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Are plasma depletions in Saturn's ionosphere a signature of time-dependent water input?

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[1] Recent radio occultation measurements by the Cassini spacecraft reveal the presence of numerous "ionospheric holes", or plasma depletions, in Saturn's upper atmosphere that cannot be explained with standard photochemical theory. The holes are remarkably similar in size and shape to artificially-created depletions first observed in the terrestrial ionosphere during the 1970s. At Earth, such vertical structures are typically caused by the enhanced loss of electrons and ions resulting from the introduction of spacecraft exhaust products (e.g., H_2O) into the atmosphere. Using a new model of Saturn's upper atmosphere, we show that a time-variable influx of water into Saturn's ionosphere could explain the observed plasma depletions. The required influxes present a target to assess for the possible sources and consequences of water processes throughout the Saturnian system. **Citation:** Moore, L., and M. Mendillo (2007), Are plasma depletions in Saturn's ionosphere a signature of time-dependent water input?, *Geophys. Res. Lett.*, *34*, L12202, doi:10.1029/2007GL029381.

1. Introduction

[2] Early theoretical calculations of Saturn's ionosphere [e.g., *McElroy*, 1973; *Capone et al.*, 1977, *Waite*, 1981] were shown by Pioneer 11 and Voyager radio occultation measurements of electron density to be too large by an order of magnitude [*Atreya et al.*, 1984]. This density excess was the result of models that favored a proton-dominated ionosphere that varied little in local time, an effect that could be remedied by a method to convert the long-lived H^+ ions into short-lived molecular ions. Two such mechanisms were proposed: (1) a reaction between protons and molecular hydrogen – which would occur only for vibrational levels 4 and higher [*McElroy*, 1973], and (2) a charge-exchange between H^+ and water group molecules streaming into the atmosphere from Saturn's rings and/or icy satellites [*Connerney and Waite*, 1984].

[3] Between 2 May and 5 September 2005, Cassini's Radio Science Subsystem (RSS) recorded twelve ionospheric radio occultations [*Nagy et al.*, 2006], representing the first new data for Saturn's ionosphere in nearly 25 years. While the six Pioneer and Voyager measurements spanned equatorial to polar latitudes over a period of two years [*Atreya et al.*, 1984], the twelve Cassini measurements are all within 10° of Saturn's equator and are separated by only a few months in time. Yet, curiously, the Cassini electron density profiles are just as variable, with highly unusual vertical structures dominating over any underlying average, making each profile just as atypical as the others. A particularly puzzling aspect of the Cassini radio occultation measurements is the presence of sharp layers of dramatically reduced plasma density near the ionospheric peak. A good example of such a profile is shown for the dawn measurement on 3 May 2005 in Figure 1a. Other Cassini observations at both dawn and dusk reveal more complicated vertical electron density structures, frequently with multiple regions of depleted plasma [*Nagy et al.*, 2006].

[4] Current models predict an ionosphere dominated by H^+, but with H_3^+ ions playing an important role as a diurnally-varying component near and below the height of peak electron density [*Majeed and McConnell*, 1996; *Moses and Bass*, 2000; *Moore et al.*, 2004]. Recently, *Moore et al.* [2006] succeeded in reproducing the average Cassini radio occultation measurements at dawn and dusk by using a constant background water influx of 5×10^6 H_2O molecules cm^{-2} sec^{-1}, along with a significantly reduced rate for the proton reaction with vibrationally-excited molecular hydrogen, $H^+ + H_2(\nu \geq 4) \rightarrow H + H_2^+$. Thus, it seems likely that the exogenic water influx first proposed decades ago [*Connerney and Waite*, 1984] indeed plays a major role in maintaining a reduced electron density at Saturn by enhancing the atomic-to-molecular conversion rate. This study explores the ionospheric implications of a time variable water flux for the first time, and also seeks to provide an explanation for the remarkable ionospheric holes observed at Saturn.

2. A Terrestrial Analog

[5] There are several methods by which an ionospheric "hole" can be created: (a) conversion of atomic to molecular ions that rapidly recombine with electrons [e.g., *Mendillo et al.*, 1975], (b) direct attachment of electrons to materials with a high electron affinity [e.g., *Bernhardt*, 1987], and (c) localized heating that produces an expansion of plasma out of the heated region [e.g., *Bernhardt et al.*, 1989]. We now explore method (a) in more detail, as it is the mechanism most likely to be acting in Saturn's ionosphere.

[6] Earth's ionosphere is dominated by the long-lived atomic ion O^+ near the peak. If O^+ is rapidly converted into a short-lived molecular ion by some artificial and localized method then an ionospheric hole will result [e.g., *Mendillo et al.*, 1987]. Several molecules (e.g., H_2, H_2O, CO_2) have the property of reacting with O^+ at the kinetic rate, which is 2–3 orders of magnitude faster than the reaction rate between O^+ and the ambient F layer molecules, N_2 and O_2. Therefore, following the introduction of any of these

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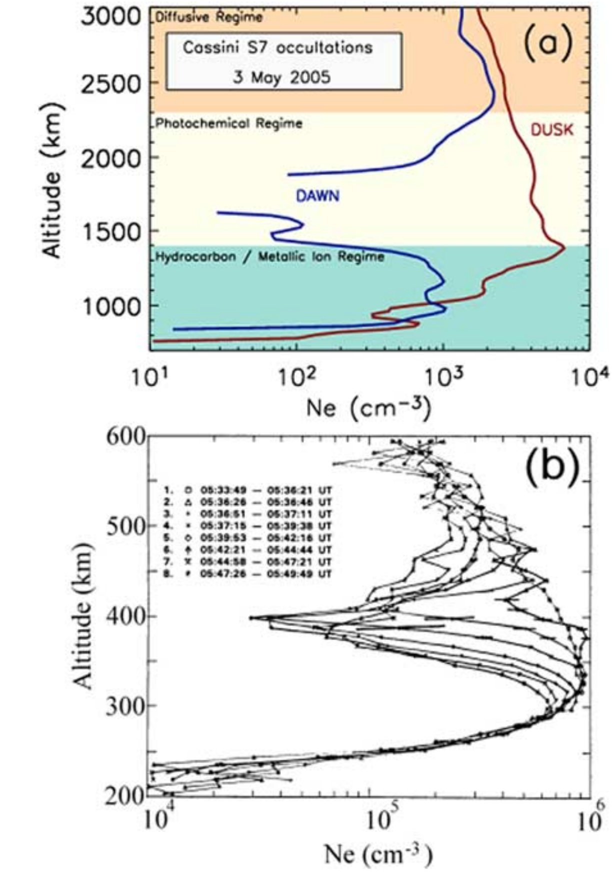

Figure 1. Unusual electron density profiles at Earth and Saturn. (a) The pair of dawn (blue) and dusk (red) profiles from Cassini's S7 radio occultation measurements on 3 May 2005 [*Nagy et al.*, 2006]. Three altitude domains are identified by shading [*Moore et al.*, 2006]: a region of photochemical equilibrium, wherein ion production/loss rates are balanced (tan), a diffusive regime dominated by transport processes (orange), and a heavy ion regime dominated by hydrocarbon and/or metallic ions (light blue). (b) Terrestrial profiles demonstrating the formation of an "ionospheric hole" in response to exhaust gases from the launch of NASA's HEAO-C satellite [*Wand and Mendillo*, 1984].

"hole-making" molecules into the Earth's F layer, rapid electron loss occurs [*Mendillo*, 1988; *Bernhardt et al.*, 1988].

[7] One of the most dramatic examples of a man-made terrestrial ionospheric hole is the factor-of-thirty reduction in electron density that was observed after the launch of NASA's HEAO-C satellite by an Atlas/Centaur rocket on 20 September 1979 [*Wand and Mendillo*, 1984]. In that experiment, the Millstone Hill incoherent scatter radar was used to measure vertical electron density profiles following the launch vehicle's release of 9.8×10^{26} H_2O molecules/s. Figure 1b shows the time-evolution of the Earth's ionosphere for this event. Prior to launch, the terrestrial ionosphere was observed to be relatively stable and smooth. However, subsequent profiles demonstrate a very rapid and expanding depletion in F layer electron densities, consistent with the chemical processes described above.

3. Modeling Ionospheric Holes at Saturn

[8] It is possible to create ionospheric holes at Saturn in a process nearly identical to the terrestrial one, except that H^+ is the initial dominant ion, and not O^+. Charge exchange reactions between H^+ and H_2O^+, and the subsequent chemistry, lead to H_2O^+ and H_3O^+ ions, which recombine with electrons at a rate more than 1000 times faster than that of protons. Therefore, should a downward surge of water occur, it would lead to a correspondingly enhanced atomic-to-molecular conversion rate and, ultimately, to rapid ion-electron loss via dissociative recombination. At lower altitudes (below ~1500 km, Figure 1a), hydrocarbon and metallic ions are more dominant [e.g., *Moses and Bass*, 2000], and therefore the hole-making capabilities of bulges of water density are correspondingly reduced.

[9] In order to study quantitatively the effects of a sudden introduction of water into Saturn's ionosphere, we first turn to a three-dimensional, time-dependent neutral gas diffusion model originally developed for Earth [*Bernhardt*, 1979]. This analytical formulation is easily adapted to Saturn, provided we can reliably estimate the background atmosphere. Neutral atmospheric parameters are taken from the new Saturn-Thermosphere-Ionosphere-Model (STIM), a global circulation model (GCM) of Saturn's upper atmosphere. Specifically, model simulation S7 from Table 1 of *Müller-Wodarg et al.* [2006] is used, except for solstice rather than equinox. Therefore, water diffusion calculations act upon a self-consistent neutral atmospheric structure that is derived from solar, gravity wave and joule heating inputs. Once the water density as a function of time and altitude is known, time-dependent ionospheric calculations can be applied in order to determine the effect of the water on Saturn electron densities [*Moore et al.*, 2004, 2006].

[10] In addition to the point-source gas diffusion model developed by *Bernhardt* [1979], 1D time-dependent neutral water diffusion calculations are performed with the STIM thermosphere using a constant flux at the topside as the boundary condition. As discussed by *Moore et al.* [2006], other neutral constituents are held constant while H_2O diffuses according to a solution of its continuity equation. Results and comparisons from these two methods of calculating water diffusion are presented in Section 4.

[11] For this study, an empirical model of solar EUV and UV radiation, EUVAC [*Richards et al.*, 1994a, 1994b], is used to drive the thermospheric GCM as well as ionospheric calculations. We use a background water flux of 5×10^6 cm^{-2} sec^{-1} [*Moore et al.*, 2006], and the reaction between H^+ and vibrationally excited H_2 (called k_1) is set at 25% the nominal value [*Moses and Bass*, 2000; *Moore et al.*, 2004]. The nominal k_1 rate is 7.5×10^{-14} cm^{-3} sec^{-1} above 2000 km; below 2000 it decreases approximately linearly from 7.5×10^{-14} cm^{-3} sec^{-1} to 1×10^{-16} cm^{-3} sec^{-1} at 800 km.

4. Results and Discussion

[12] The STIM background neutral atmosphere, along with the time-evolution of a bulge of water density resulting

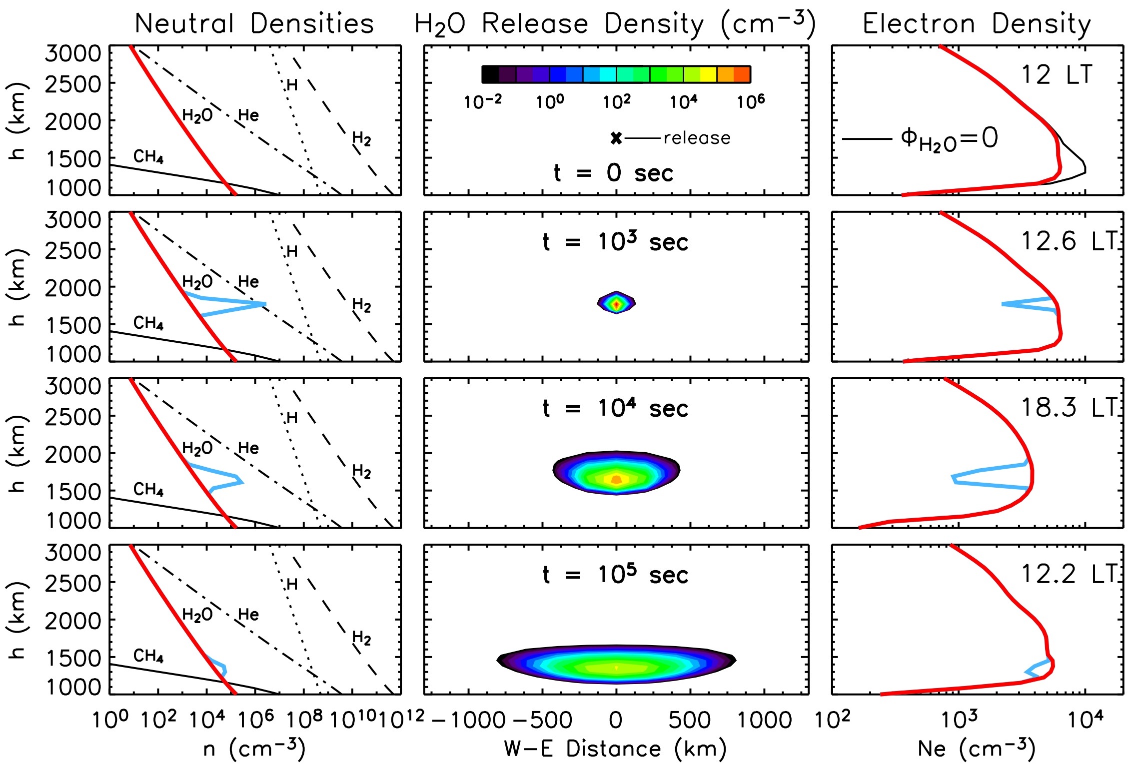

Figure 2. Time-evolution of a water release simulation at Saturn, and its ionospheric consequences. The parameters shown are (left) ambient neutral densities, (middle) water release density, and (right) electron density. Neutral gas and electron density profiles are color-coded black, red and blue: (1) black gives the over-dense ionosphere in the absence of water, (2) red corresponds to model calculations that use a constant background water influx of 5×10^6 H_2O molecules sec^{-1} [*Moore et al.*, 2006], and (3) blue shows the results of a release of 4×10^{27} H_2O molecules at 1750 km at local noon in addition to the constant background source.

from a point-source release at Saturn, is shown in the left column of Figure 2. In the middle column, the vertical and horizontal patterns of water diffusion from the release are plotted. Finally, the right column depicts the reaction of Saturn's ionosphere to the surge of water density. From Figure 2, we can see that the time-dependent effect of such a water burst in Saturn's ionosphere is dramatic, leading to a factor of ∼5 reduction in electron density in only ∼3 hours (10^4 seconds). The reduced electron densities linger for at least two Saturn days (10^5 seconds), meaning that multiple regions of reduced electron density would result if additional water injections were to occur within that time frame. Such point source releases are used to demonstrate the characteristic scales of diffusion and chemistry; calculations that describe a non-localized time-dependent water influx are discussed below.

[13] Cassini's S7 occultations (Figure 1a) reveal a relatively smooth electron density profile at dusk, followed by a dawn profile with an electron density reduced by roughly a factor of eight. In Figure 2, model calculations predict a similar reduction in electron density in terms of magnitude and location 10^4 seconds (∼3 hours) after a simulated water injection. One hour of local time (LT) on Saturn is approximately 1600 seconds; a 3 hour time frame corresponds to ∼6 Saturn LT hours (1/4 day). Therefore, a water release that occurred near local midnight would produce a plasma depletion close to that observed at dawn. Results from such a diurnal model simulation are presented in Figure 3. Figure 3a shows the local time pattern of electron density at 1750 km resulting from model calculations that include a constant background source suddenly augmented by a water injection [*Moore et al.*, 2006; *Bernhardt*, 1979]. The lower panels give electron density profiles at four specified times. Shortly after the water release, there is a precipitous reduction in electron density, followed by a slight recovery near dawn (Figure 3d). By dusk – 18 Saturn hours after the release – most of the water has diffused to lower altitudes, and the 1750 km electron density (Figure 3e) is nearly equivalent to the pre-release value. By allowing a sudden injection of water into Saturn's atmosphere, the model is able to produce ionospheric structures similar to those observed by Cassini (Figures 3c and 3d).

[14] Thus far we have examined a time-variable flux using a point-source release to approximate what may, in reality, be a brief alteration of the planetary background water influx. However, after a few hundred seconds, calculations show that a point-source release is nearly impossible to distinguish from any variation in background water source, especially if electron density measured at dawn or dusk provides the only diagnosis. The ionospheric signature of a time-variable water influx depends critically on the total number of molecules introduced (i.e., magnitude and duration of increased flux), and on the length of time a bulge of water density is resident near the electron density peak before an observation is made. In other words, a dramatic surge occurring minutes before the measurement could be

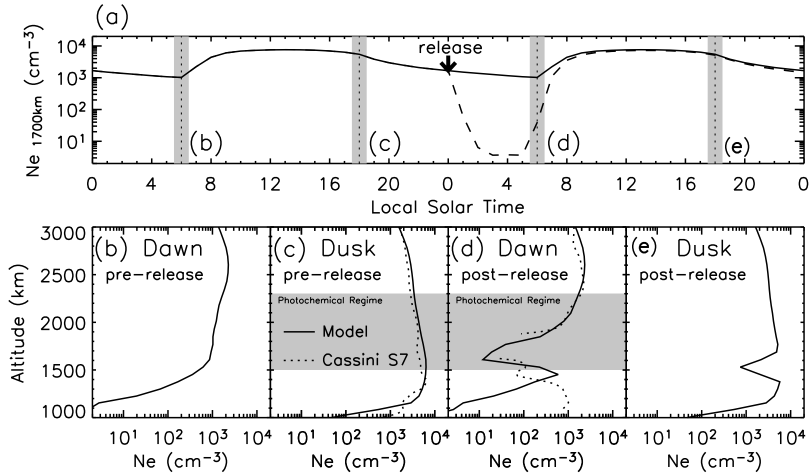

Figure 3. Model calculations illustrating a water release scenario in Saturn's ionosphere. (a) Electron density at 1750 km altitude for calculations that do (dashed line) and do not (solid line) include a water release at 1750 km at midnight. Corresponding electron density altitude profiles are shown below for four identified times. (b, c) Model results prior to the water release. (d, e) Model results after the release. Cassini radio occultation data [*Nagy et al.*, 2006] from the S7 observation pair (dotted lines) appear in panels (c) and (d) for comparison with the model within the photochemical regime (shaded).

indistinguishable from a moderate surge occurring hours before the measurement.

[15] Simulations using a time-variable topside water influx confirm, in general, the non-uniqueness of a water surge solution at Saturn. For example, Figure 4 presents the time evolution of water density for a background flux of 5×10^6 H_2O cm^{-2} sec^{-1} that is increased to 2.5×10^8 H_2O cm^{-2} sec^{-1} (a factor of 50 increase) for ~27 minutes before returning to its initial value. The resulting bulge of water density that is present 10^4 seconds after the onset of the surge is quite similar to the bulge that results from a point-source release in Figure 2, and will produce a nearly identical ionospheric depletion. If the background water flux were instead only increased to 1×10^7 H_2O cm^{-2} sec^{-1} – but one hour earlier – then the depletion would again be similar. A point-source release of water that occurred at a higher altitude than 1750 km could produce another identical depletion; only the number of molecules released and the time of the release would need to be altered. In general, the magnitude of a water-induced plasma density reduction is dictated by the amount and duration of the water density increase. Therefore, we argue here that brief surges of water influx can produce ionospheric structures similar to those observed by Cassini, but do not yet attempt to specify unique characteristics or specific sources of the water flux.

[16] It should be noted that model comparisons with radio occultation measurements are not the only possible way to identifying water-induced plasma depletions in Saturn's ionosphere, if they are present. For example, airglow at 306.4 nm from the dissociative recombination of H_2O^+ and H_3O^+ should be present in ionospheric hole regions [*Bernhardt*, 1987]. In addition, energetic particles streaming into Saturn's atmosphere will produce fast ion beams that would lead to ion-acoustic waves via a two-stream process

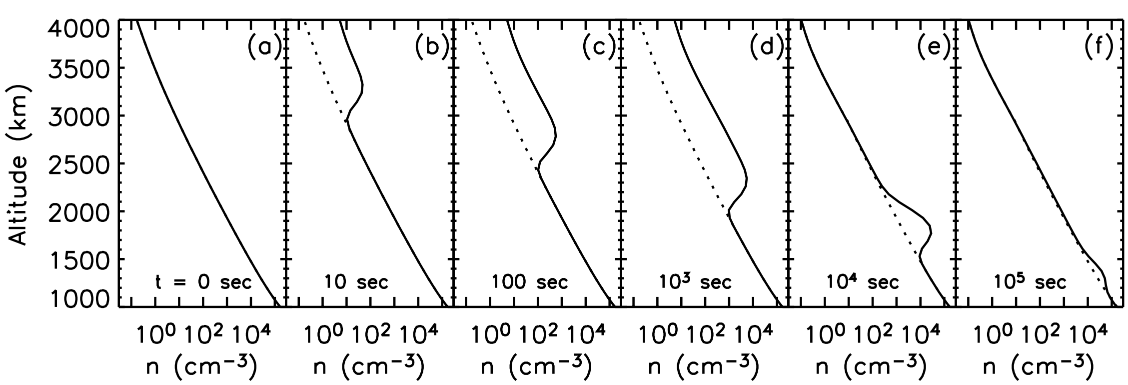

Figure 4. A time-variable topside water flux simulation. (a) The background water density, resulting from a topside flux of 5×10^6 cm^{-2} s^{-1}, also plotted in panels (b) through (f) as a dotted line. At $t = 0$ the background flux is augmented by a factor of 50 for 1600 seconds (~27 minutes). (b, c, and d) The downward diffusion of water resulting from such an increase in the topside boundary condition. Shortly after panel (d), the flux is reduced to its initial value of 5×10^6 cm^{-2} s^{-1}, and the only remnant of the period of flux increase is (e, f) the bulge of water density.

[see *Bernhardt et al.*, 2005]. Such waves should be detectable by Cassini's Radio and Plasma Wave Science (RPWS) instrument.

[17] Taken together, Figures 1, 2 and 3 offer a modeling scenario of how water vapor can affect Saturn's ionosphere: (1) a constant downward influx of water into Saturn's atmosphere will reduce modeled electron densities as well as raise the altitude of the peak electron density [*Majeed and McConnell*, 1991; *Moore et al.*, 2006] (Figure 2) and (2) an additional time-variable flux can lead to transient bulges in the water density profile that create localized regions of significantly reduced plasma density within Saturn's ionosphere (Figures 3 and 4). When a water influx was first offered as a mechanism to resolve the over-dense aspect of Saturn's ionosphere [*Connerney and Waite*, 1984], no clear evidence was available to support it. Today, there is certainly evidence for water within Saturn's magnetosphere [*Waite et al.*, 2006; *Esposito et al.*, 2005] and atmosphere [*Feuchtgruber et al.*, 1997; *Prangé et al.*, 2006]. Our point-source water release simulations are equivalent to an augmentation in the background water flux by a factor of $\sim$50 for a few tens of minutes, consistent with previous estimates and measurements [*Connerney and Waite*, 1984; *Moore et al.*, 2006]. Additionally, our results support a neutral rather than ion water source, at least for the recent Cassini observations [*Nagy et al.*, 2006], which are all at near-equatorial latitudes where the horizontal magnetic field prohibits plasma inflow. What remains unclear at present, however, is a comprehensive understanding of the source for the water influx at Saturn, and the time-variability of that water source. Further measurements are needed to address these questions, and Cassini offers a good chance of providing definitive observations of Enceladus and Saturn's rings as possible sources.

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