Energetic electrons injected into Saturn's neutral gas cloud

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Received 2 November 2006; revised 21 December 2006; accepted 26 December 2006; published 26 January 2007.

[1] We demonstrate that the population of 20–410 keV electrons observed in Saturn's inner magnetosphere result principally from recent injections. Electrons at these energies appear to survive only up to a few days in the neutral gas cloud emitted by gas jets in Enceladus's southern hemisphere. Ions of similar energies have much shorter lifetimes in the gas cloud because of charge-exchange with the ambient neutrals. We have been able to associate fluxes at different energies and times with a single past injection based on the morphology of electron spectrograms from measurements made by Cassini's Magnetospheric Imaging Instrument (MIMI). Once injected, electrons disperse in longitude but the age of the initial injection and its approximate longitude can be reconstructed. Furthermore, the shape of time-dispersed features argues against rigid corotation of the magnetospheric plasma, or a fraction thereof, and instead favors L-dependent flow shear. **Citation:** Paranicas, C., D. G. Mitchell, E. C. Roelof, B. H. Mauk, S. M. Krimigis, P. C. Brandt, M. Kusterer, F. S. Turner, J. Vande-griff, and N. Krupp (2007), Energetic electrons injected into Saturn's neutral gas cloud, *Geophys. Res. Lett.*, **34**, L02109, doi:10.1029/2006GL028676.

1. Introduction

[2] The Cassini spacecraft has been in low inclination orbit of Saturn since the summer of 2004. As it nears the planet, it passes through a region with high concentrations of neutral atoms and molecules coexisting with the icy satellites. This cold neutral gas cloud has peak densities near Enceladus and extends beyond the orbit of Rhea at $R \sim 8.7R_S$ (where $R_S = 60,268$ km), see, for instance, Johnson *et al.* [2006]. Esposito *et al.* [2005] put the neutral to ion ratio at about 30,000 times that obtained in Jupiter's magnetosphere. Data from the Magnetospheric Imaging Instrument (MIMI) reveal that these neutrals severely degrade the population of energetic ions and electrons between a few and a few hundred keV. Ions are lost primarily through charge-exchange collisions with the cold neutrals in which the energetic ions become Energetic Neutral Atoms (ENAs). Heavy ion losses near the periphery of the neutral gas cloud have been inferred through ENA imaging using data from the MIMI Ion and Neutral Camera (INCA) [Krimigis *et al.*, 2005; Mitchell *et al.*, 2005; Paranicas *et al.*, 2005]. In the densest part of the cloud, ion fluxes detected by the MIMI Charge Energy Mass

Spectrometer (CHEMS) reveal that counts are below the instrument background in many cases [Paranicas *et al.*, 2006]. Energetic electrons survive longer in the neutral cloud than ions but not indefinitely. We expect that they are losing energy through Coulomb collisions with both the cold plasma electrons and atoms and molecules in the gas. The data suggest that when populations of ions or electrons are detected, they are transient. This implies no stable radiation belt of ions or electrons between a few keV and a few hundred keV can coexist with the cold neutral cloud.

[3] In this paper, we will focus on the injection into and propagation of energetic electrons around the inner magnetosphere. We describe the propagation in terms of energetic charged particle drifts and fit it to the data from the Low Energy Magnetospheric Measurement System (LEMMS) sensor of MIMI. Details of the MIMI instrument suite are given by Krimigis *et al.* [2004]. The standard description of charged particle motion in terms of drifts is sufficient to explain basic features of the data and helps to illustrate that nearly all of the observed electrons can be related to recent injections.

[4] Previously, several studies have confirmed the relation of injections and inward transport [Burch *et al.*, 2005; Hill *et al.*, 2005; Mauk *et al.*, 2005]. This paper goes on to suggest that in the energy range considered the inner magnetosphere of Saturn is not uniformly filled with charged particles. If this is so, it means that the gas cloud is efficiently removing not only ions in the few to few hundred keV range, as expected, but also electrons. Furthermore, the icy satellites of Saturn inward of, but not including, Rhea are efficiently shielded from these charged particles by the gas cloud, except for transient injected populations. Finally, this interpretation would argue that the energetic population around 100 keV does not play the conventional role of a stable ring current.

2. Data

[5] In Figure 1, we show a color spectrogram of electron intensity as a function of time and energy. Figure 1 shows 28 hours of LEMMS data beginning on day 2005-302 at 04:00 UT. During this time interval, Cassini is initially inbound to Saturn near noon local time. It reaches a minimum distance of $L = 4.6$ near dusk and continues outbound through midnight. This plot illustrates several features that we identify as electron injections. Recent injections (largest intensities) appear at the lowest energies in the plot. The near vertical injections at the lower left-hand corner probably occurred just upstream of Cassini. The injections at 08:00 and 12:00 UT could have occurred at the same time but at different planetary longitudes. It appears that this type of injection may occur at any local time [Hill *et al.*, 2005].

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Figure 1. Spectrogram of LEMMS data showing electron fluxes detected over a wide range of energies. The intense injections at low energy are likely recent. At higher energies, older injection remnants can be seen. The hour of days 302–303 of 2005 and the dipole L shell are given.

[6] The LEMMS sensor is fixed relative to the spacecraft (it is not scanning) so that at any given time, we are essentially sampling a narrow range of local pitch angle at all energies. For this time interval, the spacecraft is within one degree of the planetary equator. Spacecraft maneuvers during the first two hours presented in Figure 1 resulted in a sampling of all pitch angles. This led to the “picket fence” quality of the recent injections that makes them look like many short injections but are likely part of the same injection.

[7] At higher energies, fainter traces appear in yellow, green and blue. These have an arc-like quality that disappears at small radial distances. Our modeling below shows that these individual faint traces probably all belong to a single injection that has aged for several days.

3. Particle Motion

[8] We assume that the injections are longitudinally-confined populations of particles that are transported radially inward in rapid bursts. Following our previous analysis [Mauk *et al.*, 2005], we assume that during these injections, electrons conserve their first two adiabatic invariants of motion. Because they are being transported to stronger magnetic fields, electrons gain energy. Particles in injections that penetrate deeper into the magnetosphere would therefore be expected to gain the most energy. This is consistent with data, where we will show one example in which the highest energies of an injection are not present at the largest L shells.

[9] For each separate injection, we assume particles are simultaneously injected at all pitch angles and L shells and lose intensity as they age. Subsequent to injection, the charged particle, or for simplicity, its guiding center, experiences 2 drifts in the azimuthal direction, the $E \times B$ drift and the gradient-curvature drift. Both are derived from the forces on the charged particle in an electromagnetic field. For the energies considered here, the net azimuthal motion of the electron guiding centers is still in the same direction as the corotation of the plasma, only slower. To calculate this rate for each L shell, particle energy and equatorial pitch angle, we use the bounce-averaged drift equations [e.g., Schulz and Lanzerotti, 1974]. For a given particle species, the total azimuthal drift rate, ω , can be expressed as the sum of the plasma rotation rate, $\Omega(L)$,

allowed here to depend on L, and the gradient-curvature drift rate, ω_D ,

$$\omega(L, E, \lambda_m) = \Omega(L) + \omega_D(L, E, \lambda_m). \quad (1)$$

The gradient-curvature drift rate depends on particle species, energy, and mirror latitude and, following *Thomsen and Van Allen* [1980], can be written,

$$\omega_D = \pm 1.97 \times 10^{-5} L E \left(\frac{E + 2mc^2}{E + mc^2} \right) \left(\frac{F}{G} \right), \quad (2)$$

where E is in MeV, and ω_D is in rad/s and negative for electrons. We have preserved their notation in using a function, “ F/G ” to express the dependence on the particle’s mirror latitude,

$$\frac{F}{G} = [1.04675 + 0.45333 \sin^2 \lambda_m - 0.04675 \exp(-6.34568 \sin^2 \lambda_m)]^{-1} \quad (3)$$

Our computation of the guiding center position is carried out in a planet-centered frame that is consistent with the SKR rotation period [Kurth *et al.*, 2007]. This frame is slightly different from the usual International Astronomical Union (IAU) body-fixed reference frame used to describe the Voyager spacecraft encounters. The SKR frame has a rotation period that varies gradually so at a given local time the planetary longitudes in the two frames could be completely different.

[10] In our previous work, it was necessary to include plasma flow shear to model ion and electron injections observed during Cassini Saturn Orbit Insertion (SOI). The shear was necessary to reproduce the sense of the dispersed features. We have confirmed on the two orbits we studied in detail that rigid corotation of the magnetospheric plasma, or a fraction thereof, does not give the correct shape of the features. To illustrate the kinds of differences between the two flow systems, we show two examples in Figure 2. These are not meant to reproduce the data, only to illustrate how the two kinds of plasma flow affect the dispersed features. For both plots, we inject electrons at all energies at 0° longitude in the SKR frame at the beginning of day 2004-179. All electrons in the injection have an arbitrary mirror latitude of $\lambda_m = 15^\circ$, which corresponds to an

Figure 2. Locations at which Cassini encounters a population of injected electrons (at 2004-179 00:00 UT) versus hour of day 2004-182 and energy. The actual Cassini trajectory is used and the spacecraft's position in dipole L is shown at the top. (a) Injection assuming magnetospheric plasma corotates at 90% of the rigid rate everywhere and (b) the same injection assuming the L-dependent corotation function discussed in the text.

equatorial pitch angle of about 59° . We plot this injection using the actual Cassini trajectory in SKR during SOI as a function of hour of day 182 of 2004. The curves represent times the spacecraft would have encountered the population at the energy indicated on the ordinate. The top plot shows a prediction using 90% rigid corotation of the magnetosphere at all L shells. The bottom plot shows the prediction of the same injection when flow shear in L is included, exactly in the manner of *Mauk et al.* [2005]. In that paper, the rigid corotation rate (Ω_{CR}) was replaced by an L-dependent rate, $\Omega(L)$,

$$\Omega(L) = \frac{\Omega_{CR}}{\left(1 + [L/L_0]^N\right)} \quad (4)$$

Here we use the parameters of their fit to the Cassini SOI data, $L_0 = 11.9$ and $N = 2.3$.

[11] Figure 2 includes the specifics of the electron drifts as given by equations (1) through (4) and the exact details of the spacecraft position in the SKR frame. Both plots show that as the spacecraft moves inward towards the planet, it detects progressively higher energy electrons from the same initial injection. In Figure 2a, the electron drift, in the reference frame rotating at 90% of rigid, is in the sense opposite to plasma corotation and goes roughly as $\sim LE$. For the spacecraft trajectory used here, this simple dependence appears to shape the solutions, i.e. decreasing L is compensated by increasing E on neighboring L shells. In Figure 2b,

the electron drift rates increase inward even faster with L because the magnetospheric corotation rate is no longer the same at all L shells.

4. Aging of Injections

[12] In Figure 3, we use the spacecraft position with respect to Saturn on days 2005-302 and 2005-303 to illustrate how an injection ages in time. We have now assumed, as we do below, that the formula of flow shear put forward by *Mauk et al.* [2005] describes the inner magnetosphere better than rigid corotation or a fraction thereof. The real LEMMS sampling during this time interval is over many different pitch angles, as we discuss below. But for this idealization, we assume all electrons have $\lambda_m = 15^\circ$. In Figure 3a, we show the results of an injection that occurred on day 2005-298 at 12:00 UT at a single longitude in the SKR frame. In Figure 3b, we show the same spacecraft observation period but with an injection that occurred 48 hours later at the same planetary longitude. Comparing the two plots, it becomes clear that as the injection ages, the spacecraft observes more instances of the injection during its orbit. One way to understand this is as follows. If we could somehow turn off gradient-curvature drifts, then the injection would remain at a single planetary longitude and the spacecraft would encounter the injection every time this longitude passed over it. But with drifts, an injection even with all the electrons at the same energy and equatorial pitch angle, becomes a spiral in R-longitude space that becomes more tightly wound with time. The spacecraft then encounters the spiral many more times as the winding increases. Because of this effect, we are able to

Figure 3. Electron injection as detected by Cassini versus hour of day 2005-302 and energy. The dipole L value of the spacecraft is given at the top. (a) Injection on day 2005-298 at 12:00 UT and (b) injection on day 2005-300 at 12:00 UT as it would appear to the sensor.

Figure 4. Same data as in Figure 1 with a change of scale just after 2005-303 00:30 UTC. Superimposed on these data is a calculation of injection positions including several very recent intense injections and the remnants of an older injection as viewed by the LEMMS sensor. Four periods are simulated when the spacecraft orientation to the planetary magnetic field was fairly stable – allowing LEMMS to detect electrons with roughly the same local pitch angle over intervals from tens of minutes to hours.

approximately date injections by the number of encounters during the spacecraft orbit. Usually the intensity supports the estimate of the time of the initial injection. Varying the longitude of injection can be used to fine-tune the fit between the calculation and the observation. This new method goes well beyond our previous one [Mauk *et al.*, 2005] by considering how old injections would appear to the spacecraft.

5. Simulated Observation

[13] In Figure 4, we have re-plotted the data from Figure 1 and superimposed our simulation of its main features. Several short periods are blocked out because of bad data and we changed the intensity scale just after the beginning of day 303. This was to accommodate a sampling change to nearly equatorial pitch angles.

[14] Superimposed on the re-plotted data in Figure 4 is our simulation of the injections we observe during this time. The faint lines represent an injection that occurred at 2005-300 09:36 and at a planetary longitude of 30° ; this was between dusk and midnight. The reason there are breaks in the traces is that we plot only the equatorial pitch angles LEMMS was sampling at those times. The other recent injections we calculate (in orange) all occurred on 2005-302 04:33 and at various planetary longitudes near dawn.

[15] The slight discrepancies in energy at a given time between the data and the simulation could be due to several different factors: the parameters of the injection (the injection time and planetary longitude), the parameters of the flow shear, and any deviations from the dipole field model. We searched parameter space for the best fit between the data and the simulation. A statistical approach would be needed next to simultaneously fit many orbits to constrain the flow shear parameters.

[16] Three other discrepancies exist between the data and the simulation. The first is the mismatch on the nightside that probably has to do with the issues mentioned above. The second is the near lack of electrons detected inward of about $6-7 R_S$. This is likely the result of the increasing cloud densities inward to Enceladus. There may have been electrons initially injected into these planetary distances (such as the feature near 19:30 UT) but these probably

did not survive very long in the cloud. The other interesting disagreement is near the upper left hand corner of the plot. Here we predict remnants of the old injection, but none are observed. These are the greatest distances the spacecraft samples in this plot and therefore it is possible, as noted above, that electrons have not crossed enough L shells to be accelerated to the energies near the top of the plot.

6. Discussion

[17] Prior to Cassini's arrival at Saturn, in situ data were limited to flybys. This seriously restricted our ability to understand measurements across L shells, energy and pitch angle. During the Cassini orbits, it came to our attention that the inner magnetosphere, particularly at the radial distances of the neutral gas cloud, did not have a significant stable population of trapped ions and electrons. Through analysis, we have shown that the fluxes that are detected could often be traced to one of two types of injections. The first type corresponds to intense injections that are not confined by local times and are prominent in the tens of keV energy range. The second type, which may occur only once every few days, extend into the hundreds of keV range.

[18] Ions in the 20–410 keV range detected inward of Rhea's orbit are likely very recent injections. Electrons in the same energy range and at the same radial distances may persist for a few days, with diminishing intensity. At energies above 1 MeV, ions and electrons are not significantly depleted by the cloud and at those energies a more typical trapped radiation environment exists [Paranicas *et al.*, 2006]. Such particles are likely energized as they move inward by crossing many L shells.

[19] In this paper, we have focused on a representative example of injection aging. We anticipate that when the data from multiple orbits are used, more constraints can be placed upon the limits of the injection ages as well as the parameters describing the rotation and shear of the plasma. We also believe this type of analysis can help us understand where the dipole approximation begins to break down for particle drift calculations. The simultaneous detection of electrons at various energies and pitch angles provides an opportunity to constrain parameters of the inner magnetosphere's dynamics.

References

- Burch, J. L., J. Goldstein, T. W. Hill, D. T. Young, F. J. Crary, A. J. Coates, N. André, W. S. Kurth, and E. C. Sittler Jr. (2005), Properties of local plasma injections in Saturn's magnetosphere, *Geophys. Res. Lett.*, **32**, L14S02, doi:10.1029/2005GL022611.
- Esposito, L., et al. (2005), Ultraviolet imaging spectroscopy shows an active Saturnian system, *Science*, **307**, 1251–1255.
- Hill, T. W., A. M. Rymer, J. L. Burch, F. J. Crary, D. T. Young, M. F. Thomsen, D. Delapp, N. André, A. J. Coates, and G. R. Lewis (2005), Evidence for rotationally driven plasma transport in Saturn's magnetosphere, *Geophys. Res. Lett.*, **32**, L14S10, doi:10.1029/2005GL022620.
- Johnson, R. E., H. T. Smith, O. J. Tucker, M. Liu, M. H. Burger, E. C. Sittler, and R. L. Tokar (2006), The Enceladus and OH tori at Saturn, *Astrophys. J.*, **644**, L137–L139.
- Krimigis, S. M., et al. (2004), Magnetosphere imaging instrument (MIMI) on the Cassini mission to Saturn/Titan, *Space Sci. Rev.*, **114**, 233–329.
- Krimigis, S. M., et al. (2005), Dynamics of Saturn's magnetosphere from MIMI during Cassini's orbital insertion, *Science*, **307**, 1270–1273.
- Kurth, W. S., et al. (2007), A Saturnian longitude system based on a variable kilometric radiation period, *Geophys. Res. Lett.*, **34**, L02201, doi:10.1029/2006GL028336.
- Mauk, B. H., et al. (2005), Energetic particle injections in Saturn's magnetosphere, *Geophys. Res. Lett.*, **32**, L14S05, doi:10.1029/2005GL022485.
- Mitchell, D. G., et al. (2005), Energetic ion acceleration in Saturn's magnetotail: Substorms at Saturn?, *Geophys. Res. Lett.*, **32**, L20S01, doi:10.1029/2005GL022647.
- Paranicas, C., D. G. Mitchell, E. C. Roelof, P. C. Brandt, D. J. Williams, S. M. Krimigis, and B. H. Mauk (2005), Periodic intensity variations in global ENA images of Saturn, *Geophys. Res. Lett.*, **32**, L21101, doi:10.1029/2005GL023656.
- Paranicas, C., D. G. Mitchell, S. M. Krimigis, D. C. Hamilton, S. P. Christon, T. P. Armstrong, N. Krupp, E. Roussos, G. Jones, and R. E. Johnson (2006), Charged particle weathering of Saturn's satellites, *Eos Trans. AGU*, **87**(36), Jt. Assem. Suppl., Abstract P24A-03.
- Schulz, M., and L. J. Lanzerotti (1974), *Particle Diffusion in the Radiation Belts*, Springer, New York.
- Thomsen, M. F., and J. A. Van Allen (1980), Motion of trapped electrons and protons in Saturn's inner magnetosphere, *J. Geophys. Res.*, **85**, 5831–5834.
- P. C. Brandt, S. M. Krimigis, M. Kusterer, B. H. Mauk, D. G. Mitchell, C. Paranicas, E. C. Roelof, F. S. Turner, and J. Vandegriff, Johns Hopkins University Applied Physics Laboratory, 11100 Johns Hopkins Road, Laurel, MD 20723-6099, USA. (chris.paranicas@jhuapl.edu)
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