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Are Saturn electrostatic discharges really superbolts? A temporal dilemma

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[1] Saturn electrostatic discharges (SED) are freely-propagating radio emissions detected in the high frequency (HF) radio band (1–40 MHz) associated with electrical discharge (i.e., lightning) from storms in Saturn's atmosphere. While SEDs responsible for the RF emission are considered to be very energetic superbolts (>10^{13} J), this determination is intimately related to the temporal nature of the discharge itself. As we demonstrate, if we assume the discharge has similar temporal properties as terrestrial cloud-to-ground discharges (with a stroke time scale ~70 μs), then indeed the discharge energy has to be ~ 10^{13} J in order account for the Cassini-observed radiated HF power of ~50 W/Hz. However, if the discharge duration is faster than the terrestrial case (i.e., ~1 μs), the energy of the discharge can be weaker than the terrestrial case since the central peak of the emission shifts closer to the HF band. Because of the near-flat SED spectra measured in the HF which favors a faster discharge, we conclude that the high level of radiated HF power from SEDs may have less to do with any extreme super-bolt strength of the discharge and has more to do with the intrinsic quick time-scale of relatively weaker discharges. **Citation:** Farrell, W. M., M. L. Kaiser, G. Fischer, P. Zarka, W. S. Kurth, and D. A. Gurnett (2007), Are Saturn electrostatic discharges really superbolts? A temporal dilemma, *Geophys. Res. Lett.*, *34*, L06202, doi:10.1029/2006GL028841.

1. Introduction

[2] One of the most interesting observations made by the radio instruments onboard the Voyager 1 and 2 spacecraft during their early 1980's flyby of Saturn was the detection of very impulsive radio bursts called Saturn electrostatic discharges (SEDs). These events detected by Voyager's Planetary Radio Astronomy (PRA) instrument were short-duration bursts observed during a fraction of the PRA radio sweep at frequencies between 20 kHz and 40 MHz. While there was some initial discussion of a ring source [*Warwick et al.*, 1981; *Evans et al.*, 1983], the events were found to be beamed consistent with an atmospheric source [*Kaiser et al.*, 1983] and to have a low frequency cutoff consistent with an emission propagating from an atmospheric source through the ionosphere [*Zarka*, 1985]. Hence, the bursts are considered the radio emission from Saturn storm-created lightning. New results from Cassini have connected episodes of SEDs to cloud storm features found at mid-latitudes, further confirming an atmospheric source [*Porco et al.*, 2005; *Desch et al.*, 2006].

[3] Figure 1 shows an example of an SED episode as detected by Cassini's Radio and Plasma Wave Science (RPWS) instrument. Since SED emissions have durations shorter than the frequency sweep rate of the receiver, the receiver detects only a portion of each event. The detection signal frequency is quasi-random: it occurs above the ionospheric cutoff at the frequency channel the receiver is tuned to at the time of the discharge. The result is that the emission has a "salt-and-pepper" morphology on a frequency versus time spectrogram like that shown in Figure 1.

[4] Based on a composite of SEDs detected by Voyager, *Zarka and Pedersen* [1983] and *Zarka et al.* [2004] found that the spectrum was relatively flat below 10–20 MHz but had a decreasing slope between f^{-1} to f^{-2} at higher frequencies up to the Voyager measurement limit of 40 MHz. Such a finding would suggest that the SED atmospheric discharge is very short (<1 μs) to account for near equal radiated energy below 20 MHz [*Farrell*, 2000; *Zarka et al.*, 2004]. *Fischer et al.* [2006a, 2006b] and *Zarka et al.* [2006] examined the SEDs detected by the RPWS instrument during 2004, when there were 4 well-defined storms that generated 95 rotational episodes, and 5400 individual events. Like previous Voyager studies, they found a nearly flat SED spectrum between 2 and 16 MHz with SED radiated power at between 40–220 W/Hz in this region. *Fischer et al.* [2006a, 2006b] noted that the spectra exhibited a mild rolloff in the SED power spectrum between 2–16 MHz as $f^{-1/2}$.

[5] *Fischer et al.* [2006a] compared the measured Cassini RPWS intensities in the HF from Earth's lightning (measured during the 1999 Cassini/Earth flyby) and Saturn's electrostatic discharge and demonstrated that the radiated SED power in the HF is 10^4 – 10^5 time greater than that in the terrestrial events. Under the explicit assumption that the SED temporal/spectral character is similar to Earth's lightning, they indicate that the dissipation energy in an SED stroke, W_d, must then be greater than 10^{13} J; at superbolt levels compared to a total energy of 10^9 J for a typical terrestrial event. We define a "superbolt" as a discharge with energy greatly exceeding that in a typical terrestrial cloud-to-ground stroke. Fischer et al. also state that the HF comparison and discharge energy derivation is strongly dependent upon a similar temporal/spectral character of SED and the terrestrial discharge and that there is the possibility that faster discharges might result in reduced discharge dissipated energy. In this work, we follow-up on Fischer et al.'s suggestion, and derive the discharge dissipa-

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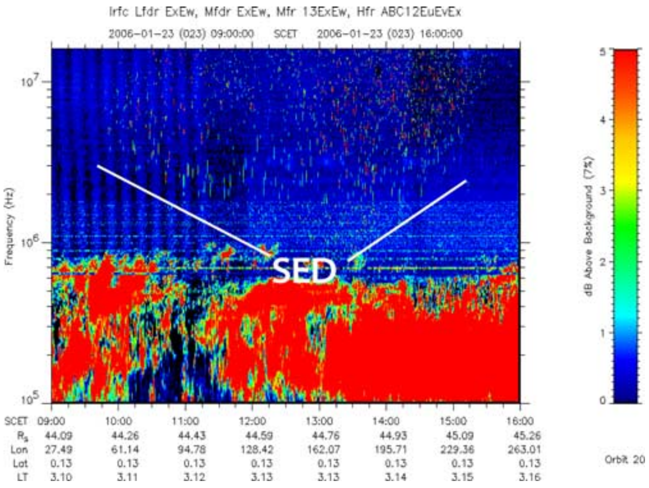

Figure 1. A Cassini/RPWS radio spectrogram showing an episode of Saturn electrostatic discharges. Each individual bursty event (bright vertical line on the spectrogram) represents an SED event that is RF emission from a Saturn lightning flash.

tion energy in a general way for comparison to both terrestrial and non-terrestrial discharge types.

2. Discharge and radiated power

[6] The primary source of radio frequency emission from a lightning discharge is the turn-on and turn-off of the current wave that propagates in an ionized channel. An analogy is quickly "flicking" an electrical switch on and off, resulting in an exponential rise and then decay in the current. This situation can be modeled in a general way as a bi-exponential current distribution of the form [*Bruce and Golde*, 1941]

$$i = i_o(\exp(-\alpha t) - \exp(-\beta t)) \tag{1}$$

In the case of the terrestrial cloud-to-ground discharge, $i_o \sim 30$ kA, $\alpha = 2 \times 10^4\ s^{-1}$ and $\beta \sim 2 \times 10^5\ s^{-1}$ and the discharge duration is on the order of 50 μs [*LeVine and Meneghini*, 1978a, 1978b]. While *Bruce and Golde* [1941] applied the case to a cloud-to-ground stroke, the function has no explicit dependence on the ground being present and only depends on three variables, i_o, α, β - parameters of a current wave in an ionized channel. The same Bruce-Golde formulism has been applied to both cloud-to-ground and intracloud lightning, only with differing i_o, α, β parameters [see *Volland*, 1984, Table 6.2]. The general formalism in equation (1) can thus apply to any fast-switching current pulse since nature tends to initiate and cease electrical currents as exponentials. The radiated electric field is a function of both i and di/dt and it is relatively straightforward to demonstrate that at high frequencies ($\omega > \beta$) this field varies as [*LeVine and Meneghini*, 1978a, 1978b; *Farrell et al.*, 1999],

$$E(\omega) \propto i_o v_o \beta / \left(\varepsilon_o c^2 r \omega^2\right) \tag{2}$$

where v_o is the current wave velocity and r is the source-observer distance. For terrestrial cloud-to-ground discharges, v_o is assumed to be ~0.3 c since the path is highly ionized. However, for partially-ionized (collisional) discharge paths, v_o can be lower. We note that the radiated power (which varies as P (ω) $\propto$ E(ω)^2 $\propto$ ω^{-4}) at high frequencies is also dependent on both the current strength (i_o) and the assumed discharge time (1/β).

[7] In the terrestrial cloud-to-ground (c-g) case, the peak spectral power is near 10 kHz. Between 0.1–5 MHz, the power spectrum tends to roll off more gradually (f^{-2}) due to channel tortuosity which adds power at wavelengths comparable to the scale size of the tortuous channel path. However, the radiated spectrum then varies as f^{-4} at HF frequencies >5 MHz [*LeVine and Meneghini*, 1978a, 1978b; *Willett et al.*, 1990].

[8] As suggested by equation (2), given a measurement of radiated HF power, a longer assumed discharge time (i.e., an Earth-like case) makes β relatively small and the discharge strength i_o must be large to be consistent with the observations in HF. Conversely, a shorter assumed discharge time makes β larger and the discharge strength i_o does not have to be as large to be consistent with the observed HF emission strength. Hence, the assumed discharge duration time is intimately connected to the derivation of discharge current and dissipation energy.

[9] Figure 2 illustrates the point. Given an SED HF emitted power at 50 W/Hz as measured by Cassini RPWS [*Fischer et al.*, 2006a, 2006b; *Zarka et al.*, 2006], if one assumes a terrestrial-like (c-g) lightning spectrum, then the discharge power has to increase by 10^4 (Curve A) to obtain power levels like those observed by Cassini. In essence, in assuming a terrestrial-like spectrum it is automatically assumed that the emission spectral peak is nearly three orders of magnitude below the HF spectral band, and that the emitted power is along the steep f^{-4} rolloff region of the spectrum. However, if we assume the discharge is simply faster-than-terrestrial (Curve B), the peak in the spectrum moves closer to the HF band, providing more radiated power directly into that band. The fact that the measured spectrum of SED is relatively flat and does not display a

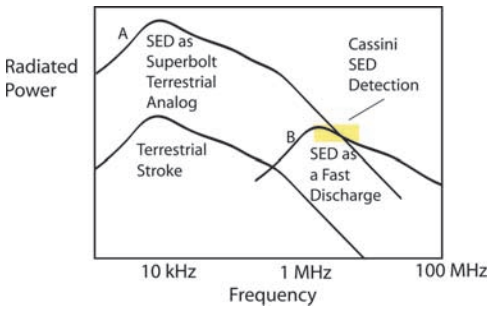

Figure 2. An illustration of two possible embodiments of the SED radiated spectrum. The first (Curve A) portraits the SED as a 10^4 times more powerful version of a terrestrial lighting cloud-to-ground discharge with the increase required to get the HF power levels consistent with those measured by Cassini. The second embodiment (Curve B) suggests that these same HF power levels can be obtained from a relatively weak but fast discharge that has peak power radiated into the HF band.

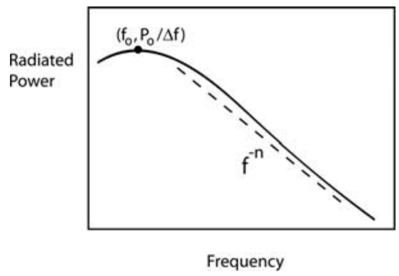

Figure 3. An illustration of the rolloff of the lightning discharge at frequencies above the peak emission. For the case of the Earth, $n \sim 2$ to 4.

steep rolloff further suggests that the spectral peak may be closer to the HF portion of the radio spectrum (i.e., Curve B) compared to a terrestrial analog. Saturn's discharge could thus simply be faster than the assumed terrestrial case to account for the radiated power density.

[10] Given Cassini's SED measurement of ~50 W/Hz of radiated power density in the HF, we want to derive an estimate of the discharge dissipation energy, W_d. To perform this calculation, we require three quantities, as illustrated in Figure 3: The power density $(P_o/\Delta f)$ and frequency (f_o) of the spectral peak of the emission, which are a direct measure of discharge power and time-scale, respectively, and also the spectral rolloff at high frequencies (f^{-n}). In the case of SED, we know the rolloff value, n, but have no direct knowledge of $(f_o, P_o/\Delta f)$. We will thus perform our determination of SED energy assuming a terrestrial analog first (an assumed f_o of 10 kHz) but then relax this constraint. First, approximately 1% of the discharge power of terrestrial lightning is radiated into the peak portion of the RF spectrum near f_o [*Volland*, 1984] allowing us to express the peak power spectral density as

$$(P_o/\Delta f) \sim 0.01(P_d/\Delta f) \sim 0.01(2\pi f_o)W_d/\Delta f \tag{3}$$

where P_d is the current discharge dissipated power, W_d is the discharge dissipated energy and Δf is the natural bandwidth of the emission. The dissipation energy and power, W_d and P_d, respectively, are those directly associated with the discharge source current while P_o is the peak radiated power from the discharge. From equation (2), we find that the radiated power spectral density $(P/\Delta f)$ at frequencies above f_o scales as f^{-n}:

$$(P/\Delta f) = (P_o/\Delta f)(f_o/f)^n \tag{4}$$

where $n \sim 4$ for an exponential-like current wave and a channel without tortuosity [*LeVine and Meneghini*, 1978a, 1978b]. Expression (4) allows us to easily relate the HF power to the peak powers at f_o by following the curve of $P = P(f)$ like that shown in Figure 3 back to the spectral peak $(f_o, P_o/\Delta f)$. For Cassini SED observations in the HF band, the average power spectral density of the 2004 SED events was found to be $P/\Delta f \sim 50$ W/Hz [*Fischer et al.*, 2006a, 2006b; *Zarka et al.*, 2006]. Combining (3) and (4) with this observational constraint we obtain

$$W_d = (100/2\pi f_o)\ (50\ \mathrm{W/Hz}(f/f_o)^n\Delta f) \tag{5}$$

The bandwidth to apply in this case is the natural bandwidth of the emission as measured in the vicinity of the spectral peak at f_o. Typically, impulsive events with exponential-like rise and decays tend to be fairly broadbanded with $f_o/\Delta f \sim 3$ (see Figures 7–11 of *Volland* [1984] for terrestrial lightning). Applying $\Delta f \sim f_o/3$ to equation (5) then yields a relatively simple expression:

$$W_d = (33/2\pi)50\ \mathrm{W/Hz}(f/f_o)^n \sim 260(f/f_o)^n \mathrm{Joules} \tag{6}$$

The derivation is consistent with a similar analysis of the HF spectral roll-off found by *Zarka et al.* [2004].

[11] Consider the case where the SED discharge is terrestrial-like in its spectral content, with a radiated emission peak at $f_o \sim 10$ kHz and a value of n near 4. For a power spectral density of 50 W/Hz measured near f = 10 MHz, we obtain a value of $W_d \sim 2 \times 10^{14}$ J for n = 4 and 8×10^{12} J for a more gentler n = 3.5. This discharge energy is a large value, comparable to the estimate reported by *Fischer et al.* [2006a]. Note that the SED discharge energy is about 10^4 times larger than the terrestrial case. Such a discharge would indeed be considered a "superbolt" and be the most intense discharge in the solar system.

[12] However, we do not know the spectral peak $(f_o, P_o/\Delta f)$ for SED and the terrestrial analog assumed (using $f_o \sim 10$ kHz in equation (6) and Curve A in Figure 2) may not apply. One could assume that the discharge is faster than the terrestrial case with a discharge scale time on the order of ~1 μs and a spectral peak, f_o, near 1 MHz. For an $n \sim 4$ rolloff, we find the discharge energy only has to be 2×10^6 J or about a factor of 500 times *less energetic* than a terrestrial cloud-to-ground stroke to be consistent with the observed 50 W/Hz HF spectral density. *Fischer et al.* [2006b] also found that the rolloff of the HF spectrum is not as steep as the $n \sim 4$ case. Thus, applying their $n \sim 0.5$ to the $f_o \sim 1$ MHz case, it is fairly straightforward to show via equation (6) that the discharge energies W_d only have to be $\sim 9 \times 10^2$ J to account for the observed HF power densities of 50 W/Hz. Thus, a relatively weak discharge lasting ~1 μs has a radiation peak close to the HF band and thus easily couples emission directly into this band, as illustrated in Figure 2. Such a weak ($<10^3$ J), fast discharge could account for the Cassini observations in the HF.

[13] The dilemma is deciding which picture of the discharge is correct: slow or fast? In the case of Jupiter's lightning [*Lanzerotti et al.*, 1996], the Galileo probe dropped below the attenuating ionosphere and obtained a set of lightning RF waveforms in relative proximity to the source. This allowed a direct detection of $(f_o, P_o/\Delta f)$. It is clear in that case that the peak radiation was near 500 Hz consistent with a slow discharge [*Farrell et al.*, 1999]. At Saturn, we do not have comparable measurements. The emissions below ~1 MHz are strongly attenuated or blocked completely by the ionosphere, obscuring a direct determination of the spectral peak value $(f_o, P_o/\Delta f)$. Consequently, a conclusive differentiation of slow versus fast discharge is not possible. However, we do know that the SED HF emission spectrum is relatively flat, which is suggestive of a quick discharge (extreme example: the Fourier transform of a delta function is an equally-balanced power spectrum). A comparison of Jovian and Saturn lightning is presented by *Farrell* [2000] and *Zarka et al.* [2004]. For a quick discharge with current peak times closer

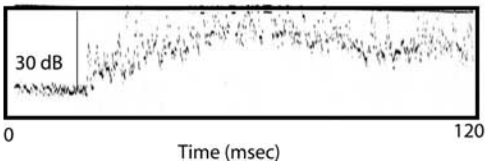

Figure 4. Voyager PRA high-resolution ($\sim$100 μs) envelop sampling of a SED event (adapted from *Evans et al.* [1983]). The event of 100 millisecond overall duration has a complex temporal structure.

to 1 μs, the peak frequency should then lie closer to the HF band. In this case, the discharge energies are required to be only a fraction of the terrestrial case to be consistent with the observed HF power. Thus, to account for the Cassini-observed SED powers, the discharges may not be superbolts, but may simply be "faster-than-terrestrial" discharge events.

3. High Resolution Measurements

[14] Further evidence of a non-superbolt nature of SED is presented by Voyager PRA's waveform envelope sampling system with $\sim$0.1 millisecond resolution. Figure 4 shows an SED event (i.e., a flash) of 120 millisecond duration (adapted from *Evans et al.* [1983]). As discussed by *Evans et al.* [1983], within this flash are many individual 1–2 millisecond impulses occurring in a fast temporal sequence, suggesting that the entire lightning flash consists of a sequence of multiple impulses. While these impulses are variable in intensity, we cannot identify one "superbolt"-like event from any of the others. The Voyager PRA measurements in this special wave envelope-sampling mode represent the finest temporal detail of the SED to date. The occurrence of these 1–2 millisecond impulses is so great that they merge in the middle of the event to form a continuum of HF emission that remains consistently at $\sim$20 dB above the background. Given our inference of a fast stroke (<1 μs), we would then suggest that each $\sim$1–2 millisecond pulse shown in Figure 4 is itself made up of a number of quick 1 microsecond discharges that are unresolved by Voyager's PRA at 100 μs resolution - they are simply accumulated/averaged in the PRA detector. In this case, it may be more appropriate to describe the energy released via integration over the many events (i.e., $W_d^{tot} \sim N W_d$). Cassini RPWS has a waveform system with temporal resolution on the order of 10 μs, which may further resolve the Voyager PRA 1–2 millisecond pulses shown in Figure 4. Unfortunately, the waveform system has to be operating concurrently with an SED, and that chance occurrence has not happened.

4. Conclusion

[15] It is tempting to think of the SED as consisting of a terrestrial-like superbolt of $>10^{13}$ J in energy. In fact, a better embodiment of the SED that fits the known observations might be a set of very fast discharges, each occurring very frequently, and each of modest intensity. The fast discharge (possibly of microsecond time scale) of modest intensity (possibly with energies below 10^3 J) can explain both the nearly-flat spectrum and 50 W/Hz power spectral densities observed in the HF. The repeatable, multi-stroke occurrence (many events repeating one after another) explains the Voyager high resolution measurements where discharge-related emissions occur so close in time as to form a continuum. An analogous emission to SEDs are possibly terrestrial transionospheric pulse pairs (TIPPS) initially reported by *Holden et al.* [1995], these being of a fast impulsive nature [*Smith et al.*, 1999], having a relatively flat spectrum in the HF [*Jacobson et al.*, 1999], and enhanced HF power (10 times as much) as compared to the typical slower cloud-to-ground stroke [*Rakov and Uman*, 2003]. TIPPS are believed to be cause by short-length intracloud discharges that are believed to radiate narrow bipolar pulses with a duration of a few μs, which could be the same situation for SED. For the Saturn case, because (f_o, $P_o/\Delta f$) is currently unmeasured for SED, a unique solution to the slow vs fast discharge model does not exist. The only information available to date to allow a differentiation is the near-flat power spectrum, which would be more consistent with an impulsive, fast discharge radiating nearly-equalized energy in the HF, which is observed by both Voyager and Cassini.

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