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A Search for Saturn Electrostatic Discharges in the Voyager Plasma Wave Data

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Voyager plasma wave data were searched for evidence of Saturn electrostatic discharges which have previously been reported by the planetary radio astronomy team following the Voyager 1 and 2 encounters with Saturn. On the basis of the radio astronomy observations, the discharges should have been observable by the plasma wave experiment on Voyager, however, there is no evidence in the plasma wave data for the phenomenon. We analyze the statistical significance and comment on the ramifications of this null result. We entertain various explanations of the lack of plasma wave observations of electrostatic discharges, including the possibility that many events are of a much shorter duration than previously reported or that there could possibly be a nonlinear distortion in the radio astronomy receiver which could artificially broaden the spectrum of the discharges.

INTRODUCTION

One of the most surprising results reported by Warwick *et al.* (1981) of the Voyager 1 planetary radio astronomy (PRA) observations near Saturn was the presence of bursts of radio noise near Saturn unlike any previously discovered planetary radio emission. They report that the so-called Saturn electrostatic discharges (SEDs) have a bandwidth extending from 20.4 kHz to at least 40.2 MHz with a total power of 10^7 to 10^8 W. The emissions are usually unpolarized and have durations of a few tens of milliseconds but sometimes last several hundred milliseconds. Warwick *et al.* ruled out telemetry errors, discharges near the spacecraft, and dust impacts as possible explanations. Perhaps the most persuasive evidence of a source associated with Saturn is the 11-hr periodicity [later refined to 10^h $10^m \pm 5^m$ by Evans *et al.* (1981)] of episodes of the SED activity. Warwick *et al.* (1981) suggested that since the peak ionospheric electron density gave a 1.37-MHz cutoff (Tyler *et al.*, 1981) the source could not be atmospheric lightning, but was more likely located in the rings.

Warwick *et al.* (1982) confirmed that SEDs were again observable by Voyager 2 but added that some of the events are polarized in a relatively complex way. The emission was also found to rotate about Saturn in searchlight-like fashion as opposed to turning on and off once every ~10 hr. Warwick *et al.* (1982) reiterated that the probable source location was in the rings at a distance of 1.81 R_S, where the Keplerian orbit period matches the SED episodic period.

On the basis of these reports and unpublished data provided by the PRA team (D. R. Evans, private communication, 1982) we determined that SEDs should be detectable with the plasma wave receivers on Voyager and searched the encounter data for evidence of the bursts. Not a single candidate event was found and we analyzed this null

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result for its statistical significance. Further, assuming the null result is significant and is in disagreement with the planetary radio astronomy observations, we discuss the implications on the various possible sources for the emission detected by the PRA receiver.

ANALYSIS OF THE SED DETECTION PROBABILITY

On the basis of extensive information made available by the Voyager planetary radio astronomy team we determined that SEDs should be detectable with the plasma wave receiver and proceeded to search for evidence of the events in the data. An examination of the Voyager 1 data for more than a day centered on closest approach and in particular a 1-hr interval near closest approach when events had been seen as low as 40 kHz by the PRA team revealed no likely SED candidates. We present in this section a discussion of the relevant instrument characteristics and an analysis of the statistical significance of a null result.

The plasma wave spectrum analyzer consists of 16 filter channels and two logarithmic compressors. Each logarithmic compressor is a detector whose output is a voltage which is roughly proportional to the logarithm of the signal strength passed by the filter currently being sampled. This study is primarily concerned with the upper portion of the frequency range covered by the spectrum analyzer. In particular, the high-frequency compressor, which has a time constant $\tau = 42$ msec, is used as a detector for the eight highest-frequency channels in the range 1.0 to 56.2 kHz. Each of the eight channels is sampled sequentially over a 4-sec interval. Every 500 msec the compressor is switched to a new channel, and just before the end of the 500-msec interval the analog output of the compressor is digitized in the Flight Data System. Further information on the Voyager plasma wave receiver can be found in Scarf and Gurnett (1977).

We analyzed the response of the system described above to an event characteristic of SEDs. On the basis of information provided by Warwick *et al.* (1981, 1982) and by D. R. Evans (private communication, 1982) we used a pulse of broadband noise (20 kHz $\lesssim f \lesssim$ 40 MHz) with a square wave envelope of duration $T = 50$ msec and a typical power flux of 4×10^{-18} W m^{-2} Hz^{-1}. The rate of occurrence of events is 0.2 sec^{-1} and for a particular interval (2330 SCET, Day 317 to 0030 SCET, Day 318, 1980) the radio astronomy experiment detected eight events at either 60 or 40 kHz (D. R. Evans, private communication, 1982). Taking into consideration that the PRA duty cycle is 25 msec/6 sec in a given channel, the eight observed events correspond to a rate of one event below 60 kHz every 3.75 sec. In fact, the radio astronomy team has utilized the nearly uniform occurrence probability over frequency to argue that the power spectrum of an individual burst is flat to above 40 MHz and the event is detected at whatever frequency the receiver happens to be tuned to at the time of occurrence.

Because the event duration is similar to the plasma wave receiver time constant, we paid particular attention to the response of the receiver to phenomena of short duration. The following analysis is most accurate for weak signals, those within about 20 db of the plasma wave receiver threshold. However, it is clear the detection capability of the instrument increases as the pulse amplitude increases, hence we are mainly concerned with the response to the weaker pulses. Figure 1 is an aid to understanding this response. The top panel, Case 0, shows the ideal case in which the timing of the event and the sampling of the plasma wave receiver channel is such that the output of the compressor is maximized. In this example, the event ends just as the output is digitized or sampled so that the compressor has had the full duration of the pulse in which to respond. The signal amplitude which is measured, then, is

$$V_{\max} = V_0(1 - e^{-T/\tau}), \qquad (1)$$

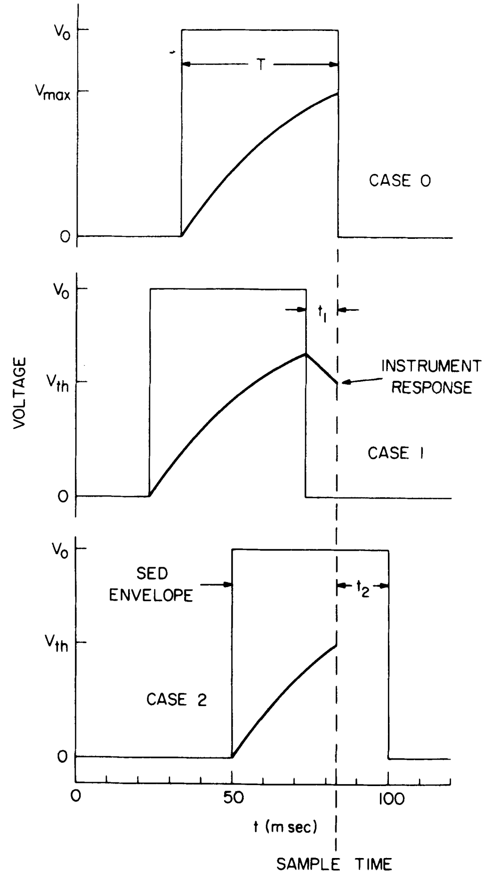

FIG. 1. The response of the plasma wave receiver to a short-duration burst with a square envelope. Case 0 represents the ideal case in which the output is sampled at the end of the pulse. Cases 1 and 2 show the more general situations when the pulse ends before or after the channel is sampled, respectively.

where V_0 is the amplitude of the input square wave pulse. Equation (1) is valid only for $T < 500$ msec.

In the more general cases shown in the middle and lower panels of Fig. 1 the end of the pulse will occur either before the sample is digitized (Case 1) or after (Case 2). In Case 1, the measured amplitude will decrease exponentially after the end of the pulse. The maximum amplitude $V_{\max}$ will have been reached at the end of the pulse and is given by Eq. (1). The amplitude then decays for a time, t_1, until the channel is sampled:

$$V = V_{\max} e^{-t_1/\tau}. \qquad (2)$$

Hence the measured amplitude is obtained by combining Eqs. (1) and (2):

$$V = V_0(1 - e^{-T/\tau})e^{-t_1/\tau}. \qquad (3)$$

In Case 2, the channel is sampled before the end of the pulse. Here, the compressor has had a time $T - t_2$ to respond to the signal:

$$V = V_0(1 - e^{-(T-t_2)/\tau}). \qquad (4)$$

The duty cycle for a given spectrum analyzer channel, then, is obtained by finding the maximum times t_1 and t_2 for which a minimum detectable signal V_{th} will result for a given amplitude, V_0. We take V_0 to be the typical amplitude corresponding to 4×10^{-18} W m^{-2} Hz^{-1}. V_0 is found using the relation

$$P(f) = \sqrt{\frac{\epsilon_0}{\mu_0}}\,\frac{V_0^2}{l_{\text{eff}}^2 \Delta f}, \qquad (5)$$

where $P(f)$ is the power flux, l_{eff} is the effective length of the antenna, 7.07 m, and Δf is the effective noise bandwidth of the filter. For the 56.2-kHz channel $\Delta f = 5950$ Hz and $V_0 = 2.12 \times 10^{-5}$ V. We can clearly and unambiguously identify an event with an amplitude of 1.16×10^{-5} V in this channel under encounter conditions present near 0000 SCET on Day 318. Hence, if we use $V_0 = 2.12 \times 10^{-5}$ V and $V = 1.16 \times 10^{-5}$ V in Eqs. (3) and (4) we can solve for t_1 and t_2 and obtain 10 and 17 msec, respectively. Therefore, a pulse occurring within a window of $t_1 + t_2 = 27$ msec around the sample time will be clearly identifiable in the plasma wave channel at 56.2 kHz.

The 56.2-kHz channel is sampled once per 4 sec, so the duty cycle is 0.027/4.0 = 0.675%. Using an event rate of one per 3.75 to 5 sec, there should be between 720 and 960 events per hour. Hence approximately five to six events should be observable in the 56.2-kHz channel in an hour.

The assumption of a square wave envelope is not an extremely restrictive one as can be seen by the response curves in Fig. 1. Any envelope which rises at least as fast as the exponential curve and falls no faster than an exponential will yield an identical result. The implicit assumption that all events have a power flux of 4×10^{-18} W m^{-2} Hz^{-1} is false. We take the typical amplitude to be the median amplitude (D. R. Evans, private communication, 1982) and, hence, half the events will fall below V_0 and half above. All events above V_0 occurring within the 27-msec window will be detected, and some of those below V_0 will be detected, depending on how weak they are and how close to the sample time those events end. Even being conservative, however, and assuming none of the events below V_0 are observable, three events should be detectable in a 1-hr interval at 56.2 kHz. The assumption that all events have $T = 50$ msec is conservative since Warwick *et al.* (1981) report that some events last several hundred milliseconds and these should be much more easily detectable. It is possible that a distribution of event durations which favors shorter durations (but which still has an average of 50 msec) could alter our conclusions, however, and we discuss this possibility in the next section.

We should point out that because the PRA and plasma wave channels are, in general, not sampled simultaneously and because both instruments have low duty cycles at a given channel, it is highly unlikely that both instruments would detect the same burst, hence we approached the search from a statistical point of view. Since the occurrence of SED events is a Poisson process, the probability of seeing no events in a 1-hr interval can be calculated by reducing the mean rate of occurrence of SEDs (~900 per hour) by the plasma wave duty cycle of 0.675% to obtain a rate of six events per hour. If we further reduce this by a factor of 2 assuming half have amplitudes too weak to be detected, the expected rate is three per hour. For a Poisson process under these conditions, the probability of seeing no events is

$$P(0) = \frac{3^0}{0!} e^{-3} = 0.0498. \qquad (6)$$

Hence there is a probability of 0.95 that one or more events would be detected in the 56.2-kHz channel during a 1-hr interval. One might argue that a more correct procedure is to treat the experiment as a Bernoulli trial for which each sample has a given probability p for revealing an event. In this case, the probability of seeing k events in an hour is

$$P(k) = \binom{n}{k} p^k (1 - p)^{n-k}, \qquad (7)$$

where n is the number of samples or trials. Solving Eq. (7) for $k = 0$, that is, for no detected events, and using $n = 900$ (one sample every 4 sec) and $p = 0.0034$, we find that $P(0) = 0.0466$. We used the number of 27-msec intervals in 1 hr and a mean occurrence rate of 900 SEDs per hour to calculate p. Hence both methods indicate that the probability of detecting at least one event is $\gtrsim 0.95$.

The primary interval that was searched for evidence of SEDs was during the episode which peaked near closest approach on the Voyager 1 trajectory (Warwick *et al.*, 1981). The 1-hr interval from 2330, Day 317 to 0030, Day 318, 1980, was judged by the PRA team to be the most likely interval for observing SEDs at low frequencies. Every measurement at 56.2 kHz during this interval was examined for sporadic events in which one measurement was at or above 1.16×10^{-18} W m^{-2} Hz^{-1}, while the measurements immediately before and after were at the nominal background level for the interval (1.04×10^{-18} W m^{-2} Hz^{-1}). The plasma wave data form the 56.2-kHz channel (as well as 31.1- and 17.8-kHz channels) for this 1-hr interval are displayed in Fig. 2. As can be seen in the top panel, only one data point is significantly higher than background and this has been identified as a telemetry error. The PRA data also contain telemetry errors at this time and no evidence of an SED event, hence there is no

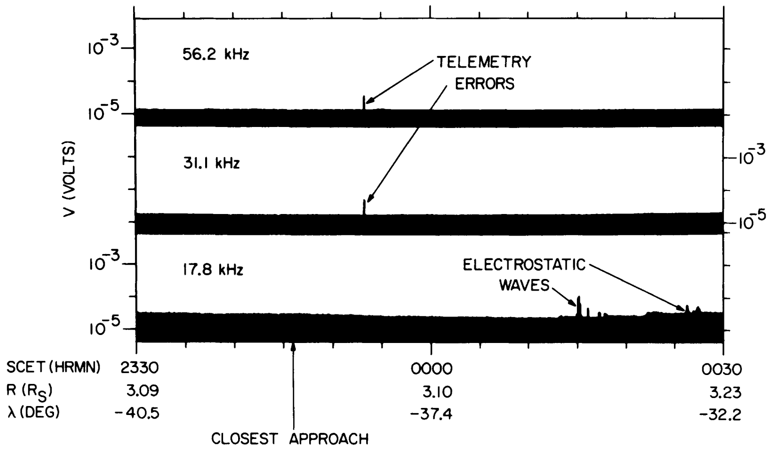

FIG. 2. Plasma wave data from the 56.2-, 31.1-, and 17.8-kHz channels from a 1-hr interval near closest approach when the PRA instrument detected several SEDs at frequencies below 60 kHz. The only bursts evident in the plasma wave data are telemetry errors and electrostatic waves. Data are from Voyager 1, November 12–13, 1980, Days 317–318.

question regarding the interpretation of this point. It is clear that no candidates for SED events are present for the 1-hr interval at 56.2 kHz plotted in Fig. 2. The same search procedure was used near the peak of the preceding episode between 1200 and 1500 on Day 317. During this time the nominal background was slightly lower, 8.85×10^{-19} W m^{-2} Hz^{-1}, and sporadic events at or above 9.83×10^{-19} W m^{-2} Hz^{-1} were searched for. Again, no candidates were found.

The 31.1- and 17.8-kHz channels were examined for the two episodes discussed above with no positive results. The data from the 31.1- and 17.8-kHz channels near closest approach are displayed in the center and bottom panels of Fig. 2. A telemetry error can be seen at 31.1 kHz, which is related to the one at 56.2 kHz discussed above. Some sporadic electrostatic waves are evident after 0015 SCET at 17.8 kHz, but each of these bursts last for a minimum of 4 sec, and therefore they cannot be SEDs. Again, there is no signature which could be considered evidence of SEDs in either of the two lower-frequency channels plotted in Fig. 2.

The spread in amplitude about the typical or median value for the bulk of the events is about 3 db (D. R. Evans, private communication, 1982), hence several events could be expected to extend well above the plasma wave receiver's threshold. The data for at least a 24-hr period centered on closest approach were plotted in a manner such that even weak spiky signals would be readily observable. Each of the three channels from 17.8 to 56.2 kHz were examined for evidence of SEDs for the entire 24-hr period. (Obviously, the events will have, on average, lower amplitudes at greater distances from Saturn if one assumes a source at or near the planet and the lower-frequency channels have detectability thresholds slightly higher than at 56.2 kHz. But we would expect that, given enough observing time, an exceptionally intense burst would be seen.) One interval, from about 0200 to 0445 on Day 318, showed some spiky emissions well above threshold, but these have been identified by both Gurnett *et al.* (1981) and Pedersen *et al.* (1981) as electrostatic waves, probably electron cyclotron harmonic emissions near the upper hybrid resonance frequency. A few other random spikes were detected which have been unambiguously identified by both the plasma wave team and the PRA team as telemetry errors. Unfortunately, the episode following closest approach was obscured by intense Saturnian kilometric radiation at the lower frequencies. We have not mentioned Voyager 2 observations because a failure in the Flight Data System on that spacecraft has cast serious uncertainty on the calibration of the upper eight frequency channels and may have reduced the effective sensitivity of the plasma wave instrument. Nevertheless, an examination of possible SED events in the Voyager 2 plasma wave data yielded no likely candidates.

DISCUSSION

The total lack of detections of SED events by the plasma wave receiver has one definite implication, that is, SEDs have a power flux of less than $\sim 2 \times 10^{-18}$ W m^{-2} Hz^{-1} at 56.2 kHz near the Voyager 1 closest approach. The consequences of this observation alone may not bear significant weight. The real problem posed is the apparent discrepancy between the PRA and plasma wave observations. Based on the planetary radio astronomy observations, the SEDs should be detectable within at least one interval of time with a confidence level of 95%. But the absolute absence of any evidence of them in the plasma wave data raises questions in our minds about the interpretation of the PRA observations.

One simple explanation is that a systematic error in the calibration of one or both of the experiments might account for the discrepancy; the SEDs may simply be below the plasma wave receiver's threshold. We compared the calibrated power flux of Saturnian kilometric radiation at several different times and found agreement to within ~2 to 3 db. In some cases, the intensity measured by PRA was greater, and in others it was less, than that measured by the plasma wave receiver. If there is any general trend, it is for the plasma wave amplitudes for a given event to be slightly higher than the PRA measurements, hence this would suggest the plasma wave receiver would be more likely to be able to observe SEDs than if there were no calibration differences as has been assumed in the analysis above. We feel that the differences may be due in part to the polarization of the kilometric radiation [to which only the PRA receiver is sensitive (Warwick *et al.*, 1977)] or to differences in the spectrum between the frequencies sampled by the PRA instrument (20.4, 39.6, and 58.8 kHz) and those sampled by the plasma wave receiver (17.8, 31.1, and 56.2 kHz).

A second explanation for the lack of SED detections by the plasma wave receiver is that the duration of a significant number of events may be considerably less than 50 msec (M. L. Kaiser and D. R. Evans, private communication, 1982). For example, if half the events had durations much shorter than the receiver time constant of 42 msec, they would be undetectable and the probability of seeing no events as calculated in Eq. (6) would be 0.22 instead of 0.05. It is clear that the distribution of event durations as a function of event frequency needs to be studied not only as a means of clearing up the discrepancy with the plasma wave observations, but also to provide theoreticians with a more informative and accurate description of the SED events.

Another possibility is that the SED spectrum does not extend down to 56 kHz and the PRA response at low frequencies may be due to a nonlinear distortion within the receiver. We stress that we do not dispute the existence of SEDs; the reported 10-hr periodicity of SED episodes is almost incontrovertible evidence that the emission is real and is not generated at or near the spacecraft. However, if the SEDs were an intense, high-frequency phenomenon, it is possible that there could be a nonlinear response in the PRA receiver which would cause spreading of the signal to low frequencies because of frequency conversion effects. Spreading down to low frequencies is a relatively common effect and, in fact, has been observed in the PRA receiver in response to strong signals detected both at Jupiter and Saturn (M. L. Kaiser, private communication, 1982). The PRA preamplifier has no high-frequency roll-off which would leave the receiver susceptible to nonlinear effects due to signals well above 40 MHz in addition to in-band signals. Conversions of this type would not be expected in the plasma wave receiver because of a roll-off in the preamplifier above ~100 kHz of about 12 db/octave. If the SED spectrum has a higher-low-frequency cutoff than that reported by Warwick *et al.* (1981), the observations could be consistent with a source below the Saturnian ionosphere, such as the atmospheric lightning source suggested by Burns *et al.* (1982).

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