Effects of ring shadowing on the detection of electrostatic discharges at Saturn


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A long-standing discrepancy exists in determinations from observations and modeling of the diurnal variation of the peak electron density of Saturn’s ionosphere. Using a new Saturn-Thermosphere-Ionosphere-Model (STIM), we examine the suggestion by Burns et al. (1983) that Saturn’s rings shadow its ionosphere causing radio penetration “holes”, thereby allowing lightning-induced radio signals (Saturn electrostatic discharges, SEDs) to escape. This lesson the need to invoke globally enhanced loss processes to account for Voyager era observations of nighttime peak density (Nmax), as low as 10^4 e/cm^3 from the SEDs. We find radio frequency “windows” produced by ring shadowing that were narrow and confined to low latitudes during the Voyager era, but are now broadly distributed over northern mid-latitudes during the Cassini era. If lightning sources occur only at near-equatorial latitudes, then the far less frequent detection of SEDs by Cassini early in its mission would be consistent with the current ionospheric morphology. Citation: Mendillo, M., L. Moore, J. Clarke, I. Mueller-Wodarg, W. S. Kurth, and M. L. Kaiser (2005), Effects of ring shadowing on the detection of electrostatic discharges at Saturn, Geophys. Res. Lett., 32, L05107, doi:10.1029/2004GL021934.

1. Introduction

Planets emit radio waves into space by a variety of natural means. There is a rich literature describing the radio emissions arising from the energetic charged particles that cause the aurora along high latitude magnetic field lines on Earth, Jupiter and Saturn (called Auroral Kilometric Radiation (AKR) at Earth, broadband kilometric, hectometric, and decametric radiation at Jupiter, and SKR at Saturn). Lightning discharges deep in a planet’s atmosphere also generate radio waves that can escape into space, with cases found at Earth, Saturn, Uranus and possibly Venus and Neptune. Optical lightning has been detected at Jupiter, as well as whistlers. As with classical optical spectroscopy, the detection of radio waves over a broad range of frequencies is a powerful remote sensing diagnostic of processes acting on planets, yielding information about sources and/or the intervening medium between source and detector.

Saturn’s lightning thus acted as a type of natural ionosonde, with a bottom-side transmitter and a topside detector. The lowest observed penetration frequencies (f_{min}) were assumed equal to the ionospheric plasma frequencies (f_p), which could be used to estimate the peak electron densities (N_{max}) during a Saturn day. The conclusion was that N_{max} varied diurnally from ~10^3 e/cm^3 (f_p = 0.3 MHz) at midnight to a value of ~10^4 e/cm^3 at midday (f_p = 3–5 MHz). While the latter (high N_{max}) did not present difficulties to the earliest models of Saturn’s ionosphere, the former (low N_{max}) did, and so Burns et al. [1983] suggested that shadows cast by Saturn’s rings might cause holes in its...
explanations offered is that lightning conditions have changed on Saturn, i.e., the sources in 2004 are simply not as strong or frequent as found in the early 1980s. The mechanism proposed by Kaiser et al. [2004] is that the shadows cast by Saturn’s great system of rings are very different in 2004 than the shadows in 1980—81, and thus the convective activity that drives lightning has changed substantially. As shown in Figure 1a, during the Voyager era the rings were very nearly in the plane containing Saturn and the Sun, and thus a relatively narrow shadow was cast upon the low latitudes of the planet, creating a type of long-lived eclipse that might lead to “hot” and “cold” areas narrowly separated, presumably fostering the development of turbulence. In 2004, the situation has changed with the rings tilted well above the Sun-Saturn plane (Figure 1b), casting broad shadows upon northern latitudes, resulting in presumably far milder gradients in tropospheric parameters, and hence little storm-induced lightning.

[8] In this brief letter, we explore the companion effects that ring shadowing would have upon the ionosphere, and thus examine if the medium that filters out which radio wave frequencies pass through the ionosphere also controls, and/or contributes to, the lower detection rate of SED by the Cassini instrumentation.

2. Early Models of Saturn’s Ionosphere

[6] Prior to the acceptance of SED-relevance to Saturn’s ionospheric diurnal morphology, the few radio occultation measurements had already challenged a theory that predicted peak electron densities of $\sim 10^5$ e/cm$^3$ at Saturn [McElroy, 1973]. The measurements near dawn and dusk gave values closer to $10^4$ e/cm$^3$, and thus additional loss processes were needed. Two mechanisms were proposed to enhance the ion loss chemistry, one involving a flux of water from the rings, converting H$^+$ to H$_2$O$^-$ [Connerney and Waite, 1984; Connerney, 1986], and a second to convert H$^+$ ions to H$_2$ via reactions with vibrationally-excited H$_2$ (suggested as a possibly important mechanism by McElroy [1973], explored for Jupiter by McConnell et al. [1982], and discussed for Saturn by Majeed et al. [1991] and Majeed and McConnell [1996]). The crux of the problem was that if the dominant ionospheric ion were H$^+$, it would recombine very slowly with electrons, and thus the densities would be high and vary little from day to night. If the dominant ion were molecular, however, then dissociative recombination would be rapid and peak densities with lower magnitudes and LT-dependent patterns could emerge. With the SED-from-lightning interpretation gaining acceptance as an ionospheric diagnostic of a strong diurnal variation [Kaiser et al., 1984b], both mechanisms were used in attempts to produce a 100-fold variation in peak electron density. Moore et al. [2004] have recently summarized past and current approaches to these issues using 12 separate simulations to explore parameter space possibilities. While additional chemical mechanisms can be invoked to match either the low nighttime values ($10^3$ e/cm$^3$) or the high daytime values ($10^5$ e/cm$^3$), no self-consistent solution could be found to match both extremes in the short (10-hour) Saturn day.

3. Cassini at Saturn

[7] While en route to Saturn, Cassini’s radio and plasma wave instrument first observed an SED event in July 2003, but subsequent detections have been infrequent, giving the early impression that SED events are more episodic and less regular during the Cassini era [Gurnett et al., 2005; Kaiser et al., 2004; Kurth et al., 2004]. One of the possible explanations offered is that lightning conditions have
the solar declination. Note that the equinox conditions for Voyager-2 involve a latitude range one-third that shown for Cassini’s conditions. In Figures 2b and 2e, maps of $N_{\text{max}}$ versus local time are given over the same latitude ranges depicted in Figures 2a and 2d. For comparison, Figures 2c and 2f give global simulation results when ring shadowing is ignored.

[12] Clearly, strong ionospheric depletions, with significant structure in space and time, result from ring shadowing. These may provide the ionospheric holes envisioned by Burns et al. [1983] that allow the lowest frequency SED signals to reach satellite receivers above the ionosphere. To show this in more detail, Figure 3a gives the minimum $N_{\text{max}}$ values found throughout the day spanning latitudes ±60°C176 latitude. During the Voyager era, the ionospheric depletions were highly confined to low latitudes. For Cassini, the rings shadow a far broader portion of the northern hemisphere, and cause (together with seasonal trends shown in Figure 2f) equally deep ionospheric depressions poleward of 20°N.

[13] In Figure 3b, the local times of the electron density minima are given using solid and dotted curves to facilitate comparisons with the $N_{\text{max}}$ patterns in Figure 3a. The lowest $N_{\text{max}}$ values occur just before sunrise (i.e., 06 LT at all latitudes for Voyager’s equinox case, and from ~03 to 09 LT for the Cassini’s solstice case). For the Voyager case, the near-equatorial ionospheric hole also extends into the daytime period (see Figure 2b). Since only high frequency SEDs were seen during the daytime hours, we propose that the trough structure was just too narrow for radio penetration at low frequencies, or that daytime lightning did not occur precisely below the trough, or it
did not have low frequencies. Clearly, detailed ray-tracing simulations are needed to resolve such cases, and these are planned. Observations and modeling are also needed of the source mechanisms for lightning on gas giant planets [e.g., Little et al., 1999; Ingersoll et al., 2000].

[14] The overall message to come from Figure 3 is that electron density values nearly an order of magnitude lower than those for an unshadowed Saturn can account for the low frequency SED events detected by Voyager at nighttime. This is consistent with the fact that the Voyager radio receiver had no stringent directional constraints to satisfy. Thus, the ionospheric depletions near the equator contributed the low frequency cut-off attributed to the nighttime ionosphere. For the Cassini case, there is clearly no problem finding regions of low electron density at all LTs in the northern hemisphere. A broad spectrum of SEDs should therefore be seen if lightning occurs in the northern hemisphere. Yet, early in its mission, Cassini has been near 16–17°S where the ionosphere is robust. If SED signatures are not routinely observed [Garnett et al., 2005], then one might well conclude that sources of lightning are not prominent at high latitudes [Kaiser et al., 2004]. If SEDs came directly from sub-satellite latitudes, Figure 2 shows that the summer solstice ionosphere would only allow penetration at f > 1 MHz.

[15] The second half of the SED dilemma deals with the high end of the SED spectrum, i.e., that daytime detections at 3–5 MHz correspond to \( \sim 1 \times 10^5 \) e/cm\(^3\). This remains a difficult problem for modelers. Moore et al. [2004] showed results for twelve possible diurnal variations of \( N_{\text{max}} \) at a latitude unaffected by ring shadowing. As described in their Table II, the elimination of the key reaction between H\(^+\) and vibrationally excited H\(_2\) has the largest impact on the overall loss process, moving daytime values of \( N_{\text{max}} \) at noon in the nominal model from \( 1.9 \times 10^4 \) to \( 1.6 \times 10^5 \) e/cm\(^3\). The long-standing problem with that adjustment is that the ionosphere is dominated by atomic ions that hardly suffer any recombination during the brief Saturn night, effectively eliminating a diurnal variation all together.

[16] The STIM simulations in Figures 2 and 3 used the latest SOLAR2000 irradiance model (v.2.25), one that yields even lower daytime electron densities than described by Moore et al. [2004]. In Figure 4, two diurnal patterns are shown to demonstrate the effects of enhanced loss by the H\(^+\)-vibrationally-excited reaction. The curves in green give the diurnal patterns for H\(^+\) and H\(_3^+\) (and their sum to give total electron density) at the ionospheric peak with this process included. For the red curves (without enhanced loss), the H\(_2\) abundances are an order of magnitude lower, and thus the diurnal pattern is dominated by the essentially constant H\(^+\) values throughout the day. The conclusion to be drawn is that strong avenues of enhanced chemical loss may not be needed to satisfy a pronounced SED variation versus local time. With ring shadowing taken into account, portions of the planet can have \( N_{\text{max}} \) values considerably lower than typical daytime values by means other than strong recombination chemistry over vast regions of the planet. Enhanced loss rates from an influx of H\(_2\)O or from the H\(_2\) vibrational loss process might then be reduced from their most robust formulations, thereby leading to a resolution of the long-standing inconsistency between SED observations and modeling of Saturn’s ionosphere.

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J. Clarke, M. Mendillo, and L. Moore, Center for Space Physics, Boston University, Boston, MA 02215, USA. (mendillo@bu.edu)

M. L. Kaiser, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA.

W. S. Kurth, Department of Physics and Astronomy, University of Iowa, Iowa City, IA 52242, USA.

I. Mueller-Wodarg, Department of Physics and Astronomy, Imperial College, London SW7, UK.