Icarus 242 (2014) 130–137

Contents lists available at ScienceDirect

Icarus

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

Seasonal and radial trends in Saturn's thermal plasma between the main rings and Enceladus

M.K. Elrod [a,b], W.-L. Tseng [c,d], A.K. Woodson [a], R.E. Johnson [a,*]

[a] University of Virginia, Charlottesville, VA 22904, United States
[b] National Institute of Aerospace, Hampton, VA 22236, United States
[c] Southwest Research Institute, San Antonio, TX 78228, United States
[d] National Taiwan Normal University, Taipei, Taiwan

ARTICLE INFO

Article history:
Received 12 December 2013
Revised 8 July 2014
Accepted 18 July 2014
Available online 9 August 2014

Keywords:
Saturn, magnetosphere
Planetary rings
Enceladus

ABSTRACT

A goal of Cassini's extended mission is to examine the seasonal variations of Saturn's magnetosphere, moons, and rings. Recently we showed that the thermal plasma between the main rings and Enceladus exhibited a time dependence that we attributed to a seasonally variable source of oxygen from the main rings (Elrod, M.K., Tseng, W.-L., Wilson, R.J., Johnson, R.E. [2012]. J. Geophys. Res. 117, A03207. http://dx.doi.org/10.1029/2011JA017332). Such a temporal variation was subsequently seen in the energetic ion composition (Christon, S.P., Hamilton, D.C., DiFabio, R.D., Mitchel, D.G., Krimigis, S.M., Jontof-Hutter, D.S. [2013]. J. Geophys. Res. 28. http://dx.doi.org/10.1002/jgra.50383; Christon, S.P., Hamilton, D.C., Mitchell, D.G., DiFabio, R.D., Krimigis, S.M. [2014]. J. Geophys. Res., submitted for publication). Here we incorporate the most recent measurements by the Cassini Plasma Spectrometer (CAPS) into our earlier analysis (Elrod, M.K., Tseng, W.-L., Wilson, R.J., Johnson, R.E. [2012]. J. Geophys. Res. 117, A03207. http://dx.doi.org/10.1029/2011JA017332) and our modeling (Tseng, W.-L., Johnson, R.E., Elrod, M.K. [2013a]. Planet. Space Sci. 77, 126–135) of the thermal plasma in the region between the main rings and the orbit of Enceladus. Data taken in 2012, well past equinox for which the northern side of the main rings were illuminated, appear consistent with a seasonal variation. Although the thermal plasma in this region comes from two sources that have very different radial and temporal trends, the extended ring atmosphere and the Enceladus torus, the heavy ion density is found to exhibit a steep radial dependence that is similar for the years examined. Using our chemical model, we show that this dependence requires either a radial dependence for Enceladus torus that differs significantly from recent models or, as we suggest here, enhanced heavy ion quenching/neutralization with decreasing distance from the edge of the main rings. We examine the possible physical processes and suggest that the presence of small grains and the precipitation of the inward diffusing high-energy background radiation onto the edge of the main rings play important roles.

1. Introduction

The heavy ions in Saturn's thermal plasma (<~300 eV) from just outside the main rings to just inside the orbit of Enceladus ($\sim 2.4R_S - 3.8R_S$; $1R_S$ = Saturn's Radius = 60,300 km) is studied using Cassini Plasma Spectrometer (CAPS) data from 2004 to 2012. The goal of this paper is to further examine the temporal and radial variation in the heavy ion plasma (Elrod et al., 2012). The O_2^+ observed by the CAPS instrument over the main rings (Tokar et al., 2005) was suggested to be formed from O_2 produced by photo-decomposition of the icy ring particles (Johnson et al., 2006a). A fraction of this O_2 is subsequently scattered, forming an extended ring atmosphere, in which the molecules become ionized contributing to the plasma in Saturn's inner magnetosphere (e.g., Johnson et al., 2006b; Martens et al., 2008). Since such a source depends on the illumination of the ring plane, the plasma density was predicted to vary over Saturn's orbit as the ring plane illumination varied from the southern hemisphere through equinox to the northern hemisphere illumination (Tseng et al., 2010, 2013a). Water group ions, labeled here as W^+ (O^+, OH^+, H_2O^+, and H_3O^+), are also directly formed in this region by ionization of neutrals in the Enceladus torus (Cassidy and Johnson, 2010; Smith et al., 2010; Tseng et al., 2011). While this source probably does not exhibit a seasonal variation, there is evidence that it fluctuates by up to a factor of four

---

* Corresponding author.

http://dx.doi.org/10.1016/j.icarus.2014.07.020
0019-1035/© 2014 Elsevier Inc. All rights reserved.

(Smith et al., 2010) and appears to depend on the position of Enceladus in its orbit (Hedman et al., 2013).

In Elrod et al. (2012) we used CAPS data from SOI to 2010 to confirm that the main rings are an important source of O_2^+ and O^+ ions inside the orbit of Mimas. We also showed that there was a steep drop in O_2^+ density, as well as in the total heavy ion thermal plasma, over that time period. Consistent with this, the Magnetospheric Imagining Instrument (MIMI) recently reported a decrease from SOI through 2010 in energetic O_2^+ density as compared to the W^+ density, followed by a recovery in 2011–2012 (Christon et al., 2013, submitted for publication). More recently a seasonal variation was reported for equatorial electron densities measured by the Radio and Plasma Wave Instrument (RPWS) (Persoon et al., 2013).

The present study of the thermal plasma extends our earlier time frame by including the 2012 data in order to determine whether or not the density increases after equinox. Because seasonal variations were assumed to be due to a ring atmosphere source superimposed on the Enceladus torus source, the seasonal variation might be expected to decrease with distance from the main rings consistent with models of the ring atmosphere. Surprising for all the years studied, the total *heavy ion* density, as well as that for the individual O_2^+ and W^+ ions, increases relatively steeply with increasing distance from the edge of the main rings for the radial ranges studied. This is the case even though the proposed seasonal variation is thought to be primarily due to molecules scattered from the ring atmosphere. After presenting the new results, we re-examine the implications of these findings.

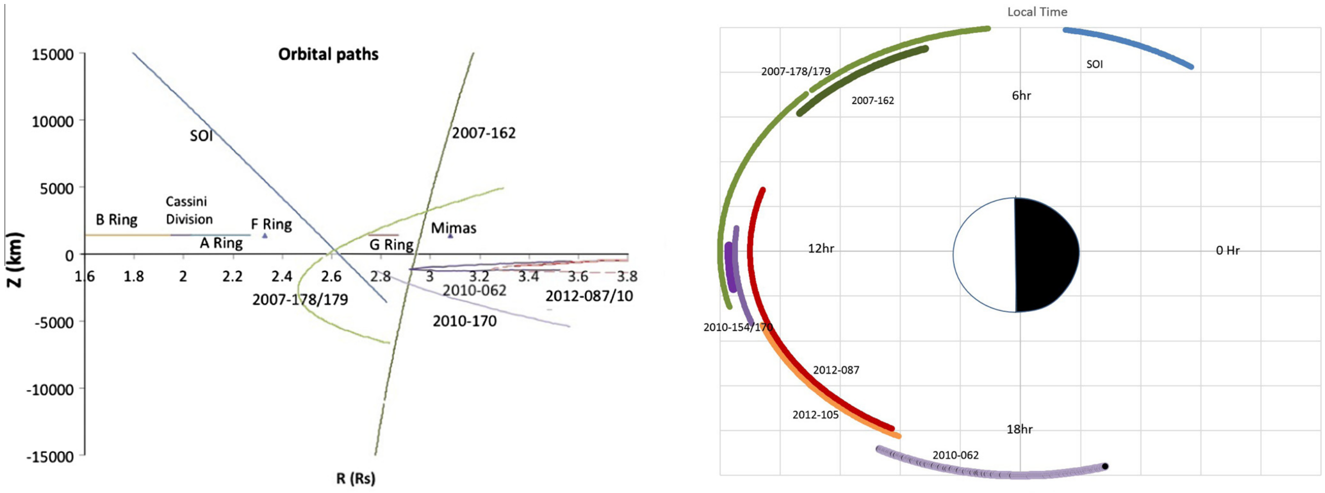
2. Analysis

We examined data in the region between $\sim 2.4 R_S$ and $3.8 R_S$ from the following passes: SOI in 2004, two in 2007 (doy 162 & 178/179), three in 2010 (doy 062, 154, and 170), and two in 2012 (doy 087 and 105). All of these passes had a periapsis within the Enceladus orbit at $\sim 4.0 R_S$ and had near equatorial segments which we focus on here. In Fig. 1 we show both the orbital paths in the R vs. Z plane and the local time for each of the orbits used in this study. Although there is a significant spread in local time, with the exception of SOI, all the passes were on the dayside, reducing the importance of the suggested orbital variations seen by the Cassini Radio and Plasma Wave Science (RPWS) Langmuir probe (Holmberg et al., 2013).

In Elrod et al. (2012) we described the method of analyzing the CAPS singles data, the correction for the significant background levels, and the fitting of the measured energy spectrum to obtain the total ion densities as well as the O_2^+ and W^+ fractions. These details are not repeated here. Unlike in Elrod et al. (2012) we only analyzed CAPS singles data taken close to the equator, having a minimum number of A-cycles, and at least 400 counts above background in order to reduce the scatter in the data. We also included the 2012 data, which was not available earlier. In Fig. 2 we show the average of the total heavy ion density for each year vs. radial distance from Saturn for those segments close to the equator ($Z < 5000$ km). Although there are variations in the total heavy ion density observed between those passes in Fig. 1 that occurred in the same year, which we will examine in the future, these variation are typically smaller than the variations between years.

It is also seen in Fig. 2 that there is an overall decrease in the heavy ion density from 2004 to 2010 and an increase from 2010 to 2012. Therefore, the lowest densities occur in 2010, the orbit closest to equinox (11 August, 2009) with apparent recovery through 2012. It is also seen that the densities, regardless of year, increase radially outward from the edge of the main rings over the region for data is shown. While there are significant changes in the magnitude of the densities between the years, the radial dependence of each of these sets is surprisingly similar. In order to better quantify the data we fit a power law in equatorial distance from Saturn, R, to each of these averaged data sets. The steep variation is roughly fit using the form $n_i = c(R/3R_S)^{12}$. Because the radial range is narrow, powers varying from ~ 10 to 14 also give reasonable descriptions. We use a power of 12 in the following and simply note that the measured radial dependence is relatively steep over the radial range shown. As the heavy ion density at $\sim 3.8 R_S$ was estimated to be $\sim 100/\text{cm}^3$ for the SOI orbit (Sittler et al., 2008), the near equatorial density at SOI eventually goes through a maximum.

As discussed in Elrod et al. (2012) and below, the SOI data ($2.4–2.8 R_S$) is dominated by O_2^+, likely from the extended ring atmosphere, with temperatures close to the fresh ion pick-up temperature, whereas the later data sets, closer to equinox ($2.5–3.6 R_S$), are dominated by W^+, likely from the Enceladus torus,



(a) (b)

Fig. 1. Orbits used in this study: (a) Position in equatorial radius, R in R_S ($1R_S \approx 60{,}300$ km in the equatorial plane) vs. distance above the equator, Z in km; for consistency in the comparisons, and to maximize the count rate, the data presented below comes from the near equatorial segments (Z within ± 5000 km). Vertical lines indicate Cassini division, F-ring, G-ring and Mimas. (b) Local times during each orbit. With the exception of SOI, most of the data was taken on the dayside between dawn and dusk.