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Energetic ion acceleration in Saturn's magnetotail: Substorms at Saturn?

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[1] The Magnetospheric Imaging Instrument (MIMI) Ion and Neutral Camera (INCA) on the Cassini spacecraft has recorded abrupt increases in energetic neutral atom flux coming from the general direction of Saturn's magnetotail. These bursts of ion activity in the tail are well correlated with enhancements in the Saturn kilometric radiation. Given the similarities between these events and substorm activity on Earth, including their dependence on interplanetary conditions, we conclude that Earth-like substorms occur within Saturn's magnetosphere. **Citation:** 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.

1. Introduction

[2] The dynamics of the Earth's magnetosphere is dominated by the energy input from the solar wind [e.g., *McPherron*, 1995], while the dynamics of Jupiter's magnetosphere is dominated by internal energy sources, primarily the rotational energy of Jupiter's very strong magnetic field and the dense plasma contained by it [*Bagenal et al.*, 2004]. Energetic particles are suddenly accelerated and/or heated in both instances, at Earth in the context of storms and substorms, in Jupiter's magnetosphere by internally driven processes such as flux tube interchange (see summary by *Krupp et al.* [2004]). The relative influence of the solar wind is roughly determined, it is thought, by the relative strengths of the rotational electric fields and the interplanetary electric field. The rotational electric fields are, in turn, established by the rotation rate of the planet and the strength of the internal magnetic field. According to this approach to scaling, Saturn lies someplace between the Earth and Jupiter with respect to the influence of the interplanetary environment.

[3] One long-standing correlation indicating the importance of solar wind input at Saturn is the dependence of Saturn kilometric radiation (SKR) on solar wind conditions [*Desch*, 1982]. More recently, HST observations of Saturn's aurora combined with both distant and nearby (Cassini) observations of the interplanetary environment have firmly established a correlation between upstream solar wind conditions, Saturn auroral activity, and SKR [*Prangé et al.*, 2004; *Kurth et al.*, 2005; *Crary et al.*, 2005; *Clarke et al.*, 2005].

[4] With the INCA sensor on Cassini, ion acceleration/heating can be imaged remotely [*Krimigis et al.*, 2004, 2005]. When Cassini is outside the magnetosphere, INCA (which is nearly bore-sighted with the optical remote sensing instruments, and has a $90^\circ \times 120^\circ$ field of view) can produce global images of most of the magnetosphere. This provides the opportunity to detect ion acceleration events while simultaneously measuring the magnetic field (and in some cases also the plasma velocity) in the magnetosheath or the solar wind. In addition, the radio and plasma wave instrument monitors the intensity of SKR, an indicator of the magnetosphere's response to solar wind conditions (primarily to the dynamic pressure).

2. Observations

[5] The clearest magnetotail ion acceleration event took place late on day 347 and early on day 348, 2004 (Figure 1). Cassini was inbound at about 1000 LT, -2° latitude, and 24 Rs. A little after 2300 on day 347 a sudden bright emission appeared, coming from the direction of the magnetotail. The ENA flux varied slightly with time leading up to the end of 347, but none of the emissions for several days before 347 2300UT were out of the ordinary, based on six months of orbital data. The ENA flux then rose steadily at all energies, to a level more than an order of magnitude higher than the baseline seen over the previous day. We will show that the signal comes from a very limited part of the sky that includes the magnetotail beyond ~ 20 Rs. Simultaneously with the increase in ENA flux, both the intensity and the bandwidth of the SKR emissions increased.

[6] Figure 2 shows a sequence of ENA images, beginning before the large event at the end of day 347 (Figure 1) and shortly before Cassini's flyby of Titan. Note that the hydrogen gas (first panel), which peaks near Saturn, falls off very slowly in density in the region beyond about 10 Saturn radii. The ENA emission in the first image frame is typical of pre-event conditions, with the bulk of the emission coming from well inside 20 Rs, and confined mainly to the equatorial plane. The day – night brightness asymmetry

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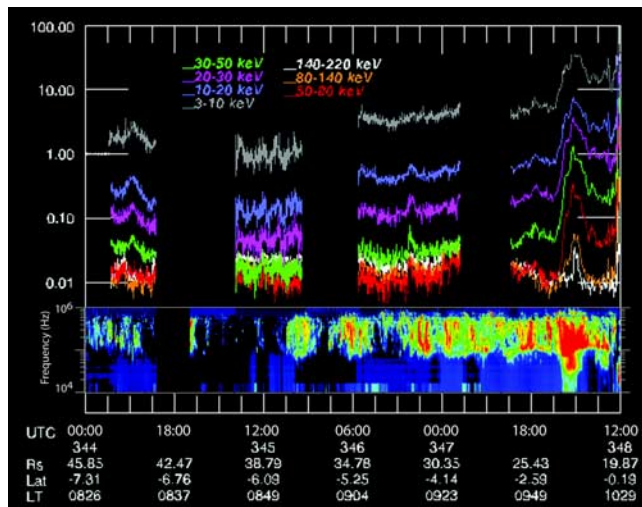


Figure 1. The total image-integrated ENA flux measured coming from Saturn. Part of the dayside magnetosphere is outside the INCA field of view (FOV), but the nightside is fully covered. The blank intervals are times when the spacecraft attitude pointed INCA away from the magnetosphere. Note that the SKR intensity enhancements (lower panel) correlate well with the ENA flux.

in this pre-event image is caused by corotation of the plasma. From Cassini's vantage point, nightside plasma is convected toward the spacecraft (adding an increment to the thermal velocity of the plasma ions) and away from the spacecraft on the dayside (subtracting an increment). This leads to the observed anisotropy, as described by *Compton and Getting* [1935]. In the second, third and fourth images the abrupt brightening of the ENA by over an order of magnitude in a new region, outside Titan's orbit, reveals a process in the magnetotail that has suddenly accelerated (or heated) plasma ions in the region. Since one does not expect strong gradients in the neutral gas density at this distance, this brightening must be explained by in-situ acceleration of ions. The first four images cover about two hours. The remaining six images are spaced farther apart in time, and record the progression of the event as the hot ion population rotates about Saturn. The first of these shows a dramatic brightening about Titan as the hot ions arrive and charge exchange in the dense Titan exosphere. The next three images show the Titan associated emission dying away as the ions rotate past Titan. The leading edge of the ion cloud moves into the dayside where it leaves the INCA FOV, then reappears (more faintly) as it rotates through dusk and back to the night side by the last image. In the last image, as Cassini approaches Titan it is dark (no hot ions envelop it) and Titan's atmosphere absorbs the emission from the far side of the magnetosphere that would otherwise be seen in that location. The general dimming of the ENA flux during this transit may have many explanations—expansion of the original hot plasma along flux tubes as it convects about Saturn; particle loss by charge exchange; adiabatic cooling as the flux tube volumes increase going from noon through dusk to midnight.

[7] During the beginning of this event Cassini was in the magnetosheath and could directly measure the (shocked) interplanetary magnetic field (IMF). Figure 3 shows that the

IMF (which exhibited strong mirror waves characteristic of the magnetosheath) was weak, but predominantly northward for hours before the event (when it turned southward, but probably too late to be causally related). The northward field extended back in time to near the beginning of day 347. The oxygen emission rose above its pre-event levels about 30 minutes earlier than did the energetic hydrogen emission.

[8] A second magnetotail ion acceleration event was imaged ten days earlier, following the passage of an interplanetary shock. In this instance, the magnetosphere produced elevated ENA emission for several days. The rise in the storm-like event is shown in Figure 4. Again, clear evidence of ion heating/acceleration appears tailward of 20 R_s, in a position consistent with the location of the tail current sheet. In this case, the magnetic field direction is variable, but predominantly northward for much of the time, with periodic southward turnings. And again, the elevated ENA emission is accompanied by significantly stronger SKR emissions.

3. Discussion and Conclusions

[9] At Earth, magnetospheric substorms are a central feature of the coupling of energy from the solar wind into the magnetosphere. In the magnetotail the key observable features are magnetic field reconfiguration (dipolarization), strong plasma flows, and plasma energization [e.g., *Nakamura et al.*, 2002].

[10] The results presented here suggest that substorms, or something very like them, play a significant role in heating ions in Saturn's magnetotail, somewhere in the region between 20 and 30 R_s. They may occur closer to the planet (15–20 R_s) if the in-situ ion and electron events seen in that region [*Krimigis et al.*, 2005] turn out to be the same phenomenon seen farther out in ENA. The enhanced SKR suggests that auroral activity is correlated with Saturn's substorms.

[11] We have shown that these events imaged in Saturn's magnetotail have many of the characteristics of substorms on Earth (location, relatively fast rise time, association with solar wind disturbances, and enhanced radio emission intensities). One of the events imaged arose essentially in isolation, with no sustained magnetospheric activity preceding it, and little apparently following. While this event directly followed a prolonged period (17 hours) of northward IMF, recent work by *Jackman et al.* [2004] indicates that this is insufficient to account for all the energy likely required for a Saturn substorm. However, the additional energy added during this interval may have been sufficient to cross a stability threshold. The event presented in Figure 4 involved repeated magnetotail activation in the context of a magnetosphere-wide storm-like event, triggered by an interplanetary shock passage and compression region, of the sort discussed by *Jackman et al.* [2004] and *Crary et al.* [2005].

[12] *Cowley et al.* [2005] suggested that Dungey-type reconnection should occur in Saturn's magnetotail, favoring the dawn side. According to that work, hot plasma accelerated at the reconnection site would then be expected to convect through dawn toward the dayside magnetopause in a matter of a few hours, and ultimately all the way to dusk.

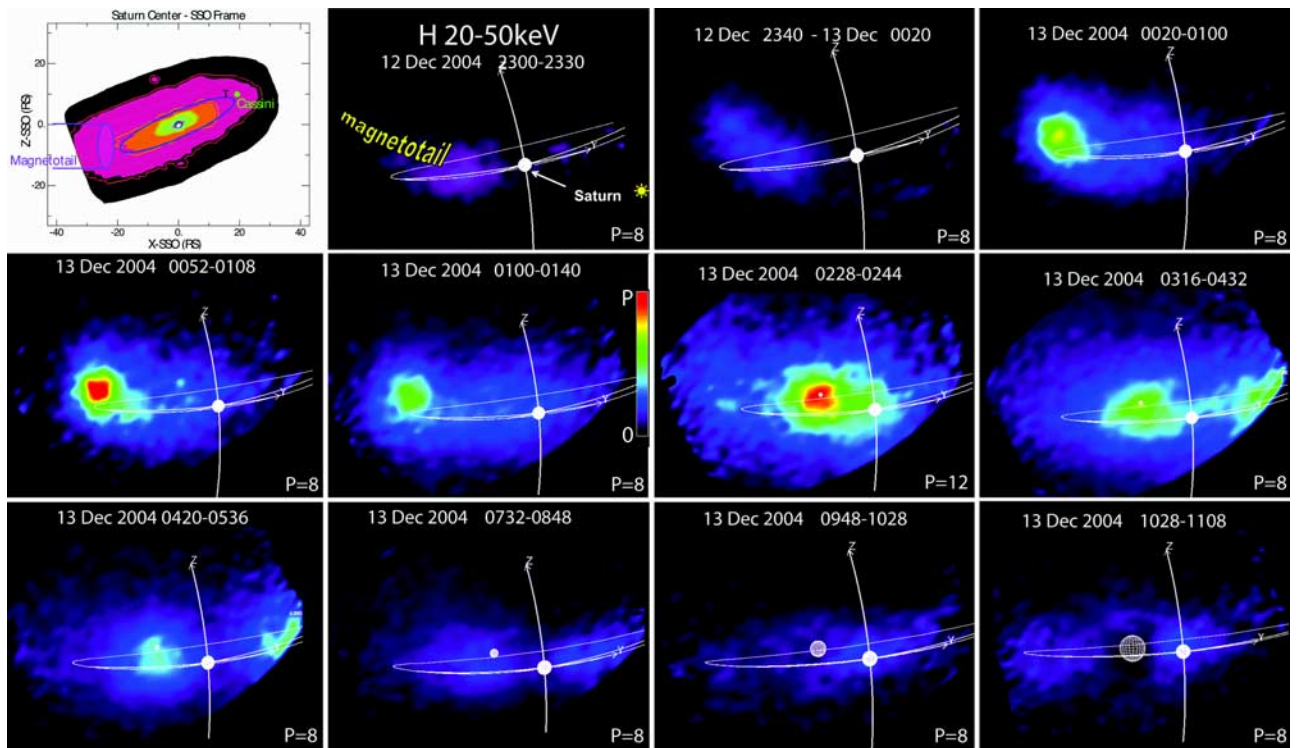


Figure 2. The first panel is a schematic of the Saturn system seen in Saturn Solar Orbital (SSO) coordinates (equivalent to GSE at Earth) from the dawn meridian in Saturn's orbital plane showing Saturn (center), Titan (T, upper right), Titan's orbit (blue ellipse), Cassini (green dot), and the approximate location of the magnetotail (assuming a hinging point at roughly 20Rs). The background for the schematic is UVIS data, taken in late 2003 and early 2004, of the distribution of hydrogen gas throughout the Saturn system [Esposito *et al.*, 2004]. The subsequent frames show ENA images of the development of the magnetotail ion acceleration event as seen from Cassini's position on December 12–13 (days 347–348) 2004, in 20–50 keV hydrogen. The first of these images shows the positions of Saturn, Titan's orbit (seen nearly edge-on), the sun, and the magnetotail in this projection, along with ENA emission typical of the 10 hours preceding the event. Using a linear color bar scaled 0 to P (Peak value, lower right of frame) throughout, the remaining frames show the rapid development of a bright emission region at a location consistent with acceleration in the magnetotail. The hot plasma then corotates, passing over Titan's dense atmosphere at 0230. By 0400, the leading edge is out of the INCA FOV on the dayside. By 0800 (bottom row, second image) the leading edge is just passing Saturn's disk on the dusk side, so it is located at ~ 2200 LT. By 1045UT, the leading edge is faintly seen to the left side of Titan, near midnight LT.

Its fate after that would depend on the characteristics of Vasyliunas-type reconnection and tailward plasma escape on the dusk side. Such motion is seen in Figure 2, though rather more quickly than suggested by Cowley *et al.* [2005]. The leading edge passed between the spacecraft and Saturn (about 0100UT, across a line of sight at $\sim 10:00$ LT), even while acceleration/heating is still going on in the tail. The passage of this front is only about 90 minutes after the event onset. This means that the event is much closer to dawn than the mid-tail, and/or the motion is faster than corotation. The leading edge of the cloud of accelerated ions moved quickly around the planet, at an estimated speed roughly 80% of rigid corotation, again crossing the line of sight to Saturn at about 0800UT. In a dipole field at $L = 20$, gradient and curvature (GC) drifts would increase the rotation rate of these energetic ions by about 15%. However, examination of the images at 50–80 keV (not shown) does not reveal an observable difference in the rotation rate, so GC drifts may not play a large role (the magnetic field is probably strongly modified by the plasma pressure of the injected ions). Further complicating the analysis, we have only line-of-sight images, and do not know the radial distance of the

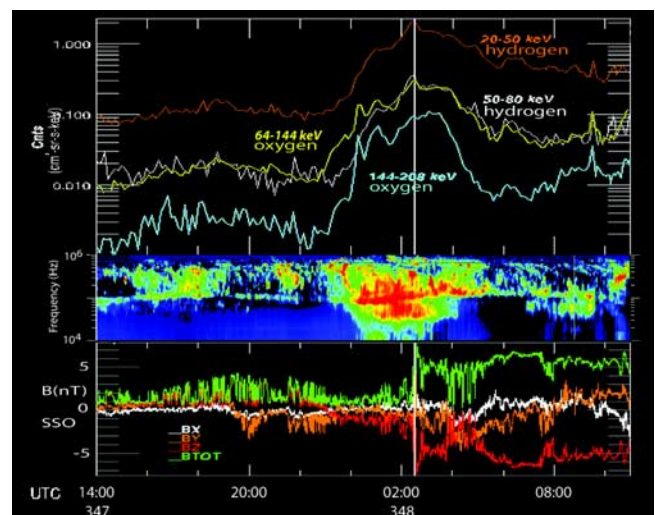


Figure 3. Hydrogen and oxygen ENA flux vs. time (top), SKR spectrogram (middle), magnetic field in Saturn Solar Orbital coordinates (bottom). Cassini's inbound magnetopause crossing is marked by the vertical white line.

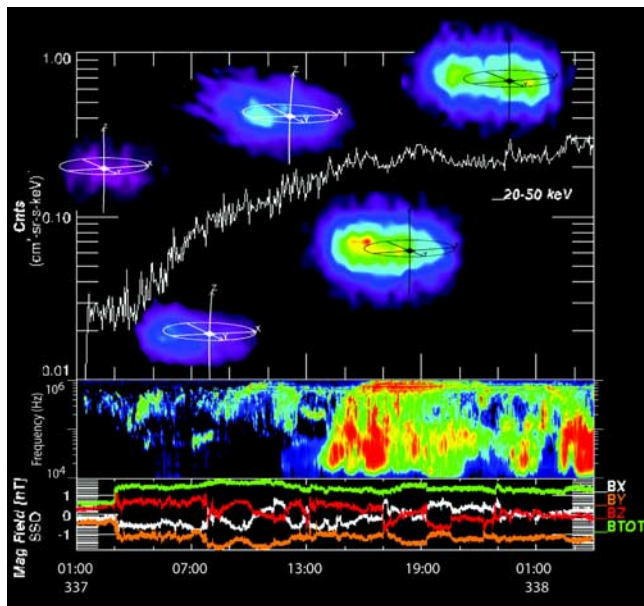


Figure 4. Solar wind shock associated event, Day 337–338, 2004. A shock passage shown in the IMF (bottom panel) passed Cassini at day 337, 0300 UT, when Cassini was at 67 Rs at 0730 LT, -10° Lat. The 20–50 keV ENA H intensity began rising an hour later (top panel). Selected images are located with the Saturn Z (rotation) axis placed vertically aligned with the time of the image, sun to the right, magnetotail to the left and angling above the Titan orbit plane. They show ENA emission on the night side, with a marked local maximum beyond the orbit of Titan by 337, 1900UT. The SKR intensity (middle panel) shows an abrupt increase at a time consistent with the intensification of the ENA fluxes.

leading edge. We do know that the plasma reached Titan at about 0230, which implies a non-radial orientation of the advancing front of hot plasma. Since at event onset the spacecraft was in the sheath at 24 Rs, and at 23.5 Rs when the hot plasma front crossed 1000LT, we can surmise that the leading edge is planetward of 20 Rs, and that the front slopes to earlier local times with increasing radial distance. This may result from any number of possible effects, including a radial gradient in the corotation lag, faster pick-up to corotation velocity in the stronger field closer to the planet, or acceleration of plasma over a broad region that is not radially oriented in the first place.

[13] Figure 3 also showed significant differences in the acceleration/heating time histories of energetic hydrogen vs. oxygen. Oxygen at all measured energies rose earlier and more steeply than hydrogen, and showed several distinct peaks in intensity while the hydrogen rose monotonically. This suggests an acceleration process that favors slow gyroperiod ions [e.g., *Delcourt*, 2002].

[14] The similarities between these events and substorm activity on Earth are striking. We conclude that Earth-like substorms occur within Saturn's magnetosphere. The fast rotating field adds phenomenology not seen at Earth.

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