The Cushion Region and Dayside Magnetodisc Structure at Saturn

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Key Points:

- The first example of a cushion region at Saturn is identified at dusk
- The dawn magnetodisc structure is less likely to break down close to the magnetopause compared to dusk
- Jupiter is more likely to have a cushion region compared to Saturn primarily due to system size

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Abstract

A sustained dipolar magnetic field between the current sheet outer edge and the magnetopause, known as a cushion region, has yet to be observed at Saturn. Whilst some signatures of reconnection occurring in the dayside magnetodisc have been identified, the presence of this large-scale structure has not been seen. Using the complete Cassini magnetometer data, the first evidence of a cushion region forming at Saturn is shown. Only five potential examples of a sustained cushion are found, revealing this phenomenon to be rare. This feature more commonly occurs at dusk compared to dawn, where it is found at Jupiter. It is suggested that due to greater heating and expansion of the field through the afternoon sector the disc is more unstable in this region. We show that magnetodisc breakdown is more likely to occur within the magnetosphere of Jupiter compared to Saturn.

Plain Language Summary

1 Introduction

At the gas giants, the presence of an internal plasma source coupled with their rapid rotation (approximately 10 hours) significantly perturbs their magnetic field configuration. Mass ejected from the moons Enceladus and Io in the inner magnetosphere of Saturn and Jupiter, respectively, becomes ionised, locking onto magnetic field lines and is accelerated towards corotation. The newly-formed plasma is centrifugally confined to the equator, radially stretching the magnetic field into a magnetodisc. This structure has been observed at all local times under expanded conditions at Saturn (Arridge, Russell, et al., 2008). At Jupiter, a region adjacent to the magnetopause where the magnetodisc structure breaks down and the field is dipolar, referred to as the "cushion region", has been identified (Went, Kivelson, et al., 2011) and is argued to be populated by mass-depleted flux tubes following tail reconnection (Kivelson & Southwood, 2005). However, this region has yet to be identified at Saturn (Went, Kivelson, et al., 2011), despite the similarities between these two systems.

At Saturn, mass that is loaded into the magnetosphere by Enceladus must be lost from the system. These water group ions, written as W^+, are eventually driven radially outwards in the low plasma beta ($\beta < 1$) inner magnetosphere via an interchange instability with the more tenuous hot plasma population in the outer magnetosphere (Gold, 1959). At larger radial distances, plasma pressure dominates ($\beta > 1$) and the magnetic field balloons until closed field lines reconnect and mass is lost in the magnetotail (Vasyliunas, 1983). Hence, mass-depleted flux tubes following nightside reconnection via this cycle, or the solar-wind driven Dungey cycle (Dungey, 1961), convect along the dawn flanks towards noon and are subsequently refilled, thus restarting the mass transport cycle. It has been suggested that a turbulent channel of mass-depleted flux tubes should then reside radially outwards of the magnetodisc, where the field geometry is dipolar due to the lower mass content and a breakdown of the disc. This region is regarded as a signature of these cycles and has been identified at Jupiter (Kivelson & Southwood, 2005; Went, Kivelson, et al., 2011). However, since the arrival of Juno, Gershman et al. (2018) found there lacked a systematic cushion region at Jupiter, possibly highlighting that this dynamical picture is incomplete.

Evidence of supercorotating return flow at dawn following Vasyliunas-type reconnection has been identified at Saturn (Masters et al., 2011). Jasinski et al. (2019) identified a region of mass depleted flux tubes in the morning sector using the data from the CAPS Electron Spectrometer (ELS) instrument (Young et al., 2004). Yet a dipolar structure has not been seen in the magnetic field data (Went, Kivelson, et al., 2011). Delamere et al. (2015) argue that the cushion region is an inevitable consequence of magnetodisc formation. However, their criteria for identifying a cushion, given by $B_\theta > B_{dipole}$ at the equator, where B_θ is the north-south magnetic field component and B_{dipole} is the dipole field strength, does not capture the structure described above. It does not consider that the current sheet magnetic field reverses sign from northward to southward towards its outer edge. This adds to the total magnetic field and therefore fulfils their criteria without that region necessarily containing expelled content from the current sheet. To identify whether the cushion is sustained over large scales, an analysis of how the global magnetic field structure varies with distance from the planet is required.

This study will use the complete Cassini orbital magnetometer dataset at Saturn (Dougherty et al., 2004) to show the first evidence of a cushion region at Saturn. This region is found to arise preferentially at dusk, rather than dawn as was previously expected. We suggest this is due to the greater heating of the magnetodisc plasma at dusk compared to dawn (Kaminker et al., 2017) and the expansion of the magnetic field as it rotates from noon through dusk, resulting in instabilities arising in the disc. We further compare the region at which magnetodisc breakdown is expected to occur and find it is on average within the magnetosphere of Jupiter but not Saturn, possibly explaining the difference between these two systems.

2 Data Selection

To search for a cushion region at Saturn, all Cassini orbits that traversed the dayside inner magnetosphere out to the magnetopause, whilst remaining near the equator ($\pm 30°$) are analysed to track how the magnetic field configuration changes with radial distance. Crossings of the dayside magnetopause are identified using the Jackman et al. (2019) catalogue. The standoff distance R_{SS} for each unique crossing, using the first or last crossing if there are multiple during a single traversal, is mapped with the Pilkington et al. (2015) dawn-dusk asymmetric magnetopause model. The local time correction introduces a maximum $\pm 0.5 R_S$ difference in R_{SS} compared to an axisymmetric model, but it is included for completeness. There are 93 suitable revolutions (Revs) from the mission that fulfil the above criteria and are shown in Figure 1.

The 1-minute resolution magnetometer data is transformed into Kronocentric Solar Magnetic (KSMAG) spherical coordinates, where r is the radial component and positive pointing away from Saturn, θ is the north-south meridional component and ϕ is the azimuthal component increasing in the direction of rotation. An 11-hour (approximate rotation period) sliding average of the data is taken to focus on the global structure and filter other variability, including the ubiquitous planetary period oscillations (PPOs) (see (Carbary & Mitchell, 2013) review and references therein).

3 Finding the Cushion Region

To identify whether a cushion exists, there must be a stable disc structure in the middle to outer magnetosphere, otherwise the field could be quasi-dipolar everywhere. There are two conditions for the magnetic field to be disc-like (Went, Kivelson, et al., 2011). Firstly, the field must be predominantly radial such that $B_r^2/B^2 > B_\theta^2/B^2$. These ratios are shown in panels b) and e) of Figure 2. However, this criterion is insufficient when Cassini is away from the equator, where a dipole field is not purely north-south. This is particularly important to consider if the current sheet is warped (Arridge, Khurana, et al., 2008). To account for this, the second criterion is for the angle between the measured magnetic field and a dipole, where we have used the Dougherty et al. (2018) model, to be $90 \pm 30°$. This angle is shown in panels c) and f) of Figure 2. When both these criteria are satisfied, we suggest that the field is disk-like.

The location 80% of the distance from the $15 R_S$ disc inner edge to the magnetopause is set as the cushion region inner edge. For instance, if the magnetopause radial position is $r = 25 R_S$ the cushion inner edge is $r = 23 R_S$. Whilst this is closer to the mag-

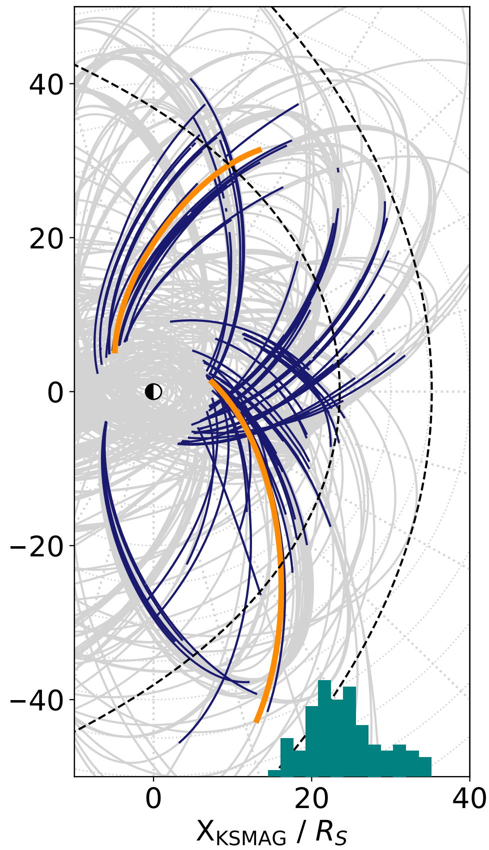

Figure 1. The complete Cassini orbital mission trajectory is shown in light grey, projected onto the equatorial plane, where the Sun is to the right. The trajectory of Cassini during the 93 Revs used in this study is shown in dark blue, where the crossing of the magnetopause occurred at the furthest radial distance on each path. The orange trajectories show the case studies in Figure 2. Magnetopause (Pilkington et al., 2015) and bow shock (Went, Hospodarsky, et al., 2011) models, assuming solar wind dynamic pressure of 0.01 nPa, are shown with black dashed curves. The histogram shows R_{SS} for each crossing.

netopause than the average inner boundary of the Jovian cushion (Went, Kivelson, et al., 2011), it is chosen due to the lack of an observed cushion thus far and the smaller magnetosphere of Saturn. It is also far enough from the magnetopause to assume we are not just measuring the shielding of the field by the boundary currents, although previous evidence of the disc persisting up to the magnetopause (Arridge, Russell, et al., 2008) shows that this effect should be negligible. We then calculate what percentage of the data fulfil the two criteria in the disc region (from $15R_S$ to the cushion inner edge). If it is more than 50%, we suggest that there exists a stable magnetodisc structure. In the cushion region (the remaining radial distance to the magnetopause), if this percentage remains approximately constant, the field has remained disc-like. If the percentage significantly reduces and the field becomes more dipolar, there is a cushion. If less than 50% of the

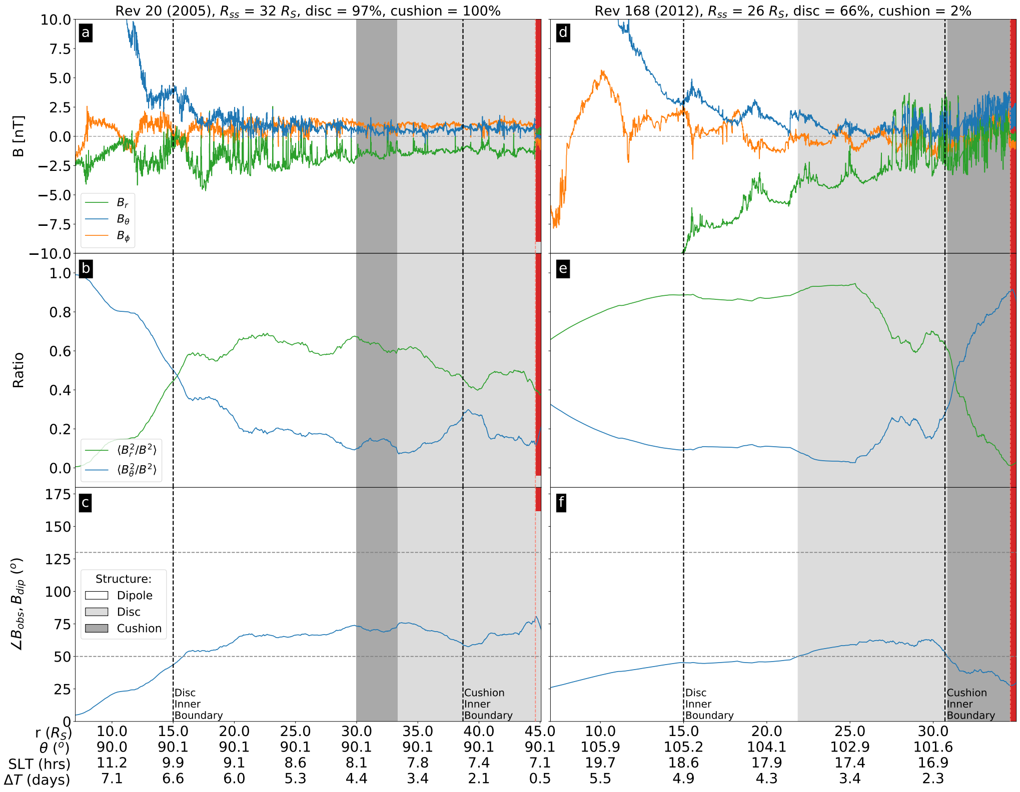

Figure 2. Two example where Cassini traversed the equatorial dayside magnetosphere of Saturn are shown as a function of radial distance. Both examples are inbound, where the time since magnetopause crossing ΔT is increasing as you move towards the planet (increasing from right to left). The top panels show the 1-minute resolution magnetic field in spherical KSMAG coordinates. The second panels show the ratio of the 11-hour smoothed radial and meridional components to the total field. The bottom panels show the angle between the measured field and the Dougherty et al. (2018) internal magnetic field model. These two quantities identify whether the disc criteria are satisfied. The panels are shaded to show if the field is dipole-like (white), disc-like (light grey), cushion-like (dark grey), or in the magnetosheath (red). The disc and cushion region boundaries are shown as vertical dashed lines. The left panels show an example at dawn where the magnetodisc is present up until the magnetopause, whilst the right panels show an example at dusk where a cushion is identified. At the bottom of the figure the radial distance (r), co-latitude (θ), Saturn local time (SLT), and ΔT are shown.

disc region has fulfilled the criteria, there is no stable magnetodisc and so we cannot check whether there is a cushion present. This ensures we see two distinct regions with persistent and sustained structures.

The change in percentage across these two regions for all 93 Revs was then calculated. The mean change in percentage was a reduction by $\mu = 6\%$ with a standard deviation of $\sigma = 24\%$. We define those Revs whose reduction in percentage is greater than $\mu+2\sigma = 54\%$ as having a cushion. The reduction in percentage is large enough to consider these as examples of a cushion and not an artefact of our method, compared to if, for instance, $\mu + 2\sigma$ was only 10% reduction.

3.1 Results

For Rev 20 in the left panels of Figure 2, the disc criteria are satisfied for 97% of the disc region and for 100% of the cushion region, showing an example of a stable magnetodisc structure that persists up to the magnetopause. The mapped standoff distance R_{SS} for Rev 20 was $32R_S$, showing that the system was significantly expanded. For Rev 168, the criteria are satisfied for 66% of the disc region. However, the percentage drops to just 2% in the cushion region and the field becomes significantly more dipolar. For Rev 168, $R_{SS} = 26R_S$, showing the system was in an expanded state. We suggest that this is the first evidence of a cushion region observed at Saturn.

A potential explanation for the Rev 168 cushion region could be that the dipolar outer boundary reflects the change in local time as Cassini moves away from noon (in time) and the magnetopause confinement of the field reduces. However, Cassini only passed through 0.2 hours of local time in the cushion region, and 1.2 hours between where the disc was first observed and the cushion region inner edge, producing a small change in the magnetopause radial position. In addition, Revs with a similar noonward trajectory where a disc was observed at dawn did not observe a dipolar outer region. Another explanation could be that the magnetosphere underwent a sudden solar wind compression. Whilst for the Rev 168 there is a small increase in magnetic field strength (∼1 nT), the data are particularly noisy in this region and the cushion was observed radially inwards of this small increase. In addition, we compared the field profile for all six potential examples of a cushion region (see Figure 3) and saw no significant increase in field strength to suggest that these are results of a solar wind compression.

This analysis was carried out for all 93 Revs. Only 15 Revs had a sustained magnetodisc and are shown in Figure 3a) in grey. The disc formed not only when the magnetosphere was expanded ($R_{SS} > 24R_S$), but even when R_{SS} was as low as $17R_S$. Of these 15 Revs, five contain potential examples of cushion regions and are highlighted in Figure 3a). For all cushion region examples, the mapped magnetopause standoff distance was greater than $24R_S$. However, a cushion does not arise whenever the magnetosphere is expanded. In particular, it does not arise preferentially at dawn as was expected.

In panel b) of Figure 3, the average magnetic field structure calculated using this subset of 15 Revs with a sustained magnetodisc is shown, revealing a local time asymmetry. When there is a magnetodisc at dawn, the structure is stable in the disc region (median of 95% for nine Revs) and this continues into the presumed cushion region (median of 100%). At dusk, when there is a magnetodisc it is on average less stable in the disc region (median of 68% for six Revs) and this significantly drops in the cushion region (median of 1%). One example was found of a stable disc that persists up to the magnetopause at dusk, compared to eight at dawn. Of the five examples of a cushion region found at Saturn, four are at dusk and one is at dawn. This result is unexpected if we assume the cushion region is a return flow channel of mass depleted flux tubes following large-scale reconnection in the tail.

For this study, the focus is on whether a significant portion of the outer boundary is persistently dipolar, reflective of the cushion region that has been observed at Jupiter, rather than being intermittently dipolar. We have taken an 11-hour average of the magnetic field data to focus on the large-scale properties of the magnetic field structure. Some examples of what appear to be signatures of an intermittent cushion were therefore removed from our analysis. We found that the overall structure at dusk is far noisier, which is reflected in the low disc region percentage at dusk in Figure 3.

4 Discussion

The magnetodisc structure maintains an equilibrium between the outward directed centrifugal force, the magnetic and plasma pressures, and the magnetic field tension in

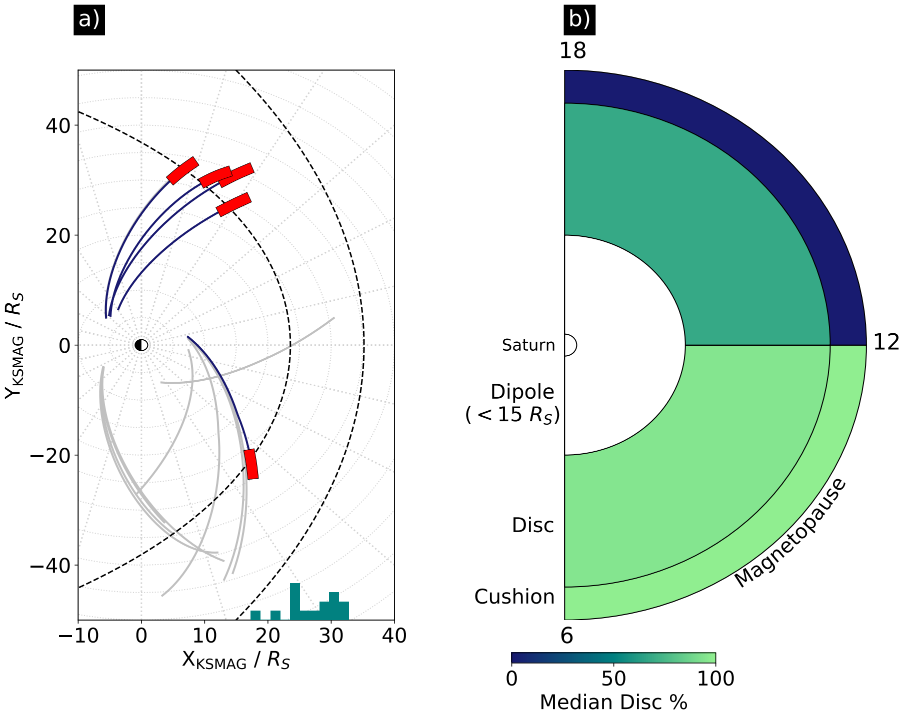

Figure 3. Panel a) shows the Cassini trajectories in a similar format to Figure 1, but only the 15 Cassini Revs where a stable disc was identified are shown in grey. The five cushion examples are shown in blue, with the cushion highlighted in red. There is one example of a disc with no cushion at dusk, but its trajectory is underneath a cushion case. Panel b) shows a representation of the average dayside configuration calculated using the 15 examples in panel a). The three radial sectors of dipole, disc and cushion are labelled and the dayside is divided into dawn and dusk local time sectors. The colorbar shows the median disc percentage. There is a distinct disc structure at dawn that persists up to the magnetopause (light green). At dusk, on average there is a less stable disc in the disc region (dark green). The field structure becomes less disc-like in the cushion region (blue), showing evidence for a dipole cushion structure at dusk.

the curved geometry that provides the inward centripetal force required to enforce sub-corotation. The field radius of curvature R_C supports this equilibrium. Magnetodisc breakdown can occur when this radial stress balance is disrupted and the magnetic field can no longer contain the plasma. Ballooning of the disc is expressed by the plasma parallel pressure being greater than the perpendicular pressure plus the magnetic tension associated with the curved field geometry. This instability can therefore lead to reconnection and plasma breaking off the disc. To identify where the force balance in the disc might break down, we can compare the gyoradii of plasma ions to identify where it approaches the length-scale R_C that is associated with maintaining the disc structure. The typical ion gyroradius of a charged particle can be expressed as

$$r_i = \frac{\sqrt{2mk_bT}}{|q|B} \tag{1}$$

where m is the particle mass, q is the charge, B is the local magnetic field strength, T is the temperature (where we assume that $T_\perp \approx T$) and where k_b is the Boltzmann constant. Went, Kivelson, et al. (2011) calculated the critical density in the disc under which stress balance would break down. However, due to a lack of data close to the magnetopause at Saturn they could not resolve this difference between the gas giants. Now the Cassini mission is complete, we can build on their work using the latest results to understand these new cushion observations.

We calculate magnetic field profiles using the complete Cassini (Dougherty et al., 2004) and Galileo (Kivelson et al., 1992) magnetometer datasets. We fit a power-law model to the increasing thermal heavy ion temperatures observed at Saturn (Wilson et al., 2017) and Jupiter (Kim et al., 2020). For both planets we assume a mass-per-charge ratio of 16 for the magnetodisc plasma, assuming it is dominated by O^+ at Saturn and is a combination of O^+ and S^{2+} at Jupiter. An expanded magnetosphere is also assumed, with $R_{SS} = 24R_S$ for Saturn and $R_{SS} = 75R_J$ for Jupiter.

Plugging these into Equation 1, we get one-dimensional gyroradii profiles as a function of radial distance shown in Figure 4. Both show an increase in gyroradius as a function of radial distance, going from 10^1 kilometres in the inner magnetosphere to 10^3 kilometres at the magnetopause standoff distance, and finally to 10^4 kilometres close to the dawn terminator.

To calculate R_C at both Saturn and Jupiter, we use the AGA/UCL Magnetodisc Model (Achilleos et al., 2010) assuming an average hot plasma index for both planets ($K_h = 2e6$ Pa m T^{-1} and $K_h = 3e7$ Pa m T^{-1} for Saturn and Jupiter, respectively, where K_h is essentially a measure of the ring current activity). For Saturn, the smallest value of R_C calculated in the middle magnetosphere was $\sim 0.70R_S$, and for Jupiter it was $\sim 0.64R_J$. For comparison, we include $R_C \sim 0.40R_J$ in the middle magnetosphere of Jupiter given by the (Nichols et al., 2015) force balance model.

Figure 4 shows that at Jupiter the gyroradius of the heavy ion population that dominates the magnetodisc current sheet is more likely, both in the average case and more so in disturbed conditions (lower field strength, higher temperature) to approach the expected radius of curvature. Past this region, the magnetohydrodynamic approximation of the magnetodisc breaks down and force balance is no longer maintained. Ballooning of the field that allows plasma to break off the disc has been identified at Jupiter (Haynes et al., 1994; Southwood et al., 1995) along with the sustained cushion region observed by Went, Kivelson, et al. (2011) in the approximate radial regions shown in Figure 4.

At Saturn, other than in perhaps the most disturbed conditions, it is unlikely to see the disc stress balance breakdown, as is observed in Figure 4. Kaminker et al. (2017) identified the noon to dusk sectors (10-20 LT) as having a greater heater rate density, calculated using fluctuations in the magnetic field. Greater heating of the magnetodisc plasma would imply a larger r_i at dusk, where the plasma could be heated and escape down the tail. There is also an asymmetry in the hot plasma pressure, which is larger at dusk compared to dawn (Sergis et al., 2017; Sorba et al., 2019). Delamere et al. (2015) found evidence of mass being lost from the disc through signatures of reconnection, given by $B_\theta < 0$, predominantly in the subsolar to dusk regions. Although it should be noted that this single criterion cannot distinguish a bent magnetic field configuration, for instance through solar wind driven warping. Nonetheless, they suggest a circulation pattern in the magnetodisc where mass is lost through patchy reconnection in the dusk flank, rather than through large-scale tail reconnection. As flux tubes rotates through dusk they are able to expand since the magnetopause no longer confines the field, resulting in a centrifugally driven increase in the parallel pressure of the plasma. This develops an anisotropy ($T_\parallel > T_\perp$) that results in the disc becoming explosively unstable at dusk (Kivelson & Southwood, 2005). There could also be a further role of the solar wind and the Dungey cycle (Dungey, 1961) in the dusk cushion formation, as well as the planetary period oscillations that thin the current sheet (Cowley et al., 2017).

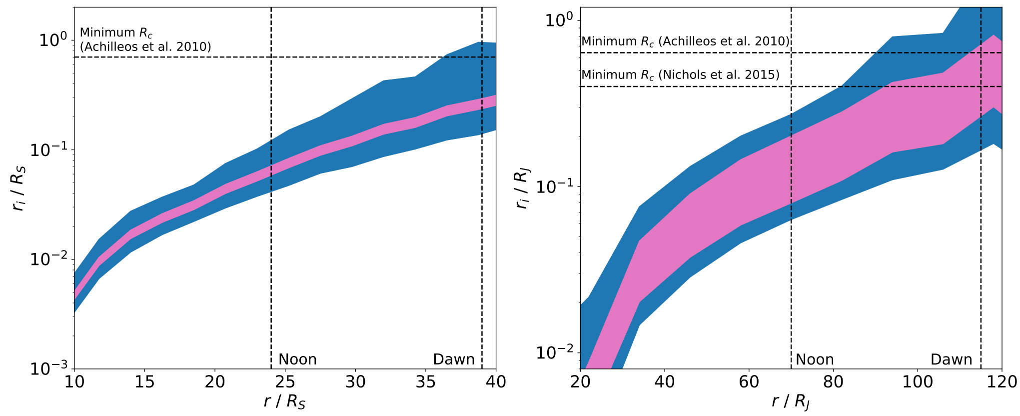

Figure 4. The gyoradius r_i of heavy ions (amu/q $\approx$ 16 for both planets) that dominate the magnetodisc current sheets at Saturn (left) and Jupiter (right), shown as a function of radial distance in units of planetary radii. The horizontal dashed lines show the minimum R_C in the middle magnetosphere given by the Achilleos et al. (2010); Nichols et al. (2015) magnetodisc models. The vertical dashed lines show the magnetopause radial distance at noon and the mapped dawn terminator using the Pilkington et al. (2015) model. We asssume an expanded state for both systems, with $R_{SS} = 24R_S$ for Saturn and $R_{SS} = 75R_J$ for Jupiter. The pink region shows r_i calculated using the average magnetic field strength, where the width represents errors in the fitted temperature models. The blue region shows r_i calculated using the standard deviations of the mean magnetic field, highlighting the variability, particularly close to the magnetopause boundary. These results show that r_i approaches R_C at Jupiter at distances between the noon and dawn magnetopause both in the average and perturbed cases, but at Saturn it is less likely for this to occur.

In this study, we have observed cases where the dipolar structure associated with plasma being absent or depleted from the equatorial region persists throughout the cushion region. However, this large-scale structure rarely occurs and instead small-scale signatures of a patchy cushion and an unstable disc are more commonly observed at dusk (e.g. Delamere et al. (2015)).

Pulsations in the ultraviolet (UV) auroral emissions have further been linked with magnetodisc reconnection and are observed to preferentially occur at dusk with patchy, diffuse signatures (Bader et al., 2019, 2020). These phenomena highlight the quieter dawn magnetodisc that maps to the aurora along field-aligned currents compared to the active and more variable dusk magnetodisc and cushion that generate these structures.

We have further compared the effect of the suprathermal ions on the magnetic field srtucture near the boundary (see Supplementary Information). We would expect their presence in the outer magnetosphere to produce a more dipolar structure, an effect observed in magnetodisc models that incorporate hot plasma (e.g. (Caudal, 1986; Achilleos et al., 2010; Nichols et al., 2015)). Under certain circumstances this effect could be relevant, but for average conditions we suggest magnetodisc breakdown more clearly describes the formation of the cushion region.

5 Conclusion

Using the complete Cassini orbital magnetometer dataset, we have identified five examples of a cushion region at Saturn, of which four were observed at dusk. These results are in contrast with the current interpretation of a cushion that suggests it is a return flow channel of mass depleted flux tubes following tail reconnection. We suggest that the cushion region is more likely to form at Jupiter primarily due to the larger system size that allows for a breakdown of the magnetodisc. At Saturn, this is less likely to occur except under certain circumstances, such as greater heating. Due to a local time asymmetry in the heating of the plasma and the expansion of the field as the plasma rotates through the afternoon sector, the dusk magnetodisc is more likely to undergo these instabilities, allowing for a cushion region to form preferentially in this local time sector.

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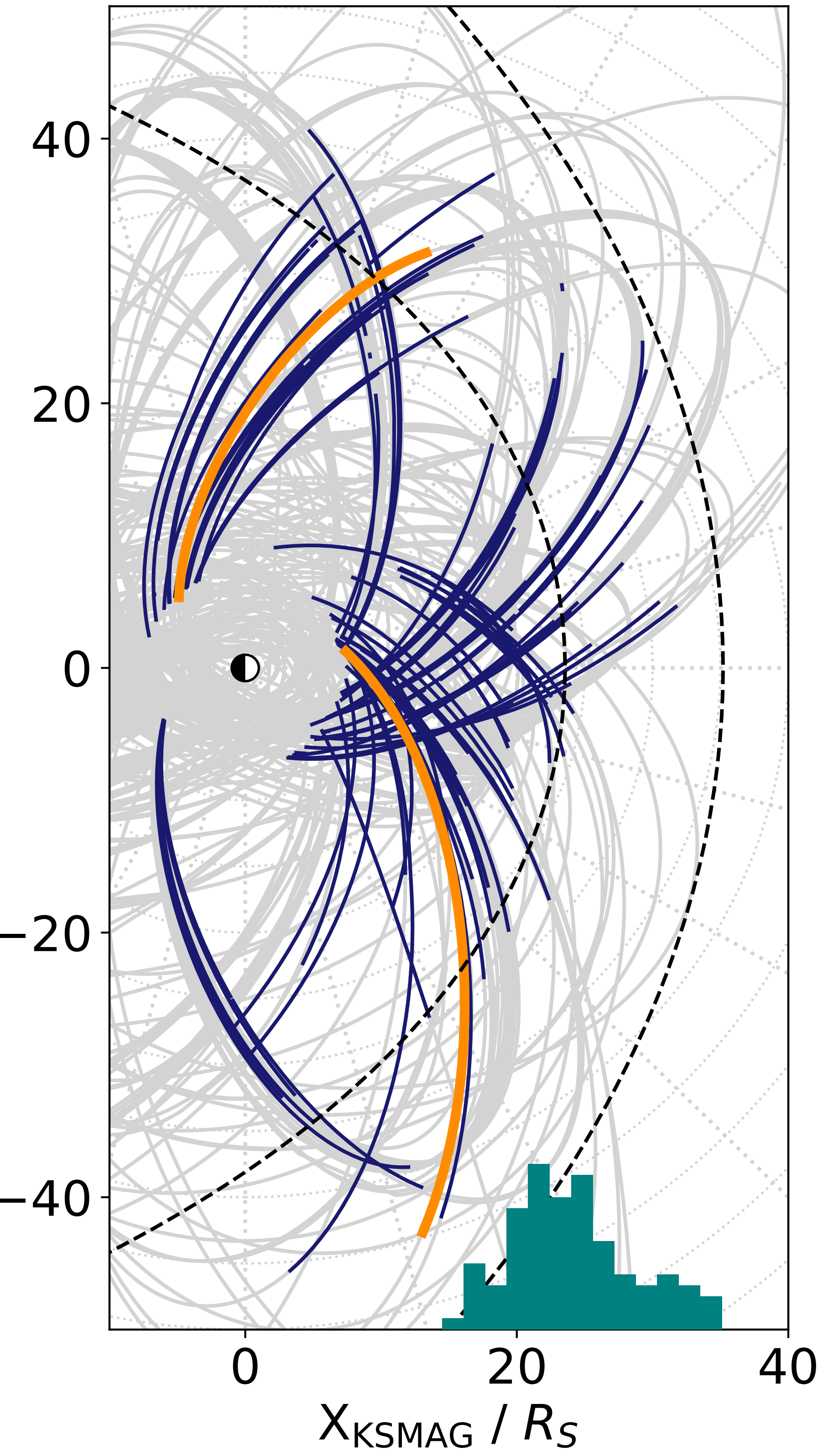
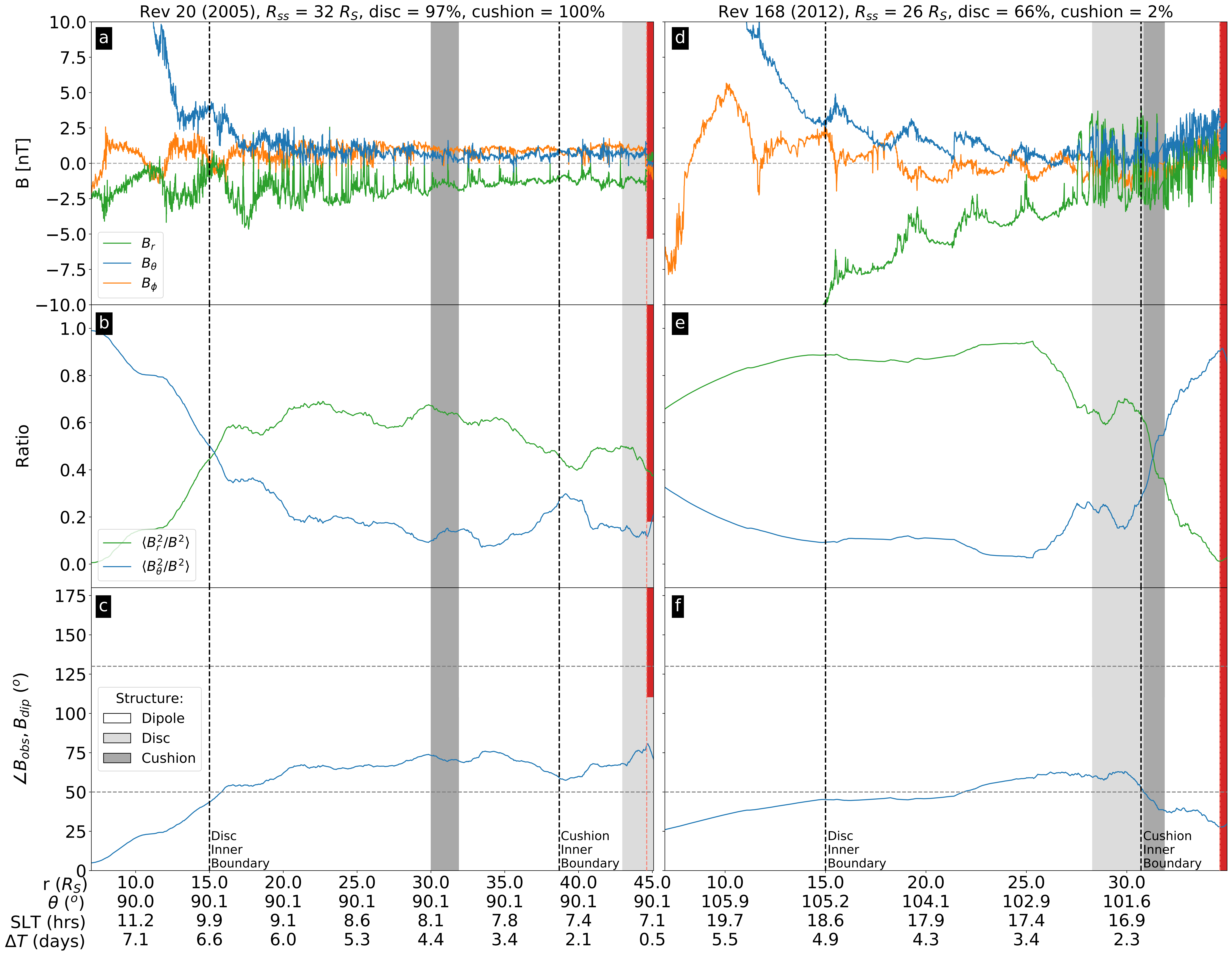
Figure 1.



40
20
0
−20
−40
0
20
40
X_KSMAG / R_S

Figure 2.



Rev 20 (2005), R_{ss} = 32 R_S, disc = 97%, cushion = 100%
Rev 168 (2012), R_{ss} = 26 R_S, disc = 66%, cushion = 2%
a
b
c
d
e
f
B [nT]
Ratio
$\angle B_{obs}, B_{dip}$ (^{o})
B_r
B_θ
B_ϕ
$\langle B_r^2/B^2 \rangle$
$\langle B_\theta^2/B^2 \rangle$
Structure:
Dipole
Disc
Cushion
Disc Inner Boundary
Cushion Inner Boundary
r (R_S)
θ (^{o})
SLT (hrs)
ΔT (days)

Figure 3.

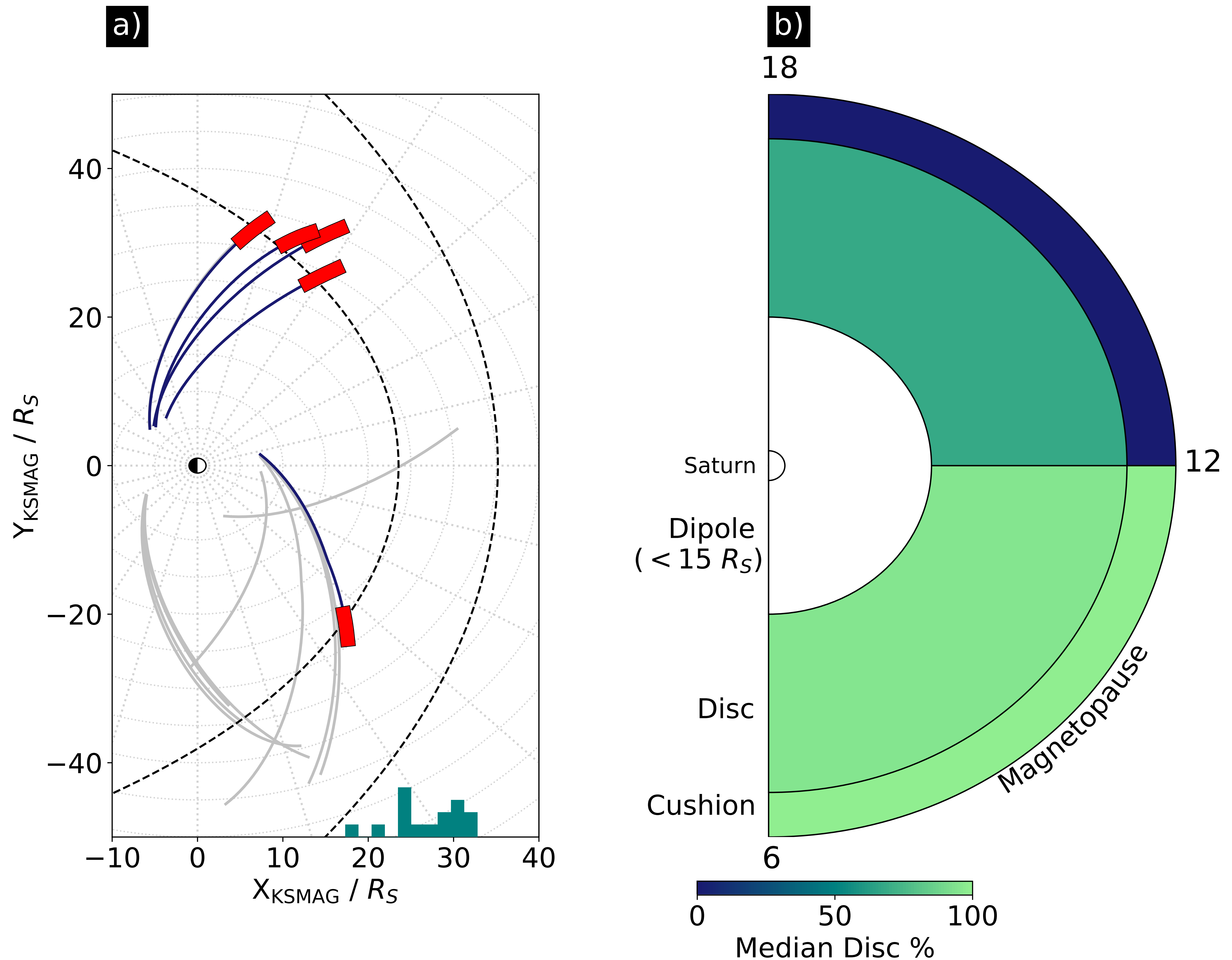
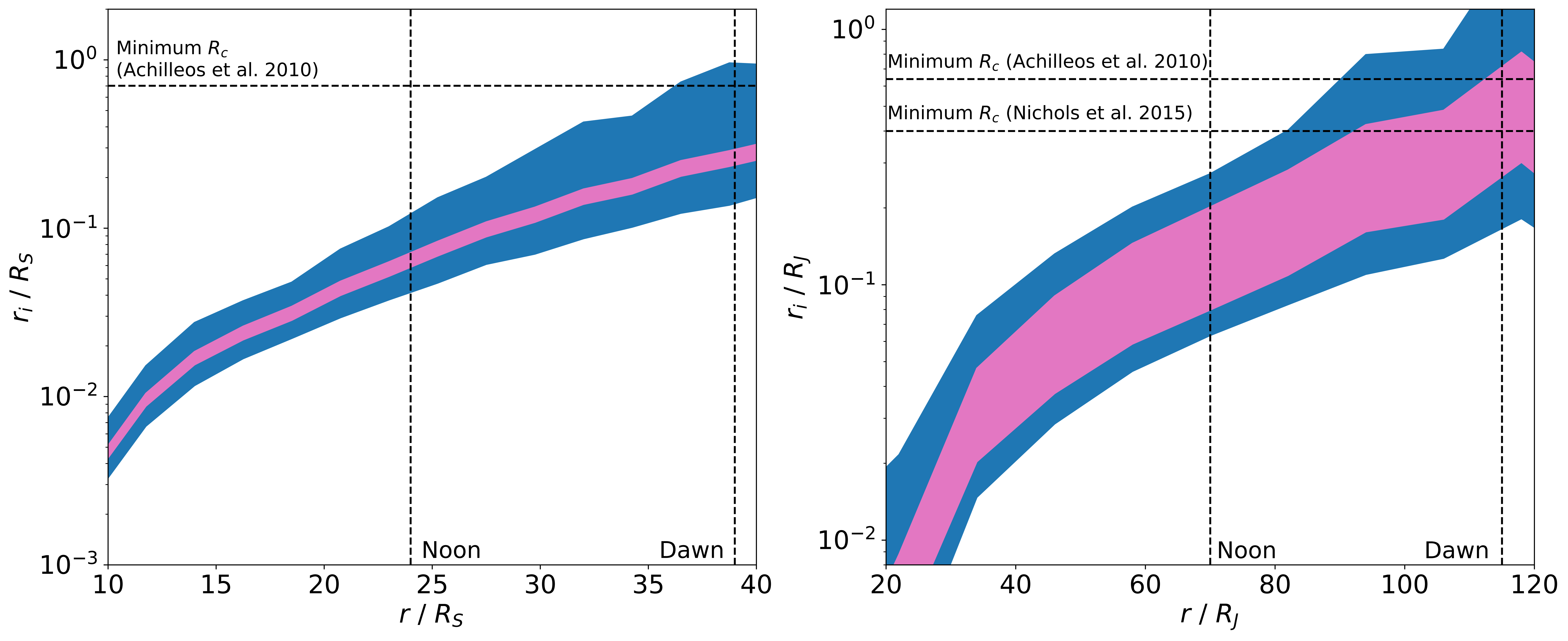

a)
b)
Y_{KSMAG} / R_S
X_{KSMAG} / R_S
40
20
0
−20
−40
−10
0
10
20
30
40
18
12
6
Saturn
Dipole
(< 15 R_S)
Disc
Cushion
Magnetopause
0
50
100
Median Disc %

Figure 4.



Minimum R_c
(Achilleos et al. 2010)
Noon
Dawn
r_i / R_S
r / R_S
10^0
10^{-1}
10^{-2}
10^{-3}
10
15
20
25
30
35
40
Minimum R_c (Achilleos et al. 2010)
Minimum R_c (Nichols et al. 2015)
Noon
Dawn
r_i / R_J
r / R_J
10^0
10^{-1}
10^{-2}
20
40
60
80
100
120