CASSINI RPWS AND IMAGING OBSERVATIONS OF SATURN LIGHTNING

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Abstract

The Radio and Plasma Wave Science (RPWS) instrument on Cassini began observing Saturn Electrostatic Discharges (SED) on a routine basis on 13 July 2004, shortly after Saturn orbit insertion (SOI). SED, first discovered by the Planetary Radio Astronomy instrument on Voyager, are widely believed to be the radio signature of lightning discharges in the atmosphere of Saturn.

In this paper we examine the extreme time variability from episode to episode of the SED burst rate and show how (1) three main storm systems occurred in 2004, (2) the storm occurrence was correlated with the appearance of a major eruptive cloud feature at about –35 degrees latitude, and (3) the variability is probably due to internally driven convection. Since little or no energy is believed to be deposited into the storm region at a depth of 10–12 bar in the atmosphere, it is presumed that the storms must be driven by an internal source whose time variation is not understood but for which the SED may act as a remote indicator. This is in contrast to the SED observed by Voyager which were nearly continuous, possibly due to the constant presence of the ring shadow as a convective driver.

As of this writing, no SED were detected from about the end of September 2004 until 9 June 2005.

1 Introduction

Saturn Electrostatic Discharges, first observed by the Voyager PRA experiment [Warwick et al., 1981] are the radio frequency manifestation of lightning, or lightning–like, discharges

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occurring in Saturn's atmosphere [Kaiser et al., 1983]. The Cassini RPWS experiment began routine measurements of SED shortly after SOI, when an intense episode of SED was observed beginning $\sim$ 0230 UT on day 195 (13 July 2004) [Gurnett et al., 2005]. Thereafter, over 80 SED episodes were observed of varying duration and intensity, until day 272 (28 Sep. 2004) when the SED abruptly stopped, not to recur again until 9 June, 2005. Prior to SOI, weak SED were observed on about a dozen occasions from about day 140; however, because the receiver was not in an ideal sweep mode for the detection of SED these were generally not recognized until post SOI.

In this paper we (1) describe the initial observations of SED by the Cassini RPWS instrument [Gurnett et al., 2004; 2005] and observations of a major eruptive cloud feature by Cassini ISS [Porco et al., 2004; 2005], (2) compare the enormous variability of the SED burst rate with those observed 25 years ago by Voyager and consider possible reasons for the vast difference, (3) show how the storm system is associated with a major eruptive cloud feature in Saturn's atmosphere, and (4) comment on a possible internal driver for the energy source of the lightning.

2 Typical Episode

A typical Cassini RPWS (frequency–time) radio spectrogram covering 3 hours of observation is shown in Figure 1. The spectrogram is dominated by Saturn Kilometric Radiation (SKR) which extends over the entire 3 hours and from about 50 kHz to 800 kHz. The SED are seen in the top of the spectrogram, extending from several MHz to the top of the band at 16.1 MHz. The individual SED bursts are actually very broadband in nature but appear narrowbanded because of the swept–frequency nature of the receiver with which they are detected. At these high frequencies natural sources of interference come from solar Type III bursts and from weak Jovian arcs, which are still detectable at Saturn. Despite this, we believe mis–identification of SED is a very low probability. Figure 2 shows the same episode as described above, but in an expanded view that shows just the frequencies above 2 MHz. Very few SED have been observed below about 2 MHz and none below 1 MHz, possibly because of a band of noise (spacecraft interferences) that starts just below 2 MHz. The episode in Figure 2 is fairly typical in that it lasts about 3 hours and extends over the entire frequency band from 2 MHz to 16 MHz. Notice that the episode onset is rather abrupt, and that the low frequency cutoff increases with time. These last two features are consistent with the observation of a source that has just risen over the radio horizon (the spacecraft is at about 6 hr local time here) and which is rotating onto the dayside under an ionosphere with increasing density plus an increased angle between the radio waves and the normal to the ionosphere [Zarka et al., 2006]. However, not every episode is by any means as well–behaved.

3 SED Variability

Figure 3 shows the observed variability in SED count rate versus time in 2004 from day 195 to day 272. The ordinate is the number of bursts observed per episode. An episode can

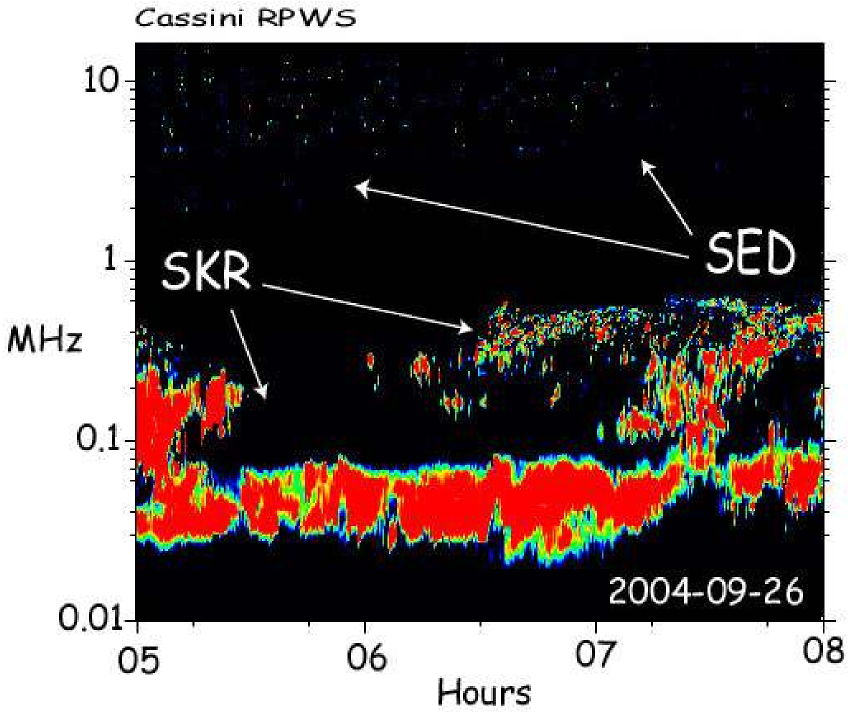

Figure 1: Cassini radio dynamic spectrogram of Saturn Kilometric Radiation (SKR) and Saturn Electrostatic Discharges (SED).

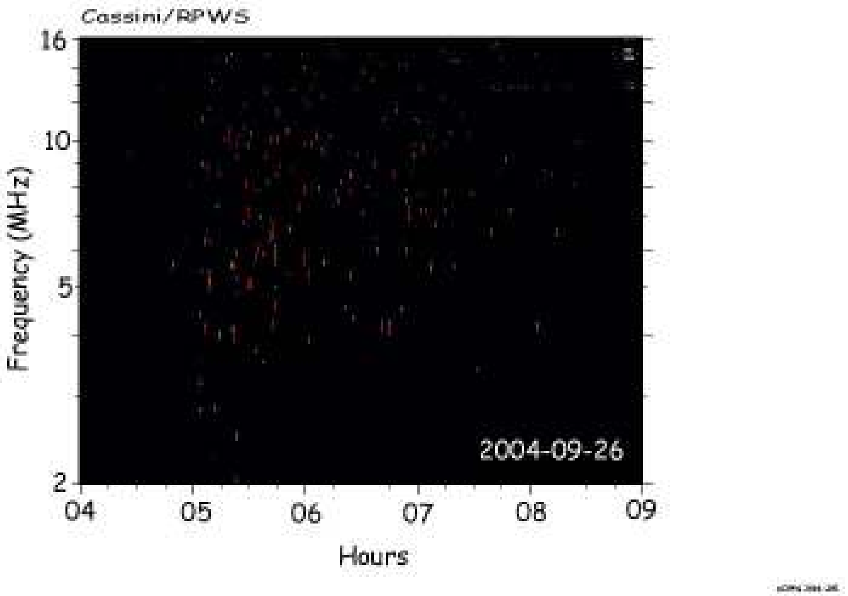

Figure 2: Cassini radio dynamic spectrogram of Saturn Electrostatic Discharges (SED).

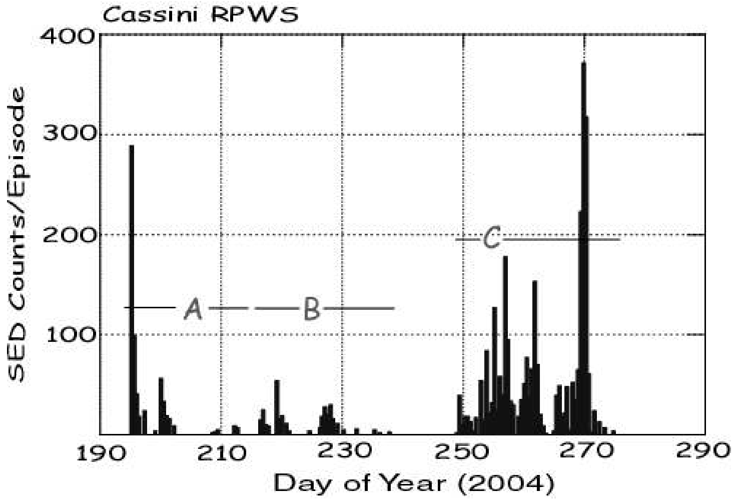

Figure 3: Organization of SED episodes into major storm systems (A, B, and C) showing extreme variability in count rates from episode to episode.

last anywhere from less than an hour to somewhat over 5 hours, with the mean being about 3 hours. The observed variability is enormous, ranging from a few bursts per episode to several hundreds. Order of magnitude changes in episode burst rates can occur over only $\sim 3-4$ episodes (30–40 hrs). Three main storm systems (A, B, and C) were observed in 2004 as indicated in the figure. Storm systems are distinguished by the inherent periodicity of the episodes and/or relatively long gaps between episodes. Some SED were also observed prior to SOI; however they are not shown here because the RPWS instrument was in a sweep mode that makes it difficult to inter–compare the rates observed prior to SOI with those shown here. (The duty cycle of the receiver was nearly constant throughout the storms A, B, and C.) Approximate time scale between systems is $\sim 20-30$ days. No SED were detected after day 272, 2004, until day 160, 2005, when another series of episodes (System D) appeared. Thus there is significant SED variability on time scales of ~ 30 hrs, ~ 20 days, and ~ 1 year. These time scales are approximate at this stage of the analysis, particularly the longest, and will be refined as further observations are made. Further statistics on the absolute intensities of these bursts can be found in Fischer et al. [2006]. This extreme variability differs significantly from the SED observed by Voyagers in 1980–1981, when the SED storm intensity and rates were uniform over time. Possibly this difference is due to the fact that the Voyager SED probably originated near the equator [Kaiser et al., 1983], while SED from the present epoch originate from near –35 to –40 degrees latitude (see below). Why this should be so is not known but may have to do with the likelihood that the equatorial SED were driven by the strong thermal gradient in the atmosphere that was established by the ring shadow, a very continuous, non–varying presence. The SED that currently originate near mid–latitudes probably are driven by internal sources of energy (also see below), which may be highly variable and tenuous in terms of their ability to force water vapor up to visible levels in the atmosphere and create eruptive, high–contrast, lightning–associated cloud features.

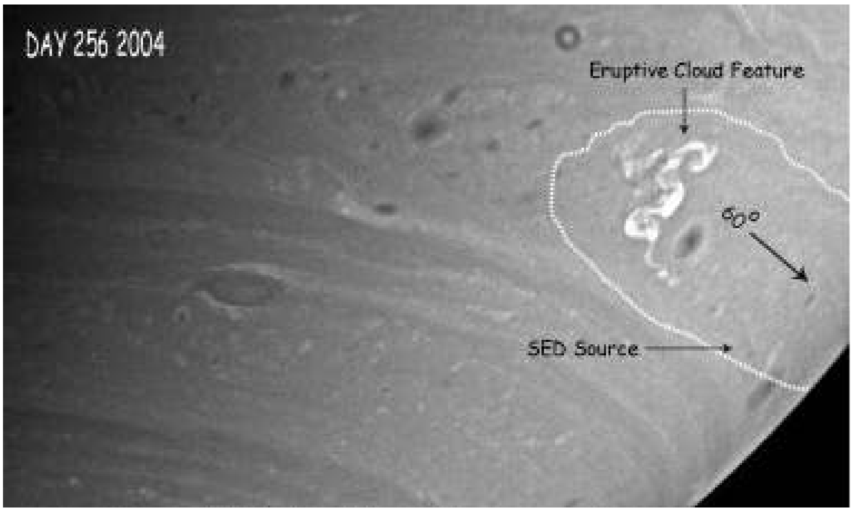

Figure 4: Cassini ISS image of a major eruptive cloud feature associated with SED. Schematic representation of SED source extending to the East by about 60 degrees in longitude is shown.

4 SED and Eruptive Cloud Features

Figure 4 is a Cassini ISS image of a major eruptive cloud feature thought to be associated with Saturn lightning [Porco et al., 2005; Gurnett et al., 2005]. Identification of a visible source for SED is important. Until now, there has been nothing to tie the RF (radio frequency) evidence of lightning to some independent observation that lends support to the lightning interpretation. This is a first big step in that direction. Major eruptive cloud features appeared at mid–latitudes (~ -35 degrees) in mid–July and early–September close to the times of the onsets of the two major SED storm systems labelled A and C in Figure 3. The latter–occurring cloud feature faded away at the same time that the SED disappeared in late September. The predominant periodicity of both the SED and the clouds was $\sim$ 10.65 hr, virtually identical with the radio rotation period of the planet [Desch and Kaiser, 1981]. The coincidence of the SED, cloud and radio periods is simply due to the apparent fact that the cloud and SED have their origin close to the latitude, just south of the westward jet, where the atmospheric wind speeds [Ingersoll et al., 1984] match the Voyager radio period. The relative phase of the SED episodes and the cloud was such that the SED episode midpoints always preceded the central meridian passage of the cloud by a constant $\sim$ 60 degrees of rotation. Thus the SED storm always begins before the cloud feature appears over the horizon as seen from Cassini, which can be explained by the hypothesis that the SED source is extended in longitude to the East by about 60 degrees, as suggested in Figure 4. This is consistent with the apparent duration of some of the storms which exceeds 0.5 rotations ($\sim$ 5 hrs) and surprisingly consistent with the derived longitudinal extent of the SED source inferred from the Voyager observations [Kaiser et al., 1983]. On the other hand, ionospheric radio propagation effects might also play a role [Zarka et al., 2006].

In summary, given (1) the coincident appearance and disappearance of the SED storms with the eruptive cloud feature in July and September, 2004, (2) the likely coincidence in latitude based on the identical rotation periods, and (3) the constant phase difference between the SED storms and the cloud, it is very likely that the two are closely related. Because there is now an identifiable atmospheric feature associated with SED, future efforts will be made to detect individual lightning flashes in the atmosphere.

5 SED Driver

The RPWS observations have shown that there is significant time variability in the SED storm intensity. When the storm appears to be 'off', even a Cassini perigee pass at 3 R_S from Saturn's atmosphere will not reveal possible very weak events that might have been undetectable 100 R_S away. Thus it appears that when the storm is not observed, for all practical purposes, it's probably off (System D is a good example for this). There is therefore an extraordinary degree of variability in the lightning storm energetics. The question is: What is driving the vertical convection that brings eruptive features to the ~ 0.5 bar level, such as those seen by the Cassini imaging team, and that are associated with the SED? What is driving the storm?

On Earth, solar UV and EUV are known to drive atmospheric convection to some extent at high altitudes [Kozyra, 2005]. Further, the Sun is quite variable in the UV, providing large scale variations on relatively short time scales that could explain the large variations seen in the SED rate. Unfortunately, the UV fluctuations that are apparent during 2004 (determined from the 10.7 cm radio flux and CaII–K line proxies for UV flux) do not match the fluctuations observed in the SED rate. Enhancements and declines in UV do not occur in any sensible way with SED rate variations. Further, the UV fluctuations tend to be periodic on a time scale of 26 days owing to a tendency to be correlated with large sunspots, whereas there is no observed periodicity in the SED rate. Investigations into possible correlations with solar wind parameters, such as pressure fluctuations inferred from RPWS solar wind density estimates and Cassini/MAG magnetic field fluctuations, have met with similar negative results. Since this exhausts the likely (and unlikely) external drivers of SED, we now examine possible internal sources.

Figure 5 shows a plot of Saturn's atmosphere in profile down to about the 10 bar level [Weidenschilling and Lewis, 1973]. We presume that the lightning is associated with vertical convection driving moisture up to the visible atmospheric level from the H_2O cloud level, which is at about the 10 bar level. There are models that are capable of doing this [Hueso and Sanchez-Lavega, 2004], and the atmospheric level to which the water vapor is driven is a function of the presumed solar abundance of H_2O (1x or 3x, e.g.) at 10 bar. Ammonia storms can also be triggered internally but ammonia does not seem to be the origin of the main convective events observed in the atmosphere [Hueso and Sanchez-Lavega, 2004]. At 10 bar, the water cloud is ~ 300 km below the 1 bar level. External sunlight is extinguished at pressures < 2 bar. Below this level it is not possible to directly excite thermal instabilities using external sources of energy. Thus we must look to internal sources to drive the needed convection from these deep levels.

The most likely internal source of energy is the factor 2–3 thermal excess emitted by Saturn that is driven by the gravitational separation of H and He and subsequent liberation of gravitational energy. This thermal excess powers Saturn's weather and leads to the

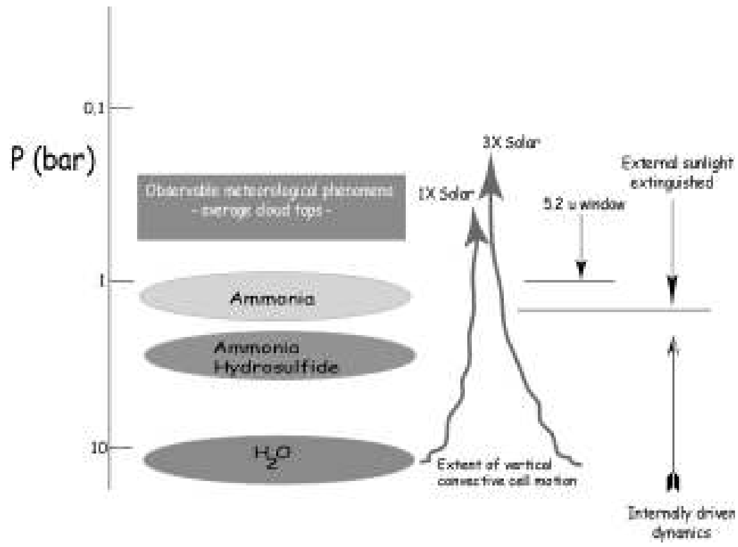

Figure 5: Model Saturn atmosphere showing cloud levels, vertical convective cell motion from the water cloud level, and level where external sunlight is extinguished (after [Weidenschilling and Lewis, 1973]).

thermal gradients necessary to drive upward convection from the water cloud. According to models [Hueso and Sanchez-Lavega, 2004], thermal gradients < 1 K across a rising parcel are adequate to trigger large–scale updrafts. The challenge for Cassini investigators is to come up with a way to monitor variations in deep interior energetic that might be convectively driven and that might possibly correlate with SED variability. Candidate probes are provided by such minor chemical constituents as ethane, phosphine or acetylene. These constituents are created deep in the atmosphere but they can bubble up to detectable levels in response to convective updrafts. Mapping these constituents and observing their long and short–term variability could provide the answer to Saturn's lightning production and variability.

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