ to 1.8), we find a concentration of order of magnitude 10^{-9} cm^{-3} for grains larger than 1 µm.

Dust distribution around the ring plane

The variation of the noise around the ring plane is shown in Figure 1. Above 20 kHz, the noise is detected during about 2 minutes (1800 km across the ring plane). This means that at 900 km from the ring plane, the noise has decreased by about 500 and is under the detection threshold.

At 1.2 kHz, a signal is detected in a much wider region due to the higher noise level at lower frequencies. It is not symmetric with respect to the ring plane : a signal has been detected from 9.5 min before the ring plane crossing (~ 9600 km) to 4.5 min (~ 4500 km) after, which means a greater dust extension on the sunlit side. On the other hand, in the non-saturated region, the increase and decrease rate correspond to an intensity ($V^2 m^{-2} Hz^{-1}$) variation from 8×10^{-13} to 10^{-13} in 30 seconds inbound and 60 seconds outbound.

The results above yield a scale height of exponential variation $H \sim 150$ km. We deduce the geometric optical depth normal to the ring plane

$$\tau \sim [n_G \pi r^2] H \sim 3.7 \times 10^7 [n_G m^{2/3}] \qquad (17)$$

where, as previously, the bracket stands for a mean over the mass spectrum with n_G in cm^{-3}, m in g, and a grain density 1 g cm^{-3} has been assumed. Equation (17) yields, for the two distributions

Unimodal. ($r = 2$ µm) : $\tau \sim 10^{-8}$

Power-law. ($dn_G/dm \propto m^{-p}$ with $p > 1$) :

$$\tau \sim 1.4 \times 2.7^p (p-1)\, 10^{7-10p} \int dm\, m^{0.67-p} \qquad (18)$$

This value depends on the parameter p ; if, for instance, $p \sim 5/3$ (which is rather close to collisional ejecta spectrum and ensures that all grain sizes contribute equally to the geometrical optical depth) and if the mass spectrum extends over about 4 decades, we obtain $\tau \sim 0.9 \times 10^{-8}$.

We find thus an optical depth of order 10^{-8} with reasonable assumptions for the grains mass spectrum. This value, which could indicate a dust torus associated with the satellite Miranda or with the rings, is probably too low to be optically detectable by Voyager.

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(Received April 17, 1986 ; accepted May 19, 1986)