Planetary and Space Science 57 (2009) 1732–1742

Contents lists available at ScienceDirect

Planetary and Space Science

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

Recurrent energization of plasma in the midnight-to-dawn quadrant of Saturn's magnetosphere, and its relationship to auroral UV and radio emissions

D.G. Mitchell[a,*], S.M. Krimigis[a], C. Paranicas[a], P.C. Brandt[a], J.F. Carbary[a], E.C. Roelof[a], W.S. Kurth[b], D.A. Gurnett[b], J.T. Clarke[c], J.D. Nichols[d], J.-C. Gérard[e], D.C. Grodent[e], M.K. Dougherty[f], W.R. Pryor[g]

[a] Johns Hopkins University Applied Physics Laboratory, MP3 E-132, 11100 Johns Hopkins Road, Laurel, MD 21042, USA
[b] Department of Physics and Astronomy, University of Iowa, Iowa City, IA, USA
[c] Center for Space Physics Boston University, Boston, USA
[d] Department of Physics and Astronomy, University of Leicester, Leicester, UK
[e] Laboratoire de Physique Atmosphérique et Planétaire Université de Liège, Belgium
[f] Blackett Laboratory, Imperial College, London, UK
[g] Central Arizona College, Coolidge, AZ, USA

ARTICLE INFO

Article history:
Received 25 November 2008
Received in revised form
6 April 2009
Accepted 8 April 2009
Available online 18 April 2009

Keywords:
Saturn
ENA
Ring current
Saturn kilometric radiation
Aurora

ABSTRACT

We demonstrate that under some magnetospheric conditions protons and oxygen ions are accelerated once per Saturn magnetosphere rotation, at a preferred local time between midnight and dawn. Although enhancements in energetic neutral atom (ENA) emission may in general occur at any local time and at any time in a Saturn rotation, those enhancements that exhibit a recurrence at a period very close to Saturn's rotation period usually recur in the same magnetospheric location. We suggest that these events result from current sheet acceleration in the 15–20 Rs range, probably associated with reconnection and plasmoid formation in Saturn's magnetotail. Simultaneous auroral observations by the Hubble Space Telescope (HST) and the Cassini Ultraviolet Imaging Spectrometer (UVIS) suggest a close correlation between these dynamical magnetospheric events and dawn-side transient auroral brightenings. Likewise, many of the recurrent ENA enhancements coincide closely with bursts of Saturn kilometric radiation, again pointing to possible linkage with high latitude auroral processes. We argue that the rotating azimuthal asymmetry of the ring current pressure revealed in the ENA images creates an associated rotating field aligned current system linking to the ionosphere and driving the correlated auroral processes.

1. Introduction

Many measurements of particles and fields in Saturn's magnetosphere (e.g., Kurth et al., 2008; Giampieri et al., 2006; Carbary et al., 2007a) exhibit modulation at a frequency close to that established by the observed modulation of Saturn kilometric radiation (SKR), which has been used to establish the Saturn Longitude System 3 (SLS3, Kurth et al., 2008). Energetic particles in the magnetotail are enhanced approximately once per SLS3 rotation, and energetic neutral atom emission bright spots recur with a period very close to that of the SLS3 period (Paranicas et al., 2005; Carbary et al., 2007b).

Although such periodicity in the energetic particle data is well established, it has not been determined whether there is a preferred local time for the energization of the particles, and if so, where. Because the spacecraft is constantly moving in local time and radius, spending much of its time outside the rotating portion of the magnetosphere and even less in the magnetic equatorial part of that rotating portion where the in situ particle intensities typically peak, pinning down the location of the onset of these events using in situ data is difficult at best. Energetic neutral atom (ENA) imaging by the ion and neutral camera (INCA), a sensor of the magnetospheric imaging instrument (MIMI) on the Cassini spacecraft, permits the remote detection and location of global scale ion acceleration events (Krimigis et al., 2004). In this paper we will show that the initiation of these recurrent acceleration events usually takes place in the midnight to dawn quadrant at radial distances of approximately 15–20 Rs (although they quickly spread to affect a region as close to Saturn as 7 Rs). We show evidence consistent with the interpretation that these events are associated with reconnection.

---

[*] Corresponding author. Tel.: +1 443 778 5981; fax: +1 443 778 0386.
E-mail address: don.mitchell@jhuapl.edu (D.G. Mitchell).

0032-0633/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.pss.2009.04.002

Energetic neutral atom emissions imaged by the MIMI INCA sensor have been used in several publications to investigate the rotational modulation of energetic ion enhancements in Saturn's magnetosphere (Krimigis et al., .2005; Paranicas et al., 2005; Carbary et al, 2007b) and to establish the instantaneous and long term locus of the energetic protons and oxygen ions in Saturn's ring current (Krimigis et al., 2007; Carbary et al., 2008b; Brandt et al., 2008). These studies have shown that Saturn's ring current is rarely symmetric (Krimigis et al., 2007; Carbary et al., 2008b), and that the energetic neutral atom enhancements produced as the asymmetric ring current charge exchanges with a roughly symmetric cold neutral gas cloud (Jurac and Richardson, 2005; Shemansky and Hall, 1992) are modulated at approximately the SLS3 period (Paranicas et al., 2005; Carbary et al., 2008a).

Carbary et al. (2008a) further determined that modulation of energetic oxygen ENA is far more regular in its period than is modulation of energetic hydrogen ENA. Paranicas et al. (2005) showed that the modulation exhibited during a particularly stable interval from day 351–358, 2004 could be explained by a combination of a symmetric steady state ring current ENA source located near 10 Rs, superposed with a rigidly corotating point source at 8 (hydrogen) to 9 (oxygen) Rs. The modulation is produced as the point source alternately moves toward and away from the observer, brightening and dimming through the combined effects of a R^{-2} dependence and the Compton-Getting effect. As pointed out by those authors, the situation is more complex—a point source is an oversimplification, and the steady loss of ions through the charge exchange process demands an ongoing replacement process; otherwise, the ENA intensities would have decreased over the seven-day interval, whereas their small observed decrease can all be attributed to R^{-2} dependence as the spacecraft moved farther from Saturn.

Left unanswered in those papers are the questions of where and how the ions are being energized to maintain their average intensity, and how the rotation modulation can at the same time be maintained very close to the SLS3 period. The latter behavior is even more puzzling when contrasted with in situ measurements of the plasma flow in the middle and outer magnetosphere (Kane et al., 2008; Mauk et al. 2005) that reveal velocities typically at a fraction of rigid corotation (the term we use to describe an azimuthal velocity sufficient to match the SLS3 period at any given radius).

Mauk et al. (2005), Paranicas et al. (2007), and Brandt et al. (2008) used the gradient and curvature drift of energetic ions and electrons in the inner to middle magnetosphere (6–12 Rs) to determine the age of energy-dispersed energetic particle injections. As a freshly injected population of energetic particles corotates about the planet in the corotation electric field, an additional azimuthal drift controls their loci as a function of time, causing energetic ions to super-corotate ahead of the cold plasma, and energetic electrons to drift against corotation, slowing their azimuthal guiding center velocity. This drift also affects the drift velocities of the ions that are converted to ENA and imaged by INCA. Therefore, the Compton-Getting induced ENA modulation caused by a combination of azimuthal asymmetry, viewing geometry and plasma velocity relative to the observer should also be ordered in energy according to the age of the particle heating event, a characteristic we make use of in the following analysis.

2. Observations

2.1. Energy dispersion of corotating oxygen ENA events

This paper uses two qualitatively different types of ENA observations to explore the question as to where, if anywhere, in local time the corotating ENA enhancements begin and/or are rejuvenated. The first type of observation is conducted from low latitude, such that the ring current is imaged edge-on, and the rotating enhancements tend to maximize as the corotation vector moves the source energetic ion population toward the spacecraft (see Fig. 1). The second type of observation is from high latitude, where the Compton Getting effects are minimized, and where the local time location of an ENA enhancement can be observed directly.

Since the Carbary et al. (2008a) study found that the periodicity was more clearly expressed in neutral oxygen emissions than in hydrogen, and because oxygen intensities at a given energy are more strongly influenced by the Compton-Getting effect than are hydrogen intensities, we restrict our analysis to the edge-on observations of energetic neutral oxygen. Fig. 2 shows whole image integrated ENA intensities for oxygen for the time period studied by Paranicas et al. (2005).

The peaks (and valleys) in the ENA intensity do not occur at the same time for all energies; rather, the peak intensity at the lowest energy lags the peak at highest energy by approximately half of the common modulation period for all ion energies, the lag decreasing with increasing energy. The modulation is consistent with a localized population of increased energetic ion intensity corotating with the plasma, while also gradient and curvature drifting in the same direction as the corotating plasma (Paranicas et al., 2005). The lower energy ions drift more slowly than those at higher energy, and so lag behind the latter, as illustrated conceptually in Fig. 1. By modeling the drift period in a dipole field, we can get a quantitative estimate of the location and time of creation of the rotating ion enhancement (Fig. 3). In this simple simulation, we calculate the time (in hours) it takes for an ion to move from a hypothetical emission local time to a local time 270° from that emission local time, measured in the direction of corotation. The green symbols track the time required for 90° pitch angle ions with a range of energies between 50 and 250 keV to travel 270°, for four different L-shells, namely $L = 8$, $L = 9$,

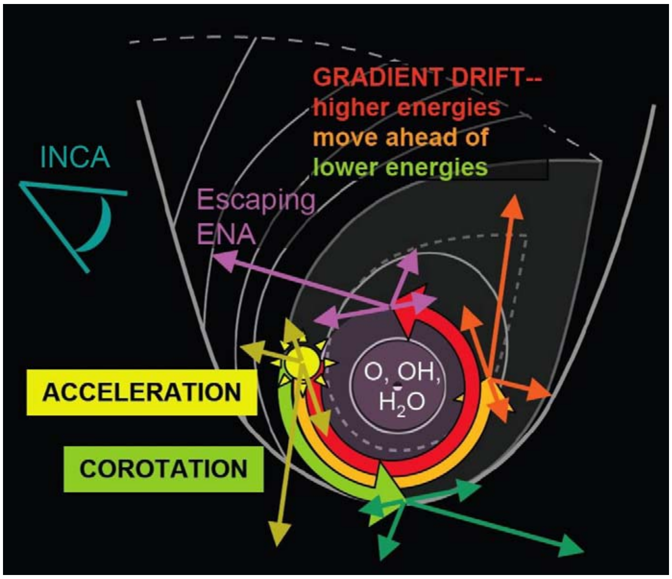

Fig. 1. Following an acceleration event (depicted here as the yellow burst near dawn; the sun is down in this figure) heated particles corotate along with the cold plasma. Some time later, low energy ions have corotated to noon, intermediate energy ions to dusk, and the highest energy ions to midnight. As the Compton-Getting effect results in higher intensities in the direction of the bulk velocity, ENA emission seen by INCA in the pre-dawn sector maximizes as the hot population approaches midnight. Since high energy ions reach midnight before low energy ions, the observed peak intensity at high energies precedes the observed peak at low energies.