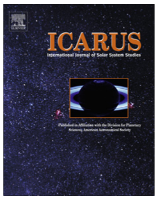
Icarus 264 (2016) 342–351

Contents lists available at ScienceDirect

Icarus

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



Effects of radial motion on interchange injections at Saturn

C. Paranicas [a,*], M.F. Thomsen [b], N. Achilleos [c], M. Andriopoulou [d], S.V. Badman [e], G. Hospodarsky [f], C.M. Jackman [g], X. Jia [h], T. Kennelly [f], K. Khurana [i], P. Kollmann [a], N. Krupp [j], P. Louarn [k], E. Roussos [j], N. Sergis [l]

[a] *APL, 11100 Johns Hopkins Rd., Laurel, MD 20723, United States*
[b] *Planetary Science Institute, 85719, United States*
[c] *Univ. Coll. London, UK*
[d] *Space Research Institute, Graz, Austria*
[e] *Lancaster Univ., UK*
[f] *Univ. of Iowa, 52242, United States*
[g] *Univ. of Southampton, UK*
[h] *Univ. of Michigan, 48109, United States*
[i] *UCLA, 90095, United States*
[j] *Max-Planck-Institut fuer Sonnensystemforschung, Göttingen, Germany*
[k] *Institut de Recherche en Astrophysique et Planetologie, France*
[l] *Academy of Athens, Greece*

ARTICLE INFO

Article history:
Received 8 May 2015
Revised 25 September 2015
Accepted 3 October 2015
Available online 14 October 2015

Keywords:
Saturn
Magnetospheres
Saturn, magnetosphere

ABSTRACT

Charged particle injections are regularly observed in Saturn's inner magnetosphere by Cassini. They are attributed to an ongoing process of flux-tube interchange driven by the strong centrifugal force associated with Saturn's rapid rotation. Numerical simulations suggest that these interchange injections can be associated with inward flow channels, in which plasma confined to a narrow range of longitudes moves radially toward the planet, gaining energy, while ambient plasma in the adjacent regions moves more slowly outward. Most previous analyses of these events have neglected this radial motion and inferred properties of the events under the assumption that they appear instantaneously at the spacecraft's L-shell and thereafter drift azimuthally. This paper describes features of injections that can be related to their radial motion prior to observation. We use a combination of phase space density profiles and an updated version of a test-particle model to quantify properties of the injection. We are able to infer the longitudinal width of the injection, the radial travel time from its point of origin, and the starting L shell of the injection. We can also predict which energies can remain inside the channel during the radial transport. To highlight the effects of radial propagation at a finite speed, we focus on those interchange injections without extensive features of azimuthal dispersion. Injections that have traveled radially for one or more hours prior to observation would have been initiated at a different local time than that of the observation. Finally, we describe an injection where particles have drifted azimuthally into a flow channel prior to observation by Cassini.

1. Introduction

Injections of charged particles in Saturn's magnetosphere can be identified in multiple Cassini data sets. In terms of morphology, it is useful to separate interchange injections from more global injection processes. Interchange-related structures represent a means of transport that leaves the background magnetic field largely unperturbed, while global processes often involve large-scale magnetic reconfiguration. Based on their analysis of many events, Mitchell et al. (2015) found the former usually occur inward of about 12 R_S (1 Saturn radius = 60,268 km), while the latter are

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* Corresponding author.
E-mail addresses: chris.paranicas@jhuapl.edu (C. Paranicas), mthomsen@lanl.gov (M.F. Thomsen), nicholas.achilleos@ucl.ac.uk (N. Achilleos), maria.andriopoulou@oeaw.ac.at (M. Andriopoulou), s.badman@lancaster.ac.uk (S.V. Badman), hospodarsky@uiowa.edu (G. Hospodarsky), c.jackman@soton.ac.uk (C.M. Jackman), xzjia@umich.edu (X. Jia), timothy-j-kennelly@uiowa.edu (T. Kennelly), kkhurana@igpp.ucla.edu (K. Khurana), peter.kollmann@jhuapl.edu (P. Kollmann), krupp@mps.mpg.de (N. Krupp), plouarn@irap.omp.eu (P. Louarn), roussos@mps.mpg.de (E. Roussos), nsergis@phys.uoa.gr (N. Sergis).

http://dx.doi.org/10.1016/j.icarus.2015.10.002
0019-1035/

more commonly observed outward of that distance. Interchange injections can be thought of as flux tube bundles (see, for instance, Burch et al., 2005) or flow channels (see below). A review of the literature on Saturn injections, including key findings, can be found in Thomsen (2013).

Southwood and Kivelson (1987) and others have described conditions under which plasma distributions are unstable to the interchange process, which involve the radial gradient of both the entropy and the density or flux tube content. Since this work is focused on features of injected distributions that are measured by Cassini, we will not address the underlying physics of the instability.

In this work, we will focus on signatures of the radial motion of interchange injections as observed in the Cassini Plasma Spectrometer (CAPS) and Magnetosphere Imaging Instrument (MIMI) data sets (Young et al., 2004; Krimigis et al., 2004). Together these data sets cover the ion and electron thermal plasma and energetic charged particle energy ranges (eV to MeV). For brevity, we will use the term “injection” to mean “interchange injection” throughout this paper.

In plasma and charged particle data, injections can be observed, when the charged particle phase space density (PSD) profiles at constant adiabatic invariants varies as a function of radial distance from the planet. For example, an injection starting at high PSD and large L that moves inward into a region of lower PSD will appear as a flux enhancement since its initial PSD is approximately conserved (e.g., Mauk et al., 2005). Similarly, an injection initiated in a region of low PSD (as at low energies and larger radial distances) will appear as a depletion in the thermal plasma in the inner magnetosphere.

In addition to data analysis, we will also describe and employ a test particle model to make more quantitative the specific features that are a focus of this work. Our model significantly expands upon an earlier model we have used to study injections in charged particles above about 10 keV only (Paranicas et al., 2010). The chief modification of our model relates to the inclusion of a finite radial speed for the injection and the consequences for the trajectories of the test particles. These details are described fully below.

2. Injection model

The picture of injections we employ is adopted from a simplified picture of the flow channels revealed by the Rice Convection Model (RCM) simulations of Liu et al. (2010). Specifically, we assume the creation of channels in which there is an inward plasma flow (i.e., a radial $E \times B$ drift motion of the particle guiding centers) with a constant value for a specified length of time, after which the inward velocity is zero. The model channel is taken to have a constant angular width in azimuth. We use a longitude system (SLS) based on Saturn kilometric radiation (SKR) modulation (see, Kurth et al., 2008, and references therein). For this model, the flow channel is always described in a corotating frame. It is important to keep in mind that this description is a better fit for some interchange injections than others. Other pictures such as flux tube bundles or even more elaborated fingers with merging and vortices (e.g., Hiraki et al., 2012), probably fit other classes of observed injections better.

Assuming the test particle’s motion can be approximated by the motion of its guiding center, we populate a grid in L shell and longitude with test particles. At each location we assume there is a range of energies at log-spaced intervals. In all, there are approximately one million test particles at the start of the simulation. We assume all particles begin to move inward from a narrow range of L shells around an L start (Ls) at constant inflow speed, conserving their first adiabatic invariant of motion in a dipolar magnetic field. In addition to this radial motion, we assume particles in the channel follow the same bulk corotation as the surrounding plasma and undergo energy- and species-dependent gradient–curvature drifts; both of these motions are in the azimuthal direction. Since the measured magnetic field strength inside injections is typically within a few percent of the surrounding field, we estimate these drifts using the background dipole of Saturn.

We compute the new characteristics of the test particles using a bounce-averaged, gradient–curvature drift approximation (Thomsen and Van Allen, 1980). Halfway between the L steps, we update the test particle’s energy and longitude. When the test particles reach the range of L shells of observation by Cassini (designated here as Lo), the simulation is stopped. Due to how our code is constructed, it is possible for observation L shells to be filled for up to 15 min leading to a small amount of azimuthal drift that can be observed in the simulations. Furthermore, this short filling time of the observation shells fits both pictures of the front of an injection channel and a flux tube bundle.

For the magnetic field orientation at Saturn, electrons have westward gradient–curvature drifts, while ions have eastward ones relative to the corotating channel. If they are not prohibited from drifting out of a flow channel, electrons can escape through the western edge and ions can escape through the eastern edge. Furthermore, the gradient–curvature drift speeds increase nearly linearly with particle energy. Burch et al. (2005) reasoned that the cross-section of a flux tube would lose particles as they drift out in this manner, the effect being more important at higher energies. They also inferred an inflow speed from this concept.

As described by Burch et al. (2005), another consequence of this drift-out effect is that the maximum energy that can be transported radially inward depends on the inflow speed. That is, for faster inflow speeds, energetic particles have less time to drift out of the flow channel during their radial transport. Thus faster inflow speeds mean higher energy particles can be delivered closer to the planet.

Fig. 1 shows an example of an injection from the CAPS data set obtained on day 2005-104 at about 1500 UTC. For this time–energy spectrogram, the colors[1] represent energy flux (energy times intensity). We propose this is an example of the drift out process that is the focus of this paper. The injection is widest below about 1 keV and narrows with increasing energy. During the plasma’s inward radial motion that is part of the interchange process, electrons drift away from the eastern edge of the flow channel towards then through the western edge (Burch et al., 2005). The effect is harder to see in cold to suprathermal plasma because that plasma travels around Saturn at nearly the local corotation speed. But at higher energies, the effect becomes very pronounced.

In creating simulated injections, we consider a narrow range of L shells (Lo) around the value corresponding to the *in situ* measurement. Near Lo, we keep track of test particles whether they are still inside the channel or whether they recently exited the channel. Cassini moves both radially and azimuthally across a flow channel when it encounters it and our model takes this into account.

The model we present here systematizes this drift-out process and provides an approach that can be exploited in the future for a much larger set of events in this class of injections to help understand the radial transport of interchange injections. It is important to note that we have carefully selected events for this study that show features we believe are due to the drift out process. Many interchange events do not show such characteristics.

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[1] For interpretation of color in Figs. 1 and 5, the reader is referred to the web version of this article.