Study of solar system planetary lightning with LOFAR

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Abstract

Radio signatures of lightning discharges have been detected by the Voyager spacecraft near Saturn and Uranus up to 40 MHz. Corresponding flux densities at the distance of the Earth are up to 1000 Jansky (Jy) for Saturn (≥ 1 event per minute above 50 Jy, with 30–300 ms duration) and up to a few tens of Jansky for Uranus. Low Frequency ARay LOFAR will allow us to detect and monitor the lightning activity at these two planets. Imaging will allow us to locate lightning sources on Saturn’s disk (even if with moderate accuracy), which could then be correlated to optical imaging of clouds. Such observations could provide new information on electrification processes, atmospheric dynamics, composition, and geographical and seasonal variations, compared to the Earth. In addition, lightning may play a role in the atmospheric chemistry, through the production of non-equilibrium trace organic constituents potentially important for biological processes. LOFAR observations can also help us to assess the existence of lightning at Neptune (marginally detected by Voyager), at Venus (where their existence is very controversial), and at Mars (possibly resulting from dust cloud charging). At Jupiter, low-altitude ionospheric layers of meteoritic origin and/or intrinsically long discharge duration seem to prevent the emission and escape of high-frequency radio waves associated with lightning. LOFAR thus presents good possibilities for the detection and study of solar system planetary lightning; we also discuss its relevance to bring new information on Terrestrial lightning-related upper atmosphere transient phenomena (sprites, TIPPs…). Instrumental constraints are outlined.

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1. Introduction

Atmospheric lightning is a transient, tortuous high-current electro-static discharge that occurs when large quantities of electric charge of opposite sign are separated over macroscopic distances (typically a few kilometers). In the chain of atmospheric processes leading to lightning, small-scale particle electrification intervenes first through collisions and charge transfer, followed by large-scale charge separation, resulting e.g. from the competition of upwards convection and gravitation. This results in the build-up of a large-scale electric field. When the amplitude of this electric field becomes larger than a critical value (breakdown field) which depends on the atmospheric pressure and composition, the energy gained by an electron over its mean free path between collisions becomes larger than the energy threshold for ionization of the intervening medium. The medium is thus ionized through a cascade of collisions, and a high-intensity current circulates to neutralize the electric field. This phenomenon is a lightning stroke, through which the stored energy is released. A lightning flash consists of many consecutive strokes. Quantitative details on these processes can be found in Uman (1987) and Gibbard et al. (1997, 1999).
Planetary lightning has been searched for and eventually studied mostly from space since 1978–1979. Russell (1991) reviews the observations at Venus by the Venera probes and the Pioneer Venus Orbiter. Desch (1992) reviews the observations at the giant planets by the Voyager 1 and 2 spacecraft. Inferred characteristics as flash rates, energy dissipation rates, and (non-)detection in various wavelength ranges have been compared for all solar system planets by Desch (1992), Russell (1993), and Zarka et al. (1995).

The interest in studying planetary lightning comes from the fact that (i) they play a role in the atmospheric chemistry, through the production of non-equilibrium trace organic constituents potentially important for biological processes (Miller, 1953), (ii) they are a signature of atmospheric dynamics and cloud structure (e.g. the absence of Venus lightning—see below—could be related to the inhibition of vertical convection by the dominant horizontal super-rotation), and (iii) they allow comparative studies of electrification processes (Rinnert, 1985).

Lightning discharges produce various electromagnetic waves:

- optical emission due to intense heating of the lightning channel;
- high-frequency (HF) radio emission up to a few tens of megahertz originating from the current channel acting as an antenna;
- very low-frequency (VLF) plasma waves below a few tens of kilohertz on the whistler mode, showing a characteristic time–frequency dispersion (Helliwell, 1965).

Of those various electromagnetic waves, HF radio emissions are the most susceptible to be detected from a distance of several AU. VLF plasma waves are ducted by magnetic field lines and density gradients and are thus constrained to remain within a few planetary radii from their source. Optical emission is generally masked by reflected/scattered sunlight from the dayside atmosphere (observation from the Earth gives only access to the dayside hemisphere, except for Venus) and from the rings (if any). Another source of “optical noise” comes from the emissions that can be excited by particle precipitations in planetary atmospheres (aurora, dayglow, electroglow). As a consequence, optical flashes have been positively identified at Jupiter only through spacecraft measurements performed close to the planet (see Desch et al., 2002 and references therein). Tentative optical detections of Venusean flashes from Venera 9 spacecraft as well as from the Earth-based telescopes have been reported (Hansell et al., 1995; Grebowsky et al., 1997), but they remain controversial (high false-alarm rate, no optical detection by the Pioneer-Venus Orbiter star sensor).

By contrast, HF radio emission from lightning, provided that it may propagate through the planetary ionosphere without strong attenuation, can be detected at large distances and suffers little competition from other planetary radio sources in the spectral range from a few megahertz to a few tens of megahertz. We know at least three planets where lightning does exist and produce HF radio emission that has been observed from large distances: the Earth (Gurnett et al., 2001), Saturn (Warwick et al., 1981), and Uranus (Zarka and Pedersen, 1986).

Fig. 1 illustrates the detection from a distance of a few planetary radii by the Voyager 1 Radioastronomy experiment (Warwick et al., 1977) of sporadic radio bursts associated to Saturnian and Uranian lightning initially named SED for Saturn’s Electrostatic Discharges and UED for Uranus’ Electrostatic Discharges. In both cases, the emission extends to the highest frequency of the receiver, 40 MHz. Fig. 2 compares the spectra of SED and UED with those of various planetary and solar radio emissions. Above ~1 MHz, only Jovian and solar radio bursts are in the band to compete with the lightning signals.

In Section 2, we examine in more details the radio spectrum produced by a lightning stroke, which depends on its temporal characteristics. Then observations and models of lightning radio emission at all planets and at Titan are presented in Section 3. In Section 4, lightning radio spectra are compared to the sensitivity of a large radio telescope like LOFAR. Section 5 deals with the

![Fig. 1](image-url)
time profile (Bruce and Golde, 1941; Farrell, 2000). Electromagnetic theory predicts that for a current channel in straight line, the distant radiated electric field spectrum will decrease in \( f^{-2} \) above the peak and thus the power spectrum in \( f^{-4} \) (LeVine and Meneghini, 1978a). Current channel tortuosity, however, flattens this spectrum so that it should be \( \sim f^{-2} \) at intermediate frequencies up to several MHz (LeVine and Meneghini, 1978b). The peak frequency \( f_{\text{peak}} \) directly reflects the characteristic time \( \tau \) of the stroke (\( f_{\text{peak}} \sim \tau^{-1} \)).

In the literature on planetary lightning, measurements or estimates of the emitted power are often given as total electric field \( E_{\text{tot}} \) in V/m at distance \( R \) from the source. For a power spectrum \( S(f) \propto E^2(f) \) varying as \( K/f^n \) \((n>1)\), between a minimum frequency \( f_{\min} \) and a maximum frequency \( f_{\text{max}} \gg f_{\min} \), we have

\[
E_{\text{tot}}^2 = \int_{f_{\min}}^{f_{\text{max}}} Kf^{-n} \, df \approx (n-1)Kf_{f_{\min}}^{-n},
\]

thus,

\[
K \approx \frac{E_{\text{tot}}^2f_{f_{\min}}^{n-1}}{n-1}.
\]

The flux density \( S(f) \) (in \( \text{Wm}^{-2}\text{Hz}^{-1} \)) at distance \( r \) can thus be estimated as

\[
S(f) \approx \frac{E_{\text{tot}}^2f_{f_{\min}}^{n-1}}{Z_0(n-1)f^0} \left( \frac{4\pi R^2}{4\pi r^2} \right),
\]

with \( Z_0 \) the impedance of free space \((Z_0 = (\mu_0/\varepsilon_0)^{1/2} = 120\pi = 377\ \Omega)\). To get an order of magnitude of the HF radio emission spectral power from lightning, we can assume that \( f_{\min} \sim f_{\text{peak}} \sim \tau^{-1} \). This implies an error smaller than a factor 2 on \( S(f) \) (a factor of 2 corresponds to the case when the spectrum has a constant level from \( f_{\min} = 0 \) to \( f_{\text{peak}} \) (Lammer et al., 2001)). If the radio spectrum decreases in \( f^{-2} \) above \( f_{\text{peak}} \), the flux density becomes simply

\[
S(f) \approx \frac{E_{\text{tot}}^2f_{\text{peak}}}{Z_0f^2} \left( \frac{R^2}{r^2} \right).
\]

### 2. High-frequency radio spectrum

A lightning flash consists of several strokes over a total duration of a few to a few tens of milliseconds. At the Earth, HF radio emission is produced in a broad spectrum peaking at \( \sim 1-10 \text{kHz} \) and decreases as \( \sim f^{-2} \) at higher frequencies. Actually, the typical spectrum of cloud-to-ground lightning is flatter than \( f^{-2} \) up to a few times \( f_{\text{peak}} \), then in \( \sim f^{-3} \) up to several megahertz, and steeper (\( \sim f^{-4} \)) at still higher frequencies. This spectrum shape is a direct consequence of the stroke duration and detection of radio emission of transient phenomena that occur in the upper atmosphere of the Earth in relation to lightning. Instrumental requirements for optimal lightning radio detection are discussed in Section 6.

### 3. Radio emission from planetary lightning

In this section, we review radio observations of planetary lightning, as well as model estimates when no radio emission was observed. From these, we derive in each case ranges for the radio flux density spectrum that would be received on Earth, independent of any consideration of the possibility to actually detect this flux. The latter, which depends on instrumental sensitivity and on the various noise sources present, is discussed in Section 4.
3.1. Observations

3.1.1. Saturn

The first positive detection of a HF radio emission associated to extraterrestrial lightning occurred in Saturn, where unexpected sporadic spikes of radio emission were discovered by Voyager 1 in 1980 (Fig. 1) (Warwick et al., 1981). They were studied with observations from both Voyagers over the Saturn flybys of 1980 and 1981. Prior to understanding their atmospheric origin (Kaiser et al., 1983), these spikes were named SED for “Saturn Electrostatic Discharge”.

SED displayed an occurrence of a few events per minute variable over the 9-month period separating the flybys by Voyager 1 and 2, a typical duration between 30 and 300 ms per event, a broadband spectrum slowly decreasing from ~20 to >40 MHz, with a typical instantaneous spectral power between 0.1 W/Hz and 300 W/Hz (Zarka and Pedersen, 1983; Zarka, 1985a,b). These spectral powers correspond to flux densities between ~0.4 and 1000 Jy (1 Jy = 10^{-26} W m^{-2} Hz^{-1}) at the Earth typical source–observer distance ~10 AU.

Close examination of the SED spectrum (Fig. 13 of (Zarka and Pedersen, 1983)) suggests that it is flat below 10–20 MHz and then decreases with a slope between f^{-1} and f^{-2} at higher frequencies. This suggests a characteristic stroke duration of about 50–100 ns. The spectrum described above is sketched in Fig. 2. During the Voyager 1 flyby, at least 1 event per minute was detected with a duration longer than 30 ms and a flux density corresponding to >50 Jy at the Earth; about ~10 events per minute had a flux density corresponding to >5 Jy at the Earth. An unsuccessful attempt to detect SED with the Nançay decimeter radiotelescope at f = 1420 MHz confirmed that the spectrum must be steeper than f^{-1} above 40 MHz (Lecacheux and Biraud, 1984).

3.1.2. Uranus

Broadband radio spikes similar to SED were detected by Voyager 2 during its encounter with Uranus in 1986 (Zarka and Pedersen, 1986). A sample dynamic spectrum is displayed in Fig. 1. These spikes named UED had an occurrence rate much lower than SED, about 7 events per hour, a comparable duration of 30–250 ms per event. Their spectrum, also sketched in Fig. 2, is steeper than that of SED, approximately ~f^{-2} (flatter below 20 MHz, much steeper above 35 MHz). They also had a weaker spectral power (a few W/Hz) corresponding to a flux density between ~0.4 and 40 Jy at the Earth (typical source–observer distance ~20 AU).

Over the ~1-day close encounter period, a total of 8 events were detected at ~15 MHz with a duration longer than 30 ms and a flux density corresponding to >5 Jy at the Earth. Three events were detected between 25 and 35 MHz with a flux density corresponding to >2.5 Jy at the Earth. No observations of Uranus lightning exist other than those made by Voyager 2.

3.1.3. Neptune

At Neptune, only 4 weak events presenting characteristics similar to SED and UED were detected by Voyager 2 during the flyby (Kaiser et al., 1991). However, dispersed whistlers were also detected near the planet, supporting evidence for atmospheric lightning (Gurnett et al., 1990).

The intensity of the 4 radio events, normalized to a distance of 25000 km (one planetary radius) ranged from 9.9 × 10^{-18} W m^{-2} Hz^{-1} at 18 MHz to 1.1 × 10^{-18} W m^{-2} Hz^{-1} at 31 MHz. This corresponds to a spectrum of f^{-4}. Scaled to a source–observer distance of ~30 AU, these numbers correspond to flux densities of 0.03–0.003 Jy at Earth. The duration of the 4 events ranges from 30 to 90 ms.

3.2. Upper limits and models of unobserved radio emission

3.2.1. Jupiter

No HF radio emission from lightning was detected at Jupiter by any visiting spacecraft (Voyagers, Galileo, and Cassini), except for the search coil on the Galileo descent probe which recorded below the ionosphere signals attributed to lightning up to 90 kHz (Lanzerotti et al., 1996). Nevertheless, we have strong evidence for the presence of lightning there: optical flashes were observed by Voyager, Galileo, and Cassini and low-frequency whistlers were detected by the Voyagers (see Cook et al., 1979; Gurnett et al., 1979; and the review by Desch et al., 2002, and references therein). Two explanations have been proposed for the non-detection of Jovian lightning in the HF radio range:

- Zarka (1985c) demonstrated that the low-altitude ionospheric layers discovered by Pioneer 10 and 11 would cause very strong absorption (several tens of dB attenuation) of radio waves generated in the atmosphere. These low-altitude ionospheric layers, with electron concentrations above 10^5 cm^{-3} at an altitude of a few hundred km above the 1 bar level, possibly have a (micro-)meteoritic origin;
- Farrell et al. (1999a) conversely proposed, on the basis of electric field measurements performed in Jupiter’s atmosphere by Galileo’s descent probe, that Jovian lightning discharges could have much longer time constants than their Terrestrial or Saturnian counterparts: a rise time of a few milliseconds at Jupiter versus tens of microseconds (Earth) to tens of nanoseconds (Saturn). The reason for these possibly “slow” lightning strokes at Jupiter is not known. They would imply radio emission spectra restricted to very low frequencies, well below Jupiter’s ionospheric
cutoff frequency. Similar slow rise times have been observed for cloud-to-ionosphere discharges (sprites) recently discovered on Earth (Sentman et al., 1995). These latter emissions are discussed in Section 5.

Following Zarka (1985c), we may estimate the radio spectrum of Jovian lightning from that of SED scaled for the different source-observer distance (∼5 AU) and for ionospheric attenuation. Comparative tables in Zarka (1985c; Zarka et al. 1995); and Desch (1992) show that Jovian lightning has energies similar or slightly lower (by a factor ∼4) than Saturnian lightning. Values for ionospheric attenuation lie between 25 dB (on the nightside) and 90 dB (on the dayside). Combining these factors, we obtain for Jovian lightning an SED-like spectrum reduced by 25–75 dB. This places the spectral peak of about 500 Hz, and including ionospheric attenuation (42 dB), these authors estimated the source. Then applying Eq. (3) with \( E_{f_{max}} = 0.05 \) or \( E_{f_{max}} = 0.01 \), we obtain for Jovian lightning an SED-like spectrum reduced by 25–75 dB. This places the spectral peak of about 500 Hz, and including ionospheric attenuation (42 dB), these authors estimated the background spectrum of Fig. 2.

3.2.2. Venus

On Venus, the existence of lightning has remained controversial for more than 2 decades. Russell (1991, 1993) summarized the pros (tentative optical or radio detections) and cons (possible spurious origin of these detections) for observational evidence of Venuvian lightning. During the two recent close-range flybys of Venus by Cassini in 1998 and 1999, the very sensitive radio receiver (RPWS) onboard the spacecraft detected no statistically significant lightning signal, while it recorded hundreds of lightning radio spikes during the Earth flyby in 1999, up to 40 dB above the detection threshold (Gurnett et al., 2001).

It was concluded that Venus lightning are either extremely rare or very weak. In the former case, the flash rate should be \( \ll 1 \) flash/h, i.e. still much lower than the rate tentatively inferred by Hansell et al. (1995). In the latter case, they must be at least 100 times weaker than their Terrestrial counterparts. They might also have a very steep spectrum at high frequencies, as proposed for Jupiter’s lightning (slow strokes). Total absence of lightning at Venus could be due to a very low vertical convection inhibited by the strong horizontal atmospheric circulation at this planet.

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3.2.3. Mars

Although no lightning has ever been detected on Mars, dust charging and substantial electric field build-up is not excluded (Farrell et al., 1999b). Specifically, large-scale dust storms and “dust devils” (localized dust storms) can generate substantial charge via triboelectric (contact electrification) processes (Eden and Vonnegut, 1973). When grains of differing compositions and sizes are in contact, they exchange charge in order to maintain a common surface potential energy (see e.g. Melnik and Parrot, 1998). Laboratory experiments indicate that smaller grains tend to become negatively charged and larger grains positively charged (Ette, 1971). In convecting dust storms with substantial vertical pressure gradients (vertical winds), the smaller (−) grains tend to be lofted upward relative to the larger (+) grains, generating a large vertical potential difference and macroscopic electric dipole moment.

Recent desert tests in Arizona and Nevada verified this electric dipole moment with electric fields within modest-sized (∼10–30 m wide) dust devils reaching...
20 kV/m (Farrell et al., 2003, 2004). The electrostatic energy density in these localized storms can exceed $10^{-4}$ J/m$^3$ (Farrell et al., 2004). Given a similar energy density in the larger Martian dust storms, which can be regional/global and 10 km in height, an atmospheric dust-loaded electrical energy of $10^{14}$ J might be present during the dust storm season. This planetary electrostatic energy is comparable to that found in over 100 terrestrial thunderstorms.

Given this anticipated electrical energy, discharge and radiation is expected. However, the exact nature of the discharge (time scale, current flow, spatial size) is unknown. Because of the lower atmospheric pressure on Mars, the atmospheric breakdown voltage is about $10^6$ V/m and the Martian discharge may take the form of a near-continuous mildly ionized coronal glow discharge (Eden and Vonnegut, 1973). On Mars, dust devil fluid forces would generate well-separated charge centers but “leakage” currents in the form of this corona would attempt to dissipate the centers thereby limiting their maximum voltages to marginally stable values (Farrell et al., 1999b). In laboratory experiments with dust grains under Martian-like pressures, both glow and filamentary discharges have been observed (Eden and Vonnegut, 1973; Mills, 1977), the latter tending to interact more with the walls. Hence, by analogy, one might anticipate filamentary discharges to the ground or other large solid object but grain–grain and/or grain–atmosphere coronal discharges within the dust storm itself.

Farrell et al. (1999b) estimated the HF electric field radiated from coronal discharges, treating the discharging grain as a small electric dipole that varies on the time-scale of the grain charge relaxation rate, $\frac{1}{\tau}$ (with $\tau$ the grain conductivity). A large number ($N$) of spontaneous small dipole radiators will generate a background HF continuum with power flux $S = (No^2Q^2\delta^2)/(16\pi^2\epsilon_0\Delta f r^2\tau)$, where $\omega = 2\pi f = 2\pi/\tau$ ($\tau$ being the discharge time), $Q$ is the amount of charge moved over a distance $\delta x$ in a grain–grain or grain–atmosphere discharge, $r$ is the source–observer distance ($\sim 0.6$ AU near opposition), and $\Delta f$ is the emission bandwidth (assumed to be $\sim f/2$). Radiation is associated with the second derivative of the dipole ($\omega^2 Q \delta x$). The number of radiating grains is equal to the grain density ($n$) in the saltation layer near the ground, where large and small grains percolate and mix, multiplied by the height of this layer ($L$) and its area over the planet (A): $N = nL A$. On Mars the saltation layer density can be $> 10^{14}$ m$^{-2}$ (Renno et al., 2003) and $L \sim 1$ m. For a planet-sized storm with $A \sim 10^{14}$ m$^2$, the number of interacting grains is $N \sim 10^3$. If each of these exchange $Q \sim 10^{-15}$ C (Melnik and Parrot, 1998) with charge rearrangement over the entire grain ($\delta x \sim 10^{-4}$ m), then $S \sim 10^{-8}$ Jy for peak emission frequencies near 20 MHz (discharge time $\tau \approx 50$ ns) and $\sim 1$ mJy for peak emission frequencies near 200 MHz ($\tau \approx 5$ ns).

This estimate assumes an incoherent HF radiation. Higher levels may be achieved if coherent radio radiation is produced through other mechanisms.

### 3.2.4. Titan

Evidence for Titan’s lightning emissions analogous to SED (i.e. TED) was searched in Voyager radio data during the close flyby of Titan on November 12, 1980 (Desch and Kaiser, 1990). At that time, Voyager 1 was in view of Titan’s nightside hemisphere and Saturn’s dayside hemisphere, so that SED were blocked by Saturn’s ionosphere below a few MHz (Zarka, 1985a) while Titan lightning might be observable at lower frequencies. Frequencies below 1.3 MHz were searched over a 1.7 h interval around closest approach to Titan, from a distance ~4400 km. No signal was found. The sensitivity threshold of the instrument was $\sim 2 \times 10^{-20}$ W m$^{-2}$ Hz$^{-1}$. The upper limit on this non-detection can be converted to a limit on the flux density of Titan lightning at the Earth (typical source–observer distance $\sim 10$ AU) of $\sim 2 \times 10^{-5}$ Jy at 500 kHz. Assuming a power spectrum in $f^{-2}$, this leads to $4 \times 10^{-3}$ Jy at 10 MHz.

Possible lightning activity on Titan was also tentatively modeled by Lammer et al. (2001) through atmospheric composition and dynamics. It was concluded that a large-scale electric field intense enough for lightning generation could build-up on the dayside hemisphere, near the subsolar point. These authors also computed the stroke characteristics, frequency spectrum, and radiated energy. Assuming a power spectrum decreasing in $f^{-2}$ from a peak at $f_{\text{peak}} \sim 4$ kHz, they estimated a radiated spectral energy of $W = 10^{-3}$ J/Hz at 500 kHz. Assuming a total stroke duration $\tau \approx 1/f_{\text{peak}} \approx 0.25$ ms, we derive a flux density at the Earth of $S = W/(4\pi r^2) = 14$ Jy at 500 kHz, i.e. $4 \times 10^{-2}$ Jy at 10 MHz. These values are much higher than the upper limit derived from the non-detection by Voyager 1. The latter should then be attributed to a very low flash rate (<1 flash/h (Lammer et al., 2001)) or to the fact that Voyager searched for lightning from Titan’s nightside.

### 4. Detectability from Earth with LOFAR

#### 4.1. Sensitivity of LOFAR observations

Fig. 3 summarizes all the observation and model results discussed in Section 3, and compares them to the sensitivity expected with the LOw Frequency Array LOFAR which should start its observations in 2006.

LOFAR’s current design (see e.g. Van Haarlem, 2001) consists of two co-located arrays of antennas covering the bands 10–90 MHz (LOFAR-LF) and 110–220 MHz.
of LOFAR will be proportional to \((A_{VC} \times A_S)^{1/2}\) for each baseline or \((\sim 100 \times A_{VC} \times A_S)^{1/2}\) for the full array. Another possibility to obtain high sensitivity is to perform observations with the virtual core plus as many stations as possible connected together as a single-phased array. The possibility of using all stations within \(\sim 50\) km of the virtual core is under study. The effective area for such observations will thus lie between that of the virtual core \((A_{VC})\) and LOFAR’s full area \((A_{LOFAR})\).

In the decameter wavelength, the sky brightness temperature is very high \((\sim 10^3-10^5)\), thus limiting the sensitivity due to fluctuations of the galactic background noise. Dulk et al. (2001) have built an empirical analytical model of the galactic background brightness \(B(f)\) (in \(\text{W m}^{-2} \text{Hz}^{-1} \text{sr}^{-1}\)) for \(f \geq 500\) kHz. It is based on >100 independent measurements from >20 observers (ground-based and spacecraft). The corresponding flux density received by a short dipole antenna, \(S(f) = B(f) \times \Omega_{\text{dipole}}\) is represented in Fig. 2 with a beam of \(\Omega_{\text{dipole}} = 8\pi/3\) sr.

For LOFAR observations, the galactic background noise level will be \(S(f) = B(f) \times \Omega(f)\) with \(\Omega = \lambda^2/A\) (see e.g. Kraus, 1966), where \(\lambda\) is the wavelength and \(A\) the effective area of the instrument \((A_{VC} \leq A \leq A_{LOFAR})\). This background noise is displayed in Fig. 3 as the light-gray shaded region bounded by the curves for \(A = A_{VC}\) (implying \(\Omega = 1.2 \times 10^{-3}\) sr for LOFAR-LF; dotted curve) and \(A = A_{LOFAR}\) \((\Omega = 3 \times 10^{-3}\) sr for LOFAR-LF; dashed curve). Note that in both cases, the beam is independent of the wavelength.

The RMS fluctuations around the average galactic noise spectrum can be written \(\sigma = B\Omega/(\delta t \times \delta f)^{1/2}\), where \(\delta t\) and \(\delta f\) are the integration time and the bandwidth of the observations. LOFAR will allow us to perform observations with an integration time as short as 1 ms simultaneously within eight frequency bands, each 4-MHz wide and positioned at any frequency within the 10–90 of 110–220 MHz ranges. These time–frequency characteristics are well adapted to planetary lightning studies: integration time should ideally be equal to flash duration for maximum sensitivity (shorter \(\delta t\) increase the RMS fluctuations level \(\sigma\), while longer \(\delta t\) dilute the useful signal in the noise); a 4 MHz bandwidth is well adapted to broadband emissions with \(f^{-2}\) spectra. Table 1 illustrates the typical sensitivity of LOFAR-LF at \(f = 15\) and 30 MHz for three integration times consistent with lightning detection. It has been assumed that the interference mitigation techniques developed for LOFAR will be effective and will allow us to reach the limitation set by the galactic background fluctuations. The \(1\sigma\) level is considered representative of the sensitivity of the observations because it will be possible to perform repeated observations with ON/OFF configuration and perform statistical analyses to characterize lightning detection.
The noise background fluctuations, i.e. LOFAR’s sensitivity, are displayed in Fig. 3 as the two gray-shaded regions bounded by $A = A_{VC}$ (dotted curves) and $A = A_{LOFAR}$ (dashed curves). The upper region corresponds to $\delta t = 1\text{ ms}$ and $\delta f = 4\text{ MHz}$, while the lower one corresponds to $\delta t = 100\text{ ms}$ and $\delta f = 4\text{ MHz}$.

### 4.2. Detectability of planetary lightning

#### 4.2.1. Saturn and Uranus

From Fig. 3, it appears clear that Saturn and Uranus will be interesting and accessible targets for radio lightning search and monitoring with LOFAR at its lowest frequencies. SED and UED as detected by Voyager have a high enough flux density ($10^{-10}\text{ to }10^{-8}\text{ Jansky}$), a long enough duration ($10\text{ to }100\text{ ms}$), and a spectrum extending to high enough frequencies to be detectable with LOFAR’s virtual core using a bandwidth $\delta f \geq 4\text{ MHz}$ and an integration time $\delta t = 10\text{ to }100\text{ ms}$. It has to be kept in mind that lightning is a transient atmospheric phenomenon probably with a variable occurrence (five times lower at Saturn during the Voyager 2 flyby than during the Voyager 1, which occurred 9 months earlier). Monitoring of lightning activity at these two planets should thus be performed on a regular basis even if with a low-duty cycle, at least until detection is achieved. Then, lightning activity could be studied more intensively and correlated with optical and infrared observations of the atmospheric structure and dynamics (see e.g. Sanchez-Lavega et al., 1991) to give a comprehensive picture of storm activity, seasonal variations, etc.

#### 4.2.2. Neptune

If one believes that the four events detected at Neptune by Voyager 2 were due to lightning, then the corresponding flux density spectrum is too weak to be detected by LOFAR. However, Voyager 2 flyby may have occurred at a period of low activity, so we suggest that a search for Neptunian radio lightning is occasionally performed with LOFAR, with the largest possible effective area (as close as possible to full array), a very low-duty cycle, and using $\delta f \geq 4\text{ MHz}$ and $\delta t \geq 100\text{ ms}$.

#### 4.2.3. Jupiter

If the non-detection of Jovian lightning in the radio range through spacecraft measurements is due to the “slow” character of the Jovian discharges, then they are definitely undetectable from Earth (the curve labeled “Jupiter (F99, high)” in Fig. 3 corresponds to optimistic estimates derived from Farrell et al. (1999)). Conversely, if it is only due to ionospheric absorption, then the corresponding radio spectrum should lie between the low and high estimates derived from (Zarka, 1985c) (resp. labeled “Jupiter (Z85, high)” and “Jupiter (Z85, low)” in Fig. 3). Only the “high” spectrum is detectable, but it corresponds from ionospheric absorption in the nightside hemisphere. The conditions for LOFAR observations should rather correspond to the “low” spectrum which is undetectable. The low-altitude Jovian ionospheric layer may be non-permanent (e.g. if due to a variable micrometeorite flux) and occasionally raise the Jovian lightning radio spectrum to the (Z85, high) level. But even in this case, the hypothetical lightning signal would be masked by the intense decameter radiation from Jupiter’s magnetosphere (Fig. 2), so we think that LOFAR observations are not relevant to the case of Jovian lightning.

#### 4.2.4. Venus

At the upper-limit set on Venus lightning intensity by Cassini-RPWS measurements (see Fig. 3), only relatively long (tens of ms) flashes observed with the full array and the broadest possible bandwidth can be detectable from Earth, near inferior conjunction. It may be thus useful to monitor Venus with a very low duty cycle in search for lightning activity. Venus lightning may also be more intense but very rare, so that part of the observations should be performed with a time integration shorter than 100 ms.

#### 4.2.5. Mars

The determination of electrical activity from Martian dust storms is significant since electricity can affect the generation of organic compounds (Mills, 1977). The ability of ground-based radio telescopes like the VLA to detect the coronal discharges from electrified Martian dust storms was recently addressed by Remno et al. (2003). They proposed that triboelectricity in regional

<table>
<thead>
<tr>
<th>$f = 15\text{ MHz (}\delta f = 4\text{ MHz})$</th>
<th>$f = 30\text{ MHz (}\delta f = 4\text{ MHz})$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>LOFAR VC</strong></td>
<td><strong>LOFAR VC</strong></td>
</tr>
<tr>
<td>$\delta t = 1\text{ ms}$</td>
<td>4.3</td>
</tr>
<tr>
<td></td>
<td>17.1</td>
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<tr>
<td>$\delta t = 10\text{ ms}$</td>
<td>1.3</td>
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<tr>
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<td>5.4</td>
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<tr>
<td>$\delta t = 100\text{ ms}$</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>1.7</td>
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</tbody>
</table>

Table 1

LOFAR-LF sensitivity in Jy (full array or virtual core only) at 15 and 30 MHz for three integration times and a bandwidth of 4 MHz.
storms could create a 10° brightness temperature increase in the microwave regime.

The HF radio emission estimated by Farrell et al. (1999b) (Section 3.2.3) leads to much lower flux density levels as illustrated in Fig. 3 below ~100 MHz (LOFAR-LF range). But this radiation has spectral and temporal characteristics very different from other planetary lightning:

- the spectrum increases as $f^3$ towards high frequencies (if the grain discharge time is of the order of a few nanoseconds);
- the predicted emission is not sporadic but long-lived, permitting detection with integration times much longer than 100 ms.

In Fig. 3, the expected level for HF radio radiation from Mars lightning is a factor ~3000 below the sky background fluctuations (with integration time of 100 ms). Extrapolating to the highest frequencies of LOFAR-HF (200–220 MHz) with a sky background level decreasing as $\sim f^{-0.5}$ and an integration time of 1 min, the expected level of Mars lightning raises to ~1.5–2 times that of sky background fluctuations. LOFAR-HF may thus have the frequency coverage and sensitivity to examine triboelectric radiative flux increases associated with the presence of regional/global dust storms on Mars, if the corona discharge is on nanoseconds time-scale. One issue is the separation of thermal black-body radiation that increases (from relatively hot dust storms) from the proposed triboelectric radiation which increases from the same regions. This separation can be addressed by comparing LOFAR measurements with Mars-orbiting IR sensors that can measure the dust-loaded atmospheric temperatures directly.

4.2.6. Titan

At Titan, extrapolation of the upper limit derived by Desch and Kaiser (1990) leads to totally undetectable levels from the Earth (Section 3.2.4). The more favourable estimate by Lammer et al. (2001) for the subsolar point—displayed in Fig. 3—still leads to undetectable levels above 10 MHz. Furthermore, this computed spectrum is over-estimated by a “dilation” factor $\delta t / \tau'$ with $\delta t$ the integration time of the observations and $\tau'$ the characteristic flash duration (which may fortunately be longer than the estimated stroke duration $\tau \approx 0.25 \, \text{ms}$). In addition, the hypothetic radio emission from Titan’s lightning should be competing with the signal from Saturn’s lightning (SED) and distinguishable from it only by means of imagery (see Section 6), in which case sensitivity should not be sufficient. By contrast, the Radio and Plasma Wave Science (RPWS) instrument onboard the Cassini orbiter of Saturn (Gurnett et al., 2004) will benefit from over 40 close Titan flybys between November 2004 and at least May 2008, in order to detect radio emission from Titan lightning in the range $f \leqslant 16 \, \text{MHz}$. As discussed by Lammer et al. (2001), prospects are favourable for positive detection with Cassini-RPWS.

5. Radio emission related to sprites and TIPPs at earth

Coming back to Earth, LOFAR will probably occasionally detect terrestrial lightning strokes, but these will rather constitute a pollution of its astronomical observations. However, other recently discovered lightning-like phenomena might be studied through their HF radio radiation: these are “sprites” and “TIPPs/SIPPs” (Trans-/Sub-Ionospheric Pulse Pairs).

Sprites are red luminous emissions attributed to mesospheric currents created by intense positive cloud-to-ground strokes, and sometimes accompanied by other luminous emissions called elves (Franz et al., 1990; Sentman et al., 1995; Rodger et al., 1998). Sprite durations are on the order of 10–300 ms, much longer than ordinary lightning. There are a number of scenarios for their generation, but all involve the large cloud-to-ionosphere electrostatic field that develops following a discharge. For example, it has been suggested that the large cloud-to-ionosphere electrostatic field that develops following the largest positive cloud-to-ground lightning strokes is susceptible to a breakdown by incident cosmic rays (in analogy to a Geiger-Muller tube), thereby producing runaway relativistic electrons that are responsible for the glow (Roussel-Dupré and Gurevich, 1996). Alternately, Pasko et al. (1998) has suggested that sprites are associated with the spatially descending ionospheric currents that are generated in response to the large step-function electric field change from the underlying positive cloud-to-ground stroke. Immediately following a discharge, the ionosphere will respond to the new arrangement in cloud charge, but the response occurs at higher altitudes first (where the temporal relaxation, $\tau = c \Sigma(z)$, is fastest) and progressively descends in height through the $D$-region over the course of milliseconds (Greifinger and Greifinger, 1976). In essence, the response is a descending current “plate” in the middle atmosphere. For very large underlying charge rearrangements (like 300 C for positive cloud-to-ground strokes), the induced current response is so intense as to generate an associated Paschen glow that forms the sprite (Pasko et al, 1997, 1998). Gamma-ray bursts produced in the atmosphere by the high-energy electron beams have also been detected from sprite-like lightning emission source locations associating the gamma rays with transient luminous events and implicating the large electrostatic fields in the process (Inan et al., 1996). Such emissions have been observed by the Gamma Ray Observatory
(GRO) satellite above thunderstorms (Fishman et al., 1994).

Intense extremely low-frequency (ELF) radiation has been related to sprites, but no HF radio emission has been observed. This may be due to their “slow discharge” nature (see Section 3.2.1) leading to a spectral peak around 10–100 Hz followed by a steep decrease at higher frequencies (Farrell, 2000). But finer spatial and temporal substructure has also been observed for sprites (Gerken et al., 2000; Valdivia et al., 1997), which could produce HF radio emission not detected due to propagation or directivity effects beamng the emission upwards. Also, the runaway electrons believed to be generated in the sprite/DC E-field process might also produce HF radio emission. To date, there has not been any study of sprite HF emission.

TIPPs are broadband electromagnetic pulses similar to those generated by nuclear explosions. They are related to a particular intense lightning called narrow positive bipolar pulses (Smith et al., 1999) with a duration of 20–30 μs, producing radio emission in the range 1–30 MHz (LeVine, 1980). TIPPs were discovered by the ALEXIS satellite (Holden et al., 1995). They are emissions in the range 20–300 MHz followed 10–100 μs later by an echo on the ground. TIPPs are up to 10^4 more powerful than ordinary lightning sferics (Desch et al., 2002), have a fixed-frequency duration of a few microseconds, and drift in the time–frequency plane over a total duration of tens to hundreds of microseconds (Jacobson et al., 1999). SIPPs are similar emissions observed from the ground at lower frequencies (between 3 and 30 MHz), probably after reflection by the ionosphere (Smith and Holden, 1996).

Is there a relation between sprites and TIPPs/SIPPs? To date, TIPP/SIPP and sprite production have not been linked, but the large electrostatic fields that develop in sprite/gamma ray production make for possible causality. LOFAR could provide new information in observing TIPPs/SIPPs over a large fraction of its frequency range higher frequencies would correspond to reflection under the ionosphere at increasingly large angles and thus sources at increasing distances. LOFAR could also make new fundamental measurements regarding HF emission, that could be correlated with ground-based and spacecraft observations at various wavelengths (optical, X, Gamma) (Blanc et al., 2003). For example, the US National Lightning Detection Network could be used to identify potential sprite-producing lightning events and a determination of positive cloud-to-ground events, sprites, and TIPPs/SIPPs could be made.

These processes may have a significant effect on the Earth's magnetosphere, in particular, by modifying the source and loss terms of the radiation belts. Effects are also expected at the conjugate point of storm areas. Sensitivity will probably not be an issue for these studies, but very high temporal accuracy is required. A possible way to achieve it is discussed in the next section.

6. Summary of instrumental constraints

Instrumental requirements for optimal lightning radio detection with LOFAR are summarized below.

Temporal constraints include time resolution/integration and timing accuracy of observations. Lightning observations will generally require short integration times, typically between 1 and 100 ms according to the target. It will be useful to try several values within each observation campaign because sensitivity will be maximum for the integration times matching the flash duration (e.g. 30 to 300 ms for Saturn, Uranus, and possibly Neptune). The case of Mars is an exception: the incoherent sum of coronal discharges within the dust storm (Section 3.2.3) lead to long-lived emission over duration >> 100 ms, thus allowing one to use integration times longer than above. Absolute timing is not a strong requirement for lightning observations, except if one wants to correlate LOFAR observations with other observations (e.g. by Cassini in orbit, or optical).

However, for sprites/TIPPs/SIPPs observations, very high temporal accuracy will be required. It may be achieved through direct access to the waveform (instead of the spectrum) as recorded by LOFAR stations and virtual core during the occurrence of such events. In order to limit the volume of data to be transferred/stored, waveform information should be recorded at the various observing sites at the command of a trigger. An obvious trigger could be the detection of electromagnetic (e.g. optical) emission from the associated positive lightning discharge related to the sprite or TIPP/SIPP (see Section 5). High-energy cosmic ray detection with LOFAR should have similar temporal requirements (Dallier et al., 2003).

Spectral constraints can be deduced from Fig. 3: it appears that the favored frequency range for planetary lightning detection is between about 10 and 40 MHz, i.e. the low-frequency part of LOFAR-LF. The case of Mars is again an exception: as the flux may increase at higher frequencies (if the discharge time is of the order of a few nanoseconds), observations with LOFAR-HF appear more suitable. Moderate spectral resolution is required (e.g. 100-kHz-wide frequency channels), but the instantaneous bandwidth must be broad in order to take advantage of the intrinsically broadband character of lightning radio emission. LOFAR is planned to observe simultaneously in eight 4-MHz bands, centered around arbitrary frequency values. With a lightning radio emission spectrum in f^-2, the use of n 4 MHz bands in parallel will increase the sensitivity of the
the expected flux density is high enough (see Fig. 3) and applicable in practice only for Saturn, for which both planetscale implies a slightly lower sensitivity. It will be maximum effective area phased array, as explained in measurements in a narrow beam (synthesized using the large-scale dust storms are detected. Jupiter and Titan tions should be performed especially when Venus and Neptune should be occasional and observa-
Cassini-Saturn tour until at least 2008. Observations of parallelandcomparedtothosefromCassindiuringthe LOFAR observationsofSaturnshouldbeperformedin observations reveal large-scale storms on Saturn. Also, should be the primary targets, especially when optical observations by a factor
\[ F = \sum_{k=1}^{n} \left( \frac{f}{f + 4(k - 1)} \right)^{\alpha} \]
with the first band centered at frequency \( f \). For \( \alpha = 2 \) and \( f = 20 \text{ MHz} \), one obtains \( F = 1, 1.7, 2.2, 2.6, 2.9 \ldots \) for \( n = 1, 2, 3, 4, 5 \ldots \) The gain in sensitivity will be more important in the case of Saturn where \( \alpha \sim 1 \) (Section 3.1.1). Thus, using several 4 MHz bands in parallel will be an advantage but is not crucial for planetary lightning detection. It may be useful to scan the spectral range of interest (e.g. 10–40 MHz) with one 4 MHz band in the course of an observation program.

Polarization should in principle not be an issue as lightning radio emission is usually unpolarized.

Regular observations are recommended at intervals of a few days/weeks for each target near opposition (near inferior conjunction for Venus). Saturn and Uranus should be the primary targets, especially when optical observations reveal large-scale storms on Saturn. Also, LOFAR observations of Saturn should be performed in parallel and compared to those from Cassini during the Cassini-Saturn tour until at least 2008. Observations of Venus and Neptune should be occasional and observations of Mars should be performed especially when large-scale dust storms are detected. Jupiter and Titan do not seem to be interesting targets for lightning observations with LOFAR.

Observations should primarily consist of total flux measurements in a narrow beam (synthesized using the maximum effective area phased array, as explained in Section 4.1) pointed at the target planet. Interferometric imaging in order to resolve lightning sources at the subplanet scale implies a slightly lower sensitivity. It will be applicable in practice only for Saturn, for which both the expected flux density is high enough (see Fig. 3) and the apparent planetary diameter is \( \sim 20'' \) near opposition (LOFAR should reach an angular resolution of 12'' at 15 MHz and 6'' at 30 MHz). Radio images of lightning sources located on the planetary disk could then be correlated with optical images. In all the cases, other than Saturn, simultaneous “ON source” and “OFF source” observations, achieved via two different phasing of the antennas in parallel (see e.g. Zarka et al., 1997), will greatly help to eliminate spurious signals and confirm detection.

LOFAR built-in capabilities for correcting ionospheric scintillations and mitigating RFI pollution in real-time will also be extremely useful for the observations described above.

7. Conclusion

This paper has focused on the possibility and interest for the LOFAR radiotelescope to detect and study HF radio emission from planetary lightning. We have compared Voyager observations performed at Saturn, Uranus, and Neptune, as well as upper limits and model predictions of unobserved radio emission at the other planets and Titan, with LOFAR sensitivity, for realistic observation parameters (\( \delta f = 4 \text{ MHz}, \delta t = 1–100 \text{ ms} \)). The sensitivity will be limited by the sky background.

It has been found that the so-called Saturn Electrostatic Discharges, actually the radio emission from Saturnian lightning with a flux density at Earth up to 1000 Jy, will be detectable with a signal-to-noise ratio high enough (up to 100 or more) to make imagery of lightning sources possible (with resolution about 10'', i.e. half the planetary radius). LOFAR will be operational when Cassini is still in orbit around Saturn. Joint stereoscopic studies will thus be possible, comparing source locations and motions, beamforming, detected flux, etc.

Based on Voyager 2 results, Uranus lightning can also be detectable with LOFAR, although with a lower signal-to-noise ratio (of the order of 10) and without possibility of imagery. Neptune and Venus are not likely to be detected, but should be monitored with a low duty cycle in search of rare intense events. Jupiter and Titan will be undetectable from the Earth due to an intrinsically low level of HF radio emission and/or attenuation during propagation and confusion with intense nearby sporadic radio sources: the auroral decameter emission in the case of Jupiter and Saturn’s lightning in the case of Titan. By contrast, the radio experiment onboard Cassini should be the best way to detect Titan lighting during the numerous close flybys that will occur in the course of Saturn’s tour (2004–2008). The case of Mars is peculiar: a large number of microscopic discharges involving dust grains elevated during large-scale dust storms are expected to result in a long-lived radio emission peaking at higher frequencies than other planetary lightning.

Optimal observing parameters have been derived for each target: frequency of observation (LOFAR-LF or -HF), bandwidth, integration time, duty cycle, mode of observation. The latter is particularly critical, consisting primarily of total flux measurements (possibly complemented by interferometric imaging only in the case of Saturn) with strong requirement for simultaneous ON/OFF comparisons.

The detection of HF radio emissions associated with the newly discovered sprites (cloud-to-ionosphere discharges) and TIPPs (electromagnetic pulses related to intense lightning) in the Earth’s atmosphere is also considered. It requires specific observation schemes allowing for very high temporal resolution.

LOFAR appears to possess characteristics that will allow study of the properties of planetary lightning at some solar system planets (Saturn, Uranus?, Neptune?) or to settle the debate about their existence at others.
(Mars, Venus). Finally, it may be useful to state that lightning from planets outside of our solar system will not be detectable by LOFAR.

References


