LA-UR- 09-006074

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Title: Plasma in Saturn's nightside
magnetosphere and the
implications for global circulation.

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Intended for: PLANETARY AND SPACE SCIENCE:
SPECIAL ISSUE 'SATURN AFTER
CASSINI'.

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**Plasma in Saturn's nightside magnetosphere and the implications for
global circulation**

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Abstract

We present a bulk ion flow map from the nightside, equatorial region of Saturn's
magnetosphere derived from the Cassini CAPS ion mass spectrometer data. The map
clearly demonstrates the dominance of corotation flow over radial flow and suggests that
the flux tubes sampled are still closed and attached to the planet up to distances of 50 R_s.
The plasma characteristics in the near-midnight region are described and indicate a

transition between the region of the magnetosphere containing plasma on closed drift paths and that containing flux tubes which may not complete a full rotation around the planet. Data from the electron spectrometer reveal two plasma states of high and low density. These are attributed either to the sampling of mass-loaded and depleted flux tubes, respectively, or to the latitudinal structure of the plasma sheet. Depleted, returning flux tubes are not, in general, directly observed in the ions, although the electron observations suggest that such a process must take place in order to produce the low density population.

Flux tube content is conserved below a limit defined by the mass-loading and magnetic field strength and indicates that the flux tubes sampled may survive their passage through the tail. The conditions for mass release are evaluated using measured densities, angular velocities and magnetic field strength. The results suggest that for the relatively dense ion populations detectable by IMS, the condition for flux-tube breakage has not yet been exceeded. However, the low-density regimes observed in the electron data suggest that loaded flux tubes at greater distances do exceed the threshold for mass loss and subsequently return to the inner magnetosphere significantly depleted of plasma.

Keywords: Saturn; magnetospheric; ions; planetary wind; magnetotail

1. Introduction

When considering the global dynamics of Saturn's magnetosphere, parallels are immediately drawn with the magnetic systems of both Earth and Jupiter. At Earth, the magnetosphere is forced into convective motion by reconnection with the interplanetary field at the dayside magnetopause and the subsequent merging of the opened field lines in the magnetospheric tail. The newly-closed field lines rotate back around to the dayside, completing the so-called Dungey cycle (Dungey, 1961).

By contrast, despite evidence for interaction with the solar wind (Walker and Russell, 1985; Khurana, 2001), the fast rotation and significant internal mass-sources in Jupiter's magnetosphere dominate the dynamics of the plasma and fields there. Vasyliunas (1983) described a possible internally-driven scenario at Jupiter, in which plasma produced by the moon Io continually loads the magnetic field lines. Due to the interchange process this plasma diffuses outward over many rotations. The filled flux tubes rotate around the dusk magnetosphere, where the reduction in solar wind confinement allows the flux tubes to lengthen. Eventually, the magnetic stress can no longer confine the plasma and the field lines reconnect or break open to release the plasma downtail as a series of plasmoids in what has previously been termed the "planetary wind" (Michel and Sturrock, 1974). The emptied flux tubes return to the dayside, depleted of plasma, to complete this circulation.

76 Saturn is also a fast rotator with a large system of rings and moons providing a continual
 77 supply of plasma to the magnetosphere through ionisation of neutral gases originating on
 78 the rings and moons (Sittler et al., 2004; Tokar et al., 2006), in particular from the active
 79 geysers on Enceladus (e.g. Dougherty et al., 2006). At small radial distances the plasma
 80 is forced into corotation with the planet (Hill, 1979; Wilson et al., 2008). However,
 81 plasma in Saturn's outer magnetosphere is found to be slowed with respect to corotation
 82 (Eviatar and Richardson, 1986; Kane et al., 2008). This slowing is indicative of outward
 83 plasma transport which leads to sub-corotation if the ionosphere is unable to supply
 84 enough current to accelerate the plasma to the larger corotation speeds at larger radial
 85 distances (Hill, 1979). Furthermore, centrifugal forces stretch the lower-strength
 86 magnetic field, until the field lines take the shape of a thin, lagging magnetodisc (Arridge
 87 et al., 2006; 2008a) a configuration which lends itself to mass-release via the Vasyliunas
 88 or 'planetary wind' model.
 89 In the Saturnian magnetotail the plasma and field properties have been described for
 90 several plasmoid-type signatures that were presumably released from mid-tail magnetic
 91 reconnection events (Jackman et al., 2007, 2008; Hill et al., 2008). Only five such events
 92 have been identified to date. In addition to these in-situ observations, remote sensing by
 93 the ENA imager detected energetic neutral atoms originating from the tail region between
 94 $\sim 20 - 30 R_S$ suggestive of local acceleration of ions associated with a substorm-type

95 energisation (Mitchell et al., 2005). Furthermore one of these bursts was associated with
 96 the in-situ observation of a plasmoid (Hill et al., 2008). Such brightenings in the ENA
 97 signature are not uncommon (Carbary et al., 2008) which suggests that the low in-situ
 98 detection rate is because Cassini has not been in a favorable viewing location during its
 99 excursions into the tail due largely to the warping of the current sheet out of the
 100 equatorial plane (Arridge et al., 2008b).
 101 Thus, there is a noteworthy amount of evidence for reconnection-related dynamics in the
 102 nightside magnetosphere. Furthermore, the evidence for mass-release in Saturn's
 103 magnetosphere is unambiguous; there is no infinite build-up of mass in the system as
 104 demonstrated by the relatively stable mass profile in Arridge et al. (2007) which suggests
 105 a fairly constant loss rate and by the presence of depleted flux tubes, which contain
 106 remnants of inner magnetospheric material in the middle and outer magnetosphere.
 107 The principal motivation of the present study is to measure directly the characteristics of
 108 the large-scale plasma flows in the nightside magnetosphere to provide insight to the
 109 dynamical processes. Are radial flows observed on a large scale both outwards,
 110 suggestive of tailward plasma release, and inwards, indicating the return of newly closed
 111 field-lines? Does the relative density of plasma on these field lines support the idea of
 112 plasma release? Can we find evidence of where the Vasyliunas and/or Dungey cycles are

113 closing in the nightside region of the tail? Can we determine whether plasma motions in
114 the tail are governed by solar wind or internal driving?
115

116 **2. Data set**

117 *2.1 Instrumentation*

118 Plasma parameters are derived from the Ion Mass Spectrometer (IMS) and the Electron
119 Spectrometer (ELS), which constitute part of the Cassini Plasma Spectrometer (CAPS)
120 (Young et al., 2004). The IMS provides energy and compositional information for ions
121 with an energy per charge (E/q) of 1 eV/e to 50 keV/e using an electrostatic analyser and
122 a subsequent time-of-flight detector. The ELS is an electrostatic analyser with
123 measurement range of 0.6 eV/e to 28 keV/e. The IMS and ELS fields of view are
124 constructed by sweeping the instrument collection apertures ($160^\circ \times 8.3^\circ$ and $160^\circ \times 5^\circ$
125 for IMS and ELS, respectively) azimuthally by an actuating platform moving at $\sim 1^\circ\text{s}^{-1}$.
126 The maximum solid-angle coverage normally allowed by the actuator is $\sim 2\pi$ sr.
127 One-minute averaged magnetic field data were obtained from the Fluxgate Magnetometer
128 (FGM) (Dougherty et al., 2004).

129

130 *2.2 Deriving plasma moments*

131 Moments of the ion distribution (density, temperature and bulk flow velocities) are
132 determined by a process of forward modelling of the assumed convective anisotropic
133 Maxwellian distributions of two species with the same bulk flow velocity (Wilson et al.,
134 2008). The best fit is selected by employing a sequence of minimisation techniques
135 applied to a comparison of the observed and simulated count rate spectrum. It is
136 necessary to pre-select the ion species to be modelled, and for the data shown here we
137 specified a light ion (H^+) and a water group (W^+) component based on lower-resolution
138 time-of-flight measurements of the IMS. Although we assume mass=17 amu for the
139 heavy ion species, the population may actually include O^+ , OH^+ , H_2O^+ and H_3O^+ ions, but
140 the derived moments are relatively insensitive to the actual composition. The calculation
141 is carried out over 14 x 32 second intervals, resulting in ion moments with a $\sim$ seven
142 minute resolution. Further details regarding the calculation can be found in Tokar et al.
143 (2006) and Wilson et al. (2008).
144 The electron moments are derived by integrating the particle distribution over three-
145 dimensional velocity space. In general, the electrons have a high thermal speed relative
146 to their bulk speed and so, in the absence of anisotropic pitch-angle distributions, do not
147 have significant directionality. Therefore, the electrons sampled in one direction can
148 generally be considered representative of the local population and in the moment

derivation the assumption of isotropy is applied to fill in the section of sky not sampled (Lewis et al., 2008). The electron spectra are averaged over an actuator cycle, which ranges from ~ one to ~seven minutes in length, depending on the actuation to remove variability caused by anisotropic variations, and have the background subtracted before integration. Bins with poor signal-to-noise were filtered out before integration to avoid introducing temperature biases to the moments (Arridge et al., *submitted*)

3. Observations

3.1 Example tail plasma sheet entry

Figure 1 contains energy-time spectrograms of the ion (top panel) and electron (second panel) data typical of the equatorial magnetotail. These data are from July 3, 2006, between 0800 UT and 1200 UT when Cassini was at ~ 27 R_S and a local time of ~ 2150. The periodic nature of the ion counts is due to the sweeping of the instrument entrance aperture through the peak of the ion flow, which is strongly directional in the spacecraft frame since the flow speed is comparable to or exceeds the thermal speed. The intermittent presence of the ions in the detector is due to the changing field of view of the instrument relative to the bulk flow direction and this is demonstrated in the field of view

plots in a spacecraft-centered frame at the bottom of the figure. The fields of view for the periods corresponding to the red bars on the spectrogram are shown. Between 0900 – 0915 UT the detector is sweeping through the direction of strictly azimuthal flow (triangle) and counts are detected allowing us to derive the actual flow direction (upside-down triangle). Note that the actual flow direction is very close to the direction expected for rigidly corotating plasma and indicates the lack of any significant radial flow at this time. In the second case (0915 – 0930 UT), the actuator does not sweep the instrument through the flow direction and the counts disappear. The energy structure of the ion counts in the top panel is due to the presence of two main ion populations, a light (primarily H^+) and a heavy (primarily water-group, denoted W^+) component, which for the same common flow velocity have energy-per-charge proportional to the ion mass (c.f. Young et al., 2005). In extracting moments these populations must be successfully identified and separated. These data demonstrate the characteristics of plasma in the outer magnetosphere and highlight the sparse nature of the ions detectable by the IMS. At the start of the interval in Figure 1, there are no ion counts due to the instrument not sampling the flow direction. The electron counts are low and have energies ~ 50-500 eV (the intense band of electrons at the lowest energies is due to spacecraft photoelectrons trapped in the potential well surrounding the spacecraft). At ~ 0900 UT the ions appear as the spacecraft reorients,

187 allowing the IMS to view the flow direction (Figure 1, bottom left). In this interval the
 188 lower-energy, light-ion peak has energy ~ 100 's eV, and the heavy ion component peaks
 189 at ~ 1000 's eV and has a larger count rate (proportional to energy flux) than the light
 190 ions. At the same time the electron counts intensify, and the energy range of the
 191 population extends from ~ 10 eV - 1000 eV as a lower-energy population is also
 192 encountered. There are noticeably higher counts of electrons than ions due to the larger
 193 electron flux for a given density and to the larger geometric factor of ELS. Near 1100 UT
 194 the electron counts decrease and the energy of the population reverts back to the range $\sim$
 195 50 – 500 eV.

196 The large-scale variability seen across the whole interval in Figure 1 is most likely due to
 197 the vertical structure of the plasma sheet, observed as the plasma sheet moves up and
 198 down across the path of the spacecraft. As is clear from these spectrograms, this structure
 199 is not obvious in the ion data. In fact, ions are only generally seen (when pointing is
 200 favourable) at the times corresponding to the regions of highest flux in the electrons,
 201 presumably near the centre of the plasma sheet.

202

203 3.2 Tail survey

204 Figure 2 shows the low-latitude passes from the Cassini orbits from 12 October 2005 to
 205 24 May 2007. Between these dates Cassini sampled the equatorial, nightside

206 magnetosphere at a range of planetocentric distances (9 to 50 R_S) and magnetic local
 207 times (2000-0600 MLT).
 208 Intervals to include in the survey were selected based on the criterion that there were
 209 sufficient counts on which to perform the ion moments analysis. Since the plasma
 210 sheet/magnetodisc is 'pushed' northward out of the equatorial plane, most encounters
 211 with it have been found near 10 - 13° in latitude at $\sim 40 R_S$. Because the plasma sheet also
 212 exhibits rotational modulation consistent with the planetary spin period (Arridge et al.,
 213 2008b) and may flap up and down in response to variations in the solar wind, entries into
 214 the plasma sheet are, in practice, sporadic.
 215 The bulk flow of the ions can only be measured if the velocity vector lies within the
 216 instrument field of view as demonstrated in Figure 1. Optimal periods are where the flow
 217 is close to the centre of the anode fan and the actuation sweep so that the detector
 218 samples the full beam. In total, 35 days between 12 October 2005 and 24 May 2007,
 219 containing plasma sheet encounters where the IMS was able to sample the peak of the ion
 220 flow were collated, providing ~ 44 hours of ion data for use in the tail survey.
 221 In Figure 3 the derived flow vectors are drawn originating from the spacecraft position at
 222 the time of measurement and projected onto the equatorial plane. The vectors are
 223 coloured by total ion density ($N_{TOT} = N_{H^+} + N_{W^+}$). The initial, most striking observation is

224 that the flows in this region are still predominately in the corotational direction, even at
 225 large distances from the planet ($\sim 50 R_S$).

226 The velocity vectors in Figure 3 indicate significantly lower flow speeds than the local
 227 corotational speed (compare with the scale arrows in Figure 3) at distances from $\sim 15 R_S$
 228 outwards. The general flow pattern illustrates the departure from purely azimuthal flow
 229 outside of $\sim 20 R_S$ in the post midnight sector, where the flow appears to be more
 230 downward. In this region the flows would not appear likely to circulate on around to the
 231 dayside region without a substantial sunward acceleration. There are departures from the
 232 purely azimuthal flow with clear instances of more radial flow in agreement with results
 233 from Voyager (Lazarus and McNutt, 1983). However, no instances of rapid radial flow,
 234 akin to the plasmoid signatures of Hill et al. (2008) (which have been included on the
 235 flow pattern for comparison) are observed. Instead, the radial flow is superimposed on
 236 the azimuthal flow as a gradual motion of the bulk plasma. There is no notable
 237 correlation of density with outwardly-moving flows.

238 Figure 4 shows several of the derived plasma properties as a function of radial distance
 239 from Saturn. In the top panel, the measured azimuthal velocity is plotted and compared
 240 with the profile for strictly corotating flow (dashed line). The second panel contains the
 241 angle between the direction of bulk and azimuthal flows for each radial distance sampled,
 242 with a line at zero marking the transition between inward and outward flow. In the third

243 panel are the proton (green) and water group (red) densities together with the W^+/H^+
 244 density ratio, and the bottom panel contains the parallel temperatures for the light (green)
 245 and heavy (red) ions.

246 It is clear that the data in all panels of Figure 4 show a marked change in the nature of the
 247 plasma and flows beyond ~ 15 - $20 R_S$. Outside of $15 R_S$ the azimuthal velocity no longer
 248 increases with radial distance and remains approximately constant at ~ 100 - 200 km s^{-1} out
 249 to $46 R_S$. The azimuthal flow velocities outside of $\sim 25 R_S$ are in accord with those
 250 derived from the MIMI-INCA data (Kane et al., 2008). Azimuthal velocities as low as
 251 $0.25 V_{CR}$ highlight the significant mass-loading on these field lines in agreement with
 252 earlier findings (Frank et al., 1980; Richardson, 1986). The subcorotation observed also
 253 is in qualitative agreement with the lagging field observed in this region (Arridge et al.,
 254 2006).

255 In general, inward bulk flows are only observed inside of $\sim 15 R_S$ as demonstrated by the
 256 negative angles plotted in the second panel of Figure 4 inside of this distance. These
 257 inward (and outward) motions are most likely the result of global magnetospheric
 258 motion.

259 Outside of $17 R_S$, only outward motion is observed, and the flow angle increases with
 260 radial distance resulting in more tailward flows (and less strictly azimuthal flows) with
 261 increased distance from the planet. Indeed, an examination of the flow pattern in Figure 3

262 shows little evidence that the dawn-region flows at larger radial distances will turn
 263 sunward and return to the dayside.
 264 Inside of 15 R_S there is a steep drop-off with distance in the densities of both the water
 265 group and light ions, although the decline of the density ratio signifies a sharper decrease
 266 in the water group ions relative to the light ions. This drop-off is as expected for a dipole
 267 field. Outside of 15 R_S the densities of both species decrease comparably with increasing
 268 radial distance as evidenced by the flat profile of the density ratio until $\sim 35 R_S$ when
 269 there is a slight increase in the density ratio.
 270 Inside of 15 R_S the parallel ion temperatures (Figure 4, third panel) increase with radial
 271 distance due to the scattering of the pick-up ion population from the inner magnetosphere
 272 (e.g. Wilson et al., 2008). Once the transition at $\sim 15 R_S$ is crossed, however, they show
 273 an almost constant or slowly declining profile.
 274 In the final panel we plot the Alfvén travel time to the planet using the local field strength
 275 and proton density. The proton density is used since it is representative of the density
 276 along the field line. Values start at sub-one hour increasing to a maximum of four hours
 277 at $> 40 R_S$.
 278 One of the most striking aspects of the ion flow pattern and associated parameters is the
 279 lack of inwardly moving flux tubes in the outer magnetosphere. Such motion would be
 280 observed if field lines that had recently undergone mass-release were returning to the

281 inner magnetosphere depleted and, due to the reduction of plasma-loading, moving at
 282 corotational or possibly even super-corotational speeds. Furthermore, the planetary wind
 283 model would favor the release of the most equatorially confined, heavy ions; hence a post
 284 mass-release flux tube should show a preferential depletion of water group ions. The
 285 remaining ions would likely have been energised in the magnetic reconnection that
 286 produced the mass release. Hence, one might expect the signature of such returning,
 287 depleted flux tubes to be low density, energised, water-depleted ions distributions moving
 288 inwards and with faster azimuthal velocities than in the ambient plasma.
 289 No such ion signature is apparent in the intervals sampled. For example, the relatively flat
 290 density ratio profile in the third panel of Figure 4 suggests that no significant water group
 291 depletion relative to the light ions is detected. The possible reasons for this are outlined in
 292 section 3.3.
 293
 294 *3.3 Why are return flows not observed in the ion data?*
 295 The lack of signatures of returning, depleted flux tubes in the intervals represented by
 296 Figures 3 and 4 could arise if a) there is no such inward flow in the region sampled, b) the
 297 inflow channels are physically much narrower in azimuth than the outflow channels
 298 (Chen and Hill, 2008), which makes them less likely to be included in this dataset, c) the
 299 IMS is never orientated such that it is looking outward to detect inward flows or d) the

300 low density, energised, post-reconnection ions have fluxes too low to be detectable by the
301 IMS. The look direction plots in Figure 1 demonstrate the situation in case c), where the
302 bottom left shows an interval with nearly complete viewing of the sky, but the bottom
303 right plot shows the pointing for an interval only sampling a portion of the sky and where
304 inflows could be missed.

305 In the case of c), we can establish whether instrument pointing introduces a bias into the
306 results by comparing how often the IMS is sampling each direction and the percentage of
307 inward or outward flows detected. In Table 1 are the durations of the look and flow
308 directions observed for inward and outward flows outside of $22 R_S$. In this region of the
309 outer magnetosphere, according to Figure 3, almost no inward flows are observed. The
310 percentage of inward flows detected relative to the time the instrument is looking
311 outward is very small and in fact can be attributed to one single data point. Upon further
312 inspection there is no noticeable difference between this data point and the surrounding
313 ones and it may be a spurious result. Nevertheless it is clear that the IMS has plenty of
314 opportunity to sample inward flows (it is looking outward for seven hours of the total
315 time), yet none are seen. Conversely, when the instrument looks inward, an abundance of
316 outward flows are detected.

317 In the case of d) we employ the ELS data, with its greater detection sensitivity, to
318 characterise the electrons in the regions sampled. This will establish whether the IMS is

338 signatures of the mass-release processes, then it occurs across the whole region sampled
339 and not preferentially in the dusk magnetosphere as proposed by Vasyliunas (1983) and
340 Cowley et al. (2004).

341 Ion densities of two of the plasmoid events identified in Jackman et al. (2007) and Hill et
342 al. (2008) (March 4 2006 and August 4 2006) are also included in Figure 5 (squares). The
343 plasmoid densities for the first case have a range of values, extending to very low values
344 at the very limit of what can be observed in the IMS. For the second case, the densities
345 are near the top of the maximum values detected in this region. Therefore, were Cassini
346 in a favorable position on the dates included in this survey, to detect passing plasmoids,
347 we would expect to detect them. Positive identification of the plasmoids in the studies of
348 Jackman et al. (2007, 2008) and Hill et al. (2008) was achieved using magnetic field data.

349 A sharp, northward-turning of the primarily southward-pointing planetary field indicates
350 that the field lines have moved from a stretched- to a plasmoid-type configuration, yet no
351 such magnetic signatures have been associated with any of the intervals in this study,
352 which all appear to be on closed field lines. Furthermore, during none of the events
353 studied here is there evidence for a large rotation of the velocity from a largely azimuthal
354 flow direction to a strongly tailward flow, also indicative of plasmoid release (Hill et al.,
355 2008), and thus we conclude that despite similarities in density, the events included in

375 of magnetic flux to the inner magnetosphere required due to flux conservation. As
376 described in section 3.3 there are a number of selection criteria that mitigate against
377 observing such features, namely the small scale-size of the inflow channels (Chen and
378 Hill, 2008), the low density expected in returning flux tubes and the likelihood of
379 favourable instrument viewing.

380 The flow pattern indicates that the observed flux tubes are likely to encounter the dawn
381 magnetopause, as the strongly dawnward flow observed implies, however, measurements
382 adjacent to the dawn magnetopause do not indicate a large build-up of plasma. Thus the
383 plasma either manages to rotate around dawn to the dayside, or it is lost either downtail
384 into interplanetary space.

385 The striking change in the characteristics of the plasma sheet beyond $\sim 15 - 20 R_S$ is most
386 likely due to the transition from the region dominated by closed flux tubes which are able
387 to complete an entire rotation of the planet (closed drift path), and the outer
388 magnetospheric flux tubes which may not remain closed as they convect through the tail
389 due to the centrifugal stresses brought on by significant mass loading. We also note that
390 this is just inside the expected hinging distance of the magnetotail current sheet (Arridge
391 et al., 2008b) and where the field lines start to become significantly stretched.

392 The Alfvén travel times in Figure 4 are shown to increase with radial distance. Travel
393 times of a few hours are consistent with a slight delay in the communication between the

412 transport process (Hill and Dessler, 1976), and is $\eta \equiv \int (n(s)/B(s))ds$, where the integral
 413 is taken along a field line. We can approximate this integral as $\eta = \int n(z(s))/B(z(s))ds$,
 414 where $n(z(s)) = n_0 \exp(-W/kT)$, n_0 is the equatorial density and T is the parallel ion
 415 temperature (both derived from the IMS data), W is the centrifugal potential and
 416 $B(z(s))$ corresponds to the field strength derived from the magnetospheric field model of
 417 Khurana et al. (2006). The centrifugal potential is derived using the assumption that a
 418 single field line rotates with the same level of subcorotation as measured at the equator.
 419 Since we derive equatorial azimuthal velocities we can work out the fraction of
 420 subcorotation, f and use $W = 0.5mf^2r^2\Omega^2$. The distance along the field line, ds is
 421 derived assuming a parabolic shaped field line in the stretched field region and we
 422 multiply the values by the mass in kg to get the flux tube mass content plotted in the top
 423 panel of Figure 6 (diamonds). There is significant spread in the data at all values of R ,
 424 indicative of the varying flux tube volumes encountered in the tail, presumably due to the
 425 cycle of mass-release and loading. The values show a slight decrease with radial distance,
 426 in particular the upper limit of the distribution of points declines with R . This suggests
 427 that despite the requirement that under no mass-loss the flux tube content is preserved,
 428 there is a loss of flux tubes with a high mass content (at the upper limit of the profile)
 429 with increasing R . Thus, those are lost downtail and what we are effectively seeing are

4.3 *Triggering mass-loss processes/Drivers of tail reconnection*

As we have shown, heavily loaded, stretched flux tubes may undergo mass-release in the tail if some threshold relating to the mass-loading rate and field strength is reached. However, it is possible that an alternative trigger may initiate the pinch-off process. For example, Bunce et al. (2005) described an energetic particle event observed in the magnetotail during SOI and attributed it to tail reconnection instigated by magnetospheric compression by a solar wind corotating interaction region (CIR). Russell et al. (2008) found that four of the five substorm events identified in Jackman et al. (2008) were triggered when Titan was within one Saturn rotation of the highly-stretched tail field lines at midnight local time.

We have not considered the effects of the external solar wind conditions or the position of Titan during the events studied here, however we propose that in cases of fast rotation, coupled with sufficient mass build-up, field lines can reconnect across the stretched current sheet and drive plasmoid formation without, necessarily, an external driver. This agrees with the proposal by Hill et al. (1974) and more recent work by Russell et al. (2008) that state that due to the inefficiency of the reconnection process at Saturn's dayside magnetosphere, accumulation of mass in the tail flux tubes may dominate plasmoid formation, not closure of open flux generated at the dayside magnetopause.

distances and no clear local time dependency in the nightside is found agreeing with
Chen and Hill, (2008).

Acknowledgements: The work at Los Alamos was performed under the auspices of the
US DOE and was supported by the NASA Cassini program. Work at Southwest Research
Institute was supported by JPL contract 1243218. Cassini is managed by the Jet
Propulsion Laboratory for NASA. Work at Imperial was supported by STFC. C.S.A. and
A.J.C. were supported in this work by the STFC rolling grant to MSSL/UCL. Part of this
work was discussed during a team meeting at the International Space Science Institute in
Bern, Switzerland. HJM, MFT, CSA and ECS acknowledge funding from ISSI to attend
this meeting.

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Table 1: Instrument look directions

The inward and outward look durations are calculated from the percentage of time within one sampling period (14 x 32 seconds) that the instrument is looking inward or outward. The sum of these percentages is greater than 100% because the instrument can often see both inward and outward flow directions within a sampling period. For this calculation we make the assumption that the radial flow component from the moment calculations within that sampling period is constant within a sampling interval, which could smooth out short duration radial motion. Only periods outside of 22 R_S have been considered.

Figure 1: Interval on July 3 2006

The top and middle panels contain time-energy spectrograms from the IMS and ELS instruments on July 3 2006. Cassini is at $\sim 27 R_S$ and at a magnetic local time (LT) of 2150. The colour scale indicates the count rate; note the different scales for the ions and electrons. The ion spectrogram highlights the low counts and sporadic coverage due to pointing and limited entries into the plasmasheet typical of the tail orbits. The third panel shows the electron density together with the density threshold of $3 \times 10^3 \text{ m}^{-3}$. Below this are field of view plots for the IMS and ELS during the 15 minute intervals indicated by the red bars. The field of view plots are in a spacecraft-centered frame (OAS). The viewing for each polar anode (1 – 8) is projected onto the sky (note that anode 2 is not displayed on the right-hand figure for clarity). A line from the observer to the centre of the plot is in the direction of positive S, (the Cassini to Saturn direction), the north-south direction ($O = S \times (\Omega \times S)$ where Ω is Saturn's spin axis and A completes the right-handed system. The azimuthal angle is shown on the outside of the outer circle and is about S, referenced to zero in the O direction. The latitudinal angle is relative to S where the inner dashed circle is 90° latitude from S. The directions from which strictly corotational and observed flows originate are indicated by a triangle and an upside-down triangle respectively. Between 0915 UT and 0930 UT the instrument was not looking into the flow direction, hence the bulk flow vector could not be determined.

Figure 2: Trajectory plot

Trajectory coverage plot for period covered in this study. The blue points denote the orbits surveyed in the ion data. The red points are where both ion and electron data were available. Only electron moments outside of $10 R_S$ and in the nightside between May 10 2006 to August 28 2006 were included in the analysis.

Figure 3: Equatorial flow pattern of ions

The velocity vector of each position was determined using the spacecraft position as the arrow's origin. Arrow length represents velocity and colour the total ion density. Scale arrows for strict corotation at radial distances of 5, 15, 25, 35 and $45 R_S$ have been indicated along with the magnitude of the corotation speed at that distance. The velocities are in a Saturn-centered equatorial system with the Sun toward the right of the figure. A sample magnetopause surface from Arridge et al. (2006) has been included for context. The flows detected during two plasmoid events on March 4 2006 and August 4 2006 (Hill et al., 2008) have been included. Note that the flow speed observed on March 4 2006 has been scaled down by $\sim 50\%$ relative to the rest of the flows for clarity.

Duration of inward and outward flow detection beyond 22 R_s

Instrument look (plasma flow) direction	Look time (of 13 hours in total)	Duration of observed flows	Duration of flows seen as a percentage of opportunities
Outward (inward)	7 hours	0.2 hours	0.02 %
Inward (outward)	13 hours	12.8 hours	98.0 %

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