GEOPHYSICAL RESEARCH LETTERS, VOL. 34, L22104, doi:10.1029/2007GL031668, 2007

Nondetection of Titan lightning radio emissions with Cassini/RPWS after 35 close Titan flybys

G. Fischer,[1] D. A. Gurnett,[1] W. S. Kurth,[1] W. M. Farrell,[2] M. L. Kaiser,[2] and P. Zarka[3]

Received 15 August 2007; revised 9 October 2007; accepted 18 October 2007; published 28 November 2007.

[1] We report on the nondetection of radio emissions associated with possible lightning flashes in Titan's atmosphere by the Cassini/RPWS (Radio and Plasma Wave Science) instrument. A valid proof for Titan lightning would be the detection of a number of bursty radio signals above Titan's ionospheric cutoff frequency, and they should be grouped near the closest approach of Cassini to Titan with an approximately quadratic fall off of signal intensity with spacecraft distance. Such a clear signature has not been detected by the RPWS instrument during the first 35 close flybys of Titan. **Citation:** Fischer, G., D. A. Gurnett, W. S. Kurth, W. M. Farrell, M. L. Kaiser, and P. Zarka (2007), Nondetection of Titan lightning radio emissions with Cassini/RPWS after 35 close Titan flybys, *Geophys. Res. Lett.*, *34*, L22104, doi:10.1029/2007GL031668.

1. Introduction

[2] After the Voyager 1 Titan flyby in November 1980, theoretical and experimental studies of Titan's complex atmospheric chemistry [*Gupta et al.*, 1981; *Borucki et al.*, 1984, 1988] were performed. These studies led to the suggestion that lightning could exist in Titan's thick nitrogen and methane dominated atmosphere, although no corresponding radio emissions were detected by Voyager's radio instrument [*Desch and Kaiser*, 1990]. With the Earth-based telescopic detection of clouds on Titan [*Griffith et al.*, 1998] and the Cassini orbiter as well as the Huygens Probe being equipped with instruments capable for the detection of lightning [*Gurnett et al.*, 2004; *Fulchignoni et al.*, 2002], there was already great interest in Titan lightning even before the arrival of Cassini/Huygens at the Saturnian system. *Navarro-González et al.* [2001] made further laboratory investigations, *Tokano et al.* [2001] developed a model for thundercloud and lightning generation, and *Lammer et al.* [2001] and *Fischer et al.* [2004] estimated the possible Titan lightning energy and the corresponding detection capability of Cassini/RPWS.

[3] *Fulchignoni et al.* [2005] reported that the Huygens Atmospheric Structure Instrument (HASI) *might* have detected the signature of lightning during the probe's descent through Titan's atmosphere. Several impulsive electric field events were detected with the mutual impedance receiver in the frequency range up to 11.5 kHz [*Schwingenschuh et al.*, 2007]. Additionally, a Schumann-like resonance was seen at 36 Hz, but its unusually high signal level and the nonconformity of its frequency with most models of Titan's surface-ionosphere cavity make it questionable if this signal was of lightning origin [*Simões et al.*, 2007]. Instead, *Béghin et al.* [2007] favored waves generated in the ionosphere of Titan as a possible source of the 36 Hz line over mechanical vibrations of the antenna. No thunder claps were identified in the acoustic sensor data of HASI [*Grard et al.*, 2006].

[4] At the time of this writing 35 close Titan flybys have been performed by Cassini, which is half of all the Titan flybys planned during the spacecraft's nominal and extended mission (until mid-2010). So in view of the latest Huygens results it is time to report on the search for Titan lightning in the RPWS data. Before we get to the analysis of RPWS data we will first discuss the observations of clouds in Titan's atmosphere.

2. Convective Clouds on Titan as a Possible Lightning Source

[5] Cassini/ISS (Imaging Science Subsystem) not only confirmed the existence of convective clouds at the South pole of Titan, but also imaged elongated midlatitude tropospheric clouds [*Porco et al.*, 2005]. Convective clouds are naturally a place where lightning discharges could occur, and a model by *Hueso and Sánchez-Lavega* [2006] has revealed that rainfall and updrafts with maximum velocities of 20 m s^{-1} may occur in Titan's methane storms. In Earth thunderclouds lightning emerges above a vertical updraft speed threshold of 6–7 m s^{-1} [*Rakov and Uman*, 2003]. In a slightly different Titan cloud model *Barth and Rafkin* [2007] get mixing ratios of cloud particles in the range of 1–10 g kg^{-1}, which is comparable to mixing ratios found in terrestrial thunderclouds [*Levin et al.*, 1983]. Although updraft speeds and cloud mass loading might be comparable to the terrestrial case, the crucial questions are still the existence of an efficient microscale cloud particle electrification process on Titan and the subsequent macroscale charge separation process. *Tokano et al.* [2001] suggested a charging of cloud particles by electron attachment, but this suggestion has not been verified experimentally. The low relative dielectric constant of methane ($\sim$1.7) is still a valid argument against the existence of lightning on Titan.

[6] The changing cloud activity as observed by Cassini/VIMS (Visual and Infrared Mapping Spectrometer) until mid-2006 has been described by *Rodriguez et al.* [2007]. VIMS, ISS [*Porco et al.*, 2005] as well as ground-based observatories [*Schaller et al.*, 2006a] have detected South polar clouds clearly in October 2004 (i.e. during Titan flyby TA) and also before. The South polar clouds were vanishing in December 2004 during flyby TB when they were partly

[1]Department of Physics and Astronomy, University of Iowa, Iowa City, Iowa, USA.
[2]NASA Goddard Space Flight Center, Greenbelt, Maryland, USA.
[3]Observatoire de Paris-Meudon, Paris, France.

0094-8276/07/2007GL031668$05.00

seen with VIMS but not with ISS and from the ground [*Schaller et al.*, 2006b]. At the same time midlatitude clouds were also imaged, which were most likely also convective in nature [*Griffith et al.*, 2005]. Patches of clouds were also detected in the Northern hemisphere around 50°–70°N at various times and altitudes of 30 to 50 km [*Griffith et al.*, 2006]. They most likely consist of ethane, which is transported to lower altitudes where it condenses, and they exhibit nonconvective characteristics and hence are not likely places for lightning. Another South pole cloud outburst was seen by VIMS in December 2005 during T9 [*Rodriguez et al.*, 2007].

[7] Interestingly, to date Earth-based observations have twice revealed dramatic increases in tropospheric cloud activity at Titan's South pole. The first one was in September 1995 [*Griffith et al.*, 1998] and the second one in October 2004 [*Schaller et al.*, 2006a]. The Cassini TA flyby (October 26, 2004) caught this cloud activity as it was dissipating, but no radio signals of lightning could be detected at this occasion. Titan lightning could also be detected optically [*Porco et al.*, 2004] by looking for flashes in the nightside images of Titan, but no results have been reported up to now.

3. RPWS: Looking for Titan Lightning Radio Emissions

[8] We note that a preliminary analysis of RPWS data of the first 6 Titan flybys done by *Zarka et al.* [2006] did not reveal any strong event, but in the following we will discuss the Titan lightning search in much greater detail.

3.1. RPWS Instrument Modes at Titan

[9] For electric field measurements the RPWS instrument is equipped with 3 monopole antennas E_u, E_v, E_w (E_u and E_v can be combined to form the dipole E_x) and various receivers [*Gurnett et al.*, 2004]. For a detection of possible Titan lightning we looked at the HF1 and HF2 bands of the HFR (High Frequency Receiver) covering the frequency ranges from 325 to 1800 kHz (HF1) and 1.8 to 16 MHz (HF2), respectively. In these two bands the HFR acts as a frequency sweeping receiver with a bandwidth of 25 kHz. In HF1 most of the time two antenna measurements (E_x and E_w) are made, whereas in HF2 preferentially only one antenna (E_x) is used. The receiver mode used for most Titan flybys for about ±2 hours around closest approach made one complete frequency sweep every 8 seconds with an integration time of 40 ms at each channel. Typically, 60 frequency steps of 25 kHz were used in HF1, and 72 steps of 200 kHz in HF2.

3.2. Computer Algorithm for the Detection of Bursty Signals

[10] In a frequency sweeping receiver a broadband signal like a lightning flash will be recorded only in those frequency channels which are sampled during the short duration of the flash, and therefore appears as a relatively narrow-band signal. The method to extract such bursty signals from RPWS data was described by *Fischer et al.* [2006a], where it was used for Saturn lightning. We use the same technique for our search for Titan lightning, and a "flash event" has to be a certain intensity threshold above the background as well as above its adjacent measurements in the same frequency channel. The intensity threshold has to be chosen in accordance with the fluctuation of the background which is also a function of the receiver integration time. *Fischer et al.* [2006a] have shown that an intensity threshold of 4 standard deviations (4σ) of the background fluctuation is an appropriate choice. For the dipole measurements in the HF1 band this threshold is about 1.6 dB in case of an integration time of 80 ms and $1.6\sqrt{2} \approx 2.26$ dB for the 40 ms integration time which was applied close to Titan. For dipole measurements with 40 ms in HF2 the fluctuation is less and the threshold of 4σ corresponds to 0.8 dB. At two flybys (T11, T15) integration times of 20 ms in HF1 and 10 ms in HF2 were used ±1/2 hour around closest approach. The usage of short integration times increases the background noise level, but also increases the sensitivity of the receiver to short impulsive bursts. Saturn lightning was detected with all 4 possible integration times of HF2 (10, 20, 40, and 80 ms).

3.3. RPWS Measurements During Titan Flybys TA and TB

[11] In Figure 1 we present the dynamic spectra recorded by Cassini RPWS during the first two close Titan flybys TA and TB as an illustrative example. One can see the color-coded intensity of radio waves as a function of time (over 2.5 hours for each flyby) and frequency (logarithmic scale from 600 kHz to 16 MHz). At first sight a lot of different signals can be seen in both spectra. It is easy to distinguish the HF1 from the HF2 band as the HF1 band below about 1.8 MHz is much more noisy and has a lot of bursty signals especially at the multiples of 100 kHz, and these frequency channels have to be excluded for the lightning search. The strong (red) emission below about 800 kHz in both spectra is the upper extent of Saturn Kilometric Radiation. During TA there are also two frequency channels in HF2 (at 4.8 and 12.6 MHz) which show an enhanced intensity, and these fixed frequency signals are clearly some kind of interference. Similarly, during TB the frequency channels of 2.4 MHz as well as around 3 MHz show some weak signals appearing to be fixed frequency shortly before Titan closest approach. An agglomeration of bursts at a relatively small frequency range like here are not likely to be caused by lightning flashes, because in a frequency sweeping receiver lightning signals should be distributed at random frequencies above the ionospheric cutoff frequency. Closest approach for TA was at 15:30 SCET and at 11:38 SCET for TB (approximately where we added "TA" and "TB" in the spectra) and in both cases the flyby altitude was slightly less than 1200 km above the surface of Titan.

[12] During TA there are also some vertically extended emissions, the biggest one around 17:15 SCET clearly exhibits the spectral characteristics of a Solar type III burst. Similarly, the vertical bursts around 16:00 SCET and the one at 17:30 SCET look like a Solar type III bursts and extend over a significant frequency interval and therefore have durations of the order of seconds, probably too long to be lightning bursts. There are also some narrow-banded (i.e. shorter) bursts in the TA spectrum (our computer algorithm identified 11), e.g. one at 16:08 SCET at 6.2 MHz with an intensity of 1.8 dB above background or another one at 17:28 at 7.0 MHz with an intensity of 1.2 dB. We do not consider them as Titan lightning simply because such

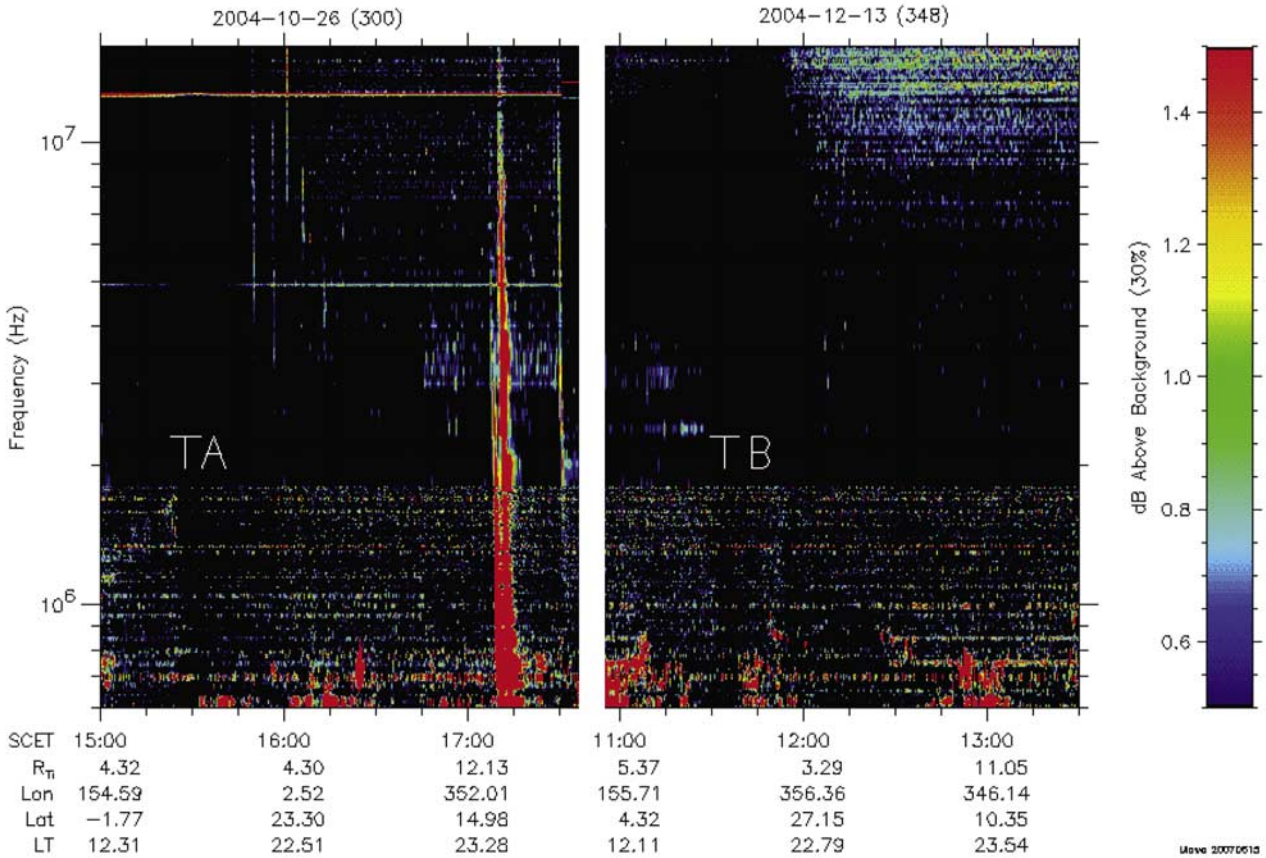

Figure 1. Dynamic spectra recorded by RPWS during Titan flybys TA (left) and TB (right) from October 26 and December 13, 2004, respectively. The ordinate gives the frequency in Hz and on the abscissa we have the spacecraft event time in hours, the distance of Cassini to Titan in Titan radii as well as its longitude, latitude, and local time as seen from Titan. The frequency scale on the left and the intensity color bar on the right are valid for both spectra.

narrow-banded bursts were frequently observed by RPWS around Solar bursts throughout Cassini's whole mission.

[13] The most eye-catching feature in the spectrum of Titan flyby TB are the bursts and the enhanced intensity starting around 12:00 SCET above about 10 MHz. The bursts in fact continue nearly until 23:00 SCET when Cassini is at a distance of more than 90 Titan radii. These bursts cannot be Titan lightning as there is no fall off of intensity with distance. Furthermore, they also appeared for several hours two days later with Cassini nearly 700 Titan radii away. We found the occurrence of these bursts to be correlated with high voltage discharges of the INCA (Ion and Neutral Camera) of Cassini/MIMI (Magnetospheric Imaging Instrument).

[14] Some weak bursts that deserve our attention during TB occur around 12:15 SCET in the frequency range from about 3 to 10 MHz. One likely possibility is that they are the peaks of Jovian decametric arcs that slightly protrude above the galactic background, since the Io-phase is around 100° at this time. These beamed Jovian radio emissions were very intense when Cassini was around Jupiter, but RPWS still detects them in 2007 with Jupiter more than 11.6 AU away from Saturn. In 2003 such Jovian radio emissions were misinterpreted as the first indication of Saturn lightning when Cassini was at a distance of about 1.1 AU from Saturn, but, using a technique of direction discrimination *Fischer et al.* [2006b] could show that they came from Jupiter. The same technique cannot be applied to the bursts of TB as it requires a two antenna measurement, and here only the dipole was used in the HF2 band. An alternative explanation for the bursts around 12:15 SCET at TB would be that the bursts around 3 MHz are a continuation of the interferences around 3 MHz appearing before closest approach and that the burst around 10 MHz belongs to the discharges caused by the INCA instrument.

[15] One interesting effect regarding the intensity of the background can be seen in Figure 1. Around closest approach the background appears in black color as Titan shields a certain portion of the sky ($\sim 0.5\pi$ sr of 4π sr at a flyby altitude of 1200 km) which causes a maximum drop in the intensity of the galactic background by about 0.6 dB.

[16] There is no way of comparing Huygens Probe measurements like those performed by HASI with RPWS observations as RPWS was powered off during flyby TC, when the Huygens Probe landed on Titan. With a flyby distance of about 60,000 km TC is not considered as a close flyby, and we count T3 as the 3rd close Titan flyby.

3.4. RPWS Measurements From T3 to T35

[17] We applied our computer algorithm for burst detection at the Titan flybys T3 to T35 when Cassini was within 100 Titan radii. In case Titan lightning radio emissions have

a similar strength as Earth lightning, they would be detected only within 35 Titan radii which corresponds to the detection distance of 14 Earth radii as found by *Gurnett et al.* [2001] for terrestrial lightning during Cassini Earth flyby. The distance of 100 Titan radii is typically traversed by Cassini in about 13 hours, since close to Titan the spacecraft has a speed similar to Titan's orbital velocity around Saturn of about 5.6 km s^{-1} or 7 to 8 Titan radii per hour. We also searched for Titan lightning visually with the help of dynamic spectra as those shown in Figure 1, which using the appropriate settings for time resolution, intensity range, and background division are generally an excellent tool for the search of bursty signals. Within 100 Titan radii to Titan, type III Solar radio emissions like those during the TA flyby were also detected at the other flybys T3, T5, T6, T9, T13, T14, T18, T20, T21, and T31. Jovian radio emissions were clearly detected at TA, T3, T5, T9, T10, T12, T19, T23, and T32, and possibly at TB, T13, T15, T21, T26, T30, and T35. The bursts related to the INCA instrument as first seen at TB were also found at T3, T8, T10, T11, T12, T14, T16, T17, T18, T19, T23, and T34.

[18] Besides the bursts related to the three categories above (Sun, Jupiter, INCA related) we only found a small number of bursts which we could label as ''unidentified''. Most of them had intensities just barely above the 4σ-detection threshold, and hence are most likely just background fluctuations as there is a certain probability (0.0032%) for a burst to have an intensity value exceeding the mean galactic background by 4σ [*Fischer et al.*, 2006a]. At the end only a handful of stronger bursts (about 40, all of them <7 dB in HF1 and <5 dB in HF2) were found up to T35 within 100 Titan radii. Those could be simply some unknown interferences because we found such stronger bursts also at arbitrary positions of Cassini and not only close to Titan.

[19] We also searched for Titan lightning using 2σ and 3σ-detection thresholds in our computer algorithm. In this way we got a certain number of events per time interval (basically background fluctuation) at an arbitrary position of Cassini. We hoped to find an increase in the number of these events per time interval close to Titan, which could mean that there are also weak bursts of Titan lightning among these events adding up to the natural background fluctuation. But, the numbers of events per time interval remained relatively constant throughout Cassini's trajectory and we found no significant agglomeration close to Titan at any of the 35 flybys.

[20] We cannot completely exclude the possibility that some of the stronger bursty signals (well above the 4σ threshold) around Titan are actually caused by sporadic Titan lightning, but there is no way to positively prove that assumption. Firstly, when there is a thunderstorm one should expect at least some tens of lightning bursts and not only isolated signals. And secondly, with a one antenna intensity measurement like in the HF2 band, the only way to confirm Titan to be the source of the signals would be a decrease of signal intensity or occurrence with $1/d^2$ with d as the distance from Cassini to Titan. We can clearly state that such a signature of Titan lightning (tens of bursts with a quadratic fall off of signal intensity) has definitely not been detected by Cassini/RPWS during any of the first 35 close Titan flybys. In case we detect such an event in future, Cassini VIMS or ISS should also spot convective clouds at the same time.

4. Discussion

[21] It was demonstrated in the previous section that one has to be careful in the interpretation of bursty electromagnetic signals. We want to emphasize how crucial it is to be aware of spacecraft interferences or other radio emissions from the Sun or Jupiter which can cause bursty signals just like lightning flashes. This holds also for electric and magnetic field measurements of other spacecraft missions that are searching for lightning at other planets (like Venus). The nonexistence of a positive proof for Titan lightning in the RPWS data up to T35 should not be misunderstood as a general proof of the nonexistence of Titan lightning. Nevertheless, it does make at least a strong statement.

[22] Another reason for the nondetection of Titan lightning with RPWS could be the blockage of radio waves by Titan's ionosphere. A reanalysis of Voyager 1 radio occultation measurements have revealed a peak electron density of 2400 cm^{-3} at an altitude of 1180 km at the evening terminator [*Bird et al.*, 1997]. This corresponds to a peak plasma frequency of about 440 kHz, hence, we should in principle be able to detect the radio waves with RPWS. But, information on the absorption of radio waves in Titan's ionosphere due to collisions is sparse and relies on theoretical modeling [*Schwingenschuh et al.*, 2001]. Further research in Titan's ionospheric physics as a result of the Cassini mission will probably shed more light on this topic in future.

[23] If terrestrial-like lightning does not exist on Titan, there might be still other forms of atmospheric electricity like smaller corona discharges [*Navarro-González et al.*, 2001] or discharges in its haze layer. Therefore, simulating discharges in the laboratory as done recently by *Plankensteiner et al.* [2007] in Titan-like conditions still can reveal important insights into Titan's complex atmospheric chemistry.

[24] The nondetection of Titan lightning signals up to now by the sensitive RPWS instrument also sets an upper limit on the radio energy of such discharges. Radio measurements of Earth lightning at 10 MHz at altitudes around 1000 km (very similar to the closest approaches of 950 km of Cassini to Titan) have revealed electric field spectral densities around 10^{-13} V^2 m^{-2} Hz^{-1} [*Horner*, 1965]. This is about 4 orders of magnitude higher than the electric field spectral density of the background as measured by RPWS. In accordance with that *Gurnett et al.* [2001] found Earth lightning signals with RPWS with an intensity up to 40 dB above background during the Cassini Earth flyby with the closest approach distance of 1186 km. If Titan lightning was present during the Cassini flybys it must be 4 orders of magnitude less powerful in the decametric frequency range compared to Earth lightning, so its source power would have to be smaller than 10^{-6} W Hz^{-1}. Another possibility is that Titan lightning might be a slow discharge which is difficult to detect since substantially slower discharges (compared to terrestrial return strokes) are not efficient radiators at high frequencies around 10 MHz [*Farrell et al.*, 1999]. Finally, Titan lightning could have been not present during the Cassini flybys due to its low or episodic

flash rate. Assuming that possible Titan lightning would have the strength of Earth lightning it would have been detected within 35 Titan radii, and Cassini spent slightly more than 300 hours within this distance up to T35. This sets an upper limit to the flash rate of 10^{-6} flashes per second, which is about 2 orders of magnitude below the upper limit of *Desch and Kaiser* [1990] for Titan, and about 8 orders of magnitude below the terrestrial flash rate [*Rakov and Uman*, 2003].

5. Conclusion

[25] An unsuccessful search for radio signals from possible Titan lightning discharges has been performed with Cassini/RPWS data. Although some bursts have been found occasionally, none of them could be unambiguously identified as Titan lightning. We have emphasized that the interpretation of any bursty signal as being due to lightning discharges has to be done with the utmost caution. The bursty signals found in RPWS data up to T35 were either spacecraft interferences, Jovian decametric arcs, Solar radio emissions, or enhanced background fluctuations, and some isolated unidentified bursts might be unknown interferences. Nevertheless, the search will continue throughout Cassini's extended mission.

References

Barth, E. L., and S. C. R. Rafkin (2007), TRAMS: A new dynamic cloud model for Titan's methane clouds, *Geophys. Res. Lett.*, *34*, L03203, doi:10.1029/2006GL028652.

Béghin, C., et al. (2007), A Schumann-like resonance on Titan driven by Saturn's magnetosphere possibly revealed by the Huygens Probe, *Icarus*, *191*, 251–266.

Bird, M. K., R. Dutta-Roy, S. W. Asmar, and T. A. Rebold (1997), Detection of Titan's ionosphere from Voyager 1 radio occulatation observations, *Icarus*, *130*, 426–436.

Borucki, W. J., C. P. McKay, and R. C. Whitten (1984), Possible production by lightning of aerosols and trace gases in Titan's atmosphere, *Icarus*, *60*, 260–273.

Borucki, W. J., L. P. Giver, C. P. McKay, T. Scattergood, and J. E. Parris (1988), Lightning production of hydrocarbons and HCN on Titan: Laboratory measurements, *Icarus*, *76*, 125–134.

Desch, M. D., and M. L. Kaiser (1990), Upper limit set for level of lightning activity on Titan, *Nature*, *343*, 442–444.

Farrell, W. M., M. L. Kaiser, and M. D. Desch (1999), A model of the lighting discharge at Jupiter, *Geophys. Res. Lett.*, *26*, 2601–2604.

Fischer, G., T. Tokano, W. Macher, H. Lammer, and H. O. Rucker (2004), Energy dissipation of possible Titan lightning strokes, *Planet. Space Sci.*, *52*, 447–458.

Fischer, G., et al. (2006a), Saturn lightning recorded by Cassini/RPWS in 2004, *Icarus*, *183*, 135–152.

Fischer, G., W. Macher, D. A. Gurnett, M. D. Desch, A. Lecacheux, P. Zarka, W. S. Kurth, and M. L. Kaiser (2006b), Discrimination between Jovian radio emissions and Saturn electrostatic discharges, *Geophys. Res. Lett.*, *33*, L21201, doi:10.1029/2006GL026766.

Fulchignoni, M., et al. (2002), The characterization of Titan's atmosphere physical parameters by the Huygens Atmospheric Structure Instrument (HASI), *Space Sci. Rev.*, *104*, 395–431.

Fulchignoni, M., et al. (2005), In situ measurements of the physical characteristics of Titan's environment, *Nature*, *438*, 785–791.

Grard, R., et al. (2006), Electric properties and related physical characteristics of the atmosphere and surface of Titan, *Planet. Space Sci.*, *54*, 1124–1136.

Griffith, C. A., T. Owen, G. A. Miller, and T. R. Geballe (1998), Transient clouds in Titan's lower troposphere, *Nature*, *395*, 575–578.

Griffith, C. A., et al. (2005), The evolution of Titan's mid-latitude clouds, *Science*, *310*, 474–477.

Griffith, C. A., et al. (2006), Evidence for a polar ethane cloud on Titan, *Science*, *313*, 1620–1622.

Gupta, S., E. Ochiai, and C. Ponnamperuma (1981), Organic synthesis in the atmosphere of Titan, *Nature*, *293*, 725–727.

Gurnett, D. A., P. Zarka, R. Manning, W. S. Kurth, G. B. Hospodarsky, T. F. Averkamp, M. L. Kaiser, and W. M. Farrell (2001), Non-detection at Venus of high-frequency radio signals characteristic of terrestrial lightning, *Nature*, *409*, 313–315.

Gurnett, D. A., et al. (2004), The Cassini radio and plasma wave investigation, *Space Sci. Rev.*, *114*, 395–463.

Horner, F. (1965), Radio noise in space originating in natural terrestrial sources, *Planet. Space Sci.*, *13*, 1137–1150.

Hueso, R., and A. Sanchez-Lavega (2006), Methane storms on Saturn's moon Titan, *Nature*, *442*, 428–431.

Lammer, H., T. Tokano, G. Fischer, W. Stumptner, G. J. Molina-Cuberos, K. Schwingenschuh, and H. O. Rucker (2001), Lightning activity on Titan: Can Cassini detect it?, *Planet. Space Sci.*, *49*, 561–574.

Levin, Z., W. J. Borucki, and O. B. Toon (1983), Lightning generation in planetary atmospheres, *Icarus*, *56*, 80–115.

Navarro-González, R., S. I. Ramírez, J. G. de la Rosa, P. Coll, and F. Raulin (2001), Production of hydrocarbons and nitriles by electrical processes in Titan's atmosphere, *Adv. Space Res.*, *27*, 271–282.

Plankensteiner, K., H. Reiner, B. M. Rode, T. Mikoviny, A. Wisthaler, A. Hansel, T. D. Märk, G. Fischer, H. Lammer, and H. O. Rucker (2007), Discharge experiments simulating chemical evolution on the surface of Titan, *Icarus*, *187*, 616–619.

Porco, C. C., et al. (2004), Cassini imaging science: Instrument characteristics and anticipated scientifc investigations at Saturn, *Space Sci. Rev.*, *115*, 363–497.

Porco, C. C., et al. (2005), Imaging of Titan from the Cassini spacecraft, *Nature*, *434*, 159–168.

Rakov, V. A., and M. A. Uman (2003), *Lightning, Physics and Effects*, Cambridge Univ. Press, Cambridge, U. K.

Rodriguez, S., et al. (2007), Following two years of Titan cloud events with Cassini/VIMS, *Lunar Planet. Sci.*, *XXXVIII*, Abstract 1338.

Schaller, E. L., M. E. Brown, H. G. Roe, and A. H. Bouchez (2006a), A large cloud outburst at Titan's south pole, *Icarus*, *182*, 224–229.

Schaller, E. L., M. E. Brown, H. G. Roe, A. H. Bouchez, and C. A. Trujillo (2006b), Dissipation of Titan's south polar clouds, *Icarus*, *184*, 517–523.

Schwingenschuh, K., G. J. Molina-Cuberos, H. U. Eichelberger, K. Torkar, M. Friedrich, R. Grard, P. Falkner, J. J. López-Moreno, and R. Rodrigo (2001), Propagation of electromagnetic waves in the lower ionosphere of Titan, *Adv. Space Res.*, *28*, 1505–1510.

Schwingenschuh, K., et al. (2007), Huygens in-situ observations of Titan's atmospheric electricity, *Geophys. Res. Abstr.*, *9*, 09326.

Simões, F., et al. (2007), A new numerical model for the simulation of ELF wave propagation and the computation of eigenmodes in the atmosphere of Titan: Did Huygens observe any Schumann resonance?, *Planet. Space Sci.*, *55*, 1978–1989.

Tokano, T., G. J. Molina-Cuberos, H. Lammer, and W. Stumptner (2001), Modelling of thunderclouds and lightning generation on Titan, *Planet. Space Sci.*, *49*, 539–560.

Zarka, P., B. Cecconi, L. Denis, W. M. Farrell, G. Fischer, G. B. Hospodarsky, M. L. Kaiser, and W. S. Kurth (2006), Physical properties and detection of Saturn's lightning radio bursts, in *Planetary Radio Emissions VI*, edited by H. O. Rucker, W. S. Kurth, and G. Mann, pp. 111–122, Austrian Acad. of Sci. Press, Vienna.

W. M. Farrell and M. L. Kaiser, NASA Goddard Space Flight Center, Greenbelt, Mail Code 695, MD 20771, USA.

G. Fischer, D. A. Gurnett, and W. S. Kurth, Department of Physics and Astronomy, University of Iowa, 203 Van Allen Hall, Iowa City, IA 52242, USA. (georg-fischer@uiowa.edu)

P. Zarka, Observatoire de Paris, F-92190 Meudon, France.