DETECTION CAPABILITY OF CASSINI FOR THUNDERCLOUD GENERATED LIGHTNING DISCHARGES ON TITAN

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Abstract

The formation of thunderclouds on Titan may be very rare due to the difficult methane condensation, but massive clouds may occasionally develop in the troposphere as is evident from recent telescopic cloud observations. A thundercloud model was developed taking into account specific conditions of methane condensation, clouds and lower ionosphere on Titan. Such clouds would rapidly attach a large amount of free electrons, which are common in Titan‘s troposphere due to the low abundance of electrophilic species such as oxygen. The entirely negative space charge in the cloud creates a temporary electric field that is sufficient to initiate cloud–to–ground lightning strokes close to the sub–solar point. Such lightning strokes on Titan could be comparable to so–called type 2 lightning strokes on Earth. In order to estimate the capability of the Cassini/RPWS (Radio and Plasma Wave Science) instrument to detect lightning discharges during several close flybys, we estimated the radiated energy of Titan lightning strokes and we show that the RPWS instrument should be able to detect electromagnetic signals from such strokes in a frequency range above 500 kHz or 1 MHz during its flyby.

1 Introduction

The likelihood of electric discharges in Titan's atmosphere has been discussed mainly from the viewpoint of organic chemistry. In analogy to the production of NO_x in the terrestrial troposphere by lightning [Borucki and Chameides, 1984], it has been suggested that some minor constituents found in Titan's atmosphere may be produced by electric discharges [Borucki et al., 1984]. There have been several laboratory experiments which investigated the formation of trace gases by electric discharges (glow, spark and corona

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discharge) [Borucki et al., 1988; Coll et al., 1995; Navarro–González and Ramírez, 1997; Fujii and Arai, 1999]. Due to the negative result of the Voyager 1 fly–by in 1980 [Desch and Kaiser, 1990] there has been no detailed theoretical study on lightning generation mechanisms on Titan. Titan's main condensate CH_4 is thought by some researchers [Rinnert, 1985; Navarro–González and Ramírez, 1997] as a poor candidate for lightning generation because of the low dielectric constant (polarisability). In recent years there has been considerable progress in the knowledge of Titan's lower atmosphere such as methane condensation [Samuelson and Mayo, 1997; Guez et al., 1997], the lower ionosphere [Molina–Cuberos et al., 1999a; 1999b; 2000; 2001], thermal structure [McKay et al., 1989] and atmospheric dynamics [Tokano et al., 1999]. The Cassini Mission with the descent of the Huygens Probe in early 2005 and numerous flybys of the Cassini Orbiter will give a good possibility for detecting possible lightning [Lammer et al., 2001].

2 Thundercloud generation on Titan

The most important requirements for the formation of convective clouds are the conditional instability of the atmosphere and the existence of some triggering mechanisms. Moist convection with formation of cumulus or cumulonimbus clouds is possible if the temperature lapse rate exceeds the moist adiabat, i.e. the atmosphere is conditionally unstable [McKay et al., 1997]. On Earth typical convection triggering mechanisms are forced lifting on mountains, cold fronts or intertropical convergence zones (ITCZ). Nothing is known about the presence of mountains on Titan and cold fronts are unlikely due to the lack of baroclinic instability, but the ITCZ seem to exist throughout the year near the equator, where the Hadley cells of both hemispheres come into contact [Tokano et al., 1999]. We suggest that in general strong convection is more likely on the day–side near the subsolar point, where the Solar input is larger.

The likelihood of condensation has been confirmed recently by the near–IR spectroscopic detection of tropospheric clouds with the UK Infra Red Telescope (UKIRT) in September 1995 by Griffith et al. [1998]. These clouds were located near 15 km altitude and covered about 9% of Titan's disk preferentially at low latitudes and were found occasionally. In a further study Griffith et al. [2000] found by the same method daily clouds in 1999. These clouds were not as large as those identified in September 1995, but they had common heights of 27 km and dissipated in about 2 hours. Re–analysis of Voyager 1's infrared spectral data by Courtin et al. [1995] could indicate that there were no extensive and thick clouds in Titan's troposphere during the flyby in November 1980.

Tokano et al. [2001] developed a thundercloud model, which is a one–dimensional (vertical) time–dependent convective cloud model including cloud electrification effects. It is based on the terrestrial thundercloud model of Tzur and Levin [1981], but was greatly modified for an application to Titan. The model domain extends from Titan's surface to an altitude of 50 km near the tropopause. The model solves a set of conservation equations to describe various atmospheric variables (vertical wind, temperature, mixing ratios of methane vapour, hydrometeors, free ions/electrons and electric charges). It takes into account convection, gravitational fall, condensation processes, turbulent mixing, entrainment of environmental air, charge transfer and resulting electrostatic force. In this model

the cloud formation begins at the condensation level at 12 km and proceeds to higher levels. The cloud top reaches an altitude of 28 km a few minutes after the start. This altitude is close to the cloud top altitude of 27 km determined by Griffith et al. [2000].

3 Thundercloud electrical structure

Electrons and ions begin to diffuse into cloud particles immediately after the formation of the cloud [Tokano et al., 2001] and due to the high electron mobility the electron attachment to the cloud is much faster than the electron production by cosmic rays, which reduces the electron concentration within the cloud to almost zero. Thus, cloud particles play a similar role as gaseous electrophilic species in reducing the concentration of electrons. The maximum charging rate due to this electron diffusion turns out to be 5×10^{-11} C m^{-3} s^{-1} for small droplets, 2×10^{-13} C m^{-3} s^{-1} for raindrops and 5×10^{-16} C m^{-3} s^{-1} for graupels [Tokano et al., 2001]. These values appear realistic considering that the maximum charging rate of raindrops due to ion diffusion is 4×10^{-17} C m^{-3} s^{-1} in the terrestrial model of Tzur and Levin [1981] and the electron mobility is 10^4 times higher than that of small ions. The electrical conductivity within the cloud is about three orders of magnitude smaller than outside the cloud. For instance at 15 km altitude the conductivity is only roughly 10^{-15} S m^{-1} [Tokano et al. 2001]. A low conductivity and low ion concentrations are observed in terrestrial thunderclouds, too [Chiu, 1978]. The cloud is entirely negatively charged due to this attachment of electrons.

Figure 1 shows the evolution of several variables for the convective charging mechanism within the cloud at an altitude of 15 km [Tokano et al., 2001]. In the first minutes the ion and electron concentrations fall to a very small level, but later (especially from $t = 200$ min. on) the cation concentration n_p increases and exceeds the initial value by several factors, while the anion and electron concentration, n_m and n_{el}, further decrease. This development in the simulation is primarily caused by the reduction of n_{el} due to the electron attachment to cloud particles. The abrupt begin of the n_p increase at $t = 200$ min is due to the restart of the ion/electron diffusion, which lowers the electron concentration.

As already mentioned the cloud rapidly attaches free electrons which are highly abundant due to the low abundance of gaseous electrophilic species, and will be negatively charged. As the electron diffusion to the cloud begins, a rapid development of the electric field strength is observed. This vertical distribution of the space charge density Q causes a steep increase of the electric field from the cloud base up to about -2.5×10^6 V m^{-1}, which is approximately the breakdown field. In other words, in case of moist convection the rapid electron attachment by itself would temporarily cause such a strong electric field that lightning may be initiated. One might ask whether lightning is at all possible with no positive charge centre or polarity within the cloud. It is possible that the conducting surface of Titan beneath the charged cloud will get positively charged due to the electrostatic influence, and so a polarity would be found between the cloud and Titan's surface and not between the upper and lower regions of the cloud. So we expect that on Titan negative cloud–to–ground discharges should occur in order to neutralize the polarity by transporting negative charge to the ground. According to the simulated vertical charge and electric field distribution the lightning stroke should have a mean length of about

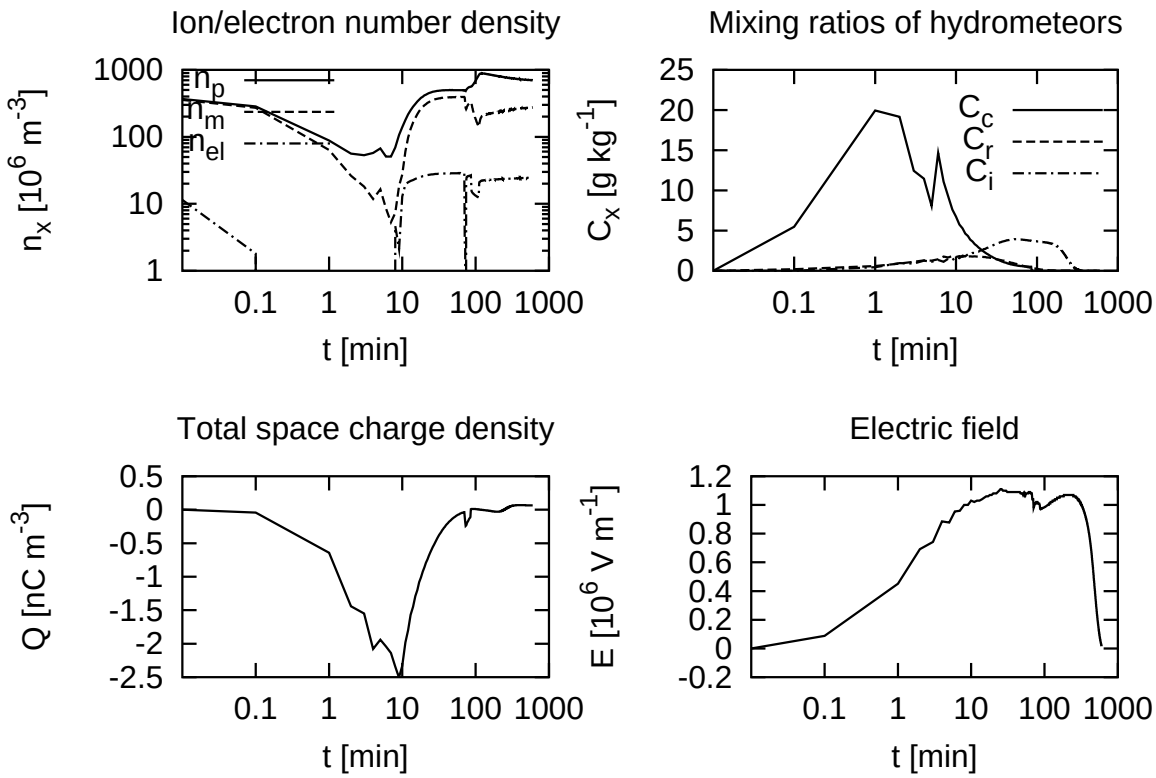

Figure 1: Time evolution of the cloud structure at 15 km altitude for the convective charging mechanism. The number densities of cations n_p, anions n_m and electrons n_{el}, mixing ratios of cloud droplets C_c, raindrops C_r and graupels C_i, the total space charge density Q and the amount of the vertical electric field $|E|$ are shown [from Tokano et al., 2001].

20 km [Tokano et al. 2001]. On the other hand, intracloud discharges (K–strokes), which are very common on Earth [Uman, 1987], would not be possible because there is no dipolar structure within the cloud. The occasional and sudden character of Titan's clouds is one key factor for the detection of Titan's possible lightning signals. We suggest that Titan lightning may occur under very favourable circumstances in extensive tropospheric clouds near the subsolar point, although the lightning frequency might be very low compared to Earth.

4 Characteristics of possible Titan lightning

Electric currents within lightning channels during return strokes (R–strokes) and intracloud strokes (K–strokes) are the main sources for the generation of impulse–type electromagnetic radiation on Earth. A lightning R–stroke is a discharge within a basically vertical channel in which excessive electrons deposited within the channel during the leader process are drained to the planetary surface [e.g. Volland, 1982a, 1995]. Bruce and Golde [1941] have described the temporal variation of the electric current I at the ground

$z = 0$ of an R–stroke with the following mathematical expressions:

$$I = I_{\alpha,\beta}\left(e^{-\alpha t} - e^{-\beta t}\right) \tag{1}$$

or:

$$I = I_{\gamma,\delta} 2sin\left(\delta t\right) e^{-\gamma t} \tag{2}$$

where $I_{\alpha,\beta}$ and $I_{\gamma,\delta}$ are the current amplitude factors, t is the time and α, β, γ and δ are eigenvalues derived from the LCM (lumped circuit model) specific eigenvalue equation [Volland, 1982a, 1982b]. The eigenvalues may be real or complex numbers, depending on the electrical conductivity σ, the diameter d and the length l of the lightning channel. The conductivity σ inside the lightning channel is about 10^4 Sm^{-1} [e.g., Volland, 1982a, 1982b; Uman, 1987; Volland, 1995]. Since the Earth and Titan atmospheres are very similar it should be justified to assume that the conductivity σ in the lightning stroke channel on Titan should also be in the same order. Generally the α, β regime (type 1 strokes) is related to aperiodic variations and the γ, δ regime (type 2 strokes) is related to damped oscillations of the current and the radiation fields.

Lightning strokes dissipate energy and a certain part of this energy is radiated as electromagnetic waves to the far field:

$$W_{rad} = \frac{2\mu_0\alpha^2\beta^2Q^2l^2}{3\pi^3c(\alpha+\beta)} \tag{3}$$

$$W_{rad} = \frac{\mu_0(\gamma^2+\delta^2)^2l^2Q^2}{3\pi^3c\gamma} \tag{4}$$

where μ_0 is the permeability of free space, l is the length of the lightning channel, c the speed of light and Q the lowered charge. A typical lightning stroke on Earth has a length of 8 km and a channel diameter of 1.5 cm. The visible part of such an R–stroke channel is typically about 5 km and the rest may be hidden within the cloud or there could also be a significant horizontal branch. Interestingly there are also cloud–to–ground lightning R–strokes on Earth which are called type 2 strokes since they have longer and wider lightning channels with a length l of about 19 km and a diameter d of about 4.5 cm. Table 1 shows typical parameters for observed type 1 and type 2 R–strokes on Earth [Volland, 1982a]. It is important to note that Titan's atmospheric composition and pressure are comparable to the Earth atmosphere, therefore the parameters of type 2 strokes on Earth (electric charge, diameter, channel conductivity) may be comparable with cloud–to–ground lightning strokes on Titan. As the channel length for possible Titan lightning should be about 20 km [Tokano et al., 2001], we can calculate possible radiated energies taking into account the variation of other lightning parameters (channel diameter and charge). Table 1 shows these parameters for possible Titan lightning with a channel length of 20 km, a lowered charge of -0.5, -1.0 or -1.5 As and a diameter of 1.6 or 4.5 cm.

Volland [1982a] showed that type 2 strokes on Earth have the same f^{-2} dependence above f_0 than type 1 R–strokes. The frequency f_0 denotes the frequency of maximal spectral energy: As the lightning can be assumed to radiate like a quarter–wave antenna, this frequency is about 10 kHz for typical Earth lightning with a channel length of 8 km and

Table 1: Parameters of observed cloud–to–ground lightning strokes on Earth (first two rows) and calculated possible Titan lightning parameters (rest of the table with channel length of 20 km): α, β, γ and δ are the eigenvalues of the lumped circuit model, Q is the total charge in the lightning stroke channel, l is the length and d the diameter of the lightning channel and W_{rad} the emitted electromagnetic energy to the far field. Lightning channel conductivity σ is 10^4 Sm^{-1}.

α[Hz]	β[Hz]	γ[Hz]	δ[Hz]	Q[As]	l[km]	d[cm]	W_{rad}[kJ]
2.0E+04	2.0E+05	–	–	-1.35	7.9	1.55	740
–	–	1.2E+04	2.3E+04	-0.49	18.7	4.56	143
3.5E+03	2.0E+05	–	–	-0.5	20.0	1.6	22
3.5E+03	2.0E+05	–	–	-1.0	20.0	1.6	87
3.5E+03	2.0E+05	–	–	-1.5	20.0	1.6	195
–	–	1.3E+04	2.1E+04	-0.5	20.0	4.5	129
–	–	1.3E+04	2.1E+04	-1.0	20.0	4.5	516
–	–	1.3E+04	2.1E+04	-1.5	20.0	4.5	1160

4 kHz for possible Titan lightning with a channel length of 20 km. We suggest that the frequency dependence should be similar to Earth and so the spectrum of the radiated energy is approximately constant at low frequencies and falls off as f^{-2} above $f_0 = 4$ kHz [Uman, 1987; Volland 1982b; Grard et al., 1995].

$$W_f = W_0 = const \qquad 0 \leq f \leq f_0 \tag{5}$$

$$W_f = W_0 \left(\frac{f_0}{f}\right)^2 \qquad f_0 \leq f \leq \infty \tag{6}$$

$$W_0 = \frac{W_{rad}}{2f_0} \tag{7}$$

With these equations we can calculate the spectral energy W_f at a certain frequency f larger than f_0.

5 Propagation of electromagnetic waves through Titan's atmosphere

Knowledge about Titan's ionospheric layers is important for the investigation of the propagation of electromagnetic waves caused by lightning discharges in its atmosphere. The upper ionospheric profile on Titan is produced by Solar photons and electron precipitation from Saturn's magnetosphere [Keller et al., 1992; Gan et al., 1992]. Grard [1992] and Grard et al. [1995] described a micrometeorid produced ionospheric layer at an altitude of about 500 km. Recently Molina–Cuberos et al. [2001] have investigated in detail the ablation of micrometeorites and the ionization of metallic ions in Titan's atmosphere. They modeled the ion–neutral chemistry of metallic ions and found that long–lived metallic ions considerably change the electron density profiles of the models which only consider Solar

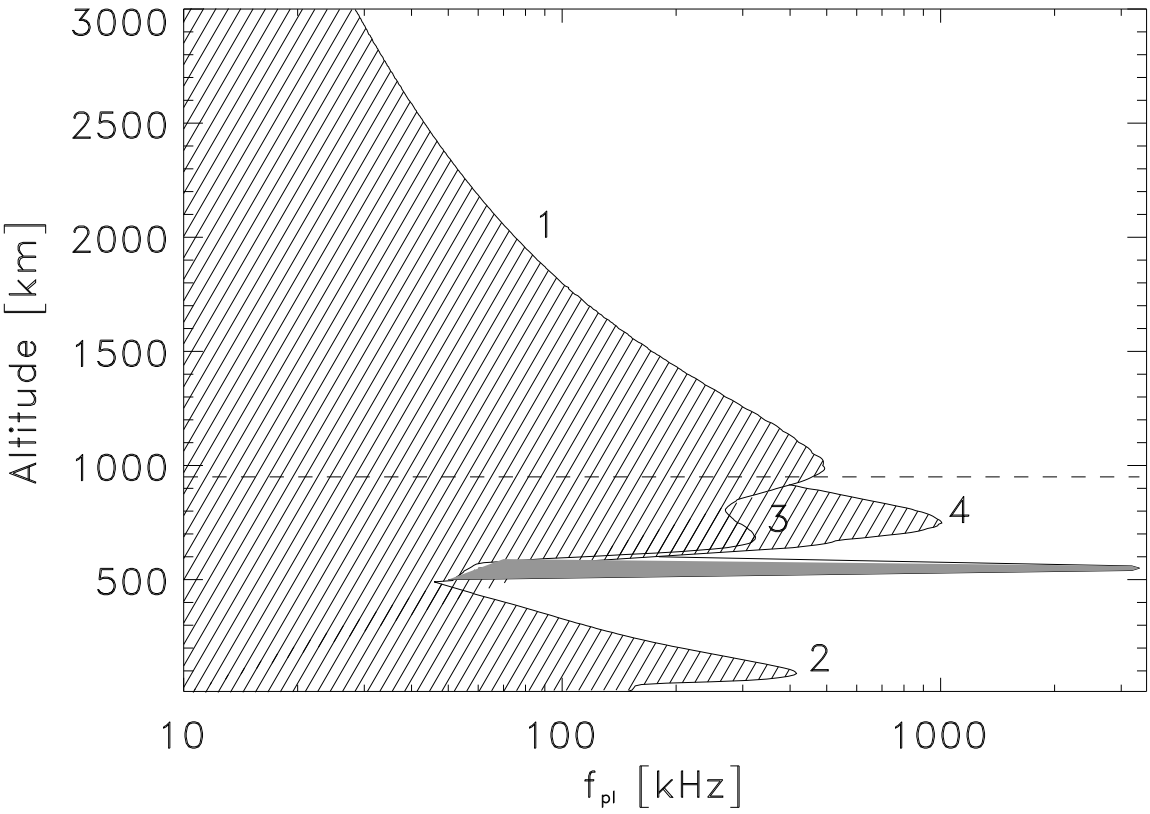

Figure 2: Plasma frequency f_{pl} in Titan's atmosphere as a function of altitude. The plasma frequency is calculated by using the electron density profiles caused by Solar radiation (1), galactic cosmic rays (2) and micrometeorites of Molina–Cuberos et al. [2001]. The dashed horizontal line shows the flyby altitude during Cassini's closest approach at 950 km altitude, which is lower than the upper ionospheric maximum. The hatched area illustrates regions where the propagation of electromagnetic waves is impossible. The ionization layer, caused by micrometeorites has a cutoff frequency at about 500 kHz, if atmospheric plasma transport processes are neglected (3), or 1 MHz if transport processes are included (4). But both profiles are much more transparent than the early estimates of about 3.5 MHz by Grard et al. [1995], which is indicated by the small shaded peak. From Lammer et al., [2001].

radiation and electrons trapped in the magnetosphere of Saturn. Molina–Cuberos et al. [2001] concluded that an ionospheric layer caused by micrometeorites should be present at around 650 km with an electron density peak of 1000 cm^{-3}. The electron density of this layer is at least 2 orders of magnitude smaller than that suggested by Grard [1992] and of similar magnitude as the one produced by Solar radiation at 1000 km altitude or by galactic cosmic rays at 90 km.

Figure 2 shows the plasma frequency f_{pl} in Titan's atmosphere as a function of altitude. The main barriers for electromagnetic waves propagating through Titan's atmosphere are the ionospheric layers caused by cosmic rays in the lower atmosphere and the layer caused by Solar radiation in the upper atmosphere. One can see from Figure 2 that these layers have cutoff frequencies of about 500 kHz. It is known from the Voyager flybys that

Titan has no intrinsic magnetic field and the field lines from the Saturn magnetosphere penetrate only to the ionopause in the upper atmosphere [Neubauer et al., 1984]. We therefore expect that signals in the whistler mode would not propagate through the three ionospheric layers as shown in Figure 2 and do not come in contact with Saturn's magnetic field lines inside Titan's lower atmosphere.

6 Detection capability of lightning signals with the Cassini/RPWS instrument

The Cassini RPWS instrument is designed to study radio emissions, plasma waves and thermal plasma in the Saturn system [Gurnett et al., 2001b]. Three nearly orthogonal electric field antennas are used for detecting electric fields over a frequency range between 1 Hz and 16 MHz. The search for lightning bursts above 500 kHz requires the use of the RPWS High Frequency Receiver (HFR), which has two modes HF1 and HF2. HF1 provides measurements over a frequency range from 125 kHz to 4.125 MHz in n×25 kHz steps. The second receiver HF2 provides measurements over a frequency range from 125 kHz to 16.125 MHz in n×50 kHz steps. Both have a bandwidth Δf of 25 kHz. The receiver integration times Δt for HF1 and HF2 are: 20, 40, 80, 160 ms and 10, 20, 40 and 80 ms [Gurnett et al., 2001b].

A lightning flash is made up of various discharge components, among which are typically two, three or four high–current pulses or R–strokes and so the total lightning flash has a duration up to 500 ms. In a negative cloud–to–ground lightning discharge, a so–called stepped leader stroke initiates the first R–stroke, in a flash propagating from the cloud to ground in a series of discrete steps [Uman, 1987]. The stepped leader itself is initiated by a preliminary breakdown within the cloud, if the established electric field is in the order of 2 to 3×10^6 Vm^{-1}. Each R–stroke lasts only several tens of μs. The separation time between the R–strokes is typically several tens of ms. The total flash time is long compared to the time of a single R–stroke, but the time where a lightning stroke emits W_{rad} is comparable to the stroke time of several tens of μs. We have estimated the radiated energy for one single lightning stroke and not for a whole flash, which on Earth consists of multiple lightning strokes multiplying the total radiated energy. If there would be more than one single Titan lightning stroke within the Cassini HFR integration time the radiated energy gets higher which makes the detection easier.

The nominal sensitivity E_0^2 for the RPWS/HF2 receiver is $\approx 4\times10^{-18}$ V^{2}m^{-2}Hz^{-1} [Gurnett et al., 2001b]. The signal threshold E of the receiver is:

$$E^2 = E_0^2 \Delta f \tag{8}$$

By using a Δf of 25 kHz, the threshold E for the detection of Titan's lightning signal is $\approx 0.3\ \mu$ Vm^{-1}. The relation between the signal threshold E, the receiver integration time Δt and the spectral energy W_f is:

$$E = \sqrt{\frac{Z_0 W_f \Delta f}{2\pi r^2 \Delta t}} \tag{9}$$

where r is the distance from the radiation source to the receiver and Z_0 is the impedance of free space (120 π Ω). Figure 3 shows the detectability of a Titan lightning stroke for a

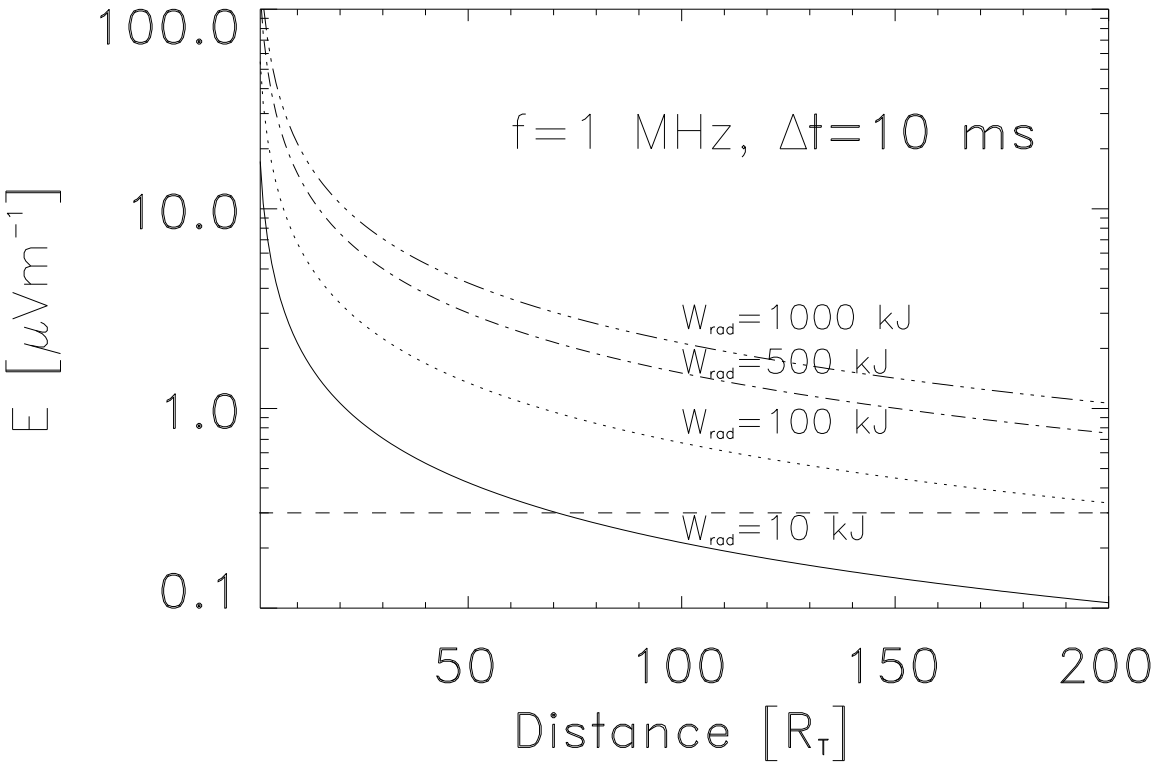

Figure 3: Signal threshold strength E as a function of distance in Titan radii for a frequency f of 1 MHz, a receiver integration time Δt of 10 ms and a frequency resolution Δf of 25 kHz. The spectral energy W_f corresponds to 4 different radiated energies W_{rad} of 10 kJ (solid line), 100 kJ (dotted line), 500 kJ (dashed–dotted line) and 1000 kJ (dashed–dotted–dotted line), which are calculated with $f_0 = 4$ kHz, $f = 1$ MHz with the equations (5) to (7). The dashed horizontal line indicates the signal threshold strength of 0.3 $\mu V m^{-1}$ of the Cassini/RPWS HF2 [from Lammer et al., 2001].

frequency f of 1 MHz, a receiver integration time Δt of 10 ms and for a variation of the total radiated energy from 10 kJ to 1000 kJ. The receiver signal threshold of the Cassini HF2 is indicated by the horizontal dashed line. Note that even for the low value of 10 kJ, the signal should still be detected by Cassini/RPWS within a distance of 70 Titan radii. It is clearly shown, that if the radiated energy is higher, the detection capability gets much better.

Since the lightning flash rate might be low it is important to have long observation times. We therefore analyzed all Cassini trajectories of Titan close flybys and found that the spacecraft would have the opportunity to observe Titan's dayside within 100 Titan radii for more than 12 hours. From our point of view the search for Titan electric discharges can be performed at all flybys at those times when Cassini is at Titan's dayside.

7 Conclusion

We showed in our study that cloud–to–ground lightning strokes resulting from the thundercloud model of Tokano et al. [2001] should be associated only with regions of strong convection near Titan's subsolar point where the Solar energy input is large. Possible Titan lightning strokes with a stroke length l of about 20 km should be comparable with so–called type 2 cloud–to–ground lightning strokes on Earth. Our study indicates that representative lightning strokes on Titan should radiate their maximum electromagnetic energy to the far field of about 100 kJ at a frequency of about 4 kHz. The RPWS instrument on board of Cassini should be able to detect electromagnetic signals above the ionospheric cutoff frequencies of about 500 kHz or 1 MHz depending on the ionospheric plasma density caused by micrometeorites, performed by the High Frequency Receiver, if a low integration time ($\Delta t \leq 20$ ms) is chosen and a flash occurs during the observational phase.

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