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An assessment and test of Enceladus as an important source of Saturn's ring atmosphere and ionosphere

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ABSTRACT

The existence of an oxygen exosphere and ionosphere in Saturn's main ring region has been confirmed by the Saturn Orbital Insertion (SOI) observations of the Cassini spacecraft. Through the ion–molecule collisions, the ring atmosphere could serve as a source of O_2^+ ions throughout Saturn's magnetosphere. If photolysis of ice in the main rings is the dominant source of O_2, then the complex structure of the ring atmosphere/ionosphere and the injection rate of neutral O_2 will be subject to modulation by the seasonal variation of Saturn along its orbit (Tseng, Wei-Ling, Ip, W.-H., Johnson, R.E., Cassidy, T.A., Erlod, M.K. [2010]. Icarus 206, 382–389). In addition, the radio and plasma wave science (RPWS) instrument onboard Cassini found that a large amount of the Enceladus-originated water-group plasma would be deposited on the outer edge of the A ring (Farrell, W.M., Kaiser, M.L., Gurnett, D.A., Kurth, W.S., Persoon, A.M., Wahlund, J.E., Canu, P. [2008]. Geophys. Res. Lett. 35, L02203). A large amount of Enceladus' plume neutrals (water-group neutrals) would collide with the main rings through collisional interaction with the ambient neutrals and plasma ions (Jurac, S., Richardson, J.D. [2007]. Geophys. Res. Lett. 34, L08102; Cassidy, T.A., Johnson, R.E. [2010]. Icarus, in press). These absorbed ions and neutrals could be recycled to neutral oxygen molecules via grain-surface chemistry to contribute the ring oxygen atmosphere. In this work, we have examined the mass budget of the ring oxygen atmosphere of Saturn taking into account such an "exogenic" source. The maximum O_2 source rate from recycling of Enceladus-originated plasma and neutrals is probably comparable or higher to the one from photolytic decomposition of ices. In the above case, the neutral O_2 source rate would be independent of the solar insolation angle. Therefore, even at Saturn's Equinox, the extended oxygen atmosphere still could be an important supplier of oxygen ions in the saturnian magnetosphere. We have performed several studies for different recycling source rates from Enceladus. These predictions need further the Cassini Plasma Spectrometer (CAPS) and the Magnetospheric Imaging Instrument (MIMI) observations to be verified in future.

1. Introduction

During SOI, measurements by both the Cassini Plasma Spectrometer (CAPS) and the Ion and Neutral Mass Spectrometer (INMS) showed the presence of oxygen atomic and molecular ions above the main rings (Young et al., 2005; Tokar et al., 2005; Waite et al., 2005). These detections confirmed the formation of the ring atmosphere and ionosphere whose existence has been proposed for a long time (Carlson, 1980; Ip, 1984, 1995, 2005; Pospieszalska and Johnson, 1991; Johnson and Quickenden, 1997; Johnson et al., 2006).

A number of theoretical works have subsequently been carried out to model the structure of the ring atmosphere and ionosphere (Ip, 2005; Johnson et al., 2006; Luhmann et al., 2006; Bouhram et al., 2006; Tseng et al. 2010). To explain the vertical extension of the O_2^+ ions, Johnson et al. (2006) invoked the momentum transfer effect in charge exchange collisions between the oxygen ions and molecules near the ring plane. This process is also important in scattering oxygen molecules (and atoms) into Saturn's upper atmosphere and the outer magnetosphere. Therefore, Martens et al. (2008) suggested that the O_2^+ ions detected by CAPS for $L = 4.5–10$ may have originated from the ring atmosphere. In addition, an O_2 atmosphere at Rhea indicated by Martens et al. (2008) has been confirmed by the INMS observations during the Rhea flyby in March 2010 (Teolis et al., 2010).

During the SOI time period when the Sun was below the ring plane at an incident angle of 24°, the total O_2 photolytic production rate was estimated to be 1.0×10^{26} molecules s^{-1} according to the laboratory measurements of the O_2 photolytic production rate from ice of $S(O_2) \sim 10^6$ molecules $cm^{-2}\ s^{-1}$ (Johnson et al., 2006). Detailed Monte-Carlo model calculations showed that the atmospheric precipitation rate of the O_2 molecules should be about 1.4×10^{25} molecules s^{-1} and the corresponding injection rate into

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the magnetosphere to be $\sim 2.4 \times 10^{25}$ molecules s^{-1} (Tseng et al., 2010). The fragments such as O, OH, O^+ and O_2^+ could be deposited on the icy grains and converted to neutral O_2 via grain-surface chemistry. Such recycling effect could be very important to increase the O_2 production over the main rings (Ip, 1997). Both Johnson et al. (2006) and Tseng et al. (2010) estimated the recycling being as an enhanced factor of 5–10 from its photolytic fragments of the ring O_2 atmosphere. It is possible that the scattered oxygen molecules of ring origin serve as a major source for the O_2^+ ions detected by the MIMI and CAPS experiments (Kirimigis et al., 2006; Martens et al., 2008). During the Equinox condition when the ring plane is seen edge-on from the Sun (such as in 2009), the solar irradiation effect should be at minimum. It is likely that the ring atmosphere will be highly depleted in this time interval (Tseng et al., 2010). This means that the population of energetic O_2^+ ions should display a seasonal variation if photosputtering is the source mechanism of the O_2 molecules.

Another important source of gas in the saturnian system are the water plumes emitted from the south pole of the icy satellite Enceladus (Waite et al., 2006; Porco et al., 2006; Hansen et al., 2006). Before the Cassini observations, the existence of a continuous supply of water gas molecules in the saturnian system has been indicated by HST measurements by Shemansky and Hall (1992) and Shemansky et al. (1993) which indicated the presence of a cloud of OH in the inner satellite system. The plasma observations of thermal plasma in the inner saturnian magnetosphere detected an extended plasma disk of heavy ions (Bridge et al., 1981, 1982; Richardson and Sittler, 1990). Theoretical models investigating the photochemical processes of the water-group neutrals (H_2O, OH, and O) and radial diffusion of ions (H_2O^+, OH^+, O^+, H_2^+, H^+ and H_3O^+) have been constructed to interpret the relation between the neutral gas cloud and the thermal plasma population (Ip, 1997, 2000; Jurac and Richardson, 2005).

The Cassini observations of the water plumes of Enceladus have confirmed the hypothesis that Enceladus must be the dominant source of the neutral gas. The copious production rate of 10^{28} $H_2O\ s^{-1}$ (Burger et al., 2007) is also in agreement with the theoretical estimate given by Jurac and Richardson (2005). On the basis of these exciting new developments, an emerging picture – as discussed below – is that the strong outgassing effect of Enceladus has control not only of the neutral cloud and plasma disc in the satellite system, but also of the ring atmosphere.

It is found that collisional interaction among the neutral H_2O and the thermal ions could lead to a significant dispersal of the neutral molecules (Johnson et al., 2006) such that about 17–30% ($\sim[1.7\text{–}3.0] \times 10^{27}$ $H_2O\ s^{-1}$) of the water molecules originating from Enceladus would collide with the main rings (Jurac and Richardson, 2007; Cassidya and Johnson, 2010). These authors suggested that such a collisional absorption effect of water molecules might explain the brightening of the outer A ring in comparison with the other parts of the ring system. Another important point is that the derived water deposit rate of 1.7×10^{27} $H_2O\ s^{-1}$ is higher than the putative photosputtering rate ($\sim 1.0 \times 10^{26}\ s^{-1}$) of O_2 molecules from the ring system. Note that in the Jurac–Richardson model, the OH number density near the A ring edge is comparable to that of H_2O. This means that if a fraction of the absorbed OH can be converted to O_2, it would constitute an important external source of the ring atmosphere.

In another related work of interest, Farrell et al. (2008) recently reported the Cassini RPWS finding that the Enceladus torus plasma is lost to ring absorption at the outer edge of the A ring at a rate of about 40 kg s^{-1}. Note that the chemical composition of the thermal population of the water-group ions has been modeled by Ip (2000). The relative abundances of the H_3O^+, H_2O^+, OH^+, O_2^+, and O^+ depend on the diffusion time scale, but model calculations indicated that the ion composition should be dominated by O^+, OH^+ and H_2O^+ ions. This suggests that if the O^+ and OH^+ ions are neutralized after absorption by the ring particles, the subsequent surface reactions like $O + O \rightarrow O_2$ and $O + OH \rightarrow O_2 + H$ will create a population of O_2 emerging from the outer A rings. The total injection rate combining both neutral gas and plasma loss rates is about $3 \times 10^{27}\ s^{-1}$ (Jurac and Richardson, 2005; Farrell et al., 2008). The recycling rate of neutral OH or O to neutral O_2 may be insufficient in a hydrogenated environment because the H and H_2 would hydrogenate them through $O + H \rightarrow OH$ and $OH + H \rightarrow H_2O$. But in fact, H_2 originating from the rings and its photolytic fragments is much easier to escape from the ring system since the scale height of the ring H_2 atmosphere is about 4 times of that of O_2 (Johnson et al., 2006). Another possibility is to form H_2O_2 on the icy grains which is stable at very low temperature $\sim$20 K. However, at ring temperature >90 K, H_2O_2 can be destroyed to form O_2 again (Johnson, private communication, 2010). Therefore, the question is what would happen if a significant fraction of the Enceladus gaseous material impinging on the outer A ring is converted to O_2.

In this work, a parameter study is performed to test if Enceladus is an important source of Saturn's ring atmosphere and ionosphere. With a 10% of Enceladus' plume material depositing on the rings, the source rate of Enceladus origin will be comparable to the maximum photolytic production rate from the rings themselves. The implications on the seasonal variations of the ring atmosphere and ionosphere and the corresponding injection rates of O_2 molecules into the saturnian magnetosphere are the main theme of this work. Section 2 outlines the model calculations based on our previous work (Tseng et al., 2010). Section 3 describes the major results on the structure of the ring atmosphere and ionosphere with different exogenic source strengths. The implications of the model ring atmospheres and the O_2 injection rates into the saturnian magnetosphere are considered in Section 4.

2. Model calculations

Along the line of the works by Luhmann et al. (2006) and Bouhram et al. (2006), Tseng et al. (2010) have produced a comprehensive Monte-Carlo model to construct the ring atmosphere and ionosphere. In this test particle code, O_2 molecules are emitted from the ring plane following a prescribed velocity distribution. Unlike the water molecules which have a high efficiency of recondensation, the oxygen molecules will continue to move around Saturn interrupted only by repeated collisions with the ring particles. The collisional probability is determined by the measured optical depth of the ring plane (Esposito et al., 1983). The O_2 molecules upon reimpact on the ring particles will be thermally accommodated in the sense that they will be emitted with the surface temperature of the ring particles. It is in this manner that a thin layer of oxygen atmosphere will be maintained. The thickness of this original population of the O_2 atmosphere is only $\sim$1000 km with a vertical scale height of $\sim$600 km. During the ballistic motion, O_2 molecules will be subject to photodissociation into oxygen atoms and photoionization into O_2^+ ions. The oxygen atoms are assumed to follow Keplerian orbital motion with the initial velocity boosted by the excess energy from photodissociation. On the other hand, the newly created O_2^+ ions will execute bouncing motion along the magnetic field as dictated by the Lorenz force and the planetary gravitational force. Momentum transfer via collision between the O_2 and O_2^+ populations will ensure the buildup of a thick disk of O_2 molecules. Detailed description of the numerical algorithm can be found in Tseng et al. (2010).

Accepting the view that a fraction of the neutral gas (O rich water-group fragments) and plasma of Enceladus origin absorbed by the A ring will be converted to O_2 molecules, we introduce a source region covering a radial width between 2.03 and 2.28R_S to