GEOPHYSICAL RESEARCH LETTERS, VOL. 10, NO. 1, PAGES 5-8, JANUARY 1983

SHOT NOISE FROM GRAIN AND PARTICLE IMPACTS IN SATURN'S RING PLANE

M.G. Aubier, N. Meyer-Vernet, B.M. Pedersen

Observatoire de Meudon, 92190 MEUDON, France.

Abstract. The ring plane event detected by the Voyager 1 and 2 Planetary Radio Astronomy experiment is distinct from Saturn kilometric radiation (SKR) and from Saturn electrostatic discharges (SED). It consists of radio noises recorded only during Saturnian ring plane crossings. Several models are tested. The electrostatic noise on the antennas resulting from the passage of electrons and ions near the antennas (quasi-thermal noise) leads to order of magnitude much lower than the observed values. Shot noise due to electrons and ions collected and/or emitted by the antennas and spacecraft can explain the noise recorded during Saturn Voyager 1 ring plane crossing and partly what is observed in the case of Voyager 2. For this latter event we must introduce the shot noise due to grain impacts. A quantitative approach of this process gives an estimation of the dust size ~ 2.3 µm just outside the G-ring.

I - The PRA Experiment

The Voyager 1 and 2 Planetary Radio Astronomy (PRA) instruments observed several radio emissions near Saturn. Besides the typical non thermal electromagnetic radiations of the planet (SKR), intense emissions were detected in several occasions. When the Voyagers went through the ring plane, near the planet, wide band noises were detected, these emissions cannot be confused with SED (Saturn Electrostatic Discharges) since their properties and occurrence are very different (Warwick et al. 1982). The two events are described in part II. Several theoretical models are tested in the following sections to account for these emissions.

II - Saturnian ring plane crossings

Voyager 1 crossed Saturn's ring plane twice. During the first passage which occurred in the vicinity of Titan (80-11-12 at ~ 05 : 52 SCET) only plasma wave emissions associated with the passage through the Titan wake were identified. For the second ring plane crossing at 04 : 20 SCET on the 80-11-13, the spacecraft was at ~ 6 R_S, and the PRA-experiment detected intense electrostatic noises from 1.2 kHz to 154.8 kHz (Pedersen et al. 1981). Its power spectrum in the PRA frequency range is given Fig. 1 (▲). From the duration of the emission (~ 10 min) and the spacecraft velocity perpendicular to the plane, we deduced a thickness (~ ± 2400 Km) of the region within the E-ring where such radio noise was emitted.

During the unique Voyager 2 ring plane crossing the PRA instrument detected an intense event (Warwick et al., 1982) which was also observed at lower frequencies (Scarf et al., 1982a). Power in the PRA channels peaked at 04 : 18 : 17 SCET on the 81-08-26. The spacecraft was at ~2.87 R_S near the location of the G-ring (2.82 R_S). The time profile was symmetrical about the peak. This central peak displays a half-power rise time of 6 seconds or less, and the overall pattern exhibits a 30 db rise time of about 1 minute. From these different time scales we deduce characteristic dimensions perpendicular to the ring plane, where these noise components are observed : ± 70 Km and ± 700 Km. The ring plane event extended from 10 Hz to 1 MHz (Fig. 1). The highest spectral density is recorded at 56 Hz by the plasma wave (PWS) instrument (Scarf et al, 1982). This emission shows no polarization and is well distinct from other Saturn radio emissions. The plasma science (PLS) instrument measured ion densities consistent with electron density $n_e \sim 300$ cm^{-3} during the ring plane crossing (Bridge et al., 1982). Thus, the local plasma frequency (~ 90 kHz) is well above the frequency at which the event spectrum peaked. Therefore, the observed emission cannot be propagating electromagnetic waves. Several mechanisms which could give rise to such intense wide banded radio noises are now investigated.

III - Quasi thermal noise

The plasma electrons and ions which pass near the antenna (but do not hit it, this will be studied in section IV) induce an electrostatic noise on the antenna. This has recently been investigated to explain noise measurements on ISEE 3 spacecraft (Meyer-Vernet, 1979 ; Couturier et al. 1981). The authors calculate the noise voltage at the terminals of a dipole antenna at rest in a stable hot plasma described by two maxwellian electron populations : a hot component (n_H, T_H) and a cold one (n_c, T_c). The ion contribution as well as the magnetic field are neglected. This is valid if the receiving frequency f is larger than the ion plasma frequency, and the electron gyrofrequency f_c is smaller than the electron plasma frequency f_p. In the general case the noise spectrum must be obtained by a numerical integration. However, if the antenna length (L) is much larger than the plasma Debye length (L_D), one can use the following approximations (in V^2 Hz^{-1}) :
if

$$f \gg f_p \ : \ V^2_{QT} \sim \frac{kT_e}{\pi\varepsilon_o L} \frac{f_p^2}{f^3} \left(1 + \frac{T_H n_H}{T_c n_c}\right) \qquad (1)$$

if

$$f \ll f_p \ : \ V^2_{QT} \sim (\pi/2)^{1/2} \frac{kT_e}{2\pi\varepsilon_o f_p L} \qquad (2)$$

where $f_p(\text{Hz}) \sim 9.10^3 \sqrt{n_e(\text{cm}^{-3})}$ and T_e the average temperature of the plasma.

$$L_D(\text{m}) \cong 7 \frac{T_e\ (\text{ev})}{n_e\ (\text{cm}^{-3})}$$

Paper number 2L1797.
0094-8276/83/002L-1797$3.00

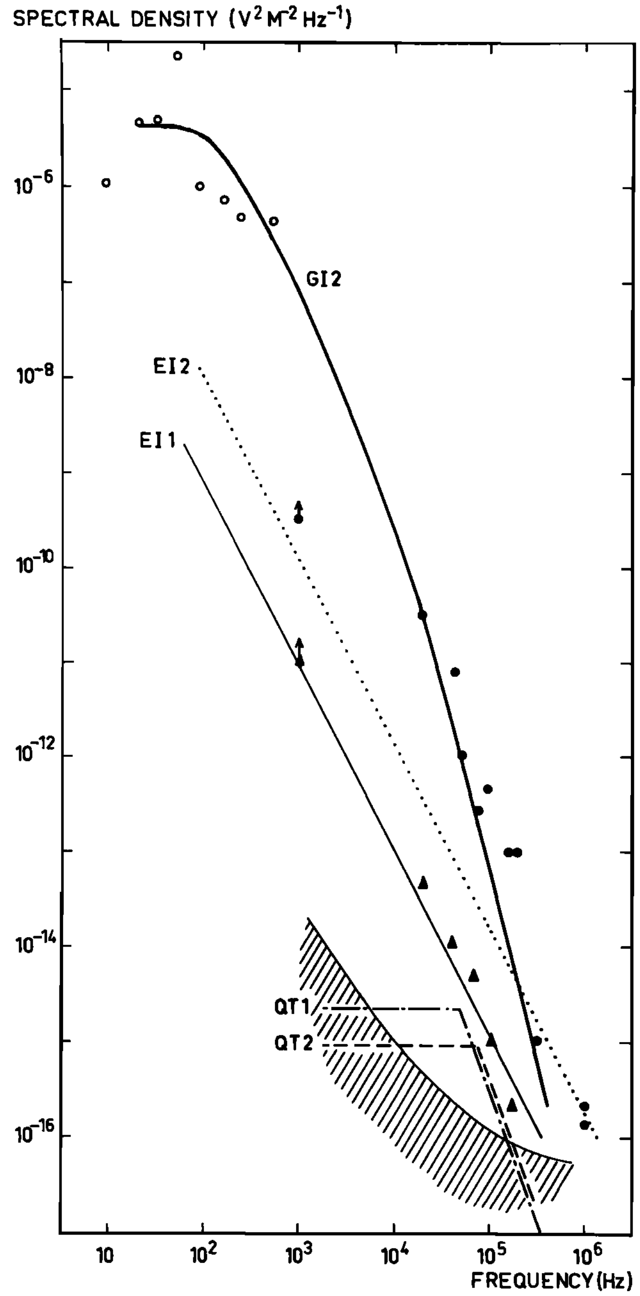

Fig. 1. Comparison between the maximum spectral densities observed during Saturn ring plane crossings { ▲ PRA-V1 (Pedersen et al., 1981) ● PRA-V2 (Warwick et al., 1982) o PWS-V2(Scarf et al., 1982)} and the models {quasi thermal noise vor V1 (-·-·-· QT1) and V2 (---- QT2), shot noise due to electron and ion impacts for V1 (—— EI1) and V2 (···· EI2) and grain impacts computed for V2 (——GI2)}.
The values pointed out by an arrow indicate that the 1.2 kHz channel was saturated. The hatched area shows the minimum detectable intensity.

Let us apply eq. (1) and (2) to the Saturnian events. During the V1 and V2 ring plane crossings the electron density was respectively $n_e \sim 20\text{cm}^{-3}$ (Pedersen et al., 1981) and $n_e \sim 300\text{ cm}^{-3}$ (Bridge et al., 1982). An estimation of $\frac{T_H n_H}{T_c n_c} \sim \frac{1}{10}$ is deduced from Bridge et al.(1981). With all these parameters equations (1) and (2) are plotted for the V1 and V2 events as QT1 (-·-·) and QT2 (---) on fig. 1. In both cases, the noise is very small compared to the observed values. We conclude that this mechanism is negligible.

IV - Shot noise of electrons and ions

Electrons and ions collected and/or emitted by the antennas and spacecraft can produce an intense shot noise. A precise calculation of this noise should take into account both the geometry of the antennas and spacecraft, (since the PRA antennas are monopoles) and the collective plasma effects on the trajectories and fields of the particles (Meyer-Vernet, 1982 b). In fact, the complicated geometry of the spacecraft precludes an exact calculation. So we shall evaluate the noise in a simple heuristic way, as for instance in Petit (1970).

Each event produces a variation of potential of amplitude ~ e/C (where C is the capacitance of the system) and duration $\tau_1 \sim R/v_T$ (where R is the collector's size and v_T the particle's thermal velocity) ; it can be approximated by a step if the observing frequency f is $< 1/\tau_1$. Since the time constant and inverse frequency are well above the time separation between two events the noise can be approximated by a mean of uncorrelated step-like events, the Fourier-transform of which is :

$$V_{EI}\ (\omega) \sim \frac{e}{C\,\omega} \quad \text{with } \omega = 2\pi f$$

The number of events per second is :

$$(J_e + J_i)\ S \cong J_e S$$

where S is the collecting surface and J_e and J_i are respectively the incident flux of electrons and ions. We have neglected the contribution of photoelectrons, since the ambient plasma densities are sufficiently high for this effect to be negligible (see, for instance, Meyer-Vernet, 1982 a). In addition, since we intend to make a rough evaluation, we have also neglected the secondary emission which will only change the present results by less than an order of magnitude. Thus, the spectral density is :

$$V^2_{EI} \cong 2\ \frac{e^2}{C^2\omega^2}\ J_e\ S \tag{3}$$

To estimate the electron flux, we need to know the collector's potential Φ and the plasma collector's characteristics. For instance, if the plasma is Maxwellian and the collector nearly spherical, an order of magnitude is :

$$J_e \sim \begin{cases} J_{oe}\ \exp\ (e\Phi/kT_e) & \text{if} \quad \Phi < 0 \\ J_{oe}\ (1 + e\Phi/kT_e) & \text{if} \quad \Phi > 0 \end{cases} \tag{4}$$

where $$J_{oe} = n_e\ \frac{kT_e^{1/2}}{2\pi m_e}$$

(n_e, T_e, m_e are electrons density, temperature and mass, k is Boltzman constant).

In addition to the approximation quoted above, eq. (3) neglects the finite time constant τ_R of the receiving system. If the frequency is such that the condition $\omega\tau_R >> 1$ is not fulfilled, then eq. (3) must be replaced by approximately :

$$V^2_{EI} \cong 2 \frac{e^2}{1/R^2_R + C^2\omega^2} J_e S \qquad (5)$$

(where R_R is the receiver resistance) i.e. in practical units :

$$\underset{\text{V}^2\text{Hz}^{-1}}{V^2_{EI}} \cong \underbrace{\frac{10^{-26}}{1/R^2_R + C^2\omega^2}}_{\Omega^{-2}} \quad \underset{\substack{\uparrow \\ \text{m}^{-2}}}{S} \quad \underset{\substack{\uparrow \\ \text{cm}^{-3}}}{n_e} \quad \underset{\substack{\uparrow \\ \text{eV}}}{T_e^{1/2}}\beta \qquad (6)$$

where $\beta = J_e/J_{oe}$ (see eq. 4) depends on the collector's potential.

Taking $S \sim 60$ m² (an approximation of the satellite surface since the PRA antennas are monopoles with much smaller surface), $C \sim 10^{-11}$ F (an approximation of the mutual capacitance), and $R_R \sim 2.10^7\ \Omega$, we obtain for $f < 3\ 10^5\ T_e^{1/2}$

$$\frac{V^2_{EI}}{L^2} \sim \frac{10^{-7}}{\underset{\substack{\uparrow \\ \text{Hz}}}{f^2} + 2.10^4} \underset{\substack{\uparrow \\ \text{cm}^{-3}}}{n_e} \quad \underset{\substack{\uparrow \\ \text{eV}}}{T_e^{1/2}} \ \beta \quad V^2Hz^{-1}m^{-2} \qquad (7)$$

Let us apply eq. (7) to the Saturnian events. We take $\beta \sim 1$ in both ring plane crossings.

During V1 encounter, the density is about $n_e \sim 20$ cm⁻³, the temperature $T_e \sim 10$ eV and eq. (7) yields for $f < 1$ MHz :

$$\frac{V^2{}_{EI}}{L^2} \cong \frac{10^{-5}}{f^2 + 2.10^4} \quad V^2Hz^{-1}m^{-2} \qquad (8)$$

Eq. (8) is plotted in fig. 1 as EI1(———) and one sees that the agreement with the experimental results (▲) is acceptable.

During V2 encounter, $n_e \sim 300$ cm⁻³, $T_e \sim 10$ eV, thus for $f < 1$ MHz :

$$\frac{V^2{}_{EI}}{L^2} \cong \frac{10^{-4}}{f^2 + 2.10^4} \quad V^2\ Hz^{-1}m^{-2} \qquad (9)$$

Eq. (9) is plotted in fig. 1 as EI2 (......) it is far below the observed values (o and ●), except at frequencies above 300 kHz.

We conclude that the noise resulting from electron and ion impacts can explain the PRA observations during V1 Saturn encounter. In the case of V2 ring plane crossing an additional mechanism is required to account for the intense emissions at frequencies lower than ~ 300 kHz.

V - Shot noise due to grain impacts

During the V2 Saturn encounter the spacecraft crossed the a region where dust grains are expected to be present. When such grains impact the spacecraft and/or antennas, the scenario depends on the impact velocity v : if it is sufficiently small (typically v < 1 - 10 km/sec, the limit depending on the grain material), the grains may give up their charge to target, as occurs for instance for medium energy electrons responsible for the shot noise calculated in the previous section. However, in the present case, the relative velocity v (~ 15 Km/sec) is so high that the grains will probably be vaporized and ionized. The resulting charge is much higher than the charge present on the grain before the impact : typically a grain with radius $a \sim 1\ \mu m$ has a charge $|Q| \sim 4\pi\varepsilon_o a\Phi \sim 10^{-16} - 10^{-14}$ Coulomb in a typical Saturnian plasma environment (see Meyer-Vernet, 1982 a), while the charges in the impact plasma for the same grains (assuming a 15 km/sec impact velocity) is $Q_i \sim 10^{-11}$ Coulomb with either sign (Fechtig et al., 1978). A part of the charge (depending on its potential) is subsequentially collected by the target with a small time constant. Thus, this yields a shot noise much more intense than if the grains were not vaporized and ionized.

This process, which is currently used for in-situ detectors of interplanetary dust (Fechtig et al., 1978), has indeed been suggested (Warwick et al., 1982, Scarf et al., 1982 a) to explain the noise observed during Saturn-Voyager 2 encounter ; however, these authors did not make a quantitative calculation of the power spectrum. This is done below, as in section IV.

First, we approximate each individual event in the following way. Before the impact, the charged (Q) grain induced a potential between the satellite and antenna (which varies from 0 to Q/C in the typical time R/v). After the impact, the grain is vaporized and ionized and a part of the charge Q_i is collected, yielding an induced potential which rises to about Q_i/C. Since $Q_i >> Q$, we neglect the grain's charge Q. The potential variation is approximated by :

$$V(t) = 0 \qquad\qquad t \leqq 0$$

$$V(t) = (1-e^{-t/\tau_i})\ Q_i/C \quad t > 0$$

which takes into account the rise time τ_i of the process, as measured for detectors. We take $\tau_i \sim 25\ \mu sec$ (Fechtig et al. 1978). The Fourier transform of V(t) is :

$$V(\omega) = \frac{Q_i}{C} \left(- \frac{1}{i\omega} + \frac{1}{i\omega - 1/\tau_i}\right)$$

Let n_G be the ambient grain density. The number of events per second is $N \sim \frac{1}{4} n_G Sv$. The power spectrum is :

$$V^2_{GI} = N|V(\omega)|^2$$

$$V^2_{GI} = N \frac{Q^2{}_i}{C^2\omega^2} \left(1 - \frac{1}{1 + 1/\tau^2{}_i\omega^2}\right) \qquad (10)$$

We note that if $\omega << 1/\tau_i \sim 4.10^4$, then $V^2_{GI} \sim \frac{NQ_i{}^2}{C^2\omega^2}$

and if $\omega >> 1/\tau_i \sim 4.10^4$, then $V^2_{GI} \sim \frac{NQ_i{}^2}{C^2\tau^2{}_i\omega^4}$

We also note that, as in section IV, the receiver time constant should be taken into account, yielding approximately :

$$V^2_{GI} \cong N \frac{Q_i{}^2}{1/R^2_R + C^2\omega^2} \left(1 - \frac{1}{1 + 1/\tau_i{}^2\omega^2}\right) \qquad (11)$$

The collected charge upon impact of a grain of mass m_G can be described by the empirical law $Q_i \sim \alpha m_G\ v^\beta$, where the parameters α and β depend on the velocity range, on the target and particle material and on the geometry (see Dietzel et al., 1973). Since these quantities are not well known, we can only estimate an order of magnitude for the charge per unit of mass :

$$Q_i/m_G \sim 0.5 \text{ Coulomb/gram}$$

for $v = 15$ km/sec and $\tau_i \sim 25$ μsec.

Assuming a density 1 g/cm³ for grains and other parameters as in section IV, Eq. (11) yields in $V^2\ Hz^{-1}\ m^{-2}$ units :

$$\frac{V^2{}_{GI}}{L^2} = \frac{10^{-6}N}{f^2 + 2 \times 10^4}\, a^6(\mu m)\left(1 - \frac{1}{1 + \frac{4\ 10^7}{f^2}}\right) \qquad (12)$$

The best fit of eq. (12) to the maximum intensities for the Voyager 2 event is obtained for $N_{(m^{-3})}\ a^6{}_{(\mu m)} \sim 10^5$. With the collecting surface $S \sim 60$ m² this yields :

$$n_{G(m^{-3})}\ a^6{}_{(\mu m)} \sim 0.4$$

With the impact frequency N = 500/sec measured by Scarf et al. (1982 b) which corresponds to a density $n_G \sim 2\ 10^{-9}$ cm⁻³, we obtain a grain size

$$a \sim 2.3\ \mu m$$

It is important to note that this determination of a, which enter with exponent 6 in eq.(12), is very weakly dependant on the parameters and particularly on the value of N, contrary to the estimation of n_G.

The sharp time profile of the radio noise event can be interpreted as the evolution of the grain density n_G along the spacecraft trajectory. The width of the central peak indicates a decrease of n_G along the spacecraft trajectory. The width of the central peak indicates a decrease of n_G by a factor 2 over ± 70 km perpendicularly to the ring plane. The overall pattern represents a density decrease of a factor 10³ over ± 700 Km.

Due to the slope of the power spectrum, f^{-4} at high frequencies, the grain impact noise leads to too weak intensities compared to the observations f > 300 kHz. In this frequency range the electron and ion impact process can account for the observations.

Up to now we have implicitly assumed that all the grains have the same size. In fact, it is expected that the blocks in the main rings have a large size spectrum (Henon, 1981). Though the grain sizes are determined by rather different mechanisms than the large blocks (elimination by electromagnetic forces, electrostatic disruption, etc ...) their sizes may also well be distributed in a large spectrum. In this case, eq. (12) should use the mean value

$$< n_G\ a^6 > = \int_{amin}^{amax} \frac{dn}{da}\, a^6\, da \sim 0.4$$

Then a further estimation of the grain size needs an hypothesis about the size distribution. For instance, assuming a power spectrum and using an independant measurement such as the optical depth should yield the parameters of this law.

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(Received July 8, 1982;
accepted October 29, 1982.)