Planetary and Space Science 77 (2013) 126–135

Contents lists available at SciVerse ScienceDirect

Planetary and Space Science

journal homepage: www.elsevier.com/locate/pss

Modeling the seasonal variability of the plasma environment in Saturn's magnetosphere between main rings and Mimas

W.-L. Tseng *, R.E. Johnson, M.K. Elrod

University of Virginia, Charlottesville, VA 22904, USA

ARTICLE INFO

Article history:
Received 22 December 2011
Accepted 3 May 2012
Available online 11 May 2012

Keywords:
Saturn's rings
Plasma composition
Magnetosphere
Seasonal variability

ABSTRACT

The detection of O_2^+ and O^+ ions over Saturn's main rings by the Cassini INMS and CAPS instruments at Saturn orbit insertion (SOI) in 2004 confirmed the existence of the ring atmosphere and ionosphere. The source mechanism was suggested to be primarily photolytic decomposition of water ice producing neutral O_2 and H_2 (Johnson et al., 2006). Therefore, we predicted that there would be seasonal variations in the ring atmosphere and ionosphere due to the orientation of the ring plane to the sun (Tseng et al., 2010). The atoms and molecules scattered out of the ring atmosphere by ion–molecule collisions are an important source for the inner magnetosphere (Johnson et al., 2006; Martens et al., 2008; Tseng et al., 2010, 2011). This source competes with water products from the Enceladus' plumes, which, although possibly variable, do not appear to have a seasonal variability (Smith et al., 2010). Recently, we found that the plasma density, composition and temperature in the region from 2.5 to 3.5 R_S exhibited significant seasonal variation between 2004 and 2010 (Elrod et al., submitted for publication). Here we present a one-box ion chemistry model to explain the complex and highly variable plasma environment observed by the CAPS instrument on Cassini. We combine the water products from Enceladus with the molecules scattered from a corrected ring atmosphere, in order to describe the temporal changes in ion densities, composition and temperature detected by CAPS. We found that the observed temporal variations are primarily seasonal, due to the predicted seasonal variation in the ring atmosphere, and are consistent with a compressed magnetosphere at SOI.

Published by Elsevier Ltd.

1. Introduction

Saturn's oxygen ring atmosphere and ionosphere was discovered by the Cassini spacecraft in 2004. Both the Ion and Neutral Mass Spectrometer (INMS) and the Cassini Plasma Analyzer (CAPS) detected O_2^+ and O^+ ions over the main rings during the Saturn Orbital Insertion (SOI) in 2004 (Tokar et al., 2005; Waite et al., 2005) as well as a comparable component of electrons (Coates et al., 2005). Johnson et al. (2006) suggested that the primary source is photolytic decomposition of water ice producing neutral O_2 and H_2. The measurements also indicated that the ion–molecule collisions between the newly formed ions O_2^+/O^+ and neutral O_2 determined the ion density distribution detected by CAPS at high altitudes above the main rings. Using the photolytic model we also predicted that there would be significant seasonal variations in the density of the ring atmosphere and ionosphere since the neutral O_2 production rate depends on the solar incident angle with respect to the ring plane (Tseng et al., 2010). The ion–molecule collisions, which account for the observed vertical distribution, also scatter O_2, H_2, O and H beyond the ring plane into the magnetosphere and into Saturn's atmosphere. Once ionized, they are a source of O_2^+ and H_2^+ ions in the magnetosphere seen by Cassini Magnetospheric Imaging Instrument (MIMI) (Krimigis et al., 2005) and CAPS (Martens et al., 2008; Tseng et al., 2011). Therefore, the seasonal variations should also be reflected in the density of these ions in the region outside the main rings.

However, the suggested seasonal variations are complicated by the deposition of water products from the Enceladus' plumes onto the A-ring as described by measurements and modeling (Jurac and Richardson, 2007; Farrell et al., 2008; Cassidy and Johnson, 2010). As with the dissociated oxygen in the ring atmosphere, the absorbed oxygen rich ions and neutrals from the Enceladus torus could be recycled via grain-surface chemistry contributing to the atmosphere over the main rings and the atoms and molecules scattered into the magnetosphere (Tseng and Ip, 2011). Hansen et al. (2011) monitored the Enceladus plume activity using the Cassini Ultraviolet Imaging Spectrograph (UVIS) and found that they appeared to be stable. Although the INMS measurements suggested the source rate is variable (Smith et al., 2010), no seasonal variability was apparent. So, the Enceladus torus contribution to the ring atmosphere can mitigate the

* Corresponding author.
E-mail address: wt7b@virginia.edu (W.-L. Tseng).

0032-0633/$ - see front matter Published by Elsevier Ltd.
http://dx.doi.org/10.1016/j.pss.2012.05.001

seasonal variation in the ring atmosphere. Despite the uncertainties in the recycling efficiency, the non-detection (or upper limit) of H_2^+ ions over the B-ring by the Cassini CAPS at SOI has helped constrain the source rates (Tseng et al., 2011).

Elrod et al. (submitted for publication) examined the CAPS plasma data between 2.5 and 3.5 R_S from 2004 to 2010 including a comparison with Voyager 2 data from Richardson (1986) where R_S is one mean Saturn radius (60,300 km). They showed that there were large variations over that time period in the ion density, temperature and composition. A significant drop in the ion density and temperature was found between 2005 and 2010 as compared to Voyager 2 data and Cassini data at SOI (2004). They also found that the O_2^+ was the dominant heavy ion at SOI, but the O_2^+ density was comparable to or less than the water-group ion (hereafter referred to as W^+) density in the period of 2005–2010. Using preliminary results from the model described in detail here, they concluded that, although the possible variability in the Enceladus source might contribute, the observed variations were primarily seasonal due to the predicted seasonal variation in the ring atmosphere.

In this work, we developed a one-box ion chemistry model for the plasma in the region between 2.5 and 3.5 R_S to explain the complex and highly variable plasma environment that was detected by CAPS. First, an updated ring atmosphere model is described in Section 2, since this atmosphere is affected by the recently observed change in the ring particle temperatures from solstice to equinox which was absent in our earlier model (Tseng et al., 2010). In Section 3, our ion-chemistry model, combining the Enceladus torus and the seasonal ring atmosphere sources, is presented. The simulations are carried out for both SOI and equinox conditions and the results are in a remarkable agreement with the trends found in the CAPS data. In Section 4, we solved a set of continuity equations for the plasma energy in order to understand the low ion temperature detected after SOI. It is found that ion energy lost to momentum transfer during ion–molecule collisions can roughly account for decrease of ion temperature. Finally, a summary is given in Section 5.

2. Revised ring atmosphere model: neutral source rates of O_2 and H_2 at SOI and equinox

In our previous paper (Tseng et al., 2010), we studied the structure and time variability of Saturn's ring atmosphere and ionosphere using a fixed ring temperature $T=100$ K accounting only for the change in solar UV flux on the O_2 production rate. However, the average temperature of Saturn's ring particles also changes significantly with the change in the solar incident angle as revealed by the Cassini Composite Infrared Spectrometer (CIRS) data (Flandes et al., 2010): $T\sim100$ K at solstice and $T\sim60$ K at equinox. Since this change primarily occurs for the A- and B-ring particles, which are the principal source of the ring atmosphere, the photo-production of O_2 and H_2 and recycling on the ring particles are significantly modified by this change in the particle temperatures. Therefore, we re-examine the time variability of Saturn's ring atmosphere and ionosphere allowing for the effect of solar illumination angle and the ring particle temperature. In addition we consider the influence of the deposition of oxygen from Enceladus torus onto the A-ring.

O_2 production by UV photons depends on the UV flux and, hence, on the solar incident angle with respect to the ring plane as well as the ring particle temperature. In our earlier work in 2010, we used $Q(O_2)=c\times10^6$ molecules cm^{-2} s^{-1} with a fixed ring temperature $T=100$ K. This was based on the model in Johnson et al. (2006) to describe the observed plasma densities primarily over the B-ring with the parameter c accounting for recycling of dissociated oxygen and oxygen ions on the ring particle surfaces. At $T=100$ K and solar incident angle $\gamma=24^\circ$ the neutral O_2 source rate was computed from laboratory data to be $\sim1.0\times10^{26}$ s^{-1} at SOI due to photolytic decomposition of water ice. Since the calculated ion densities were roughly a factor of 20 smaller than our recent re-analysis of the CAPS data over the B-ring at SOI (Elrod et al., submitted for publication), the effective source at SOI was estimated to be $\sim2.0\times10^{27}$ s^{-1} ($c\sim20$) accounting for recycling (e.g. Johnson et al., 2006), the influences of Enceladus' plumes (Tseng and Ip, 2011), the solar activity and, possibly, the simplified ion–molecule interactions.

Earlier we estimated a photolytic O_2 source rate $\sim1.0\times10^{25}$ s^{-1} near equinox again assuming an average ring particle temperature of $T=100$ K (Tseng et al., 2010). Using the same model but with an average temperature of ~60 K near equinox (Flandes et al., 2010), the photolytic source rate is severely quenched by a factor of $\exp(-\alpha/kT)$ where α is an activation barrier, which is somewhat uncertain. Here we use $\alpha\sim0.03$ eV for the photo-production of O_2 (e.g., Johnson, 2011). Using $T=60$ K as the average temperature of the particles gives a photolytic yield a factor of ~10 reduction, in addition to the decrease due to the solar illumination angle, or $\sim1.0\times10^{24}$ s^{-1}. In absence of CAPS data over the main rings near equinox, we allow that recycling of desorbed oxygen and the contribution of oxygen from Enceladus could also enhance this source rate by the same factor as summarized in Table 1. Fortunately, the conclusions discussed below are not critically dependent on the exact size of the equinox ring atmosphere source rate, but only on the fact that the source rate is significantly smaller than that at SOI.

The momentum transfer during collisions between primarily O_2^+ ions and neutral O_2 molecules creates a component of O_2 molecules scattered into the magnetosphere (Johnson et al., 2006; Martens et al., 2008; Tseng et al., 2010). Fig. 1 shows the calculated radial profiles of the neutral O_2 column density from the rings to a radial distance of 10 R_S for the SOI and equinox source rates and for an intermediate source rate. Once ionized, they contribute to the local magnetospheric plasma. It is seen that the neutral O_2 column density over the main rings can be roughly scaled to the O_2 source rate. But, outside the main rings, the scattered population formed by ion–molecule collisions changes nearly quadratically with the source rate, as it depends on both the neutral and the ion density. That is, when the O_2 source rate becomes ten percent of SOI source rate, the scattered O_2 column density outside the main rings drops to be roughly one percent of SOI value.

The azimuthally symmetric spatial distributions of the O_2^+ ions produced by photoionization over the main rings are shown in Fig. 2 for (a) equinox and (b) SOI phase. It is clearly seen that the O_2^+ source rate depends on the orientation of the ring plane to the Sun with the O_2^+ density significantly lower at equinox. The structure and main features (such as the asymmetry above and

Table 1
Summary of the neutral O_2 and H_2 source rate of main rings.

Source rate (s^{-1})	SOI ($\Upsilon=24^\circ$ & $T=100$K)	Equniox ($\Upsilon=2^\circ$ & $T=60$K)
O_2[a]	1.0×10^{26}	1.0×10^{24}
O_2[b]	2.0×10^{27}[c]	2.0×10^{25}
H_2[a]	2.0×10^{26}[d]	2.0×10^{24}

[a] Photolytic source rate.
[b] Corrected for recycling which includes contributions of oxygen from Enceladus deposited on the A-ring (see discussion in Section 2).
[c] Correction based on calibration to the CAPS SOI data (Elrod et al., submitted for publication).
[d] No detection (or upper-limit) of H_2^+ to help us constrain the neutral H_2 source.