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Atmospheric Electricity at Saturn

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Abstract The Cassini mission provides a great opportunity to enlarge our knowledge of atmospheric electricity at the gas giant Saturn. Following Voyager studies, the RPWS (Radio and Plasma Wave Science) instrument has measured again the so-called SEDs (Saturn Electrostatic Discharges) which are the radio signature of lightning flashes. Observations by Cassini/ISS (Imaging Science Subsystem) have shown cloud features in Saturn's atmosphere whose occurrence, longitudinal drift rate, and brightness were strongly related to the SEDs.

In this paper we will review the main physical parameters of the SEDs. Lightning does not only give us clues about the dynamics of the atmosphere, but also serves as a natural tool to investigate properties of Saturn's ionosphere. We will also discuss other lightning related phenomena and compare Saturn lightning with terrestrial and Jovian lightning.

Keywords Saturn: lightning · Saturn: atmosphere

1 Introduction

In this review paper we will focus on the new Cassini/RPWS observations of lightning on Saturn, which we continue to call Saturn Electrostatic Discharges (SEDs). This term was introduced by Warwick et al. (1981) due to the initially unknown origin of these impulsive radio bursts. When first detected by the Voyagers, an anomalous extension to very low

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frequencies led Warwick et al. (1981, 1982) and Evans et al. (1982) to the conclusion that discharges in Saturn's rings might be responsible for the SEDs. But, using an argument of visibility Kaiser et al. (1983) could show that SEDs should stem from an atmospheric source. As the atmospheric origin is now well established (see Sect. 4) and SEDs are essentially electromagnetic waves the term "SED" could be considered as a kind of misnomer. On the other hand, the total energy of a lightning flash in a thunderstorm stems from the electrostatic energy of oppositely charged clouds. Hence, the usage of "SED" can still be considered appropriate in this sense, and to avoid confusion we refrain from creating a new name.

In Sect. 2 we will briefly describe the instruments which have detected SEDs or related phenomena. In Sect. 3 we will tabulate all SED measurements so far and discuss their occurrence in storms and episodes. Section 4 is devoted to the periodicity of SED episodes providing a first clue about the latitude of the lightning storm in Saturn's atmosphere. In Sect. 5 we will discuss further physical parameters like SED intensity, frequency spectrum, burst duration and rate. SEDs can be used as a natural tool to investigate Saturn's ionosphere, which will be shown in Sect. 6. In Sect. 7 the structure of Saturn's atmosphere and the possible source location of SEDs in the water clouds will be discussed. In Sect. 8 we will mention lightning related phenomena like whistlers and speculate about the possibility of sprites, elves, or gamma ray flashes at Saturn. The final summary of Sect. 9 will be in the form of a table comparing the most important properties of SEDs with terrestrial lightning.

2 Instruments for Lightning Detection at Saturn

2.1 Observations by Spacecraft

SEDs were first detected by the Voyager 1 PRA (Planetary Radio Astronomy) experiment during the Voyager 1 Saturn encounter in November 1980 (Warwick et al. 1981). In August 1981 the identical PRA instrument onboard of Voyager 2 also detected SEDs during Voyager 2's encounter with Saturn (Warwick et al. 1982). The PRA instrument consists of two orthogonal antennas with a length of 10 m, and a frequency sweeping receiver in the frequency range of 1.2 kHz to 40.5 MHz (Warwick et al. 1977). The PRA performs a scan from high to low frequencies within 6 seconds through its whole frequency range, and the receiver dwells at each of its 198 frequency channels for about 30 ms. Most SEDs were detected in the HF part of the PRA (above 1.2 MHz), but on the nightside of Saturn some SEDs were also detected in the LF part below 1326 kHz (Zarka and Pedersen 1983). No SEDs were detected by the PWS (Plasma Wave System) of the Voyagers operating in the frequency range from 10 Hz to 56.2 kHz in 16 logarithmically spaced frequency channels (Kurth et al. 1983).

The Cassini/RPWS instrument can use any of its three electric antennas of 10 m in length (or a combination of them) to detect SEDs in its High Frequency Receiver (HFR) (Gurnett et al. 2004). SEDs were detected only in the HF1 and HF2 band of the HFR, which (like the PRA) acts as frequency sweeping receiver. The time for a scan through these two bands can vary as number of used antennas, start frequency, frequency step size and integration time can be set to different values. The typical mode consists of the following scan lasting for 16 seconds: HF1 sweeps from 325–1800 kHz in 60 frequency steps of 25 kHz with an integration time of 80 ms and using two antennas; followed by a sweep through HF2 from 1825–16025 kHz in 143 frequency steps of 100 kHz with an integration time of 40 ms and using only one antenna. PRA as well as RPWS have a high rate mode to monitor SED amplitude variations with a time resolution of the order of 0.1–1 ms. RPWS can even use its Wideband Receiver at SED frequencies with a time resolution of a few tens of μs, and some SEDs were caught recently with this mode. Evans et al. (1983) showed that the SED amplitude envelope exhibits slowly varying fluctuations for several tens of ms as well as more rapid fluctuations lasting less than 1 ms.

Besides producing radio emissions, lightning also produces optical emissions that can be detected by imaging instruments. Unsuccessful attempts were made to image lightning flashes on the nightside of Saturn with the Voyager cameras (Burns et al. 1983), partly due to the sunlight reflected from the rings (ring shine). Similar attempts were made with Cassini/ISS, but no flashes have been seen so far (Dyudina et al. 2007). The Cassini/ISS is also equipped with a narrow-band Hα filter (Porco et al. 2004), as this atomic hydrogen line is expected to be prominent for a lightning flash at Saturn (Borucki et al. 1996). Another reason for this non-detection could be that the lightning-producing water clouds at Saturn are at a deeper level compared to Jupiter, which leads to complete absorption of the light from the flashes. This will be further discussed in Sect. 7. Nevertheless, the Cassini/ISS has imaged bright storm cloud eruptions at a latitude of 35° South correlating with the occurrence of SEDs (Porco et al. 2005; Dyudina et al. 2007).

2.2 Earth-based Measurements

The clouds related to the SED storm of early 2006 were, in fact, first observed by amateur astronomers on Earth (Fischer et al. 2007a). The occurrence rate of such remarkable cloud features and lightning storms throughout one Saturnian year ($\sim$ 29.5 Earth years) is not known. Hence, such observations could be especially valuable after the end of the Cassini mission, since Konovalenko et al. (2006) have succeeded in detecting SEDs with the world's largest radio telescope UTR–2 in the decametric frequency range in early 2006. As the SEDs are particularly strong radio emissions with a flux of $\sim$ 100 Jansky at Earth their detection from Earth was anticipated (see also Zarka et al. 2008, this issue). Three previous attempts by Lecacheux and Biraud (1984) and Zarka et al. (1997, 2006) had resulted in non-detection for the former and marginal or ambiguous one by the latter.

3 Occurrence Rate of Saturn Electrostatic Discharges

Since both Voyagers detected SEDs during their Saturn encounters it seemed possible that SEDs (like Earth lightning) are a permanently present feature. The Cassini/RPWS measurements displayed in Fig. 1 show that this is clearly not the case. There are long intervals of time with no SED activity. No SEDs were detected from early 2006 until late 2007 for about 21 month. A new SED storm has started on November 27, 2007, and is still ongoing after five months at the time of the correction of this paper (late April 2008). In order to see the various SED storms more clearly we have not displayed this long inactive time interval and the most recent SED storm in Fig. 1. The SED storms after Cassini SOI (Saturn Orbit Insertion, DOY 183, 2004) were labeled A, B, and C by Gurnett et al. (2005). A smaller storm happening before SOI was labeled storm 0 (zero) by Fischer et al. (2006a). Only one storm occurred in 2005 (storm D), and early 2006 RPWS observed the SEDs of the big storm E (Fischer et al. 2007a). The RPWS instrument was capable of SED detection nearly all the time, and sparse data gaps are indicated in Fig. 1 by the light grey background color. There were only two longer time intervals of about 9 days each, when no data were retrieved from RPWS. The first one was right before storm A, and we might have missed some SEDs at

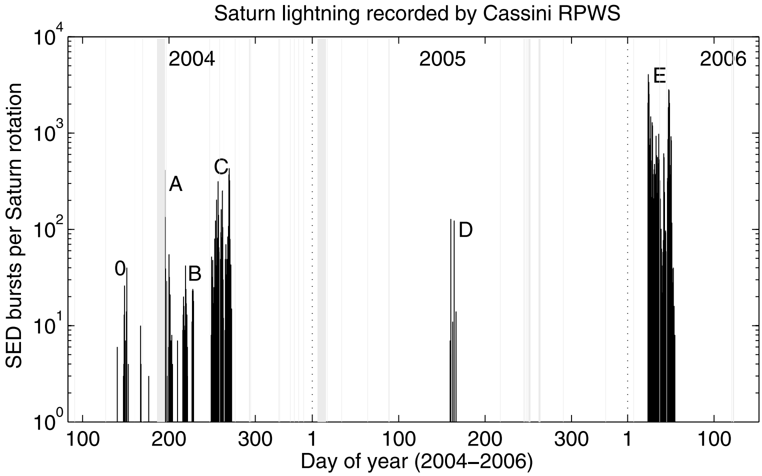

Fig. 1 Number of detected SEDs per Saturn rotation as a function of time. Cassini/RPWS data gaps are indicated by a *light gray* background color

Table 1 Summary of all SED storms detected by radio instruments on Voyager (V1, V2) and Cassini (0 to F). The table was adapted from Fischer et al. (2007a), and the higher number of V2 episodes here comes from Warwick et al. (1982) instead of Zarka and Pedersen (1983)

Name	Date: month, year	Number of SEDs in number of episodes	Recurrence period of episodes
V1	Nov. 1980	18000 in ∼ 16	10 h 09 min (±6 min)
V2	Aug. 1981	5000 in ∼ 14	10 h 00 min (±7 min)
0	May 2004	100 in 8	10 h 35 min (±6 min)
A	July 2004	800 in 15	10 h 43 min (±2 min)
B	Aug. 2004	300 in 16	10 h 40 min (±2 min)
C	Sept. 2004	4200 in 49	10 h 40 min (±1 min)
D	June 2005	300 in 6	10 h 10 min (±10 min)
E	Jan./Feb. 2006	43400 in 71	10 h 39.8 min (±0.4 min)
F	Nov. 2007 until ?	TBD	Around 10 h 40 min

this instant. The second one was in January 2005 around the landing of the Huygens Probe on Titan, but no SEDs were detected around that time. The Cassini mission gives us the opportunity to follow the full lifetime of a Saturn lightning storm, whereas the Voyagers only captured snapshots due to their single passages.

In Table 1 we have summarized all SED storms observed so far by the Voyagers as well as Cassini. We have listed their identifying name, the month and year when they were recorded, the number of SEDs and episodes, plus the episode's recurrence period. SEDs are organized in episodes simply because the causative lightning storm can be either on the side of Saturn facing the spacecraft or on the opposite site (and below the radio horizon), from where it cannot be detected. In the course of one SED storm the numbers of SEDs per episode (or per Saturn rotation) can exhibit a significant variability. Numbers of SEDs per episode ranged from just a few bursts to several hundreds or even a few thousands in the case of storm E.

Altogether (Voyagers and Cassini) ~ 72,000 SEDs (in ~ 195 episodes) have been detected so far, and more than half of them were recorded during the "giant" storm E of early 2006 (Fischer et al. 2007a). Analysis of the SED storm F is not completed yet, and so it is not included in the previous numbers.

4 Periodicity of SED Episodes and Location of Lightning Storms

An inspection of the recurrence periods of episodes of the various storms (last column of Table 1) shows that there are basically only two different classes: Storms 0, A, B, C, and E (and also F) have a period close to 10 h 40 min, whereas storms V1, V2, and D have a period around 10 h 10 min. Storms A, B, and C were associated with a prominent cloud feature at a planetocentric latitude of 35° South, which was nicknamed the "dragon storm". Its occurrence coincided with the occurrence of SEDs, and from Voyager as well as Cassini wind speed measurements it is known that this latitude is associated with a near-zero wind speed relative to the Voyager radio period, i.e. it has a period close to 10 h 40 min. Furthermore, the brightness of the "dragon storm" clouds correlated well with the number of observed SEDs (Porco et al. 2005; Dyudina et al. 2007). The usage of different filters to image different depth of Saturn's atmosphere allowed Dyudina et al. (2007) to see dense clouds reaching high altitudes suggesting strong updrafts, which are a well known feature of terrestrial thunderclouds (Rakov and Uman 2003). Similarly, during the "giant" SED storm E there was another prominent cloud feature again at 35° South (the same holds for the recent storm F). This cloud feature can be seen in Fig. 2 on the right side, and the prominent "dragon storm" is on the left. Fainter clouds can be imaged in Saturn's atmosphere at various latitudes (linked to different wind speeds and periods) practically all the time. But, such prominent clouds like the "dragon storm" were absent on the surface of Saturn during the several-months-long periods when the SEDs were absent.

The parallel occurrence of SEDs from storm E and the cloud feature is illustrated in Fig. 3, where the sub-spacecraft western longitude ranges of Cassini during each SED episode are indicated by nearly vertical lines. The nearly horizontal thick line close to the

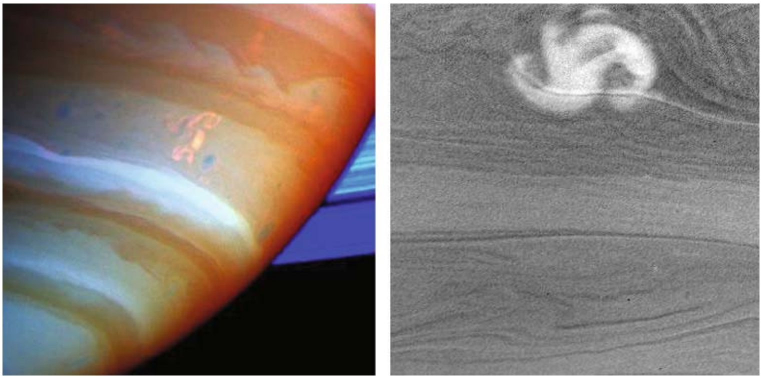

Fig. 2 The "dragon storm" as imaged by Cassini/ISS on September 13, 2004 (*left*), and the prominent cloud feature during SED storm E imaged on January 27, 2006 (*right*). The left false—color image was taken on Saturn's dayside, while the right contrast—enhanced image was taken at the nightside. Both storms were located at a planetocentric latitude around 35° South (from http://saturn.jpl.nasa.gov/, © NASA)

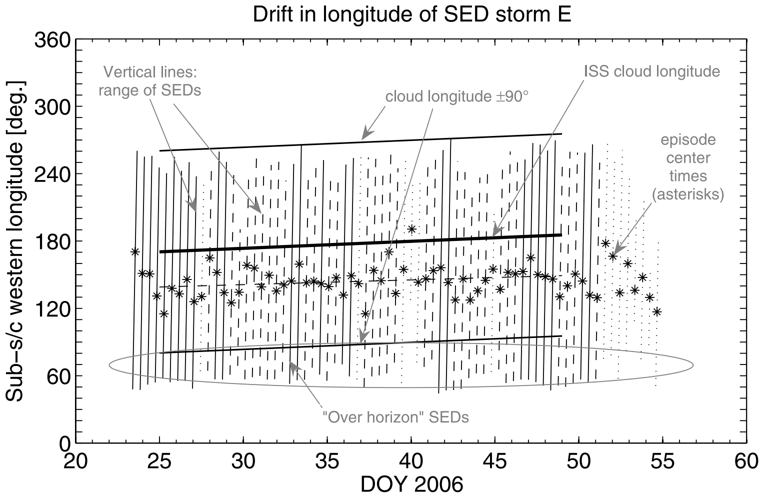

Fig. 3 Sub-spacecraft western longitude ranges (Voyager SLS) for storm E episodes as a function of day of year 2006. *Dotted lines* denote weak episodes with less than 50 SEDs, *dashed lines* denote episodes with 50 to 500 SEDs, and *solid lines* denote strong episodes with more than 500 SEDs. The *asterisks* mark the western longitudes at the center times of the episodes. The *nearly horizontal lines* and the "*over horizon*" SEDs are labeled in the figure and are explained in the text (adapted from Fischer et al. 2007a)

middle of the episodes gives the western longitude of the ISS observed cloud system, which was located around 170° on DOY 25 and drifted westward with a rate of 0.6° per day. This line is also shifted by ±90° in both directions indicating the appearance and disappearance (at ∼ 90° and ∼ 270° sub-spacecraft western longitude, respectively) of the visible cloud system at the horizon. Since Cassini was on the morning side of Saturn the cloud system appeared on the nightside, passed the morning terminator, and disappeared on the dayside. The SED episodes end either exactly when the visible cloud disappears at the dayside horizon or slightly before that, which can be attributed to radio wave absorption in Saturn's ionosphere at grazing incidence angles. But, it is evident from Fig. 3 that the SEDs started before the visible cloud was seen with the Cassini cameras. They are marked by the grey ellipse in Fig. 3 and we call them "over horizon" SEDs, as the radio horizon extends as much as 45° below the visible horizon. Zarka et al. (2006) explains this effect by an electron density decrease with local time at Saturn's nightside ionosphere which leads to temporary trapping of the SED radio waves. The drift of the ISS imaged cloud system corresponds to a period of (10.665 ± 0.001) h. For the determination of the recurrence period of SED episodes Fischer et al. (2007a) used the so-called center time of an episode, which is the mean time of all SEDs within one episodes. The center times are indicated by the asterisks in Fig. 3, and a straight line fit (from DOY 25 to 48 when the cloud was imaged) is given by the dashed line close to the asterisks. Its slope corresponds to a period of (10.662 ± 006) h, which is in good agreement with the period of the imaged cloud.

The period of SED storms V1, V2, and D around 10 h 10 min corresponds to the rotation of Saturn's equatorial atmosphere. But, no corresponding cloud features by the Voyager cameras have been reported, and also some faint clouds observed at the equator during the small SED storm D do not really match the SED occurrence (Dyudina et al. 2007; Fischer et al. 2007a). Nevertheless, it seems possible that due to strong vertical and latitudinal wind shear in Saturn's equatorial region, updrafting clouds are diluted and spread over a huge area and therefore cannot be clearly seen. The period and other characteristics (like episode and flash durations and the low frequency cutoff due to the ionosphere) of these SED storms clearly point to longitudinally extended storms in Saturn's equatorial atmosphere. In summary, up to now only two latitudes at Saturn have been found to produce SED storms, which are the equatorial region and the "storm alley" at 35° South.

5 Some More Physical Parameters of SEDs

5.1 SED Intensity and Frequency Spectrum

The radio emissions of SEDs are much stronger than the radio emissions from terrestrial lightning in the frequency range of a few MHz. Zarka et al. (2006) as well as Fischer et al. (2006b) found spectral radio source powers of the order of 10 to 100 W Hz^{-1} for SEDs confirming the previous Voyager measurements by Zarka and Pedersen (1983). This is a factor of 10^4 stronger than terrestrial flashes, which makes SEDs detectable from great distances. With RPWS SEDs were first detected far beyond 300 Saturn radii (Fischer et al. 2006a). This corresponds to a staggering distance of about 3000 Earth radii compared to only 14 Earth radii, within which RPWS detected terrestrial lightning during its Earth flyby (Gurnett et al. 2001). We note that radio emissions detected by RPWS in July 2003 at a distance of more than 1 AU from Saturn, which were initially interpreted as SEDs, turned out to be radio emissions (decametric arcs) from Jupiter (Fischer et al. 2006c). This factor of 10^4 in radio power, measured in fact only in a relatively small frequency range, has led some authors to conclude that the total energy of SEDs might be 4 orders of magnitude above the typical terrestrial lightning energy of 10^9 J ("superbolt"). Farrell et al. (2007) have shown that this is not necessarily the case and that this question is actually related to the temporal nature of the discharge itself and the resulting shape of the frequency spectrum. With f denoting the frequency, the spectrum of terrestrial lightning shows a roll-off with f^{-2} or even steeper above 1 MHz. This is distinctly different from what Zarka et al. (2006) and Fischer et al. (2006b) found for the SED spectrum being essentially flat or with a roll-off of only $f^{-0.5}$ from 4–16 MHz. For the Voyager SEDs Zarka and Pedersen (1983) and Zarka et al. (2004) found a relatively flat spectrum up to 20 MHz, and a decrease with f^{-1} to f^{-2} from about 20–40 MHz. This spectral behavior suggests that an SED consists of a series of very short pulses less than 1 μs (Farrell et al. 1999, 2007).

5.2 SED Burst Duration and Burst Rates

Similar to a terrestrial flash, an SED probably consists of many subpulses, and the total duration of one SED can be as long as a few hundred milliseconds. Most SEDs are somewhat shorter and the SED duration can be well described by a distribution with an exponential decrease in number of SEDs n with increasing burst duration t. In such a distribution described by $n \propto \exp(-t/t_0)$ the storm C SEDs had an e-folding time t_0 of (37 ± 3) ms similar to the 41 ms found for the Voyager 1 SEDs by Zarka and Pedersen (1983). The e-folding times of storms D and E were found to be somewhat longer with (48 ± 12) ms and (49 ± 3) ms, respectively (Fischer et al. 2007a).

SED burst rates (number of recorded SEDs per time interval) depend strongly on the distance of the spacecraft to the thunderstorm in Saturn's atmosphere. The closer the spacecraft is the more low intensity bursts can be observed. The maximum rate found by the Voyagers was 1 SED every 4 seconds, which was measured around closest approach of Voyager 1 when it was just 2 Saturn radii above Saturn's 1-bar level (Zarka and Pedersen 1983). A remarkable burst rate of 1 SED every 2 seconds was measured by RPWS during the second episode of the giant storm E with Cassini at a distance of 45 Saturn radii. If Cassini would have been at a distance of only 2 Saturn radii at that time, the flash rate can be extrapolated to some tens of SEDs per second using the distribution of SED intensities (Fischer et al. 2007a), which is much higher than what was measured by Voyager 1 at this distance. The flash rates also varied significantly in the course of SED storm E, but the high flash rates lasted typically for 3 to 4 Saturn rotations, which is longer than one Earth day. We note that a single thunderstorm on Saturn with a diameter around 2000 to 3000 km (Dyudina et al. 2007) and a depth of the order of 200 km (see Sect. 7) has approximately the same volume as the whole terrestrial troposphere.

6 Saturn Lightning as a Tool to Investigate Saturn's Ionosphere

6.1 Peak Electron Densities Derived from the Low Frequency Cutoff of SED Episodes

The broadband SED radio waves can be measured by RPWS only when their frequency is above the peak plasma frequency of Saturn's ionosphere. Hence, assuming straight line of sight propagation, the peak electron plasma frequency $f_{pe,peak}$ can be easily determined from the low frequency cutoff f_{cutoff} of SED episodes with the equation $f_{pe,peak} = f_{cutoff} \cos(\alpha)$, with α being the angle of incidence. These three quantities change with time in the course of one SED episode, as the storm rotates with Saturn's atmosphere and passes various local times under the ionosphere. The shape of this low frequency cutoff f_{cutoff} is indicated in Fig. 4 for one SED episode. This figure is a so-called dynamic spectrum showing the color-coded intensity of radio emissions as a function of time and frequency. The SEDs are the short vertical bursts, that due to the sweeping nature of the receiver appear as narrow-banded signals, although they are intrinsically broadband. The patchy emission at the bottom is Saturn Kilometric Radiation (SKR). At the abscissa we have indicated the times, when the visible cloud appeared and disappeared at the horizon, and when it was at the central meridian (CM) as seen from Cassini. Hence, all SEDs observed before 22:22 SCET are essentially "over horizon" SEDs, which Zarka et al. (2006, 2008, this issue) attribute to an ionospheric propagation effect. It can also be seen that the SEDs are slightly less intense on the dayside (Cassini is at 6 LT), which is caused by higher electron densities resulting in increased radio wave absorption. In Fig. 4 SEDs disappear about half an hour before the visible cloud disappears at the dayside horizon, which is due to the long ray path through the absorbing ionosphere at angles close to grazing incidence. Using the low frequency cutoff of some SED episodes Fischer et al. (2007a) determined the peak electron density as a function of local time. In the range from midnight to 9 LT the peak electron density increased by more than one order of magnitude from 4×10^3 to 8×10^4 cm^{-3}, consistent with what Kaiser et al. (1984) had found for the Voyager 1 SEDs.

Fischer et al. (2007a) found that the frequency minima of storm E episodes were in the range from 770–2300 kHz where there were enough SEDs to see a clear minimum. In Fig. 4 for example, the frequency minimum is around 1 MHz, in the more noisy HF1 band (below 1.8 MHz) of the HFR. For all observed SEDs in the year 2004 (storms 0, A, B, C) Fischer et al. (2006a) could not identify any SEDs below 1.3 MHz, and the lowest frequency channels where SEDs were observed for storm D and E were close to 1070 kHz and 770 kHz, respectively. Generally, at Saturn the frequency range from 3–1200 kHz is dominated by SKR which has highly variable lower and upper frequency limits. With RPWS

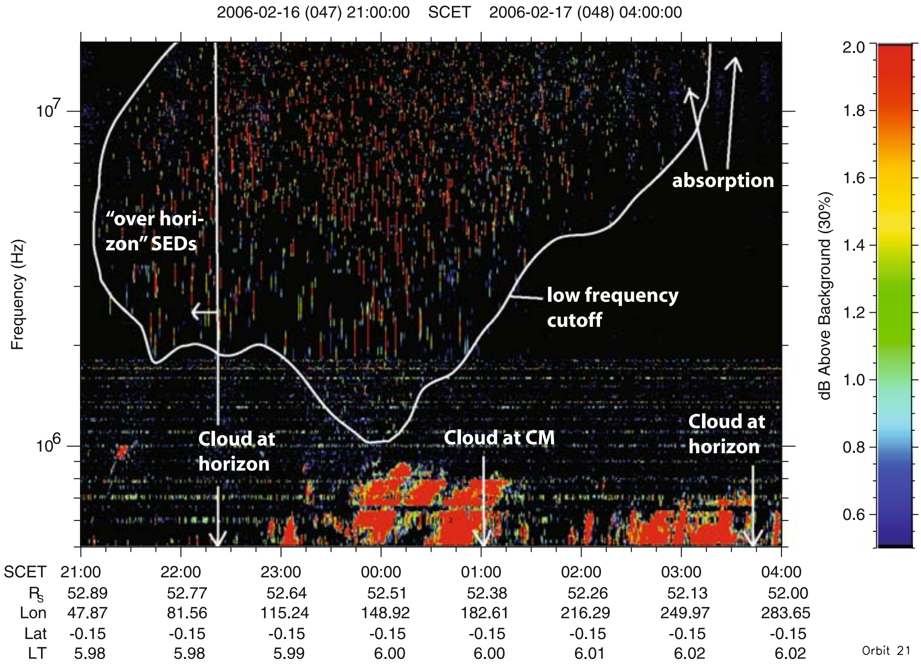

Fig. 4 Dynamic spectrum of SED episode number 56 of storm E. CM stands for central meridian, and it can be seen that the visible cloud is at the CM as seen from Cassini around 01:00 SCET (Spacecraft Event Time). On the abscissa orbital parameters of Cassini are indicated (distance from the center of Saturn in Saturn radii, longitude and latitude, as well as local time). For further explanations see text

clearly no SEDs could be observed below the SKR. An exceptional event had occurred during the SED episode around closest approach of Voyager 1 at Saturn, where SEDs had been observed as low as 20 kHz (Warwick et al. 1981; Zarka and Pedersen 1983). We believe that the anomalous low frequency extension of the Voyager 1 SEDs is either caused by ionospheric holes caused by an influx of water from the rings (Connerney and Waite 1984) or by bursty signals of a different nature that have been misinterpreted as SEDs. Zarka (1985a) and Fischer et al. (2007a) have given convincing arguments showing the consistency of various SED properties with an atmospheric source and the inconsistencies related to a ring source. The combined ISS and RPWS observations (Porco et al. 2005; Dyudina et al. 2007; Fischer et al. 2007a) have finally established a connection between observed cloud features and SEDs. In the next subsection we will discuss that SED radio waves get highly polarized in the magnetoplasma of Saturn's ionosphere, implying that the source of SEDs must be below Saturn's ionosphere.

6.2 Polarization of SEDs

Fischer et al. (2007b) analyzed the polarization measurements of SEDs, which were performed below a frequency of 2 MHz (HF1 band) with RPWS during SED storm E early 2006. They found that SEDs are highly polarized ($\sim 80\%$) with a particularly high degree of circular polarization, and there was exclusively one sense of rotation, which was found to be right-handed with respect to the wave propagation direction. They could explain these measurements in the frame of magneto-ionic theory by calculating Appleton's equation for typical ionospheric conditions on Saturn's nightside ionosphere. In the magnetoplasma of Saturn's ionosphere the SED radio waves experience two possible modes of propagation, which are generally elliptically polarized with opposite rotation sense. Fischer et al. (2007b) found that different cutoff frequencies of these two modes as well as a differential absorption effect lead to the dominance of the ordinary mode below 2 MHz, and the extraordinary mode is highly attenuated. Since the angle between Saturn's magnetic field at the latitude of the storm at 35° South and the direction of wave propagation is larger than 90°, the ordinary mode should show right-handed polarization (with respect to the direction of wave propagation), which is consistent with the observations. Fischer et al. (2007b) note an interesting analogy between terrestrial TIPPs (Transionospheric Pulse Pairs) and SEDs, as both are related to intracloud lightning, are strong radiators in the high frequency range and also have a flat spectrum there. Finally, TIPPs (like SEDs) also show a high circular polarization after passage through the ionosphere (Shao and Jacobson 2002).

7 The Structure of Saturn's Atmosphere

7.1 Lightning on Jupiter as a Comparison

Due to the compositional similarity between Jupiter's and Saturn's atmosphere, we shortly discuss lightning at Jupiter (see comprehensive review by Desch et al. 2002 and new review by Yair et al. 2008, this issue) before proceeding to the structure of Saturn's atmosphere. Lightning at Jupiter was detected optically by the cameras on-board the Voyagers (Cook et al. 1979), Galileo (Little et al. 1999), Cassini (Dyudina et al. 2004), as well as New Horizons (Baines et al. 2007). Radio emissions from Jovian lightning have been detected in the form of whistlers (Gurnett et al. 1979) in Jupiter's magnetosphere as well as sferics with the Galileo Probe inside Jupiter's atmosphere (Rinnert et al. 1998). Interestingly, no high frequency (HF) radio component (similar to SEDs) above the cutoff frequency of Jupiter's ionosphere has been detected, which according to Zarka (1985b) is due to the strong absorption of the radio waves in Jupiter's lower ionospheric layers. Farrell et al. (1999) attributes the non-detection of the HF component to the decrease of spectral power of Jovian spherics with increasing frequency as it was measured by the Galileo Probe. Borucki and Williams (1986) as well as Dyudina et al. (2002) applied a Monte Carlo model to describe the scattering of light from Jovian flashes in Jupiter's atmosphere. In both papers the best agreement between model and observations is obtained when the lightning source is located in a Jovian water cloud at or below a pressure level of 4–5 bars. Gibbard et al. (1995) as well as Yair et al. (1995) have modeled the generation of lightning in Jovian water clouds using a charge separation mechanism similar to that which operates in terrestrial thunderstorms (Rakov and Uman 2003). Both conclude that a Jovian thundercloud is able to build up a strong electric field required for lightning discharges as long as there is sufficient water abundance.

7.2 At What Depth is the SED Source Located?

Figure 5 illustrates the cloud structure in Saturn's hydrogen and helium atmosphere, which shows three distinct cloud layers. The figure was drawn after the equilibrium cloud condensation model of Atreya and Wong (2004), who used elemental abundances of 5 times the solar value. The outermost cloud layer consists of ammonia (NH_3) ice particles and is followed by an intermediate ammonium hydrosulfide (NH_4SH) cloud layer.

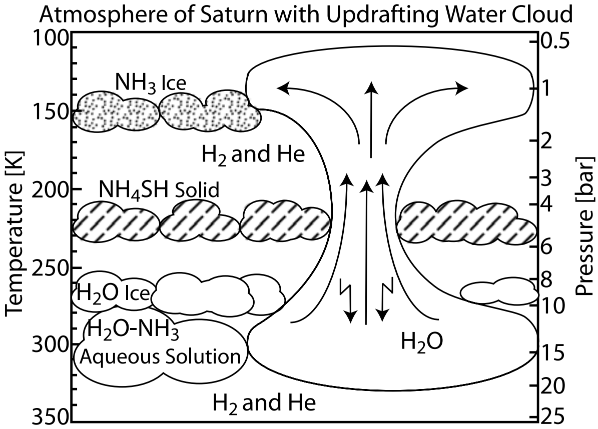

Fig. 5 Sketch of the three-layered cloud structure in Saturn's atmosphere with an updrafting water cloud with lightning activity

The deep water cloud (H_2O) has a cloud base around the 20 bar level and might consist of droplets of an aqueous solution of ammonia in water at lower levels and ice particles above. Jupiter's cloud structure is essentially similar, except that the greater gravity of Jupiter leads to a higher temperature lapse rate and clouds condense at lower pressure levels. As observations of Jovian lightning point to the water cloud as source region for lightning, it is straightforward to assume that Saturn lightning also has its origin in the water clouds. Furthermore, the greater depth of water clouds in the model of Saturn's atmosphere allows us to explain why direct flashes of lightning have not been optically detected up to now. Similar to Desch et al. (2006), we presume that SED activity is related to vertical convection driving the water cloud up to the visible atmospheric level, where it has been observed as bright eruptions by Cassini/ISS (Porco et al. 2005; Dyudina et al. 2007) overshooting the uppermost ammonia cloud layer (see also Fig. 2). We have sketched such an updrafting water cloud in Fig. 5, which has been theoretically modeled by Hueso and Sánchez-Lavega (2004). They conclude that water storms on Saturn are more difficult to trigger compared to Jupiter, but they can be very energetic reaching vertical velocities of the order of 150 $\mathrm{m\,s^{-1}}$. Since external sunlight does not penetrate much further than down to the pressure level around 2 bars, Saturn's weather at deep pressure levels is most likely driven by an internal source of energy, which exhibits thermal gradients initiating the upward convection of the water cloud (Desch et al. 2006).

SEDs might originate from a pressure level around 8 to 10 bars, roughly 200 to 300 km below the 1-bar level. The temperature at those levels is around 255–275 K, which is the same temperature range at which most cloud particles get charged in terrestrial thunderclouds and where the strongest electric fields can be found (Rakov and Uman 2003). At such high pressure levels the breakdown electric field should be higher than in terrestrial thunderclouds. Roussel-Dupré et al. (2008, this issue) found that the hydrogen-helium atmosphere of Saturn decreases the critical electric field necessary for breakdown, in the case of conventional breakdown by a factor of 2, and for runaway breakdown by a factor of 6.3 compared to air at Earth. This has to be linearly related to the gas particle density at standard conditions ($\sim 2.65 \times 10^{25}$ $\mathrm{m^{-3}}$ at 1 bar and 0°C). At the SED source the particle density should be a factor of ~ 10 higher, leading to a conventional breakdown field of $\sim 1.5 \times 10^{7}$ $\mathrm{V\,m^{-1}}$ being a factor of ~ 5 above the terrestrial one. Similarly, the threshold field for runaway breakdown at Saturn's 10-bar level would be $\sim 3.4 \times 10^{5}$ $\mathrm{V\,m^{-1}}$ or a factor of ~ 1.6 above the terrestrial value. These higher breakdown fields would allow more charges to accumulate before it comes to a breakdown, which supports the idea that Saturn lightning is more powerful than Earth as well as Jupiter lightning.

8 Phenomena Related to Saturn Lightning

8.1 Whistlers at Saturn

The observation of a whistler at Saturn was reported by Akalin et al. (2006). It was detected by the Wideband Receiver of RPWS on October 28, 2004, on a magnetic field line with an L-shell value of $L \approx 6.5$. The whistler signal lasted for about 2 seconds and was recorded in a frequency range of 200–400 Hz, and Akalin et al. (2006) measured a dispersion of 81 $\mathrm{Hz}^{1/2}$ s. Using a model for the plasma distribution along the magnetic field line they concluded that the whistler originated in the northern hemisphere of Saturn at an invariant latitude of 67°. Another whistler was possibly detected in spring 2007 and is currently under investigation.

The scarcity of whistler observations so far is probably due to the very restrictive conditions for their detection. First, the spacecraft must be relatively close to the planet. Second, the causative lightning must occur very close to the foot of the magnetic field line that passes through Cassini. Third, appropriate wideband observerations without interference, such as from Cassini's reaction wheels, must be available. It is easy to explain why Cassini did not detect whistlers during SED activity, as the lightning storms were either located at the equator or at a planetocentric latitude of 35° South, the latter corresponding to $L \approx 1.44$. Only during SOI was Cassini that close to Saturn, but no SEDs were detected at that time, and for most detected SEDs Cassini was even outside of Saturn's magnetosphere. However, there is no good explanation why RPWS did not detect SEDs around the whistler event of October 2004.

8.2 Could There Be a Global Atmospheric Circuit at Saturn?

Aplin (2006) discusses the question of the existence of a global atmospheric circuit at Saturn driven by Saturn lightning. Aplin (2006) argues that some necessary conditions for an electric circuit are not fulfilled at the gas planets like two conductive layers (ionosphere and "surface") relative to a less conductive atmosphere. Sentman (1990) modeled the conductivity of Jupiter's shallow interior and suggested the existence of a planetary-ionosphere cavity, where Schumann resonances could be excited between the ionosphere and the so-called conduction boundary depending on the wave frequency. A similar model for Saturn is presented in this book, where Simões et al. (2008, this issue) calculated the frequencies of 0.93 Hz, 1.63 Hz, and 2.34 Hz as the three lowest Schumann eigenmodes with a Q-factor around 7.

8.3 Sprites, Elves, and Gamma Ray Flashes at Saturn?

We note that the content of this subsection is rather speculative as neither sprites, nor elves or gamma ray flashes have been detected at Saturn. However, our increasing knowledge about these phenomena at Earth allows us to consider their existence at other planets.

Terrestrial (red) sprites are transient optical emissions above thunderstorms at mesospheric altitudes of 40–90 km. They are believed to be caused by conventional breakdown or runaway electrons due to a strong electrostatic field, which is often produced by a strong

Table 2 A comparison between Saturn and Earth lightning

Saturn lightning	Earth lightning
• Sporadic occurrence, but SEDs can go on for several weeks to months with a highly variable flash rate	• Permanent presence of ~ 100 flashes per second, but typically only a few hours at one place
• Flash duration few hundred ms	• Similar flash duration as SEDs
• Spectral radio power ~ 100 W/Hz, but not necessarily "superbolts"	• Power in radio range at a few MHz smaller by factor of $\sim 10^4$
• Nearly flat spectrum (up to 20 MHz)	• Spectral fall-off with $1/f^2$ (> 1 MHz)
• Highly polarized due to propagation in Saturn's ionosphere	• TIPPs but not return strokes get polarized in Earth's ionosphere
• Giant convective storm systems (~ 3000 km in diameter)	• Individual storms of few tens of km, but grouping possible ("mesoscales")
• Up to now SEDs only observed at equator and 35° South (makes whistler observations difficult)	• Most lightning over land in tropical regions and much less frequent at high latitudes
• SED source probably in updrafting water clouds at 8–10 bar	• Charge separation in thunderclouds at a few km altitude around freezing level
• Elves more likely than sprites (modeling needed); gamma ray flashes hardly detectable from space	• Existence of sprites, elves, and gamma ray flashes established in recent years

positive cloud-to-ground stroke (Rakov and Uman 2003). Elves are lightning-induced luminous discs expanding horizontally in a circular form with an observed duration less than 1 ms (Fukunishi et al. 1996). The likely source of elves is the interaction of lightning return-stroke radiation fields with the electrons of the lower ionosphere. The existence of high altitude discharges at Earth was in fact anticipated by Wilson (1956) as the lower gas density at high altitudes combined with thunderstorm electric fields should allow electron acceleration and breakdown.

For the existence of sprites it is necessary that the local thunderstorm electric field exceeds the critical field E_k for conventional breakdown for an interval long enough for the formation of a "streamer". Roussel-Dupré et al. (2008, this issue) found that the scaled critical electric field E_k/N (divided by the particle density N) for Saturn's hydrogen atmosphere is about half of that of air or ~ 60 Td (1 Townsend (Td) $= 10^{-21}$ V m^2). We have no knowledge of Saturn's thunderstorm electric fields, and a macro-physical model would be required for their estimation. We note that an electrostatic dipole field decreases with $1/r^3$ with r as the distance, whereas a lightning radiation field decreases only with $1/r$. Given the extraordinary radio power of SEDs compared to Earth lightning, the existence of elves at Saturn seems more probable than the existence of sprites.

Terrestrial gamma ray flashes (TGFs) were observed by the Burst and Transient Signal Experiment onboard the Compton Gamma Ray Observatory and were related to thunderstorms by Fishman et al. (1994). The source location of TGFs is not yet exactly known; Williams et al. (2006) inferred a source altitude around 15–21 km, i.e. not so far from the thundercloud tops. An important issue for the detection of TGFs is their attenuation in the terrestrial atmosphere. Suszcynsky et al. (1996) show an attenuation length of about 100 m for gamma rays with energies in the MeV-range at standard conditions in air, which corresponds to a mass thickness of 11 $\mathrm{g\,cm^{-2}}$. A mass thickness of the same order of magnitude can be expected in Saturn's atmosphere at the 10-bar level, as the 10 times higher particle density is compensated by a factor of 14 being the ratio between the molecular masses of air and H_2. Hence, the attenuation length close to the SED source at 10 bar would be $\sim$ 140 m, which would make their detection with satellites impossible. We estimate that gamma rays caused by bremsstrahlung of runaway electrons at Saturn would be only detectable by satellites in case their source region is above the 100 mbar pressure level, which is 100 km above the 1-bar level.

9 Summary: A Comparison between Saturn and Earth Lightning

Instead of a written summary we present Table 2 comparing the most important properties of Saturn lightning mentioned in this paper with terrestrial lightning (Rakov and Uman 2003).

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