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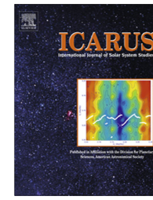

Saturn ring rain: Model estimates of water influx into Saturn's atmosphere

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A B S T R A C T

Recently H_3^+ was detected at Saturn's low- and mid-latitudes for the first time (O'Donoghue et al. [2013]. Nature 496(7444), 193–195), revealing significant latitudinal structure in H_3^+ emissions, with local extrema in one hemisphere mirrored at magnetically conjugate latitudes in the opposite hemisphere. The observed minima and maxima were shown to map to regions of increased or decreased density in Saturn's rings, implying a direct ring–atmosphere connection. Here, using the Saturn Thermosphere Ionosphere Model (STIM), we investigate the "ring rain" explanation of the O'Donoghue et al. (O'Donoghue et al. [2013]. Nature 496(7444), 193–195) observations, wherein charged water group particles from the rings are guided by magnetic field lines as they "rain" down upon the atmosphere, altering local ionospheric chemistry. Based on model reproductions of observed H_3^+ variations, we derive maximum water influxes of $(1.6–16) \times 10^5$ H_2O molecules $cm^{-2}\,s^{-1}$ across ring rain latitudes (~23–49° in the south, and ~32–54° in the north), with localized regions of enhanced influx near −48°, −38°, 42°, and 53° latitude. We estimate the globally averaged maximum ring-derived water influx to be $(1.6–12) \times 10^5\,cm^{-2}\,s^{-1}$, which represents a maximum total global influx of water from Saturn's rings to its atmosphere of $(1.0–6.8) \times 10^{26}\,s^{-1}$. The wide range of global water influx estimates stems primarily from uncertainties regarding H_3^+ temperatures (and consequently column densities). Future ring rain observations may therefore be able to reduce these uncertainties by determining H_3^+ temperatures self consistently.

1. Introduction

1.1. Water in Saturn's ionosphere

A source of exogenous water has long been inferred at Saturn, particularly as a means to reduce calculated ionospheric densities in order to reproduce observed values. Early Saturn ionospheric models (e.g., McElroy, 1973; Capone et al., 1977) predicted electron densities an order of magnitude larger than those later measured by the Pioneer 11 and Voyager spacecraft (Kliore et al., 1980; Kaiser et al., 1984; Lindal et al., 1985). One chemical effect of introducing oxygen bearing compounds into Saturn's upper atmosphere is to convert H^+ – a long-lived major atomic ion in outer planet ionospheres – into a short-lived molecular ion that quickly dissociatively recombines, thereby reducing the net electron density.

While a number of modeling studies have been able to derive a range of water influxes that adequately explain the Pioneer and Voyager radio occultation measurements (e.g., Connerney and Waite, 1984; Majeed and McConnell, 1991, 1996), directly constraining the influxes observationally has proven more difficult. The first unambiguous direct detection of water in Saturn's upper atmosphere came from the Infrared Space Observatory (ISO; Feuchtgruber et al., 1997), which measured an H_2O column abundance of $(0.8–1.7) \times 10^{15}\,cm^{-2}$ and was used to derive a global water influx of $\sim 1.5 \times 10^6$ H_2O molecules $cm^{-2}\,s^{-1}$ (Moses et al., 2000). Subsequent studies based on Submillimeter Wave Astronomy Satellite and Herschel Space Observatory measurements found global influx values within a factor of 2 of the Moses et al. results (Bergin et al., 2000; Hartogh et al., 2011). Despite predictions of latitudinally varying water influxes (e.g., Connerney, 1986), no observational confirmation of such variations has been made to date, with only ambiguous detections of latitudinally varying water concentrations in the ultraviolet (e.g., a 2σ-detection of $2.70 \times 10^{16}\,cm^{-2}$ at 33°S latitude: Prangé et al., 2006), and preliminary indications of larger equatorial water densities from Cassini Composite InfraRed Spectrometer (CIRS) observations (Bjoraker et al., 2010).

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A counter-intuitive trend in electron density with latitude was revealed after the arrival of Cassini at Saturn, based on the 31 new radio occultation measurements published to date (Nagy et al., 2006; Kliore et al., 2009). Despite being near Saturn's equinox, with the sun directly overhead at low-latitudes, electron densities were found to be lowest at Saturn's equator and to increase with latitude, a behavior that Moore et al. (2010) were able to reproduce by introducing a water influx that peaked at Saturn's equator and decreased with latitude. Such a water influx profile is in agreement with predictions by models investigating the evolution of Enceladus' water vapor plumes (Jurac and Richardson, 2007; Cassidy and Johnson, 2010; Fleshman et al., 2012). While a ring-derived ionized influx may yet be present, there are only five published Cassini radio occultations at latitudes that map magnetically to Saturn's rings, and therefore there is insufficient latitudinal resolution in the electron density observations to clearly identify any of the expected local extrema that would result from possible ring-derived influxes.

1.2. Saturn ring rain observations

Recently H_3^+ was detected at Saturn's low- and mid-latitudes for the first time (O'Donoghue et al., 2013), revealing significant latitudinal structure in H_3^+ emissions, with local extrema in one hemisphere mirrored at magnetically conjugate latitudes in the opposite hemisphere. Furthermore, the observed minima and maxima were shown to map to regions of increased or decreased density in Saturn's rings, implying a direct ring–atmosphere connection. The H_3^+ ion has a relatively short chemical lifetime; its dominant loss process is dissociative recombination with electrons. While oxygen bearing compounds such as OH and H_2O have typically been introduced into models of Saturn's ionosphere as a means of reducing the electron density through charge exchange with H^+, they also impact H_3^+ densities, primarily by reducing dissociative recombination rates. Therefore, the sharp latitudinal structures observed by O'Donoghue et al. (2013) – which cannot be explained by solar ionization effects – likely represent a proxy for external oxygen influxes (Connerney, 2013). Here, using the Saturn Thermosphere Ionosphere Model (STIM), we estimate the upper limits for ring-derived atmospheric ion influxes implied by the ring rain observations, and we use those values to derive lower limits on ring mass loss rates.

2. Methods

2.1. Ring ion influx

Saturn's rings are composed primarily of water ice bodies (e.g., Cuzzi et al., 2010 and references therein) between 1 cm and 20 m in size (Zebker et al., 1985; French and Nicholson, 2000). Solar UV photon-induced decomposition of ice leads to the production of an O_2 ring atmosphere, which can accumulate both above and below the ring plane due to a long lifetime and frequent interactions with ring particles (Johnson et al., 2006). Two Cassini instruments detected a ring ionosphere during Cassini's orbital insertion in 2004, finding evidence of O^+ and O_2^+ ions (Tokar et al., 2005; Waite et al., 2005), likely the result of photoionization of O_2. Models of Saturn's ring ionosphere support the dominance of O^+ and O_2^+, and further find that within the radius where Keplerian and corotation velocities are equal in the ring plane, $\sim 1.8R_S$, ring ions spiral along magnetic field lines and precipitate into Saturn's atmosphere with near unit efficiency. Outside of this radius initially trapped ions can also later be scattered into the loss cone (Luhmann et al., 2006; Tseng et al., 2010). Therefore, as O_2^+ and O^+ are the dominant ring ionosphere ions, they are also the ring-derived ions most likely to precipitate into Saturn's atmosphere.

As O_2^+ ions dissociatively recombine with electrons extremely rapidly – roughly three times faster than H_3^+ ions in Saturn's ionosphere – any precipitating O_2^+ will lead to a chain of photochemical reactions that produce primarily OH (via $O + H_2$) and H_2O (via $OH + H_2$) in the thermosphere and lower atmosphere (e.g. Moses et al., 2000). An influx of H_2O or H_2O^+ would lead to similar chemistry, as the products of dissociative recombination reactions between H_3O^+ (formed rapidly from H_2O^+) and electrons include OH and H_2O. In other words, an external flux of neutrals (e.g., H_2O) or ions (e.g., O_2^+) can lead to similar number densities of oxygen-bearing molecules in Saturn's atmosphere, and it is these molecules that charge-exchange with H^+. The subsequent rapid dissociative recombination of the resulting charge-exchange products (e.g., H_3O^+) then leads to the required reduction in Saturn's electron densities and the subsequent decrease in H_3^+ chemical loss rates. The most important remaining distinction between ionized and neutral influxes is their deposition latitude, as ions are constrained to precipitate along magnetic field lines. Therefore, in order to maintain consistency with previous Saturn ionospheric literature, we treat the ring rain influx inferred from H_3^+ observations here as a "water" influx. In this way derived fluxes can be compared directly with previous results, and the language of this text is simplified. Finally, it should be noted that water from Saturn's rings may also be more efficiently transported in the form of charged sub-micrometer grains rather than ions (e.g., Connerney, 2013), a possibility that remains to be evaluated.

2.2. Temperatures in Saturn's upper atmosphere

The observations of O'Donoghue et al. (2013) report the intensity of H_3^+ emission (in $nW\,m^{-2}$) versus planetocentric latitude. (All latitudes quoted in this manuscript are planetocentric unless specified otherwise.) In order to compare those observations with model results, a conversion between intensity and vertical column content is required. Typically, the intensity of two or more discrete ro-vibrational spectral lines of H_3^+ can be used to determine its temperature and subsequently its density (Miller et al., 2000). The O'Donoghue et al. observations unfortunately lacked sufficient signal-to-noise to carry out such a derivation. Therefore, in order to estimate the H_3^+ temperatures that correspond with the ring rain observations, we follow a three step process: (1) determine the most realistic representation of the behavior of neutral exospheric temperature with planetocentric latitude, $T_{exo}(\phi_{pc})$, based on ultraviolet solar and stellar occultations; (2) use STIM to find the temperature differential between the exobase and the altitude of H_3^+ ions (typically $\sim$2700–3000 km and $\sim$1200 km above the 1 bar pressure level at Saturn, respectively); and (3) apply the STIM temperature differential to a functional form of $T_{exo}(\phi_{pc})$ (see below), yielding neutral temperature predictions at H_3^+ altitudes, $T_{H_3^+}(\phi_{pc})$.

Early Voyager analyses of solar and stellar occultations suggested that Saturn's exospheric temperature could be as high as 850 K (Broadfoot et al., 1981; Festou and Atreya, 1982). However, subsequent Voyager 2 reanalyses found a temperature closer to 420 K (Sandel et al., 1982; Smith et al., 1983), a value also supported by modern reanalyses of occultations by both Voyager spacecraft (Vervack and Moses, submitted for publication). Given the limited number of Voyager observations and the uncertainties in analyzing them, it was not possible to use them to construct a complete latitudinal trend for Saturn upper atmospheric temperatures. However, recent analyses of 15 solar (Koskinen et al., 2013) and 3 stellar (Shemansky and Liu, 2012) occultations by Cassini, in combination with previous Voyager results, now allow for a more realistic estimate of the behavior of upper atmosphere temperature with latitude.

Fig. 1 presents the upper atmosphere temperature measurements described above (aside from the values above 800 K), as well