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


a Space Science and Applications, Los Alamos National Laboratory, P.O. Box 1663, D466, Los Alamos, NM 87545, USA
b Mullard Space Science Laboratory, Holmbury St. Mary, Dorking, Surrey, RH5 6NT, UK
c Centre for Planetary Sciences at UCL/Birkbeck, University College London, Gower Street, London, WC1E 6BT, UK
d Space and Atmospheric Physics Group, Imperial College London, Prince Consort Road, SW7 2BW, UK
e Institute of Geophysics & Planetary Physics, University of California, Los Angeles, CA 90095-1567, USA
f Heliophysics Sciences Division, Geospace Physics Laboratory/Code 673, NASA/Goddard Space Flight Center, 8800 Greenbelt Road, Greenbelt, MD 20771, USA

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A B S T R A C T

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 50R 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 the ion mass spectrometer (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.

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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.

Saturn is also a fast rotator with a large system of rings and moons providing a continual supply of plasma to the magnetosphere through ionisation of neutral gases originating on the rings and moons (Sittler et al., 2004; Tokar et al. 2006), in particular from the active geysers on Enceladus (e.g. Dougherty et al., 2006). At small radial distances the plasma is forced into corotation with the planet (Hill, 1979; Wilson et al., 2008). However, plasma in Saturn’s outer magnetosphere is found to be slowed with respect to corotation (Eviatar and Richardson, 1986; Kane et al., 2008). This slowing is indicative of outward plasma transport that leads to subcorotation if the ionosphere is unable to supply enough current to accelerate the plasma to the larger corotation speeds at larger radial distances (Hill, 1979). Furthermore, centrifugal forces stretch the lower-strength magnetic field, until the field lines take the shape of a thin, lagging magnetodisc (Arridge et al., 2006, 2008a) a configuration which lends itself to mass-release via the Vasyliunas or ‘planetary wind’ model.

In the Saturnian magnetotail the plasma and field properties have been described for several plasmoid-type signatures that were presumably released from mid-tail magnetic reconnection events (Jackman et al., 2007, 2008, submitted; Hill et al., 2008). Only nine such events have been identified to date. In addition to these in-situ observations, remote sensing by the ENA imager detected energetic neutral atoms originating from the tail region between ~20 and 30 Rs suggestive of local acceleration of ions associated with a substorm-type energisation (Mitchell et al., 2007) which suggests a fairly constant loss rate and by the observed and simulated count rate spectrum. It is necessary to pre-select the ion species to be modelled, and for the data shown here we specified a light ion (H+) and a water group (W+) component based on lower-resolution time-of-flight measurements of the IMS. Although we assume mass = 17 amu for the heavy ion species, the population may actually include O+, OH+, H2O+ and H2O ions, but the derived moments are relatively insensitive to the actual composition. The calculation is carried out over 14 × 32 s intervals, resulting in ion moments with a ~7 min resolution. Further details regarding the calculation can be found in Tokar et al. (2006) and Wilson et al. (2008).

The electron moments are derived by integrating the particle distribution over three-dimensional velocity space. In general, the electrons have a high thermal speed relative to their bulk speed and so, in the absence of anisotropic pitch-angle distributions, do not have significant directionality. Therefore, the electrons sampled in one direction can 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 ~1 to ~7 min 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., 2009).

3. Observations

3.1. Example tail plasma sheet entry

Fig. 1 contains energy–time spectrograms of the ion (top panel) and electron (second panel) data typical of the equatorial magnetotail. These data are from 3 July, 2006, between 0800 and 1200 UT when Cassini was at ~27 Rs 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 and 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 Fig. 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, allowing the IMS to view the flow direction (Fig. 1, bottom left). In this interval the lower energy, light ion peak has energy ~100 eV, and the heavy ion component peaks at ~1000 eV, and has a larger count rate (proportional to energy flux) than the light ions. At the same time the electron counts intensify, and the energy range of the population extends from ~10 to 1000 eV as a lower-energy population is also encountered. There are noticeably higher counts of electrons than ions due to the larger electron flux for a given density and to the larger geometric factor of ELS. Near 1100 UT the electron counts decrease and the energy of the population reverts back to the range ~50–500 eV.

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

3.2. Tail survey

Fig. 2 shows the low-latitude passes from the Cassini orbits from 12 October, 2005 to 24 May, 2007. Between these dates Cassini sampled the equatorial, nightside magnetosphere at a range of planetocentric distances (9–50 \( R_S \)) and magnetic local times (2000–0600 MLT).

Intervals to include in the survey were selected based on the criterion that there were sufficient counts on which to perform the ion moments analysis. Since the plasma sheet/magnetodisc is ‘pushed’ northward out of the equatorial plane, most encounters with it have been found near 10–13° latitude at \( \sim 40 R_S \). Because the plasma sheet also exhibits rotational modulation consistent with the planetary spin period (Arridge et al., 2008b) and may flap up and down in response to variations in the solar wind, entries into the plasma sheet are, in practice, sporadic.

The bulk flow of the ions can only be measured if the velocity vector lies within the instrument field of view as demonstrated in Fig. 1. Optimal periods are where the flow is close to the centre of the anode fan and the actuation sweep so that the detector samples the full beam. In total, 35 days between 12 October, 2005 and 24 May, 2007, containing plasma sheet encounters where the IMS was able to sample the peak of the ion flow were collated, providing \( \sim 44 \) h of ion data for use in the tail survey.

In Fig. 3 the derived flow vectors are drawn originating from the spacecraft position at the time of measurement and projected onto the equatorial plane. The vectors are coloured by total ion density (\( N_{\text{TOT}} = N_{H^+} + N_{W^+} \)). The initial, most striking observation is that the flows in this region are still predominately in the corotational direction, even at large distances from the planet (\( \sim 50 R_S \)).

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

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Fig. 4 shows several of the derived plasma properties as a function of radial distance from Saturn. In the top panel, the measured azimuthal velocity is plotted and compared with the profile for strictly corotating flow (dashed line). The second panel contains the angle between the direction of bulk and azimuthal flows for each radial distance sampled, with a line at zero marking the transition between inward and outward flow. In the third panel are the proton (green) and water group (red) densities together with the \( W^+ / H^+ \) density ratio, and the bottom panel...
contains the parallel temperatures for the light (green) and heavy (red) ions.

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

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

Outside of \( 17 R_S \) only outward motion is observed, and the flow angle increases with radial distance resulting in more tailward flows (and less strictly azimuthal flows) with increased distance from the planet. Indeed, an examination of the flow pattern in Fig. 3 shows little evidence that the dawn-region flows at larger radial distances will turn sunward and return to the dayside.

Inside of \( 15 R_S \) there is a steep drop-off with distance in the densities of both the water group and light ions, although the decline of the density ratio signifies a sharper decrease in the water group ions relative to the light ions. This drop-off is as expected for a dipole field. Outside of \( 15 R_S \) the densities of both species decrease comparably with increasing radial distance as evidenced by the flat profile of the density ratio until \( \sim 35 R_S \) when there is a slight increase in the density ratio.

Inside of \( 15 R_S \) the parallel ion temperatures (Fig. 4, third panel) increase with radial distance due to the scattering of the pick-up ion population from the inner magnetosphere (e.g. Wilson et al., 2008). Yet once the transition at \( \sim 15 R_S \) is crossed they show an almost constant or slowly declining profile.

In the final panel, we plot the Alfvén travel time to the planet using the local field strength and proton density. The proton density is used since it is representative of the density along the
field line. Values start at sub-1 h increasing to a maximum of 4 h at \(>40 R_S\).

One of the most striking aspects of the ion flow pattern and associated parameters is the lack of inwardly moving flux tubes in the outer magnetosphere. Such motion would be observed if field lines that had recently undergone mass-release were returning to the inner magnetosphere depleted and, due to the reduction of plasma-loading, moving at corotational or possibly even super-corotational speeds. Furthermore, the planetary wind model would favour the release of the most equatorially confined, heavy ions; hence a post-mass-release flux tube should show a preferential depletio of water group ions. The remaining ions would likely have been energised in the magnetic reconnection that produced the mass-release. Hence, one might expect the signature of such returning, depleted flux tubes to be low density, energised, water-depleted ions distributions moving inwards and with faster azimuthal velocities than in the ambient plasma.

No such ion signature is apparent in the intervals sampled. For example, the relatively flat density ratio profile in the third panel of Fig. 4 suggests that no significant water group depletio relative to the light ions is detected. The possible reasons for this are outlined in Section 3.3.

### 3.3. Why are return flows not observed in the ion data?

The lack of signatures of returning, depleted flux tubes in the intervals represented by Figs. 3 and 4 could arise if (a) there is no such inward flow in the region sampled, (b) the inflow channels are physically much narrower in azimuth than the outflow channels (Chen and Hill, 2008), which makes them less likely to be included in this dataset, (c) the IMS is never orientated such that it is looking outward to detect inward flows or (d) the low density, energised, post-reconnection ions have fluxes too low to be detectable by the IMS. The look direction plots in Fig. 1 demonstrate the situation in case (c), where the bottom left shows an interval with nearly complete viewing of the sky, but the bottom right plot shows the pointing for an interval only sampling a portion of the sky and where inflows could be missed.

In case of (c), we can establish whether instrument pointing introduces a bias into the results by comparing how often the IMS is sampling each direction and the percentage of inward or outward flows detected. In Table 1 are the durations of the look and flow directions observed for inward and outward flows outside of \(22 R_S\). In this region of the outer magnetosphere, according to Fig. 3, almost no inward flows are observed. The percentage of inward flows detected relative to the time the instrument is looking outward is very small and in fact can be attributed to a single data point. Upon further inspection there is no noticeable difference between this data point and the surrounding ones and it may be a spurious result. Nevertheless, it is clear that the IMS has plenty of opportunity to sample inward flows (it is looking outward for 7 h of the total time), yet none are seen. Conversely, when the instrument looks inward, an abundance of outward flows are detected.

In case of (d) we employ the ELS data, with its greater detection sensitivity, to characterise the electrons in the regions sampled. This will establish whether the IMS is effectively 'blind' to such a low-density population. For this purpose electron densities for all passes into the magnetotail plasma sheet outside of \(\sim 10 R_S\) from May 10, 2006 to August 28, 2006 (Fig. 2) were used in addition to those dates corresponding to the ion events shown in Fig. 3.

We first compare the ion and electron densities from the tail in Fig. 5. We limit the electron density used to values \(>10^3 \text{m}^{-3}\), since densities below this most likely correspond to lobe measurements (Arridge et al., submitted). The ELS densities are shifted by an empirically determined factor to make them agree with the ion densities when both are measured. There is a lack of low-density points in the ion data set at low radial distances (<20 \(R_S\)); this can be attributed to a selection effect. At low radial distances there are more intervals with higher fluxes which are selected for the survey in preference to the lower flux events.

Fig. 5 shows that the ion densities derived for the intervals presented in Figs. 3 and 4 are essentially all near the upper edge of the range of electron densities at any given radial distance. We attribute this to the lower sensitivity of ion detection, with the abundant presence of lower electron densities revealing an additional, lower-density population unseen in the IMS data and potentially representing the anticipated depleted flux tubes returning to the inner magnetosphere. There is no clear correlation of the low-density electron regions with local time or radial distance, suggesting that if these are signatures of the mass-release processes, then it occurs across the whole region sampled and not preferentially in the dusk magnetosphere as proposed by Vasyliunas (1983) and Cowley et al. (2004).

Ion densities of two of the plasmoid events identified in Jackman et al. (2007) and Hill et al. (2008) (March 4, 2006 and August 4, 2006) are also included in Fig. 5 (squares). The plasmoid densities for the first case have a range of values, extending to very low values at the very limit of what can be observed in the IMS. For the second case, the densities are near the top of the maximum values detected in this region. Therefore, were Cassini

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**Table 1**

<table>
<thead>
<tr>
<th>Instrument look (plasma flow) direction</th>
<th>Look time (of 13 h in total) (h)</th>
<th>Duration of observed flows (h)</th>
<th>Duration of flows seen as a percentage of opportunities (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outward (inward)</td>
<td>7</td>
<td>0.2</td>
<td>0.02</td>
</tr>
<tr>
<td>Inward (outward)</td>
<td>13</td>
<td>12.8</td>
<td>98.0</td>
</tr>
</tbody>
</table>

Instrument look directions. The inward and outward look durations are calculated from the percentage of time within one sampling period (14 x 32 s) 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. This could smooth out short-duration radial motion. Only periods outside of 22 \(R_S\) have been considered.

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**Fig. 5. Density with distance from the planet and the centre of the current sheet: total ion density (\(\text{H}^+\) and \(\text{W}^+\)) (blue) over plotted on the corrected electron density (green) against radial distance. The ion density of two of the plasmoid events from Jackman et al. (2007) and Hill et al. (2008) are plotted as black squares (44 \(R_S\); March 4, 2006 and 49 \(R_S\); August 4, 2006). Densities <2.5 x 10^3 \(\text{m}^{-3}\) are not included as they are assumed to be lobe regions. Ions are only detected above a limiting density (which is \(R\) dependent). However, electrons are detected at densities lower than this. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)**
in a favorable position on the dates included in this survey, to
detect passing plasmas, we would expect to detect them.
Positive identification of the plasmas in the studies of Jackman
et al. (2007, 2008) and Hill et al. (2008) was achieved using
magnetic field data. A sharp, northward-turning of the primarily
southward-pointing planetary field indicates that the field lines
have moved from a stretched- to a plasmoid-type configuration,
yet no such magnetic signatures have been associated with any
of the intervals in this study, which all appear to be on closed
field lines. Furthermore, during none of the events studied here is
there evidence for a large rotation of the velocity from a largely
azimuthal flow direction to a strongly tailward flow, also
indicative of plasmoid release (Hill et al., 2008), and, thus we
conclude that despite similarities in density, the events included
in this study are not plasmoid signatures and are still on closed
field lines attached to the planet.

4. Discussion

4.1. Saturn’s magnetospheric tail

From the ion moments computed from IMS measurements,
complemented and enhanced by those from the ELS dataset, the
following picture emerges regarding Saturn’s magnetospheric tail:
In the outer magnetosphere (~> 20 Rs) the plasma and flows
are markedly different from those observed inside of 20 Rs. We
find the magnetotail plasma sheet to be a water group-laden
region that is still circulating at 50 Rs, and Hill et al. (2008), the low density expected in returning flux tubes
features, namely the small scale-size of the inflow channels (Chen
and Hill, 2008), indicates that the magnetosphere can contain the plasma pressure
out to large distances. However, the level of subcorotation is a
signature that Saturn’s ionosphere is unable to enforce full
corotation on the mass-loaded field lines. Furthermore, during none of the events studied here is
there evidence for the dynamic process that should ultimately
result in the loss of mass from the system of closed field lines, nor
the return of magnetic flux to the inner magnetosphere required
due to flux conservation. As described in Section 3.3 there are
a number of selection criteria that mitigate against observing such
features, namely the small scale-size of the inflow channels (Chen
and Hill, 2008), the low density expected in returning flux tubes
and the likelihood of favourable instrument viewing.

The flow pattern indicates that the observed flux tubes are likely
to encounter the dawn magnetopause, as the strongly
downward flow observed implies; however, measurements ad-

dominate to the dawn magnetopause do not indicate a large build-up
of plasma. Thus the plasma either manages to rotate around dawn
to the dayside, or it is lost either downhill into interplanetary
space.

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

The Alfvén travel times in Fig. 4 are shown to increase with
radial distance. Travel times of a few hours are consistent with a
slight delay in the communication between the distant field line
and the ionosphere resulting in the corotation lag observed.

We underline that the analysis here has not indicated whether
solar wind driving is instrumental in the motions of the outer
magnetospheric plasma. With a detailed compositional analysis, it
may be possible to distinguish flux tubes populated by solar wind
plasma (He++) via dayside (or nightside) reconnection, from flux
tubes containing heavy ions with an origin in the inner mageto-
sphere. Due to the ubiquitous presence of water group ions, all the
relatively dense intervals analysed here will fall into the latter
category.

Finally, we have identified a lower-density population revealed
by the electron observations at all radial distances and local times,
which may include signatures of returning flux tubes, although
we are unable to derive their motion.

4.2. Flux-tube content and threshold for field-breaking

We can attempt to characterise any mass-loss by estimating
the flux-tube content versus radial distance in the region of the
magnetosphere sampled. The flux-tube content, in the absence of
sources and sinks, is conserved for a given flux tube during the
outward transport process (Hill and Dessler, 1976), and is
\[ \eta = \int (n(s)/B(s)ds, \] where the integral is taken along a field line.
We can approximate this integral as \( \eta = \int (n(s)/B(s))ds, \) where
\( n(s) = n_0 \exp(-W/kT), \) \( n_0 \) is the equatorial density and \( T \) is the parallel ion temperature (both derived from the IMS data), \( W \) is the centripetal potential and \( B(s) \) corresponds to the field strength derived from the magnetospheric field model of Khurana
et al. (2006). The centripetal potential is derived using the
assumption that a single field line rotates with the same level of
subcorotation as measured at the equator. Since we derive
equatorial azimuthal velocities we can work out the fraction of
subcorotation, \( f \) and use \( W = 0.5mf^2r^2Q^2 \) the distance along the
field line, \( ds \) is derived assuming a parabolic-shaped field line in
the stretched field region and we multiply the values by the mass
in kg to get the flux-tube mass content plotted in the top panel of
Fig. 6 (diamonds). There is significant spread in the data at all
values of \( R \), indicative of the varying flux tube volumes
encountered in the tail, presumably due to the cycle of mass-
release and loading. The values show a slight decrease with radial
distance, in particular the upper limit of the distribution of
points decline with \( R \). This suggests that despite the requirement
that under no mass-loss the flux tube content is preserved,
there is a loss of flux tubes with a high mass content (at the upper
limit of the profile) with increasing \( R \). Thus, those are lost
downtail and what we are effectively seeing are the “survivors” of
the mass-loss process or Vasyliunas cycle. Despite the paucity of
data points between ~25–35 Rs and 35–43 Rs there is a rather
invariant width to the distribution of points. The constant spread
of points indicates that the flux tube content is, in general,
preserved, but it cannot be preserved for those above a certain
limit.

We can quantify this limit by testing whether the flux tube
content observed is theoretically sufficient to break-open the
magnetic field in the tail. This breaking limit is achieved when the
mass per unit flux \( \eta \) exceeds a critical limit related to the tail field,
\( B_t \geq \eta > B_F/\mu_0 V_b \) (Goertz, 1983), where \( B_t \) is the value of the lobe
field strength above and below the plasma sheet at that distance.
The lobe field strength is obtained from values corresponding to
to those points at which the density is \( < 10^3 \text{ m}^{-3} \).

To apply this criterion to Saturn’s tail, we use the values for \( \eta \) in
the top panel of Fig. 6 and over plot the estimated critical limit for
strict corotation (solid line) and the observed subcorotation (crosses). If the plasma were strictly corotating some of the measured intervals would exceed the critical value. However, the slowing of the flux tubes allows them to circulate through the tail without the need to release plasma since the measured flux tube contents are well below the theoretical limit for field-breaking. In the second panel is the ratio of the mass per unit flux to the critical limit which is approximately level.

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.

5. Conclusions

We have used ion moment data from the Cassini-IMS instrument to describe the nature of the plasma sheet dynamics in the Saturnian magnetotail. The corotational flow suggests there is a population which is most likely on closed field lines still rotating with the planet, albeit at a slower rate due to the heavy load. The ubiquitous presence of water group ions, together with the constancy of the amount of water group ions relative to light ions implies that mass-release has not occurred for the intervals for which we have derived ion parameters, since we would expect the preferential release of the equatorially confined heavy species. Such a mass-laden state represents flux tubes that are not yet ready to break-off and release plasma downtail, though they may yet do so at greater distances since we find little evidence for their return to the dayside. Through theoretical considerations we strengthen the case for these flux tubes having survived their passage through the tail because the centrifugal force on the plasma sheet is not large enough to exceed the restraining tension in the magnetic field and break it open to release the plasma (Vasyliunas, 1983). The low-density electrons have revealed a population which may well be the return flow from mass-release processes in the tail; however, these intervals are too tenuous to produce detectable ions, and therefore by default excluded from our analysis. We note that these depleted plasma sheet regions are seen at all radial distances and no clear local time dependency in the nightside is found agreeing with Chen and Hill (2008).

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