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Key Points:

- We calculate the magnetospheric drag torque on Saturn's polar thermosphere across equinox using current profiles derived from Cassini data
- Contrary to recent suggestion major seasonal variations are confined to the polar open field region and do not occur in the auroral region
- Comparison of the torques with the periods of planetary period oscillations does not suggest a direct connection between these quantities

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Seasonal Dependence of the Magnetospheric Drag Torque on Saturn's Northern and Southern Polar Thermospheres and its Relation to the Periods of Planetary Period Oscillations

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Abstract We calculate the magnetospheric drag torques on Saturn's northern and southern polar thermospheres during late southern summer in 2008 and northern spring in 2012-2013 using previously derived profiles of ionospheric meridional coupling currents determined from high-latitude Cassini magnetic field data. We show that the drag torques in the "winter" and "summer" auroral regions are near equal at $\sim 2.3 \times 10^{16}$ N m, contrary to the recent discussion of Brooks et al. (2019, https://doi.org/10.1002/ 2019JA026870) who suggest that significant seasonal differences should occur in these regions. Instead, seasonally dependent torques occur in the adjacent polar open field regions, where the "winter" and "summer" torques are $\sim 0.3 \times 10^{16}$ and $\sim 1.8 \times 10^{16}$ N m, respectively. We derive a simple rotating disc model of the polar thermosphere and estimate the speed of the poleward flow from midlatitudes required to balance these torques in steady state, finding values of tens of m s^{-1} consistent with previous numerical modeling. Comparison of the calculated torques with concurrent periods of the northern and southern planetary period oscillations (PPOs) does not suggest a direct connection between these quantities as proposed by Brooks et al., 2019, showing at the least that significant additional factors must be involved. We further note some issues with their scenario for dual modulation of radio emissions, previous observations having shown that the principal oscillatory PPO field-aligned currents that modulate the emissions rotate in the auroral region with periods $\sim 10.7 \pm 0.1$ hr, propagating through the more slowly rotating ~15-20 hr period outer magnetospheric plasma, with implications for the proposed "atmospheric flywheel" picture.

1. Introduction

A principal finding of the Cassini orbital mission at Saturn has been the ubiquitous modulation of essentially all magnetospheric plasma-related parameters near the planetary rotation period, despite the perfect axisymmetry of the planetary magnetic field to within measurement uncertainty (Cao et al., 2020; Dougherty et al., 2018). Such modulations are routinely observed, for example, in the magnetic field, plasma properties, energetic particles, and plasma waves, as well as auroral ultraviolet (UV), infrared, and radio emissions (e.g., Andrews et al., 2010; Bader et al., 2018; Badman et al., 2012; Carbary, 2017; Cowley & Provan, 2017; Lamy, 2017; Provan, Lamy, et al., 2019; Ramer et al., 2017; Ye et al., 2010). In this paper we will refer to this ensemble of oscillatory phenomena collectively as "planetary period oscillations" (PPOs). In fact such observations reveal that the Saturn system is generally modulated at two close but distinct periods, one associated with the northern polar region and the other with the southern polar region, which vary with Saturn's seasons by up to $-\pm 1\%$ about a typical central period of -10.7 hr (e.g., Andrews et al., 2012; Cowley et al., 2016; Gurnett et al., 2009; Lamy, 2011, 2017; Provan et al., 2012, Provan, Cowley, et al., 2019; Ye et al., 2018). Specifically, in the early phase of the Cassini mission in 2005–2008 during post-solstice southern summer, the northern period ~10.6 hr was shorter than the southern period ~10.8 hr, while later in the mission in 2015–2017 around northern summer solstice the period difference reversed sense, with the northern period increasing to ~10.8 hr to become longer than the southern period which shortened to ~10.7 hr. Between these intervals, more closely spaced northern and southern periods followed equinox in mid-2009, though with the southern period ~10.7 hr remaining somewhat longer than the northern period ~10.65 hr,



culminating in an interval of near coalesced periods ~10.7 hr during 2013–2014 prior to the separation and reversal indicated above (e.g., Lamy, 2017; Provan et al., 2014, 2016).

In a recent paper Brooks et al. (2019) have proposed that these dual variable periods are connected with the rotation periods of the northern and southern polar thermospheres and have discussed in detail the factors that influence the differential rotations of these regions responding to seasonally varying magnetospheric drag forces. They note in particular that while Saturn's deep atmosphere must rotate at some common period not precisely known, and while the magnetospheric plasma in steady state will also rotate at a common period north and south on a given flux shell in the absence of large field-aligned voltages, at least on closed field lines though not necessarily on open polar field lines, intermediate layers of the atmosphere will generally rotate differentially north and south due particularly to the seasonally dependent value of the ionospheric Pedersen conductivity. In a steady state, the angular velocity of the polar thermosphere in the northern and southern hemispheres is determined by a balance between the magnetospheric drag torque mediated through ion-neutral collisions in the Pedersen conducting layer of the ionosphere, and the input of angular momentum from the essentially infinite reservoir formed by the deep interior, likely transferred predominantly by meridional atmospheric circulation involving poleward transport from mid-latitudes (Smith et al., 2007; Smith & Aylward, 2008). The equal and opposite collisional torque on the plasma is then transferred along closed field lines by the large-scale magnetosphere-ionosphere coupling current system thus set up, to supply the angular momentum required by plasma pick-up and outward radial transport in the subcorotating magnetospheric plasma (e.g., Pontius & Hill, 2009). On open field lines the torque-related currents result in twisting of the field lines in the tail lobes (Isbell et al., 1984). It is then a physically reasonable initial expectation that the magnetospheric drag torque will be higher in the summer than in the winter ionosphere at Saturn, due to higher ionospheric densities and conductivities in summer than in winter, such that the summer thermosphere should rotate with a longer period than that of the winter thermosphere, in outline accord with the behavior of the PPO periods described above. In steady state, both thermospheres will rotate with periods intermediate between those of the deep interior and of the subcorotating magnetospheric plasma. While no detailed picture of the envisaged connection between thermospheric rotation periods and PPO periods is proposed by Brooks et al. (2019), they do briefly describe a scenario (their section 6) in which dual PPO modulation periods are generated, one on closed field lines rotating near the summer thermospheric period, and the other on winter polar open field lines rotating near the winter thermospheric period.

Brooks et al. (2019) present a mainly qualitative discussion of the seasonal dependence of Saturn's thermospheric flow, citing the lack of detailed knowledge of both angular momentum transport in Saturn's upper atmosphere and the seasonally dependent ionospheric conductivities. They conclude their paper by noting that a window into the ionospheric conductivity issue might be obtained by examining magnetosphere-ionosphere coupling current signatures in Cassini magnetic field data, predicting that the field-aligned currents should connect preferentially to the summer hemisphere. However, a number of detailed studies have previously been published in which the properties of the polar current systems north and south, disentangled from the rotating oscillatory PPO currents flowing in the same regions, have been derived from such magnetic field data (Bradley et al., 2018; Hunt et al., 2014, 2015, 2018). These studies employ essentially all of the magnetic field data available from sufficiently high-latitude passes during the 13-year Cassini mission, covering both southern and northern summer conditions either side of equinox, so that seasonal variations can also be addressed.

In this paper we thus review and extend these previous results and consider them in relation to the discussion of Brooks et al. (2019). Specifically, in sections 2 and 3 we newly calculate the magnetospheric drag torques exerted on Saturn's northern and southern polar thermospheres during two intervals in which the most latitudinally extended polar ionospheric current profiles have been derived from Cassini magnetic field data. The first interval corresponds to late southern summer in 2008 (Hunt et al., 2014, 2015), while the second corresponds to northern spring in 2012–2013 (Bradley et al., 2018), such that the nature of the drag torques present during these intervals and their seasonal differences can be addressed. In section 4 we consider the consequences of these results for the meridional transport of angular momentum into the polar thermosphere required in steady state and present a simple analytic model that illustrates the process. Section 5 focuses on possible connections, or otherwise, between the calculated torques and the contemporaneous PPO periods as discussed by Brooks et al. (2019). We also comment on their proposed scenario for dual





Figure 1. Sketch illustrating the vectors employed to calculate the drag torque on Saturn's thermosphere using Equation 1. The vertical arrowed line represents Saturn's spin/magnetic axis centered at O, while the black dashed line indicates the Pedersen ionospheric layer (an oblate spheroid as in Equation 6). The blue arrow shows the position vector \mathbf{r}_i from the planet's center of a point in the ionosphere, while the green arrow shows the meridional ionospheric current \mathbf{i}_i at that point tangent to the ionospheric layer, and the black arrow shows the ionospheric planetary magnetic field vector \mathbf{B}_i at that point. The field vector lies tangent to the magnetic field line indicated by the arrowed black solid line, on which the value of the flux function *F* is a constant as indicated. The red arrow shows the torque vector $d\mathbf{T}_i$ orthogonal to \mathbf{r}_i given by Equation 1.

modulation of the PPO periods and on the implications of the relationship between the PPO periods and the observed plasma subcorotation periods in Saturn's magnetosphere for their proposed "atmospheric flywheel" picture.

2. Magnetospheric Drag Torque on the Polar Thermosphere

In this section we derive theoretical expressions that allow simple calculation of the magnetospheric drag torque on Saturn's thermosphere from empirically determined ionospheric current profiles. We first note that the drag torque on the thermosphere is equal to, and can thus be calculated from, the electromagnetic force on the plasma associated with the ionospheric current. This arises because the drag torque on the thermosphere and the corotational torque on the ionospheric plasma are equal and opposite by Newton's third law, both being mediated by ion-neutral collisions in the Pedersen layer. In a steady state the corotational torque on the plasma is then balanced by the electromagnetic torque associated with the current, which is thus just equal to the drag torque on the thermosphere.

2.1. Calculation of Magnetospheric Drag Torque From Meridional Current Profiles

The magnetospheric drag torque on volume element dV_i of the thermosphere about origin O, conveniently taken as the planet's center, associated with ionospheric current density j_i at position vector r_i is hence given by

$$\boldsymbol{dT}_{i}^{'} = \boldsymbol{r}_{i} \times (\boldsymbol{j}_{i} \times \boldsymbol{B}_{i}) \, dV_{i}, \tag{1a}$$

where B_i is the planetary magnetic field in the ionospheric layer. Integrating in altitude through the Pedersen conducting region, taken to be a thin layer, the torque on area element dA_i is then

$$\boldsymbol{dT}_i = \boldsymbol{r}_i \times (\boldsymbol{i}_i \times \boldsymbol{B}_i) \, \boldsymbol{dA}_i, \tag{1b}$$

where \mathbf{i}_i is the horizontal current per unit length flowing in the ionosphere. A sketch illustrating these vectors is shown in Figure 1, where the blue arrow indicates position vector \mathbf{r}_i drawn from the planet's center O, the green arrow the ionospheric current \mathbf{i}_i tangent to the ionospheric layer shown by the black dashed line oblate spheroid, the black arrow the planetary magnetic field \mathbf{B}_i in the ionospheric layer tangent to the field line shown by the arrowed black solid line, and the red arrow the torque vector $d\mathbf{T}_i$ directed orthogonal to \mathbf{r}_i . The current is taken be meridional, $\mathbf{i}_i = i_m \hat{\mathbf{m}}$, where unit vector $\hat{\mathbf{m}}$ is directed in the ionospheric layer away from the pole in each hemisphere as shown in Figure 1, such that i_m is positive directed equatorward in both hemispheres. We then have $\mathbf{i}_i \times \mathbf{B}_i = -i_m |B_{in}|\hat{\boldsymbol{\varphi}}$, where $|B_{in}|$ is the magnitude of the planetary magnetic field normal to the ionospheric current-carrying layer, and $\hat{\boldsymbol{\varphi}}$ is the unit vector in the azimuthal direction (positive in the direction of planetary rotation). Taking the cross product with the radial vector in Equation 1 yields both cylindrical radial (ρ) as well as axial (z) components of the torque vector (Figure 1), but the former integrate in azimuth to zero assuming axial symmetry. The remaining axial component of the drag torque is given by

$$dT_{iz} = -R_i \sin\theta_i i_m |B_{in}| dA_i = -I_m d\Phi_i, \tag{2}$$

where R_i is the radial distance of the ionospheric element, θ_i is the colatitude measured from the corresponding pole in each hemisphere, and the negative sign indicates a torque whose moment is directed in the sense opposite to planetary rotation for i_m positive (equatorward) in each hemisphere (Figure 1). The quantities in the second expression on the right side of Equation 2 are $I_m = R_i \sin \theta_i i_m$, the



ionospheric meridional current per radian of azimuth, the specific quantity determined from Cassini magnetic field data by Hunt et al. (2014, 2015, 2018) and Bradley et al. (2018), and $d\Phi_i = |B_{in}| dA_i$, the magnetic flux through arbitrary ionospheric area element dA_i . Again assuming axisymmetry we integrate in azimuth to consider an annular ionospheric element of area dA_i^* around the axis, located, for example, between colatitudes θ_i and $\theta_i + d\theta_i$ with respect to either the northern or southern poles, to obtain the azimuth integrated torque associated with the current flowing in this annular element

$$dT_{iz}^{*} = -I_{m}d\Phi_{i}^{*} = -2\pi I_{m}dF_{i} = -I_{m}^{*}dF_{i},$$
(3)

where $d\Phi_i^*$ is the magnetic flux through the annular element. In the second expression on the right side of Equation 3, F_i is the flux function of the planetary field in the ionosphere, effectively the magnetic flux per radian of azimuth, thus related to the magnetic flux by $F_i(\theta_i) = \Phi_i(\theta_i)/2\pi$, where $\Phi_i(\theta_i)$ is the magnetic flux threading the ionosphere between (either) pole and northern or southern colatitude θ_i . We also note that in the third expression on the right side of Equation 3 the quantity $I_m^* = 2\pi I_m$ is the total azimuth-integrated meridional current *flowing* at a given colatitude. Writing the azimuth integrated drag torque for convenience as $dT_D^* = -dT_{iz}^*$, the total azimuth-integrated drag torque due to currents flowing in the ionospheric segment between (northern or southern) colatitudes θ_{i1} and θ_{i2} (with $\theta_{i2} > \theta_{i1}$), where the flux functions are $F_{i1} = F_i(\theta_{i1})$ and $F_{i2} = F_i(\theta_{i2})$, respectively, is thus given by

$$\Delta T_D^* = \int_{F_0}^{F_{12}} I_m^*(F_i) dF_i.$$
(4)

2.2. Ionospheric Flux Function

Here we employ an expression for the flux function corresponding to the principal first three terms in the spherical harmonic expansion of the axisymmetric planetary field, corresponding to the dipole, quadrupole, and octupole fields, given by

$$F(r,\theta) = R_{\rm S}^2 \sin^2\theta \left[g_1^0 \left(\frac{R_S}{r}\right) + \frac{3}{2} g_2^0 \cos\theta \left(\frac{R_S}{r}\right)^2 + \frac{1}{2} g_3^0 (5\cos^2\theta - 1) \left(\frac{R_S}{r}\right)^3 \right],\tag{5}$$

where *r* is radial distance from the planet's center, θ is colatitude specifically from the northern pole, and R_S is Saturn's 1 bar equatorial radius equal to 60,268 km. The field coefficients employed following Dougherty et al. (2018) are $g_1^0 = 21,140.2$, $g_2^0 = 1,581.1$, and $g_3^0 = 2,260.1$ nT, though the use of values from any related recent model would produce only marginal differences. The flux function is related to the poloidal field components by $\mathbf{B} = (1/r\sin\theta)\nabla F \times \hat{\boldsymbol{\varphi}}$, and since \mathbf{B} is hence perpendicular to ∇F , the flux function is such that the surface F = constant defines an azimuthally symmetric flux shell of field lines passing between the northern and southern ionospheres, as indicated in Figure 1. Points in the northern and southern ionospheres with equal values of the flux function thus lie on the same flux shell as each other, allowing detailed comparison of northern and southern values on the same set of field lines. The value of the flux function in the ionosphere F_i at northern colatitude θ_i is given by putting $r = R_i(\theta_i)$ into Equation 5, where the radius of the conducting layer is taken to lie 1,000 km above the International Astronomical Union 1 bar reference spheroid (e.g., Galand et al., 2011). We then have

$$R_i(\theta_i) = \frac{R_e R_p}{\left(R_e^2 \cos^2 \theta_i + R_p^2 \sin^2 \theta_i\right)^{1/2}},\tag{6}$$

where equatorial radius $R_e = 61,268$ km and polar radius $R_p = 55,364$ km. The effect of the quadrupole (g_2^0) term in Equation 5 is such as to make the ionospheric field strength somewhat stronger in the northern hemisphere, ~75,000 nT at the northern pole, compared with the southern hemisphere, ~61,700 nT at the southern pole. It can be seen from Equations 3 and 4, however, that the torques in the northern and southern ionospheres associated with a given flux shell F_i to $F_i + dF_i$ depend only on the northern and southern values of the azimuth-integrated currents flowing, I_m^* , and not directly on the ionospheric field strengths. In effect the increased length of the lever arm in the weaker field region on a given flux



shell (the r_i term in Equation 1) is exactly balanced by the reduced strength of the ionospheric field B_i . Equal azimuth-integrated ionospheric currents in the two hemispheres on a given flux shell produce equal axial torques north and south, despite the hemispheric asymmetry in the planetary field.

3. Seasonal Dependence of Northern and Southern Drag Torques

We now employ the results derived in section 2 to calculate the magnetospheric drag torques exerted on Saturn's northern and southern thermosphere from the current profiles obtained from Cassini magnetic field data in the earlier studies cited above. We concentrate on data from two intervals of highly inclined Cassini orbits during which coverage of the polar and auroral regions was optimal, spanning field lines mapping in the ionosphere from within a few degrees colatitude of either pole to at least ~21° colatitude in the subauroral region (mapping in the equatorial plane to ~6 R_S). The first interval occurred between February and December 2008 (Cassini revolutions [Revs] 59–95) during late southern summer, analyzed by Hunt et al. (2014, 2015), while the second occurred between June 2012 and July 2013 (Cassini Revs 168–194) during northern spring, analyzed by Bradley et al. (2018). Both sets of trans-periapsis passes principally spanned nightside local times, so the results may be compared directly.

To derive such current profiles the spacecraft orbit must be sufficiently inclined to the equatorial plane and with a sufficiently small near-equatorial periapsis (less than $\sim 10 \text{ R}_{S}$) that both polar and auroral field lines are near fully traversed during periapsis passes. Data from sufficient such passes must also be obtained that the mean current profile associated with plasma subcorotation, of main interest here, can be separated from the comparably large rotating oscillatory currents of the PPO systems. In addition to the optimal orbit intervals outlined above, current profiles have also been derived spanning the dawn, dusk, and dayside sectors from further sequences of highly inclined orbits during the final phase of the Cassini mission spanning northern summer solstice in May 2017, specifically by Hunt et al. (2018) for the F ring orbits (Revs 251-270) between October 2016 and April 2017, and by Provan, Lamy, et al. (2019) and Hunt et al. (2020) for the proximal orbits (Revs 271-293) between April 2017 and end of mission in September 2017. In regions of latitudinal overlap these profiles generally show similar properties to those derived by Hunt et al. (2014, 2015) and Bradley et al. (2018), apart from small latitude shifts associated with the solar wind-related daynight asymmetry about the pole. However, while the data from these passes newly reveal properties of the perturbation fields extending deep into the interior of the magnetosphere, they provide less complete coverage of the polar region at highest latitudes. Indeed, the proximal orbit data cover only part of the auroral region and equatorward thereof, hence contributing less to our discussion. However, the F ring orbit data do extend across the whole of the auroral regions and partly poleward thereof and will be discussed relative to the 2008 and 2012-2013 data in section 5.

3.1. Seasonal Conditions and PPO Periods

Figure 2a shows the latitude of the Sun at Saturn over the interval 2005-2017 spanning much of the Cassini orbital mission (July 2004–September 2017). Time along the bottom of the plot is shown in days with t = 0corresponding to 00 UT on 1 January 2004 (essentially the start of the Cassini science mission), while start of year markers are shown along the top of the plot. The latitude of the Sun passed through zero at vernal equinox in mid-August 2009, marked by the left hand vertical dashed line, and reached maximum values ~27° at northern summer solstice in late May 2017 marked by the right hand vertical dashed line. The vertical blue bars show the two principal intervals during which ionospheric current profiles were derived from the Cassini magnetic field data as described above. During the first interval analyzed by Hunt et al. (2014, 2015) the solar latitude varied between -8° and -4° , such that the region between the pole and -6° colatitude was in permanent sunlight in the southern hemisphere, while being in permanent darkness in the northern hemisphere. During the second interval analyzed by Bradley et al. (2018) the solar latitude varied between $+15^{\circ}$ and $+19^{\circ}$, such that the region between the pole and $\sim17^{\circ}$ colatitude was in permanent sunlight in the northern hemisphere, while being in permanent darkness in the southern hemisphere. Despite these differences in seasonal detail, for simplicity it is convenient below to refer to these hemispheric seasonal conditions as "summer" and "winter," respectively, in both cases. The vertical red bar on the right shows the interval of F ring orbits from which less complete profiles were determined by Hunt et al. (2018), as mentioned above. This interval occurred immediately prior to northern summer solstice in late May 2017, such that the region between the pole and $\sim 26^{\circ}$ colatitude was in permanent sunlight in the northern hemisphere,





Figure 2. Plot of relevant parameters versus time over the Cassini orbital mission from the beginning of 2005 to the end of 2017. Time is given in days since 00 UT on 1 January 2004 at the bottom of the plot, while start of year markers are indicated at the top of the plot. Figure 2a shows the solar latitude at Saturn, which passed through zero at vernal equinox in mid-August 2009 as marked by the left hand vertical black dashed line, and reached maximum values ~27° at northern summer solstice in late May 2017 marked by the right hand vertical black dashed line. Figure 2b shows the northern (blue) and southern (red) PPO periods over the interval as determined from magnetic field data (solid lines) by Andrews et al. (2012), Provan et al. (2013, 2016), and Provan, Cowley, et al. (2019), and SKR data (dotted lines) by Ye et al. (2018). The vertical blue bars show the intervals of the two magnetic field data studies yielding profiles of the ionospheric currents employed to determine the drag torques on the northern and southern thermospheres, the first corresponding to late southern summer in 2008 (Hunt et al., 2014, 2015), and the second to northern spring in 2012–2013 (Bradley et al., 2018). The vertical red bar shows the F ring orbit interval near the end of mission in 2016–2017 from which less complete ionospheric current profiles are able to be derived (Hunt et al., 2018).

thus spanning the whole polar ionosphere down to subauroral latitudes, while being in permanent darkness in the southern hemisphere.

Figure 2b shows for comparison the rotation periods of the northern (blue) and southern (red) PPO modulations, as derived over the interval from magnetic field data (solid lines) by Andrews et al. (2012), Provan et al. (2013, 2016), and Provan, Cowley, et al. (2019), and from Saturn kilometric radiation (SKR) emissions (dotted lines) by Ye et al. (2018). The SKR periods derived by Lamy (2011, 2017) are essentially similar over common intervals of determination. Both data sources provide very similar results over the intervals of the relevant studies. The PPO periods had near-maximal separation, southern ~10.83 hr longer than northern ~10.60 hr, during the first interval (first blue bar), in basic conformity with the expectation that the drag torque on the southern thermosphere should be greater than that on the northern thermosphere under the late southern summer conditions prevailing. As indicated in the introduction, however, the two periods then converged to near-common values ~10.7 hr over a ~2 (Earth) year interval spanning vernal equinox and remained more closely spaced but with the southern period generally still longer than the northern during the following ~2.5 (Earth) year interval, until coalescing for ~1 (Earth) year in mid-2013. During the second interval (second blue bar), which occurred immediately prior to the interval of coalescence, the southern period was ~10.69 hr while the northern period was ~10.64 hr, despite the more strongly developed northern spring seasonal asymmetry conditions prevailing in the polar regions, which should imply a greater magnetospheric drag torque in the northern hemisphere than in the southern. During the F ring orbit interval (red bar), however, the two periods had separated in a reversed sense, with the northern period ~ 10.79 hr now longer than the southern ~10.68 hr, again in basic conformity with the expectation that the drag torque on the northern thermosphere should be greater than that on the southern thermosphere under the northern summer conditions prevailing.



3.2. Meridional Ionospheric Current Profiles

We thus now examine the drag torques in the northern and southern hemispheres during the principal intervals discussed above, calculated from the ionospheric current profiles determined by Hunt et al. (2014, 2015) and Bradley et al. (2018). As indicated above, in these studies azimuthal magnetic field profiles obtained on sequences of polar region passes over ~1 (Earth) year covering the full range of PPO phases were combined to determine both the rotating oscillatory PPO-related fields and currents as well as the steady subcorotation-related fields and currents on which they are superposed. The current profiles derived do not therefore represent "spot" values, but rather conditions persisting over an interval of at least ~1 (Earth) year, though still short compared with Saturn's ~29 (Earth) year orbital period. Only the steady currents will be considered here.

The current profiles are shown in Figure 3, where the total azimuth-integrated meridional current I_{m}^{*} (MA) is plotted versus the ionospheric flux function F_i (GWb rad⁻¹) determined from Equations 5 and 6. We note that the azimuth-integrated currents I_m^* shown here correspond to the meridional currents per radian of azimuth Im derived and plotted by Hunt et al. (2014, 2015) and Bradley et al. (2018) multiplied by a constant factor of 2π , as in Equation 4, assuming approximate axisymmetry. Specifically, Figure 3b shows the northern (blue) and southern (red) current profiles determined by Hunt et al. (2014, 2015) from the late southern summer data obtained during 2008, while Figure 3c similarly shows the northern (blue) and southern (red) current profiles determined by Bradley et al. (2018) from the northern spring data obtained during 2012-2013. Symbols joined by solid lines show the measured values from the above analyses, where summer and winter data are shown as circles and squares, respectively, while dashed lines show values extrapolated to the poles $(F_i = 0)$ in regions not sampled by the spacecraft, as will be outlined below. Uncertainties in the measured I_m^* values estimated by Bradley et al. (2018) are typically ~±0.5 MA. The divergence of the meridional currents I_m^* implied by their variation with colatitude is accommodated by field-aligned currents flowing to and from the magnetosphere. Where the meridional current increases with colatitude (F_i value) the current flow is downward from the magnetosphere into the ionosphere, while where it decreases with colatitude the current flow is upward out of the ionosphere into the magnetosphere, with the total azimuth-integrated field-aligned current flow between any two points being equal to the difference in I_m^* values between those points. Overall, these data thus require the presence of field-aligned currents ~6-9 MA flowing downward into the polar ionosphere in the region between the pole and $F_i \approx 6-8$ GWb rad⁻¹, the latter (as discussed below) corresponding to the poleward part of the auroral region, then closing in an essentially equal upward current flow in the region to $F_i \approx 10-12$ GWb rad⁻¹ corresponding to subauroral latitudes. Though not of direct relevance to the results of this study, we note that in the magnetosphere these currents are manifest as sweepback effects on closed field lines and field twisting effects on open tail field lines, with the currents being closed cross-field at large distances through the equatorial plasma and the magnetopause current layer, respectively (Cowley et al., 2005; Isbell et al., 1984).

For purposes of reference, Figure 3a also shows the northern (blue) and southern (red) ionospheric colatitudes measured from each pole corresponding to the flux function values. We recall from section 2 that the flux function is constant on a given flux shell, so that ionospheric points north and south with the same value of F_i and in the same local time sector may be regarded as magnetically conjugate in the region of closed field lines, and as magnetically equivalent points on open field lines extending into the tail lobes. According to the recent study of electron density depletion by Jasinski et al. (2019), the open-closed field line boundary (OCB) at Saturn occurs on average at a colatitude of 12.7° in the northern ionosphere and at a conjugate colatitude of 14.0° in the southern ionosphere. Similar values were previously determined in the multi-instrument study by Jinks et al. (2014). This position is indicated in Figure 3 by the left hand vertical dashed line, the region poleward thereof thus being referred to as the "polar open region" as indicated at the top of Figure 3. The region immediately equatorward then corresponds to the "auroral region" as also marked in the figure (see, e.g., Bader et al., 2019), which we take to extend to 17.5° in the northern ionosphere marked by the right hand vertical dashed line and hence to 19.4° in the southern ionosphere (mapping to ~10 R_s in the equatorial plane). It is in this auroral region that the main PPO-related currents are found to flow (Bradley et al., 2018; Hunt et al., 2014, 2015), leading to significant PPO-related modulations of auroral region field-aligned currents, together with Saturn's auroral and radio emissions (e.g., Bader et al., 2018; Lamy, 2011). We do not consider here the weaker perturbation fields and inferred currents





Figure 3. Profiles of the meridional ionospheric current in the northern and southern hemispheres (blue and red solid symbols and lines, respectively) determined from analyses of Cassini magnetic field azimuthal component data, plotted versus the ionospheric flux function F_i (GWb rad⁻¹) determined from Equations 5 and 6. Summer and winter data are shown as circles and squares, respectively. For reference purposes Figure 3a shows the corresponding ionospheric colatitudes (deg) measured from the northern (blue) and southern (red) poles. Figure 3b shows the meridional current profiles determined by Hunt et al. (2014, 2015) from data acquired in 2008 during late southern summer conditions, while Figure 3c similarly shows the meridional current profiles determined by Bradley et al. (2018) from data acquired in 2012-2013 during northern spring. In both cases the quantities shown are the azimuth-integrated total meridional currents I_m^* (MA), related to the currents per radian of azimuth I_m presented by the above authors by multiplication by 2π , assuming approximate axisymmetry. The dashed portions of each curve adjacent to the pole are values extrapolated beyond the region sampled by the spacecraft, taken to be linear with colatitude from zero at the pole itself to the first measured data point (circle) in the "summer" hemispheres, and to be zero from the pole to the first positive data point (square) in the "winter" hemispheres. The vertical dashed lines indicate the three regions discussed, namely, the "polar open region" from the pole to the OCB at 12.7° in the northern hemisphere (14.0° in the southern hemisphere), the "auroral region" to 17.5° in the northern hemisphere (19.4° in the southern hemisphere), and the "subauroral region" at larger colatitudes beyond.



found in the "subauroral region" at larger colatitudes, since the findings of Provan, Lamy, et al. (2019) suggest that these azimuthal fields are not directly associated with plasma subcorotation. Specifically, they show that these generally weaker fields are continuous within the innermost magnetosphere across the boundary of field lines that map through Saturn's outer ring region at ~2.3 R_S in the equatorial plane, and even across kronosynchronous orbit at ~1.86 R_S where the sense of the azimuthal field perturbations associated with an ionosphere-ring interaction current system would be expected to reverse (Xin et al., 2006). In the innermost region they then interface with the azimuthal fields occurring on field lines that lie inside the inner edge of Saturn's D ring (Dougherty et al., 2018; Provan, Lamy, et al., 2019). While the latter intra-D ring fields are likely driven by azimuthal shearing flows in the near-equatorial thermosphere (Khurana et al., 2018), the physical origin of the larger-scale subauroral perturbation fields is yet to be determined.

Comparison of Figures 3b and 3c shows that systematic seasonally dependent differences are indeed observed in the meridional current system as previously pointed out by Bradley et al. (2018). However, as we now discuss, the main differences occur in the polar open region, while differences in the auroral region are less significant. In the summer hemispheres shown by the circles, the southern hemisphere (red) in Figure 3b and northern hemisphere (blue) in Figure 3c, the azimuth-integrated currents rise steadily from ~3 MA at the poleward limits of observation in each hemisphere (solid portions of the profiles extending typically to ~6°-7° colatitude from each pole) up towards ~5 MA near the OCB. In the winter hemispheres shown by the squares, however, the northern hemisphere (blue) in Figure 3b and southern hemisphere (red) in Figure 3c, the currents have small and likely unphysical negative values near the $\sim\pm0.5$ MA uncertainty level at the smallest colatitudes observed, then increase very rapidly to similar ~5 MA values over a narrow region a degree or two wide just poleward of the OCB. Given the quoted typical uncertainties, the differences in the summer and winter polar profiles are clearly significant. Hunt et al. (2018) have also used a statistical measure to examine the differences in the currents observed in the northern and southern polar regions between late southern summer in 2008 and near-northern solstice in 2016-2017 (similar to the profiles in 2012–2013 as discussed in section 5) and have shown these differences to be statistically significant. These seasonal differences must clearly be related to the differences in solar illumination of the polar atmospheres and hence the ionization and conductivity of the polar ionospheres, with the conductivity of much of the winter polar open region ionosphere being effectively zero.

Such large systematic seasonal effects are not present in the adjacent auroral regions, however, where the currents in the winter hemispheres rise quite abruptly across the OCB to ~6 MA, to become comparable to the currents in the summer hemispheres. The currents in the summer hemispheres also rise somewhat with increasing colatitude in the poleward part of the auroral region, peaking in the central auroral region at ~9 MA in the southern summer data in Figure 3b, somewhat larger than the conjugate winter current, but only at ~7 MA in the northern summer data in Figure 3c, thus remaining comparable with the conjugate winter current in this case. Such auroral region increases in ionospheric current in both the summer and winter hemispheres are presumably due to the effect of auroral particle precipitation into the atmosphere, which clearly has a larger influence on the ionospheric conductivity in this region than does solar illumination. The expectation of Brooks et al. (2019) (their section 2) that differential particle precipitation associated with differential auroral region is thus not borne out by these data. We also note that in both data sets the ionospheric current in the equatorward part of the auroral region declines with colatitude to smaller values more rapidly in the summer hemisphere than in the winter hemisphere, such that the winter current

Consideration of the auroral region currents in Figures 3b and 3c also suggests a tendency for the currents in the southern hemisphere to be a little larger than those in the northern hemisphere irrespective of season. This could be a consequence of the weaker ionospheric magnetic fields in the southern hemisphere compared with the northern hemisphere, which may act both to somewhat enhance weak diffusion particle precipitation into the southern hemisphere compared with the northern hemisphere as reported by Bader et al. (2020), as well as to increase the conductivity (the mobility) of the ionization produced.

3.3. Northern and Southern Polar Magnetospheric Drag Torques

We now consider the implications of these results for the magnetospheric drag torque on the polar thermosphere in the two hemispheres, which according to Equation 4 is given for a specified region of the



Table 1

Numerically Integrated Values of the Azimuth Integrated Magnetospheric Drag Torques T_D^* in Units of 10^{16} N m Exerted on the Polar Open and Auroral Regions of Saturn's Thermosphere, and the Summed Values, Calculated from Equation 4 Using the 2008 Southern Summer and 2012–2013 Northern Spring Meridional Current Profiles

		2008	2012-2013		
Region	NH ^a winter	SH ^b summer	NH summer		SH winter
Polar open region ^c	0.21	1.68	1.93		0.43
Auroral region ^d	2.24	2.71	1.96		2.45
Total polar region ^e	2.45	4.39	3.90		2.88

^aNorthern hemisphere. ^bSouthern hemisphere. ^cRegion from the northern pole to the OCB at 12.7° colatitude in the northern ionosphere, magnetically equivalent to 14.0° colatitude from the southern pole in the southern ionosphere. ^dRegion from the OCB to 17.5° in the northern ionosphere, magnetically equivalent to 19.4° colatitude from the southern pole in the southern ionosphere. ^eSum of the polar open and auroral region values.

ionosphere by the integral under the I_m^* versus F_i profiles such as those shown in Figures 3b and 3c. The current profiles thus directly imply that there is indeed a systematic seasonal difference in the magnetospheric drag torques, but one which principally relates to the polar open regions rather than to the auroral regions. To make numerical estimates of the overall drag torques, however, we first extrapolate the observed profiles (solid symbols and lines in Figures 3b and 3c) into the unobserved regions close to both poles. In the summer hemispheres (circles) we assume a linear variation of the current with colatitude from zero at the pole up to the first measured value, as shown by the appropriately colored dashed lines in Figures 3b and 3c. The meridional current must fall to zero at the pole since the azimuthal flow speeds are zero there irrespective of the overall angular velocities. We note, however, that the currents in the region of extrapolation close to the pole contribute only modestly to the overall torque values as given by the area under the curves. In the winter hemispheres (squares) we assume that the currents are zero throughout the unobserved poleward region, up to the colatitude where the derived winter profiles reach positive values, as also shown by the appropriately colored dashed zero lines in Figures 3b and 3c.

To determine the torques prevailing during the 2008 late southern summer and 2012–2013 northern spring intervals, we thus numerically integrate under the I_m^* versus F_i profiles in Figures 3b and 3c as indicated by Equation 4, considering separately the contributions of the polar open regions and the auroral regions, together with the summed total values. The results are given in Table 1, where all azimuth-integrated torques are given in units of 10^{16} N m, and are also summarized in the sketches shown in Figure 4. A large seasonal difference between summer and winter torques is clearly present in the polar open regions as anticipated above, with the summer values $\sim 1.7-1.9 \times 10^{16}$ N m being a factor of ~ 6 larger than the winter values $\sim 0.2-0.4 \times 10^{16}$ N m. No such distinction is found between the summer and winter torques in the auroral regions, however, where the values in the summer hemispheres are $\sim 2.0-2.7 \times 10^{16}$ N m, while the values in the summer region torques in the polar open region, due both to the generally larger currents present and the larger "lever arm" lengths, despite the smaller $\sim 5^{\circ}$ latitudinal width of the auroral region compared with $\sim 13^{\circ}$ for the polar open region.

Rather, as mentioned in section 3.2, the distinction in the auroral region appears to be between the two hemispheres themselves, with the torques in the southern hemisphere $\sim 2.5-2.7 \times 10^{16}$ N m being somewhat larger than those in the northern hemisphere $\sim 2.0-2.2 \times 10^{16}$ N m irrespective of season. Judging from the uncertainties in the individual current values determined by Bradley et al. (2018), the uncertainties in the integral values are likely better than $\sim 5\%$, that is, better than $\sim \pm 0.1 \times 10^{16}$ N m, such that the north-south hemispheric difference, having a mean value of $\sim 0.5 \times 10^{16}$ N m, appears to be significant.

Combining these values into total torques on the polar regions (open plus auroral) north and south, it can be seen that the torque in the summer hemisphere is larger than that in the winter hemisphere during both intervals, $\sim 4.4 \times 10^{16}$ N m in the summer and $\sim 2.5 \times 10^{16}$ N m in the winter for the 2008 data, and $\sim 3.9 \times 10^{16}$ N m in the summer and $\sim 2.9 \times 10^{16}$ N m in the winter for the 2012–2013 data. These



(a) 2008 Late southern summer



Figure 4. Sketches summarizing our calculated values of the azimuth-integrated magnetospheric torques applied to the northern and southern polar thermospheres during (a) the 2008 late southern summer interval analyzed by Hunt et al. (2014, 2015) and (b) the 2012–2013 northern spring interval analyzed by Bradley et al. (2018). In each diagram the blue areas indicate the polar open regions, the red areas the auroral regions, and the yellow areas the subauroral regions. The numbers in the blue and red areas indicate the azimuth-integrated axial magnetospheric torques applied to these regions in units of 10¹⁶ N m (as in Table 1), approximately proportional to the length of the arrows shown, whose directions indicate the sense of the applied force. The total torque on each hemisphere is also indicated. The large arrows on the right indicate the solar latitude during each interval.

differences are principally due to the contribution of the open field region, whose seasonal effect is amplified by the apparent hemispheric effect in the auroral region in southern summer conditions (as in 2008), but is muted by that effect in northern summer conditions (as in 2012–2013). The summer/winter total torque ratio is factor of ~1.8 for the 2008 data, but reduces to ~1.4 for the 2012–2013 data. The total thermospheric torques, northern and southern hemispheres combined, are approximately equal at ~6.8 × 10¹⁶ N m for both intervals.

In summary, the basic effect found here in which the magnetospheric drag torque in the summer hemisphere exceeds that in the winter hemisphere is in accord with the expectations discussed by Brooks et al. (2019). However, the fact that the differential torque principally involves the polar open field region and not the auroral region was not anticipated. We further consider this and other related topics in section 5.

4. Supply of Angular Momentum to the High-Latitude Thermosphere

In this section we briefly explore some consequences of the empirically determined magnetospheric drag torques on Saturn's thermosphere calculated in section 3 from the Cassini ionospheric current profiles. Specifically, we estimate the strength of the meridional flow from midlatitude to high latitude that numerical modeling has shown to be the most significant effect supplying angular momentum to the polar thermosphere and derive a simple theoretical model to illustrate the process. We also make simple estimates of time scales involved in the response of the atmospheric system to temporal changes.

4.1. Estimate of the Required Poleward Flow Speed

As indicated in section 1, and as also discussed by Brooks et al. (2019), the numerical modeling results of Smith et al. (2007) and Smith and Aylward (2008) have shown that by far the most important source of angular momentum balancing magnetospheric drag on the polar thermosphere is via the bulk transport of atmospheric gas from lower latitudes. Gas from the lower atmosphere moves upward into the thermosphere at middle latitudes, flows poleward within the Pedersen-conducting region, and returns to the lower atmosphere, depleted of angular momentum, in the polar region. A return flow of gas from high to middle latitudes must then occur in the lower atmosphere, tapping angular momentum from the effectively infinite planetary reservoir, before rising once more into the thermosphere. The thermospheric part of this continuous flow cycle is described in the above simulations by Smith et al. (2007). In this way angular momentum is transferred from the body of the planet to the magnetospheric plasma, which is transported outward and lost eventually to the heliosphere. Using this picture, the empirical torques determined in section 3 can be used to estimate the strength of the poleward ther-

mospheric flow. Specifically, we consider the poleward flow near the equatorward boundary of the auroral region, at colatitude θ_{iB} from the corresponding pole (mapping equatorially to ~10 R_S), and the flux of angular momentum that such a flow carries to higher latitudes. Given a meridional velocity v_{mB} in the Pedersen



layer, taken positive directed poleward in each hemisphere, the azimuth-integrated poleward mass flux across this boundary is

$$\dot{M} = 2\pi\sigma R_{iB} \sin\theta_{iB} v_{mB},\tag{7}$$

where σ is the thermospheric mass per unit area integrated in height through the layer and R_{iB} is the radial distance of the Pedersen layer from Saturn's center given by Equation 6. The angular momentum per unit mass of gas at the boundary is $(R_{iB}\sin\theta_{iB})^2\Omega_B$, where Ω_B is the angular velocity of the thermospheric gas at the boundary (measured in the inertial frame), so that from Equation 7 the angular momentum flux transported by the flow into the polar thermospheric region is

$$\dot{J} = \dot{M} (R_{iB} \sin \theta_{iB})^2 \Omega_B = 2\pi \sigma (R_{iB} \sin \theta_{iB})^3 \Omega_B \nu_{mB}.$$
(8)

A lower limit on the required poleward flow speed v_{mB} is obtained by equating \dot{J} to the total azimuth-integrated magnetospheric drag torques T_D^* given in Table 1, assuming that all the angular momentum of the poleward-moving gas is depleted in the poleward region. This lower limit is thus given by

$$v_{mB} = \frac{T_D^*}{2\pi\sigma (R_{iB} \sin\theta_{iB})^3 \Omega_B}.$$
(9)

If only a fraction *K* of the angular momentum flux \dot{J} is depleted in the process, then the required flow speed will be increased by a factor 1/K.

To determine the cylindrical radius of the boundary, $\rho_{iB} = R_{iB}\sin\theta_{iB}$, we take $\theta_{iB} = 18.5^{\circ}$ to sufficient approximation in both hemispheres, yielding $\rho_{iB} \approx 17,750$ km. For definiteness we also take the atmospheric angular velocity at the boundary Ω_B to be the System III value $\Omega_B \approx 1.64 \times 10^{-4}$ rad s⁻¹. Due to the rapid fall with height of the mass density within the thermosphere, to sufficient approximation we also take the height-integrated atmospheric mass per unit area within the Pedersen layer to be equal to the column-integrated mass per unit area above the base of the Pedersen layer, equal to P_b/g where P_b is the pressure at the base of the layer and g is the acceleration due to gravity, approximately 10 m s⁻². From the results of, for example, Galand et al. (2011), we take the base of the Pedersen layer to lie at ~850 km above 1 bar consistent with the modeling of Smith and Aylward (2008), where the atmospheric pressure is $P_b \approx 4 \times 10^{-5}$ mb = 4×10^{-3} Pa. We thus have $\sigma \approx P_b/g \approx 4 \times 10^{-4}$ kg m⁻². Substituting these values into Equation 9 yields a lower limit poleward flow speed of

$$v_{mB} \approx 4.35 \times (T_D^* (\text{N m})/10^{16}) \text{ m s}^{-1},$$
 (10)

where $(T_D^*(N m)/10^{16})$ is the empirical azimuth-integrated magnetospheric drag torque in units of 10^{16} N m (as given in Table 1). Taking the mean of the two winter total drag torques in the table of 2.7×10^{16} N m yields a lower limit poleward flow of ~12 m s⁻¹, while the mean of the two summer total drag torques of 4.1×10^{16} N m yields a lower limit poleward flow of ~18 m s⁻¹. These values are towards the lower end of the results of Smith and Aylward (2008), who quote values for the poleward flow speed in the Pedersen layer in their models in the range ~10 - 100 m s⁻¹.

4.2. Simple Theoretical Model

We now derive a simple but instructive theoretical model that illustrates the overall thermospheric processes discussed in section 4.1. We treat the polar thermosphere in the Pedersen layer as a flat rotating cylindrical disc of gas, a reasonable geometric approximation in the region within ~20° colatitude of either pole encompassing the auroral region (Figure 3a). For purposes of illustration, however, we employ for definiteness parameters associated with the northern hemisphere. The gas within the disc has a mass per unit area (integrated in height through the disc) σ , which is taken to be an approximate constant, and rotates with angular velocity $\Omega(\rho)$, where ρ is the perpendicular distance from the planetary/disc rotation axis (equivalent to $R_i \sin \theta_i$ in previous sections). The drag force on the disc per unit area is $i \times B$, where i is the horizontal current per unit length flowing in the ionosphere within the disc, and B is the planetary polar magnetic field also



taken to be constant in magnitude and directed perpendicular to the disc along the spin axis. Again taking the current to be meridional $\mathbf{i} = i_m(\rho)\hat{\rho}$ where i_m is positive directed away from the pole as in section 2, and $\mathbf{B} = B\hat{z}$, then yields the force per unit area $\mathbf{i} \times \mathbf{B} = -i_m(\rho)B\hat{\varphi}$. Neglecting weaker viscous terms, the azimuthal component of the momentum equation in the inertial frame is

$$\sigma\left(\frac{\partial(\rho\Omega)}{\partial t} + \frac{\nu_{\rho}}{\rho}\frac{\partial(\rho^{2}\Omega)}{\partial\rho}\right) = -i_{m}(\rho)B,$$
(11)

where v_{ρ} is the meridional thermospheric velocity in the $\hat{\rho}$ direction.

We first assume a steady state so that the initial time-dependency term on the left side of Equation 11 is zero. We also write $v_{\rho} = -v_m$ where v_m is positive when the flow is directed towards the pole as for v_{mB} in section 4.1. Equation 11 then becomes

$$\frac{d(\rho^2 \Omega)}{d\rho} = \frac{I_m(\rho)B}{\sigma v_m},\tag{12}$$

where $I_m(\rho) = \rho i_m(\rho)$ is the meridional ionospheric current per radian of azimuth, positive directed equatorward, as in section 2. We now integrate Equation 12 between radial distances ρ_1 and $\rho_2 > \rho_1$ where the thermospheric angular velocities are taken to be Ω_1 and Ω_2 , respectively. Equation 12 then provides the following relation between these quantities

$$\rho_1^2 \Omega_1 = \rho_2^2 \Omega_2 - \frac{B}{\sigma v_m} \int_{\rho_1}^{\rho_2} I_m(\rho') d\rho', \qquad (13)$$

where the first term on the right represents conservation of angular momentum in the poleward flow, while the second is due to the effect of the magnetospheric drag torque. We note that in Equation 13 we have made the simplest possible approximation that v_m is independent of distance from the pole, which is likely not at all realistic close to the pole itself. However, the reduction in mass flux towards the pole thereby implied, varying with radial distance proportional to ρ , can be viewed as being accommodated by downward transport of thermospheric gas into the lower atmosphere in this region, as indicated in section 4.1.

For purposes of illustration we take a very simple model for the ionospheric current profile, in which the azimuth-integrated current increases linearly with radial distance from the pole, intended to represent the current in the summer hemisphere between the pole itself and the central part of the auroral region. We thus put $I_m(\rho) = I_o(\rho/\rho_o)$ for $0 \le \rho \le \rho_o$, where I_o is the maximum value of the current in the polar profile, typically ~1–1.5 MA rad⁻¹, and $\rho_o \approx 14,500$ km corresponds to a colatitude of ~15° in the northern hemisphere (see Figure 3). Taking ρ_2 in Equation 13 to correspond to ρ_o , while ρ_1 corresponds to some general point $\rho \le \rho_o$, we have from Equation 13 the simple solution

$$\frac{\Omega(\rho)}{\Omega_o} = (1 - \alpha) \left(\frac{\rho_o}{\rho}\right)^2 + \alpha, \tag{14a}$$

where Ω_o is the angular velocity of the gas at the outer limit of the solution where the current is maximum, taken to be some reasonable fraction of rigid corotation. Key dimensionless parameter α which determines the nature of the solution is given by

$$\alpha = \frac{I_o B}{2\sigma \nu_m \rho_o \Omega_o},\tag{14b}$$

whose value is essentially determined by the unknown poleward flow speed ν_m , while the values of the other parameters on the right side of Equation 14b are known, at least approximately. If the flow speed is sufficiently large that α is less than unity, Equation 14a shows that the solutions diverge continuously from angular velocity Ω_o at ρ_o to $\Omega \to +\infty$ as $\rho \to 0$, as the large angular momentum flux carried by the poleward flow is not matched by the effect of the drag torque. If on the other hand the flow speed



is smaller with α greater than unity, the solutions diverge continuously from Ω_o at ρ_o to $\Omega \rightarrow -\infty$ as $\rho \rightarrow 0$, with the smaller angular momentum carried by the poleward flow now being insufficient to match the effect of the drag torque. However, a singular solution exists when α is equal to unity in which the two effects just balance, such that the angular velocity of the gas remains constant in the poleward flow, equal to Ω_o .

Although this calculation is based on a number of highly simplifying assumptions, it indicates that physically appropriate solutions exist when $\alpha \approx 1$. Setting this condition in Equation 14b gives

$$\nu_m \approx \frac{I_o B}{2\sigma \rho_o \Omega_o} = \frac{3T_D^*}{4\pi \sigma \rho_o^3 \Omega_o},\tag{15}$$

where, using the same notation as in section 4.1, T_D^* is the total drag torque poleward of ρ_o given by $T_D^* = 2\pi I_o B \rho_o^2/3$. Comparison of the second form on the right side of Equation 15 with Equation 9 in section 4.1, derived assuming total depletion of the angular momentum flux in the poleward flow by the magnetospheric drag torque, shows that they are equivalent, apart from a numerical factor of 1/K = 3/2, where K = 2/3 is the fractional depletion factor introduced in section 4.1. Taking parameter values related to those in section 4.1 of $\sigma \approx 4 \times 10^{-4}$ kg m⁻², $\rho_o \approx 14,500$ km (~15° northern colatitude as above), $\Omega_o \approx 1.6 \times 10^{-4}$ rad s⁻¹, $I_o \approx 1$ MA rad⁻¹, and $B \approx 75,000$ nT (the northern hemisphere value), then yields a value for the poleward flow speed $v_m \approx 40$ m s⁻¹, which again seems reasonable in terms of the modeling results of Smith and Aylward (2008). The equivalent summer ionosphere value derived from the discussion in section 4.1 was a lower limiting value of ~20 m s⁻¹. A related model could also be applied to the winter hemisphere, but only to the auroral region where significant ionospheric currents flow such that a significant magnetospheric drag torque is applied. The model would then be truncated in the polar region where the currents drop to near-zero values, such that no poleward flow and coupling to the atmosphere at midlatitudes is required to maintain the thermospheric rotation present.

4.3. Thermospheric System Response Time Scales

We now use the more general form of the azimuthal component of the momentum equation given by Equation 11, including time dependency, to estimate some response time scales of the thermospheric system. This equation defines two such time scales related to two different processes. The first is the time scale associated with the transport of angular momentum by the poleward flow given by the terms on the left side of the equation. Writing by order of magnitude $\partial/\partial t \approx 1/\tau_{flow}$ where τ_{flow} is the response time scale and $\partial/\partial \rho \approx 1/L_m$ where L_m is a meridional length scale, these two terms give simply

$$f_{flow} \approx \frac{L_m}{\nu_m},$$
 (16)

that is, the time scale is just given by the time required by the gas to travel poleward by length scale L_m at meridional speed v_m . If we put $L_m \approx 15,000$ km, corresponding to essentially the whole of the high-latitude region where the drag torque is applied, and $v_m \approx 40$ m s⁻¹ as inferred in section 4.2, we find $\tau_{flow} \approx 100$ hr, that is, about 10 planetary rotations. The time scale is correspondingly reduced for variations on correspondingly shorter spatial scales.

The second time scale relates to the thermospheric response time to changes in magnetosphere-ionosphere coupling, which might be due, for example, to magnetospheric responses to changes in the local interplanetary medium. The meridional current per unit length (positive equatorward) in Equation 11 is given by $i_m = \sum_P B\rho(\Omega - \Omega_{mag})$, where \sum_P is the Pedersen conductivity of the ionosphere and Ω_{mag} is the angular velocity of the magnetospheric plasma in the inertial frame, the time scale for the response of the thermosphere to a change, for example, in Ω_{mag} is given in similar manner to Equation 16 by

$$\tau_{MI} \approx \frac{\sigma}{\Sigma_P B^2}.$$
(17)

Taking the above values for σ and B, together with $\Sigma_P \approx 2$ mho (e.g., Moore et al., 2010), leads to a time scale $\tau_{MI} \approx 10$ hr, that is, about one planetary rotation. Typical variations in the conductivity by at least a factor of



two about the above value then yield related inverse variations in the coupling time scale. However, particularly in the auroral regions the Pedersen conductivity may be enhanced by magnetospheric particle precipitation to values perhaps as high as ~10 mho (Galand et al., 2011), in which case the response time would be reduced to a modest fraction of a planetary rotation. In this case the thermospheric response time to variations in magnetospheric coupling then becomes comparable with the response/propagation time scale in the outer magnetosphere itself, of order the hemisphere-to-hemisphere propagation time along outer field lines at the Alfvén speed. From analysis of conjugate auroral signatures associated with ULF waves propagating in the auroral region, this time scale has been estimated by Meredith et al. (2013) to be ~80 min.

Overall, the thermospheric response time scales identified here are thus relatively short, typically a few to several planetary rotations. As emphasized by Brooks et al. (2019), however, this does not preclude the existence of longer response time scales operating as well, such as those associated with slow diffusive processes not included in Equation 11, and the coupling of the thermosphere to the more massive and more slowly responding lower atmosphere below.

5. Relation of Results to the Discussions of Brooks et al. (2019)

As outlined in section 1, Brooks et al. (2019) made a largely qualitative discussion of the effect on Saturn's thermosphere due to magnetospheric drag, emphasizing that subcorotation in the summer thermosphere should be greater than that in the winter thermosphere due to increased ion-neutral collisional drag in summer compared with winter, associated with increased ionospheric ionization, Pedersen conductivity, and magnetosphere-ionosphere coupling currents. They also relate in general terms these anticipated seasonally varying thermospheric rotation periods with the seasonally varying PPO periods observed in magnetospheric magnetic field, plasma particle, and SKR data. While no general model is proposed, they do outline (their section 6) a scenario for the generation of dual PPO/SKR periods, taken for sake of argument to correspond to southern summer conditions. In this section we consider these discussions in relation to the Cassini studies of Saturn's high-latitude quasi-steady and PPO-related current systems by Hunt et al. (2014, 2015, 2018) and Bradley et al. (2018), encompassing essentially all of the relevant data from high-latitude passes available during the mission, which Brooks et al. (2019) themselves do not consider. We particularly examine their discussions in relation to the magnetospheric drag torques calculated in sections 2 and 3.

5.1. Seasonal Dependence of the Polar Magnetospheric Drag Torque

As previously reported by Bradley et al. (2018), summer-winter differences in the subcorotation coupling currents are indeed found in the Cassini magnetic data, switching senses between hemispheres between late southern summer in 2008 and northern spring in 2012-2013 (Figures 3b and 3c). Consequently, as indicated by Brooks et al. (2019), clear seasonal hemispheric differences in the magnetospheric drag torques on Saturn's thermosphere also occur, as presented in Table 1. The mean value of the magnetospheric torque on the two summer hemispheres (the southern in 2008 and the northern in 2012–2013) is $\sim 4.1 \times 10^{16}$ N m, compared with $\sim 2.7 \times 10^{16}$ N m on the two winter hemispheres, thus differing by a factor of ~ 1.6 . The uncertainties in these values are estimated to be $\sim \pm 0.1 \times 10^{16}$ N m. However, as outlined in section 3, and contrary to the discussion of Brooks et al. (2019), these differences do not mainly involve the coupling currents and drag torques in the auroral regions as they supposed, but principally the polar open region at higher latitudes. Instead, the coupling currents and drag torque in the auroral regions appear insensitive to Saturn's seasons, with mean values in the two summer hemispheres and the two winter hemispheres both being \sim 2.3 × 10¹⁶ N m (with similar estimated uncertainties), an effect we attribute to seasonally independent precipitation of auroral plasma into the two hemispheres. In the polar open region poleward of the auroral region, however, the mean torque in the two summer hemispheres is $\sim 1.8 \times 10^{16}$ N m, comparable with though a little lower than that in the auroral region, while the mean value in the two winter hemispheres is a factor of ~6 smaller at ~0.3 \times 10¹⁶ N m. In support of the likely generality of these findings, we note that similar hemispheric asymmetries were also present in the poleward parts of the less complete dayside current profiles obtained from the F ring orbit sequence closer to northern summer solstice in 2016-2017 (red bar in Figure 2), as reported by Hunt et al. (2018).

An additional important result of the above Cassini magnetic data studies has been the finding that the primary rotating oscillatory field-aligned currents of the northern and southern PPO systems are collocated



with and superposed on the primary subcorotation field-aligned currents in the auroral region (Bradley et al., 2018; Hunt et al., 2014, 2015, 2018, 2020; Provan, Lamy, et al., 2019). They are also of comparable magnitude. In general, PPO modulations with both northern and southern periods are observed in both hemispheres, though with a larger amplitude by a factor of ~2 in the "generating" hemisphere compared with the opposite "responding" hemisphere (e.g., Bradley et al., 2018). The rotating oscillatory modulations of these PPO-related field-aligned currents then give rise to the similarly rotating PPO modulations in the UV auroral intensity in the auroral region, generally with both periods similarly being present in both hemispheres (e.g., Bader et al., 2018). Wave-particle interactions directly related to auroral electron acceleration processes also generate the SKR radio emissions (e.g., Lamy et al., 2010), the sources of which are known to be located within the auroral region (Lamy et al., 2009), rotating around the auroral oval with the same generally dual PPO periods (e.g., Andrews et al., 2011; Lamy, 2011). An important consequence of our finding concerning the lack of seasonality in the magnetospheric drag torques in the auroral region itself is then that if the observed seasonal PPO period variations are indeed related to the differential torques and differential thermospheric subcorotation generated thereby as Brooks et al. (2019) propose, the seasonal variation in drag does not occur directly in the auroral regions themselves where the SKR emissions originate, but principally in the polar open regions where the seasonal drag torque differences occur. The differential effects must then be communicated equatorward to the adjacent thermosphere in the auroral region at lower latitudes.

We further comment that although a connection between seasonally differential magnetospheric drag torques and seasonally differential thermospheric rotation periods may seem reasonable at a basic physical level, as Brooks et al. (2019) assume, such a connection may not be entirely inevitable. In the simple theoretical model presented in section 4.2 based on the numerical modeling results of Smith and Aylward (2008), the drag torque on the polar thermosphere is balanced in steady state by thermospheric poleward flows in both hemispheres that carry angular momentum from the lower atmosphere at mid-latitudes. Conservation of angular momentum then causes the angular velocity of the poleward flowing gas to increase with increasing latitude, while the drag torque causes it to decrease (Equation 13), and simple model solutions exist in which the angular velocity may increase or decrease with latitude depending on the strength of the poleward flow, or indeed may remain entirely constant at the same value as that near the equatorward boundary of the auroral region (Equation 14). Indeed, if we take $\Omega \approx \text{constant} = \Omega_o$ in the poleward flow in Equation 11, then the poleward speed required to maintain this angular velocity independent of latitude is simply given by

$$v_m(\rho) = \frac{i_m(\rho)B}{2\sigma\Omega_o} = \frac{I_m(\rho)B}{2\sigma\rho\Omega_o},\tag{18}$$

which turns into Equation 15 on taking the specific empirically based form for the current per radian of azimuth $I_m(\rho) = I_0(\rho/\rho_0)$ employed in section 4.2. The associated divergences in poleward atmospheric mass flux could in principle be accommodated by vertical transport from and to the lower atmosphere. Clearly detailed modeling is required to elucidate this issue.

5.2. PPO Dual Period Scenario

Having proposed that seasonally varying north-south differential magnetospheric drag is linked to seasonally varying differential thermospheric rotation periods, Brooks et al. (2019) further relate the inferred differential thermospheric rotation periods to the observed seasonally varying differential rotation periods of the northern and southern PPO systems. As indicated above, no detailed general physical picture is proposed, but in their section 6, they discuss a scenario intended to represent southern summer conditions. They suppose that the southern thermosphere with stronger ion-neutral drag and coupling currents is tightly coupled to the subcorotating plasma on closed auroral region field lines, while the northern thermosphere with weaker ion-neutral drag and coupling currents is more tightly coupled to the lower atmosphere and rotates with a shorter period, thus, for example, corresponding to the sense of the hemispheric difference in observed PPO/SKR periods in 2008 (Figure 2b). It is then suggested that because the magnetospheric plasma in a near-steady situation must rotate with a common rotation period at all points along a given closed field line (assuming field-aligned potentials are not significant), the SKR modulations due to rotation on the field line must similarly rotate with a common period, that is, near to the southern thermosphere-ionosphere-



magnetosphere rotation period in both hemispheres. Emissions modulated at the shorter northern thermospheric rotation period are then proposed to occur on northern polar open field lines that are magnetically unconnected with the southern hemisphere and thus do not rotate with the southern period, as the effect of the hypothesized weaker northern auroral region drag and coupling currents extends poleward into the polar region. In this way emissions specifically from the northern (winter) hemisphere may exhibit dual modulation periods, as is often observed (e.g., Lamy, 2011, 2017).

There are a number of issues, however, with this scenario. First, as discussed in section 5.1, any seasonal thermospheric effects associated with seasonally dependent magnetospheric drag must be imposed by the seasonally dependent torques present in the polar open region and transferred equatorward to the seasonally insensitive auroral region and not the other way round as in the above scenario. Second, as also mentioned in section 5.1, the principal sources of SKR emission lie in the auroral region where the intense upward directed field-aligned currents flow and not at polar region latitudes on open field lines (Lamy et al., 2009). Third, and most importantly, the observed PPO/SKR periods are not at all directly connected with the rotation period of the subcorotating magnetospheric plasma as Brooks et al. (2019) suppose. As seen in Figure 2b, over the full range of seasonal conditions, the northern and southern PPO/SKR periods have never been observed to have periods smaller than minimum values ~10.6 hr, nor larger than maximum values ~10.8 hr (e.g., Provan et al., 2016, and references therein). By comparison, plasma particle observations in the near-equatorial magnetosphere indicate plasma azimuthal velocities corresponding to ~60-70% of near-rigid corotation on inner auroral region field lines (radial distances ~10 Rs), falling to ~40-50% of rigid corotation on outer closed magnetospheric field lines (e.g., Kane et al., 2020; Wilson et al., 2017). These values imply plasma rotation periods ~15-17.5 hr on inner auroral region field lines, increasing to ~21-26 hr in the outer magnetosphere, at all points much longer than either the northern or the southern PPO periods at their most extreme values. Rather, the Cassini observations cited above show that the intimately related and similarly rotating auroral region magnetic, auroral, and SKR PPO-related modulations all rotate with shorter periods, propagating relative to the strongly subcorotating auroral region magnetospheric plasma as in the theoretical/modeling pictures discussed, for example, by Jia et al. (2012) and Hunt et al. (2014).

If the PPO periods are then indeed reflective of the rotation periods of the northern and southern thermospheres, this implies that the much larger lags observed in the rotation of the magnetospheric plasma are primarily due to slippage in the ionosphere between the plasma and the thermosphere. This conclusion is contrary to the "atmospheric flywheel" picture discussed by Brooks et al. (2019), which proposes instead that the primary slippage occurs within the slowly responding neutral atmosphere, dominantly in the summer hemisphere, with only small and possibly variable slippages occurring between the thermospheric gas and the plasma in the ionosphere. If one accepts the "atmospheric flywheel" picture, however, the implication is that the PPO periods are not at all connected with the thermospheric rotation periods, but with the shorter rotation periods of atmospheric layers lying deeper within Saturn's atmosphere where the angular velocities are closer to that of the deeper atmosphere. Thermospheric measurements are required to determine which of these scenarios applies.

5.3. Empirical Relation Between Drag Torque and PPO Periods

Despite the considerable relational uncertainties outlined in section 5.2, it is nevertheless worthwhile to examine in more detail the seasonally dependent magnetospheric drag torques calculated here (Table 1) and the concurrent PPO rotation periods shown in Figure 2b, for evidence, or otherwise, of an empirical connection. Comparison of these data, however, does not suggest a clear or detailed relation between these quantities as proposed by Brooks et al. (2019). Observed conditions do indeed follow such expectation during southern summer conditions in 2008, when the total drag torque in the southern hemisphere exceeded that in the northern hemisphere by a factor of ~1.8 (Table 1), while the southern PPO period was longer than the northern spring in 2012–2013, when the hemispheric asymmetry in the total drag torque had approximately reversed, the northern torque now exceeding the southern torque by a factor of ~1.4 (Table 1), while the southern PPO period (Figure 2b). While Brooks et al. (2019) (their section 6) acknowledge that explanation of the PPO behavior during the post-equinox interval is not immediately obvious in their terms, the reality and significance of the



discrepancy is brought into sharper focus given the values of the prevailing drag torques during the two intervals calculated here. We further note from Figure 2b that similar PPO conditions had prevailed for ~2.5 (Earth) years in the post-equinox interval, from 2011 to mid-2013, and that the magnetospheric drag torques themselves refer to magnetic data obtained over a ~1 (Earth) year interval during 2012–2013, thus representing typical conditions persisting over at least such time scales. It thus seems unlikely that rapidly varying coupling conditions combined with longer atmospheric response time scales were responsible for the discrepancy, thus pointing to additional physical factors not considered so far being involved in the determination of the PPO periods. One such potential factor that has been discussed, so far without clear conclusion, is the occurrence of the Great White Spot storm that erupted in Saturn's northern midlatitude troposphere in December 2010, whose stratospheric effects were still discernible until mid-2013 (Cowley & Provan, 2013, 2015; Fischer et al., 2014).

The lack of simple connection is also indicated by comparison of the current profiles determined by Bradley et al. (2018) from the 2012–2013 northern spring data shown in Figure 3c with the profiles determined by Hunt et al. (2018) from the 2016-2017 F ring data under near northern summer solstice conditions (red bar in Figure 2a). Detailed comparison plots are provided in Figure 19 of Provan, Lamy, et al. (2019). Although the F ring orbit current profiles extend only modestly poleward of the OCB to ~10° northern colatitude in the northern hemisphere and ~11° southern colatitude in the southern hemisphere (compare with Figure 3), it is clear that in the data ranges available, they exhibit similar values and the same basic seasonal differences poleward of the OCB as found by Bradley et al. (2018). That is, currents fall rapidly to small values poleward of the OCB in the southern winter hemisphere, but decline with similar magnitude more slowly with declining colatitude in the northern summer hemisphere. The similarity in the profiles is in accord with the observation that the southern PPO period had hardly changed between the two intervals, from ~10.69 hr in during northern spring in 2012–2013 to ~10.68 hr near northern summer solstice in 2016-2017 (Figure 2b). However, the northern period changed very markedly between the two intervals, from ~10.64 hr in 2012-2013, shorter than the near-constant southern period, to ~10.79 hr in 2016-2017 (Figure 2b), longer than the southern period, while there is no indication in the available current data of significant increases in the drag torque in the northern hemisphere between these two intervals. Again, these comparisons do not suggest a direct connection between the drag torques and the PPO periods, showing at the least that additional factors must be involved.

6. Summary

A recent paper by Brooks et al. (2019) has provided a largely qualitative theoretical discussion of the relationships between the magnetospheric drag torque on Saturn's polar thermosphere and the rotation periods of the thermosphere, the PPO modulations, and the magnetospheric plasma, focusing particularly on seasonally dependent differential effects in the northern and southern auroral regions. In this paper we have newly calculated the drag torques present during two intervals either side of Saturn vernal equinox in 2009, using previously published latitude profiles of the meridional ionospheric coupling currents derived from magnetic field data acquired on ~1 (Earth) year-long sequences of high-latitude Cassini passes. These current profiles correspond to late southern summer data from 2008 derived by Hunt et al. (2014, 2015) and to northern spring data from 2012–2013 derived by Bradley et al. (2018). The results have then been considered in relation to the discussion by Brooks et al. (2019). Principal findings are as follows.

- 1. We have shown that in the axisymmetric approximation the magnetospheric torque exerted on the polar thermosphere can be conveniently calculated by integrating the azimuth-integrated meridional current with respect to the planetary field flux function over any specified latitude range. This formulation has then been applied to the previously derived seasonally dependent empirical current profiles indicated above.
- 2. Contrary to the argument by Brooks et al. (2019) that major seasonal differences in magnetospheric drag torque should occur in the two auroral regions, the magnetic data show that the coupling currents and hence drag torques are relatively insensitive to season in these regions, a result we attribute to the dominant effect of auroral particle precipitation rather than insolation in producing ionospheric ionization in these regions. The mean drag torques in the two winter and the two summer auroral regions are both $\sim 2.3 \times 10^{16}$ N m, equal within estimated uncertainties of $\sim \pm 0.1 \times 10^{16}$ N m.

- 3. Rather, strongly seasonally dependent currents and hence drag torques are confined to the polar open field region poleward of the auroral region, where coupling currents decline gradually from auroral region values towards zero at the pole in the summer hemisphere, but drop rapidly to small values poleward of the auroral region in the winter hemisphere. The mean drag torque in the two summer polar open field regions is $\sim 1.8 \times 10^{16}$ N m, similar to but a little less than the drag torques in the adjacent auroral regions, but falls to $\sim 0.3 \times 10^{16}$ N m in the two winter hemispheres. Any seasonal effect on the thermospheric rotation period must thus be transferred from the polar open region to the auroral region, rather than vice versa.
- 4. Following the numerical models of Smith et al. (2007) and Smith and Aylward (2008), we have estimated the speed of the poleward thermospheric flow within the polar Pedersen layer required to balance the calculated magnetospheric drag torques in steady state. Assuming the angular momentum carried by the flow from midlatitudes is fully depleted in the polar region, we calculate a lower limit poleward speed of ~12 m s⁻¹ in the winter hemisphere and ~18 m s⁻¹ in the summer hemisphere. If only a fraction *K* of the angular momentum is depleted, these values increase by a factor 1/K.
- 5. A simple illustrative theoretical model of such a thermospheric flow system has been derived using a flat cylindrical disc approximation, and employing an ionospheric current profile suggested by the empirical summer hemisphere data, we have shown that solutions exist in which the thermospheric angular velocity increases or decreases indefinitely in the poleward flow, depending on the poleward flow speed, while in a singular solution the angular velocity remains constant. Arguing that physical solutions are those which do not diverge to large positive or negative values, but remain constant to a first approximation, yields a poleward flow speed of ~40 m s⁻¹ in this case. This value, together with those in point (c), is consistent with the modeling results of Smith and Aylward (2008), who quote poleward flow speeds in their models in the range ~10–100 m s⁻¹.
- 6. Relatively rapid thermospheric responses to temporal changes relate to two processes. The first is the time scale for meridional transport of atmospheric angular momentum at the poleward flow speeds indicated in (c) and (d) above, ~100 hr if the whole open plus auroral polar region is considered, but reducing in proportion to the length scale if latitudinally more restricted regions are involved. The second is the response to changes in the azimuthal magnetospheric drag force, which is ~10 hr for non-auroral Pedersen conductivities of ~2 mho, but reduces in inverse proportion for higher conductivities in the auroral region.
- 7. Despite their overall similar seasonal variations, comparison of the calculated hemispheric drag torques with concurrent values of the northern and southern PPO periods does not suggest a direct connection between these quantities as proposed by Brooks et al. (2019). This finding indicates at least that additional physical factors must be involved.
- 8. Observations further show that the PPO periods have no direct connection with the rotation period of the magnetospheric plasma, as was proposed by Brooks et al. (2019) in their dual PPO period scenario. PPO periods lie within the narrow range ~10.7 \pm 0.1 hr, while magnetospheric rotation periods are typically ~15–25 hr on auroral field lines where the principal PPO field-aligned currents flow. The rotating oscillatory PPO currents, together with related magnetic, auroral, and SKR modulations, propagate in the sense of planetary rotation through the more slowly rotating magnetospheric plasma.
- 9. If the PPO periods are approximately reflective of auroral region thermospheric rotation periods, the majority of the observed magnetospheric subcorotation lag must occur in the ionosphere between the thermosphere and plasma, contrary to the "atmospheric flywheel" picture for Saturn proposed by Brooks et al. (2019). If, on the other hand, one accepts the "atmospheric flywheel" picture with consequent strong subcorotation in the auroral thermosphere due to weak coupling with the lower atmosphere, the PPOs must relate to conditions lying deeper within Saturn's atmosphere where rotation periods are shorter. Thermospheric measurements are required to decide between these scenarios.

Data Availability Statement

Calibrated magnetic field and radio data from the Cassini mission are available from the NASA Planetary Data System at the Jet Propulsion Laboratory (https://pds.jpl.nasa.gov/). PPO periods shown in Figure 2b obtained from Cassini magnetic field data are available from the University of Leicester Research Archive (http://hdl.handle.net/2381/42436), while periods obtained from Cassini SKR data were derived from



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phases provided as Supporting Information: Data Set S1 in Ye et al. (2018) (https://doi.org/10.1029/ 2018GL077976).

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