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Non-detection of impulsive radio signals from lightning in Martian dust storms using the radar receiver on the Mars Express spacecraft

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[1] Here we report the results of a nearly five-year search for impulsive radio signals from lightning discharges in Martian dust storms using the radar receiver on the Mars Express spacecraft. The search covered altitudes from 275 km to 1400 km and frequencies from 4.0 to 5.5 MHz with a time resolution of 91.4 μs and a detection threshold of 2.8×10^{-18} Watts m^{-2} Hz^{-1}. At comparable altitudes the intensity of terrestrial lightning is several orders of magnitude above this threshold. Although two major dust storms and many small storms occurred during the search period, no credible detections of radio signals from lightning were observed.

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1. Introduction

[2] Mars is known to have intense dust storms on spatial scales ranging from large planetary events [*Gierasch*, 1974; *Cantor et al.*, 2001] to small dust devils [*Thomas and Gierasch*, 1985]. At Earth it is well established that wind-blown sand and dust can generate electric fields with strengths greater than 100 kV/m [*Schmidt et al.*, 1998]. These field strengths are generally below the ~3 MV/m threshold required to produce electrical discharges in Earth's atmosphere [*Delory et al.*, 2006]. However, because of the much lower atmospheric pressures at Mars and the corresponding lower breakdown threshold, ~20 to 30 kV/m, it has been suggested that electrostatic charging in Martian dust storms could cause lightning-like electrical discharges [*Eden and Vonnegut*, 1973; *Sentman*, 1991; *Melnik and Parrot*, 1998; *Farrell et al.*, 1999; *Zarka et al.*, 2004; *Renno and Kok*, 2008]. Recently, *Ruf et al.* [2009] reported periodic fluctuations in the non-thermal microwave emission from a Martian dust storm that they attribute to the excitation of *Schumann* [1952] resonances by electrical discharges. In this paper we report the results of a search for impulsive HF (high-frequency) radio signals from lightning in Martian dust storms using the radar receiver on the Mars Express spacecraft.

[3] The Mars Express spacecraft, which was launched on June 2, 2003, carries a 0.1 to 5.5 MHz radar called MARSIS (Mars Advanced Radar for Subsurface and Ionosphere Sounding) that is designed to perform sub-surface and ionospheric sounding [*Picardi et al.*, 2004]. The spacecraft has an eccentric orbit with a periapsis altitude of 275 km, an apoapsis altitude of 10,400 km, and an inclination of 86°. Although the primary purpose of MARSIS is radar sounding the radar receiver can be used to monitor the background noise level, including signals that might be attributed to lightning. The approach that we have used is to search all of the available data for signals above the background noise level, and then see if these signals could be attributed to known dust storms. The search covered a period of nearly five years, from August 14, 2005, shortly after commissioning, to the most recent data processed, which was on March 17, 2010.

2. Instrumentation

[4] The MARSIS instrument consists of a 40-m tip-to-tip electric dipole antenna, a transmitter, a receiver, and a command and data processing system. The instrument has two modes of operation, one for sub-surface sounding and the other for ionospheric sounding. In the ionospheric sounding mode, which was used for this study, the transmitter steps through 160 logarithmically spaced frequencies ($\Delta f/f \approx 2\%$) from 0.1 to 5.5 MHz. The echo intensities obtained during each frequency sweep are displayed on a color-coded plot of delay time, Δt, versus the transmitter frequency, f. This plot is called an ionogram (see Figure 1). The horizontal trace labeled "surface reflection" is the radar echo from the surface of Mars, and the two traces labeled "ionospheric echo" and "oblique ionospheric echo" are echoes from the ionosphere [see *Gurnett et al.*, 2005]. The strong signals along the left side of the ionogram, and in a narrow horizontal band along the top of the ionogram, are decaying electrostatic disturbances excited in the plasma during the transmitted pulse. A typical ionospheric sounding pass lasts about 40 min and starts at an altitude of 1200 to 1400 km on the inbound leg, continues through periapsis at about 275 km, and ends at an altitude of 1200 to 1400 km on the outbound leg.

3. Data Analysis

[5] It is obvious from Figure 1 that there are large areas in the ionogram where no radar echoes are detected. It is in these regions that we can search for signals from lightning discharges. The MARSIS instrument is well suited for such a search. The noise level of the MARSIS preamplifier is

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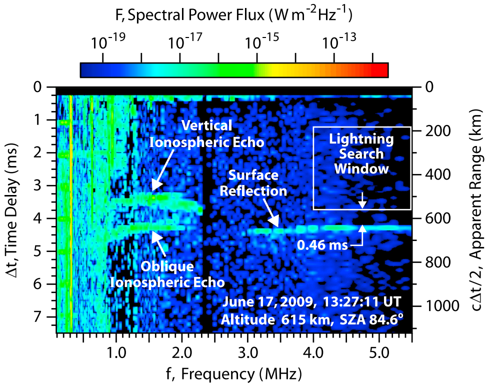

Figure 1. An ionogram showing the received spectral power flux as a function of time delay, Δt, and frequency, f, for a radar sounding at an altitude of 615 km. In order to avoid radar echoes and other types of interference, the search for lightning was limited to the rectangular window labeled "Lightning Search Window."

very low, so low that the noise level is determined almost entirely by the galactic radio noise background. At Earth radio impulses from lightning discharges occur over a very broad frequency range, from a few kHz to several tens of MHz, and on very short time scales, from a few μs to several tens of ms [*Rakov and Uman*, 2003]. If lightning from dust storms at Mars is even remotely similar to terrestrial lightning then the MARSIS receiver should be able to easily detect such discharges.

[6] Because of the very large volume of data that must be processed it was not practical to visually examine all of the ionograms. Instead, we settled on a semi-automated search in which we only examined ionograms that had signals above a pre-selected threshold. In order to avoid contamination by radar echoes and other interference effects, we restricted the search to the rectangular box labeled "Lightning Search Window" in Figure 1. The right edge of the box was determined by the highest frequency of the receiver, which is 5.5 MHz. The left edge of the box was set at 4.0 MHz to eliminate most ionospheric echoes, which are seldom above 4 MHz. The upper edge of the box was set at a time delay of Δt = 1.24 ms in order to eliminate the transient disturbances that persist for a fraction of a millisecond after the transmitter pulse. The lower edge of the box is variable and was selected to be 0.46 ms above the expected time delay of the surface echo, which varies with the spacecraft altitude.

[7] In order to set the detection threshold, we had to first make an accurate determination of the fluctuations in the galactic radio noise background. To obtain an accurate determination of the background noise level, measurements were obtained for two passes near apoapsis, where any lightning signals that might be present would have a greatly reduced intensity due to the increased range. These data were carefully inspected to make certain that they were not contaminated by known radio emissions, such as solar radio bursts or radio emissions from Jupiter. The resulting intensity distribution for all of the pixels in the lightning search window is shown by the red lines in Figure 2. This distribution includes a total 1.86×10^5 samples. The average value of the distribution is 9.8×10^{-20} Watts m^{-2} Hz^{-1}, which is very close to the galactic radio noise background given by *Dulk et al.* [2001] at 4.0 to 5.5 MHz. As can be seen the probability distribution has a rather wide spread. The large spread is due in part to the very short integration time, i.e., 91.4 μs ~ 1/B, where B = 10.4 kHz is the bandwidth of the receiver. The short integration time was driven by the desire to achieve the best possible range resolution for the radar. Note that the highest background level detected is 2.8×10^{-18} Watts m^{-2} Hz^{-1}. Since no background signals were observed above this level during the high altitude calibration, this spectral power flux was adopted as the lightning detection threshold.

[8] Having set the threshold for identifying possible lightning events we next proceeded to make a similar probability distribution for the nearly 5 years of data available, all of which are at altitudes less than 1400 km. This distribution initially revealed 186 ionograms out of a total of 365,254 that had spectral power fluxes above the detection threshold. Visual inspection showed that 161 of these ionograms had elevated intensities due to ionospheric radar echoes, type III solar radio bursts, and various types of spacecraft-generated interference. After eliminating these 161 ionograms the resulting probability distribution is shown by the black lines in Figure 2. As can be seen this probability distribution is very close to the high altitude background given by the red lines. However, there were still 186 − 161 = 25 ionograms for which we could not identify a known source. These 25 ionograms, which are indicated by the cross-hatching, contained 40 pixels with intensities above 2.8×10^{-18} Watts m^{-2} Hz^{-1}. Given the very small number of events above the threshold (40 out of a total of 2.53×10^8 samples), the close similarity to the overall shape of the background probability distribution, and the lack of significant outliers, one could make a reasonable argument that these events are just part of the normal fluctuations in the galactic background. However,

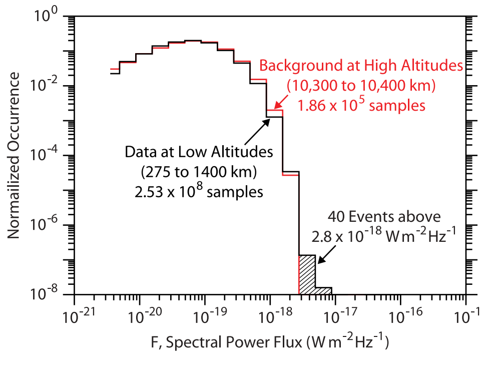

Figure 2. The red line gives the distribution of the galactic background noise in the lightning search window during two approximately 10-minute calibration passes at high altitudes, near apoapsis. Based on these calibrations the lightning detection threshold was set at 2.8×10^{-18} Watt m^{-2} Hz^{-1}. The black line gives a similar distribution (after visually eliminating all known types of radio signals and interference) for all of the low altitude measurements obtained during the nearly 5-year study. Forty events (in the cross-hatched region) remained above the lightning detection threshold. None of these events could be associated with a dust storm.

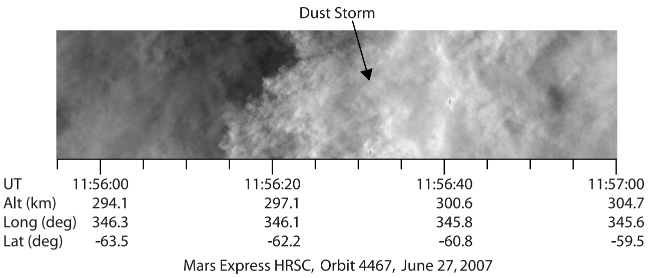

Figure 3. A high-resolution nadir viewing image from the HRSC camera on Mars Express as the spacecraft passed directly over a very active dust storm on June 27, 2007. No impulsive radio signals were observed that could be attributed to lightning during this pass.

in the next section we carry out a detailed investigation to see if any of these events are associated with dust storms.

4. Dust Storm Imaging

[9] To search for dust storms that might be responsible for the 40 events above the detection threshold, we have used images from the Mars Orbiter Camera (MOC) on the Mars Global Surveyor (MGS) spacecraft and the Mars Color Imager (MARCI) on the Mars Reconnaissance Orbiter (MRO) spacecraft. These instruments are described by *Malin et al.* [2001, 2010]. Together the MOC and MARCI cameras provide a nearly ideal capability for identifying dust storms on Mars. By providing pole-to-pole swaths in the local afternoon once per orbit, they provide a global overview of dust storm activity once per Martian day (sol). Although the time coincidence with the MARSIS observations is not exact, local dust storms can last for 1–2 sols, and larger regional dust storms can last for many sols. Therefore, the MOC and MARCI images provide an excellent capability for determining whether a dust storm is active at any given time or location on Mars. Although it has a much narrower field of view, we also sometimes used the narrow-angle High Resolution Stereo Camera (HRSC) on Mars Express [*Neukum et al.*, 2004].

[10] To determine whether a dust storm was present during any of the 40 events in the cross-hatched region of Figure 2, we examined the closest MOC and/or MARCI images to the times that these events occurred. The criterion for comparison was to look for a dust storm within 250 km of the Mars Express sub-spacecraft point. Because of total internal reflection by the ionosphere, radio signals from lightning are not expected to be detected beyond about 250 km from the sub-spacecraft point. A summary of these imaging observations is given in Table S1 of the auxiliary material.[1] Except for three ionograms (# 15, 16 and 17) where no observations were available, none of the events occurred during active dust storms. In three ionograms (# 3, 4 and 5) elevated levels of high altitude dust were present, but no active regions of uplifting dust were observed. One ionogram (#2) had 10 pixels with sporadic levels above the detection threshold at about 5.3 to 5.5 MHz. This ionogram is shown in Figure S1 of the auxiliary material. Neither the previous ionogram, nor the following ionogram, showed elevated intensities, and the MOC and HRSC images did not show any evidence of a dust storm at this time. We believe that the events in this ionogram are probably due to some type of spacecraft-generated interference, although the exact source is unknown.

[11] Although no dust storms could be associated with the 40 events above the detection threshold, many MARSIS observations were obtained in which no events were detected while passing directly over active dust storms. These include a major planetary-scale dust storm in the southern hemisphere that lasted more than a month, from about June 15 to August 1, 2007, and another shorter-duration dust storm that occurred near the southern icecap from March 29 to April 8, 2009. Out of a total of 163 passes over these two storms with simultaneous MARSIS data and HRSC imaging, 41 showed active dust storms. A particularly impressive HRSC image of a very active dust storm is shown in Figure 3. No radio signals above the detection threshold were observed during this pass, or any of the other passes with active dust storms. Other smaller isolated storms have also been investigated. One such case is the dust storm for which *Ruf et al.* [2009] reported evidence of electrostatic discharges from 19:14 to 22:40 UT on June 8, 2006. MOC images show that this dust storm was active from June 6 to 8. Although no MARSIS observations were available at the exact time of the Ruf et al. observations, Mars Express passed almost directly over this storm about 20 hours before the microwave observation by Ruf et al. and about 2–1/2 hours after the nearest MOC image of the storm, and no radio signals were detected. Unfortunately, no HRSC images were available during this pass.

5. Conclusion

[12] After nearly five years of MARSIS observations, no radio signals were detected in the frequency range from 4.0

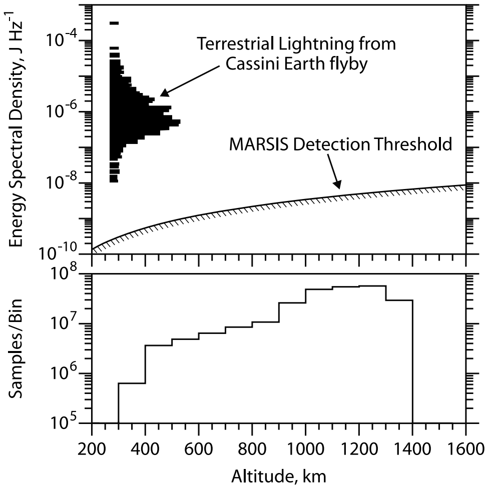

Figure 4. (top) MARSIS lightning detection threshold in Joules Hz^{-1} as a function of altitude, assuming that the source is directly below the spacecraft. (bottom) Altitude distributions of all the measurements obtained during the study. Also shown in Figure 4 (top) is the energy distribution of terrestrial lighting obtained during the Cassini flyby of Earth [*Gurnett et al.*, 2001], corrected for the 91 μs integration time of the MARSIS instrument.

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2010GL044368.

to 5.5 MHz that can be credibly attributed to electrical discharges in Martian dust storms. Thus, all we can do is put an upper limit on the radio emission from lightning at Mars in this frequency range. Because lightning is an impulsive event, it is useful to express this limit in terms of the energy spectral density per discharge (i.e., Joules Hz^{-1}). This quantity is obtained by multiplying the detection threshold (2.8×10^{-18} Watts m^{-2} Hz^{-1}) by the receiver integration time, 91.4 μs, and the area of a spherical surface around the source, $4\pi R^2$, where R is the range to the source. The threshold energy for detecting lightning then depends on the distance to the source, which we take to be the altitude of the spacecraft. The resulting threshold energy spectral density is shown as a function of altitude in Figure 4 (top). Figure 4 (bottom) shows the corresponding altitude distribution of the observations. To illustrate the excellent sensitivity of the MARSIS instrument, Figure 4 (top) also shows the energy distribution of terrestrial lightning obtained from a similar instrument during the 1999 Cassini flyby of Earth [*Gurnett et al.* 2001]. This plot shows that MARSIS would be able to easily detect terrestrial lightning, by a margin of as much as 10^3 to 10^5, depending on the altitude. Although MARSIS did not detect electrical discharges at 4.0 to 5.5 MHz, our results do not rule out the possibility of discharges that radiate most strongly at much lower frequencies, such as sprites [*Farrell et al.*, 1999], or at much higher frequencies, such as coronal discharges [*Zarka et al.*, 2004].

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