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Special Section:
Cassini's Final Year: Science Highlights and Discoveries

Mapping Saturn's Nightside Plasma Sheet Using Cassini's Proximal Orbits

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Key Points:
- The UCL/AGA (University College London/Achilleos-Guio-Arridge) magnetodisk model describes very well the additional magnetic field in the Saturnian magnetodisk and can project high-latitude data to the equator
- The previously reported quiescent and disturbed states of the Saturnian ring current are also identified in the 6.5-day period of the Cassini proximal orbits
- The temporal (6.5-day) variability in the nightside magnetosphere of Saturn during Cassini's proximal orbits is comparable to the average local time asymmetry

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Abstract Between April and the end of its mission on 15 September, Cassini executed a series of 22 very similar 6.5-day-period proximal orbits, covering the mid-latitude region of the nightside magnetosphere. These passes provided us with the opportunity to examine the variability of the nightside plasma sheet within this time scale for the first time. We use Cassini particle and magnetic field data to quantify the magnetospheric dynamics along these orbits, as reflected in the variability of certain relevant plasma parameters, including the energetic ion pressure and partial (hot) plasma beta. We use the University College London/Achilleos-Guio-Arridge magnetodisk model to map these quantities to the conjugate magnetospheric equator, thus providing an equivalent equatorial radial profile for these parameters. By quantifying the variation in the plasma parameters, we further identify the different states of the nightside ring current (quiescent and disturbed) in order to confirm and add to the context previously established by analogous studies based on long-term, near-equatorial measurements.

Plain Language Summary Highly energized charge particles are trapped in the rapidly rotating magnetic cavity (the magnetosphere) of Saturn. Subject to the strong centrifugal potential, these particles, with energies in the order of few keV to few MeV, deform the dipole magnetic field of the planet and form an equatorial disk shaped structure, the magnetodisk. In this study we present how a theoretical magnetodisk model can be combined with Cassini particle data and accurately describe the field and plasma properties of the Saturnian magnetodisk. We further demonstrate how the previously observed variability of the electric current encircling the planet, the ring current, is also clearly identified in the measurements obtained during the 22 Cassini proximal orbits of nearly identical geometry. We find that this short-time temporal variability is comparable to the documented local time asymmetry of the ring current.

1. Introduction

During its long (>13 years) mission as a dedicated orbiter of Saturn, Cassini covered almost all parts of the planet's magnetosphere and returned a wealth of in situ and remote observations of magnetospheric particle and magnetic field properties. The Saturnian plasma sheet, in particular, was extensively studied during the last decade. Its three-dimensional structure and its dynamical (periodic and episodic) variability was revealed through multi-instrumental data analyses (e.g., Arridge et al., 2011; Carbary et al., 2015; Cowley & Provan, 2017; Kellett et al., 2011; Krupp et al., 2009; Nemeth et al., 2015; Sergis et al., 2011, 2017; Thomsen et al., 2017; Wilson et al., 2015, 2017) and modeled by several sophisticated approaches (e.g., Achilleos, Guio, & Arridge, 2010a; Arridge et al., 2011; Cowley & Provan, 2017; Jia & Kivelson, 2012).

One of the characteristics of Saturn's plasma sheet is its intense variability on relatively short time scales (of few minutes to few hours) that is persistently present in the properties of the hot (keV range) ion population and the corresponding suprathermal pressure component). Based on the hot plasma variability, and in particular on the measured radial profile of the hot plasma beta (ratio of the hot plasma pressure to the magnetic pressure), two distinct states of the Saturnian ring current were identified as long ago as Cassini's initial prime mission: a "quiescent" and a "disturbed" ring current (Sergis et al., 2007).

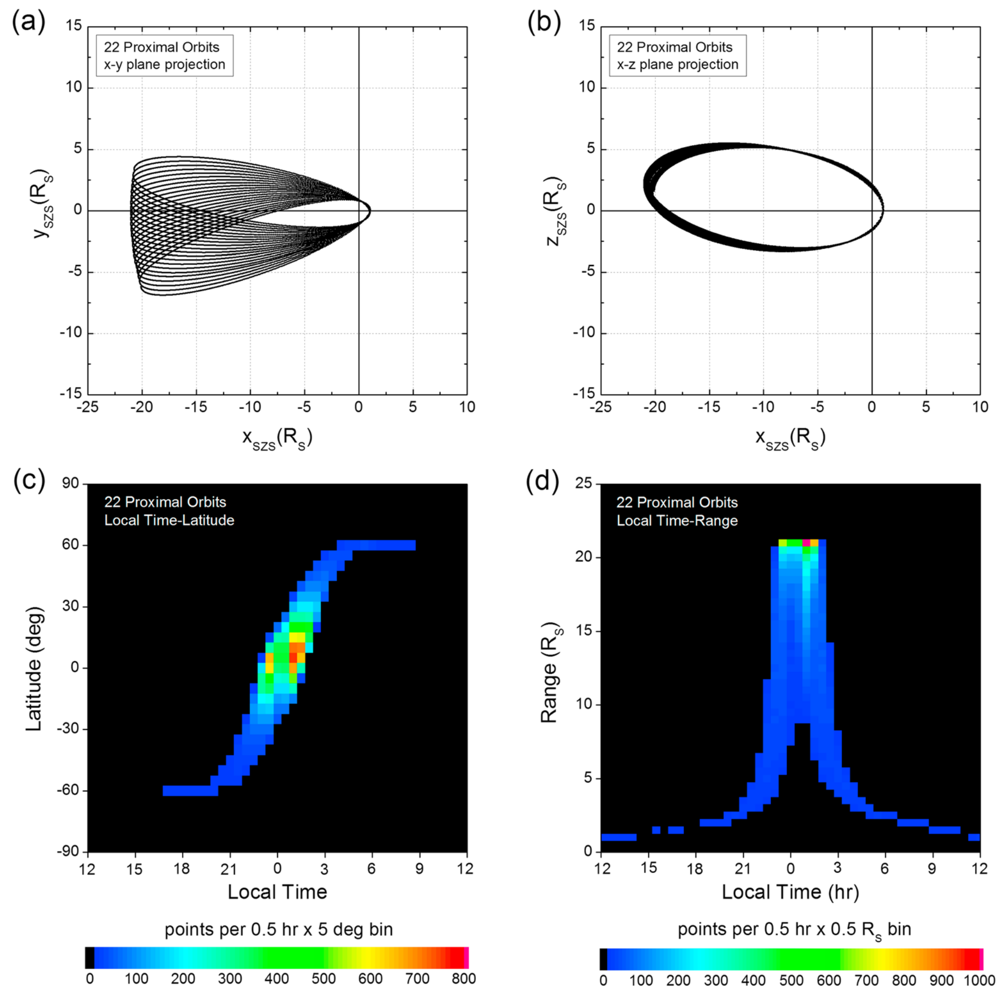

Figure 1. Overview of Cassini's proximal orbits: (a) x-y plane projection, (b) x-z plane projection, (c) density distribution in the local time-latitude parameter space, and (d) density distribution in the local time-range parameter space. The coordinates are in the Saturn-centered SZS coordinate system (*z*-axis parallel to Saturn's spin axis, *x*-axis roughly sunward in the Sun-spin axis plane, and *y*-axis completes the system, pointing roughly toward dusk).

The University College London/Achilleos-Guio-Arridge (UCL/AGA) magnetodisk model is a magnetostatic model, adapted from that of Caudal (1986) for the Jovian system. The axisymmetric model solves for both magnetic field and plasma pressure throughout the magnetospheric volume, using observed profiles of plasma properties on the equatorial plane (see Achilleos, Guio, & Arridge, 2010a, for more details). In so doing, the model quantifies the degree of radial "stretching" of the dipolar field lines of the planet's internal field, imposed by the disk plasma's rotational motion and pressure.

In this work we focus on the hot component of the particle population ($E > 3$ keV) that, although tenuous, carries the larger part of the plasma pressure, compared to the dense thermal plasma that dominates the particle number density. We attempt to determine whether the previously documented intense variability of the plasma sheet (e.g., quiescent versus disturbed state) in this energy range is primarily a temporal effect or is correlated to the magnetospheric spatial topology (e.g., linked to local L-shell and/or the local time sector). We further examine the L-shell profile of hot plasma properties, derived from Cassini data, and attempt to assess their contribution to the dynamics of the Saturnian system. In addition, the comparison of our "mapped" equatorial hot plasma pressure profiles—derived from "magnetically mapping" the high-latitude pressures with the model—with previous, directly observed equatorial profiles allows us to validate the model's use and its assumption of an energetic population with uniform pressure along field lines.

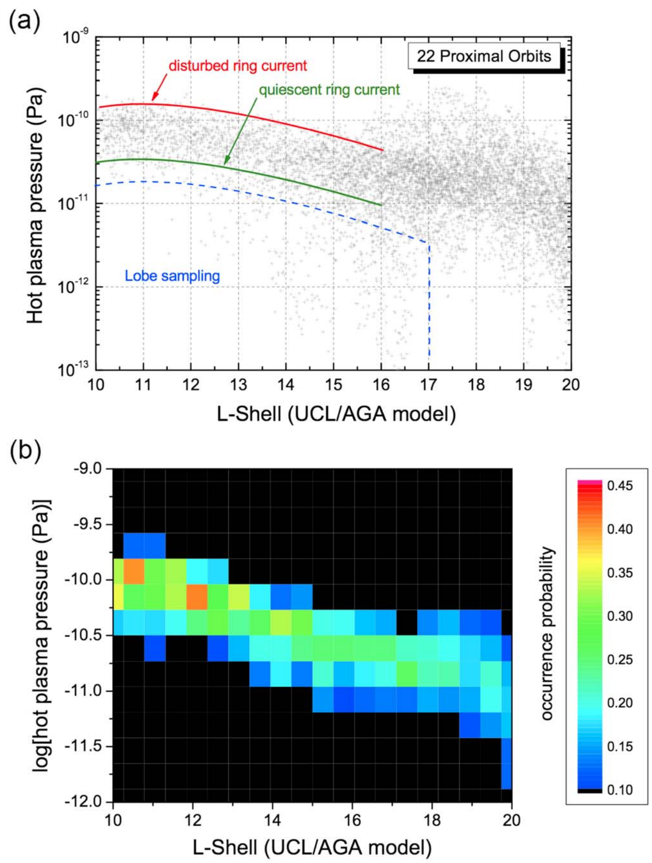

Figure 2. (a) L-Shell (UCL/AGA model) profile of the hot plasma pressure measured during the 22 proximal orbits of Cassini. The disturbed and the quiescent ring current states are marked, together with suspected lobe sampling, (b) the same distribution given as an occurrence probability map in the L-shell-log (P) parameter space. UCL/AGA = University College London/Achilleos-Guio-Arridge.

2. Observations and Methodology

The 22 proximal orbits of Cassini covered the period between 22 April and 15 September 2017 (end of the mission), and presented a unique characteristic: These 22 passes had a period of 6.5 days with very similar geometry and spatial coverage (Figure 1). This set of orbits allowed us for the first time to explore the temporal variability of the nightside plasma sheet in a time scale of the order of 1 week. As the spatial coverage remained very stable and repeatable from orbit to orbit, we had a unique opportunity to observe the range of the dynamics associated with this time scale, along a nearly fixed spatial "swathe" through the magnetosphere.

We used energetic (>3 keV) ion measurements from the three sensors of the Magnetospheric Imaging Instrument (MIMI) onboard the Cassini spacecraft (Krimigis et al., 2004) to compute the particle pressure for the corresponding energy range during the 22 Cassini proximal orbits, following the methodology introduced by Sergis et al., 2007, 2009. Similarly to Sergis et al., 2017, the computed suprathermal pressure includes also the contribution from H_2^+ ions, in addition to the main contributions, protons (H^+) and water product ions (W^+). The adopted time resolution for the computation was 10 min, to ensure reliable statistics, given the typical count rates in the region of interest, without compromising the detailed spatial coverage. In addition, the hot plasma beta was computed using the same time resolution as the corresponding in situ magnetic field measurements from the Cassini magnetometer (MAG; Dougherty et al., 2004). We should note, however, that the total particle pressure, the total plasma beta, and the associated pressure gradient component of the ring current, all contain the contribution from the thermal ions, which is not addressed in this study. Nevertheless, beyond L = 10 where this work's focus resides, the hot plasma pressure contribution is usually well over 50%.

In order to produce the corresponding equatorial L-shell pressure and beta profiles, we employ the UCL/AGA magnetodisk model (Achilleos, Guio, & Arridge, 2010a), computed for a dayside magnetopause standoff distance of 25 R_S, close to the mean value for the probability distribution of this quantity at Saturn (Achilleos et al., 2008), and use the model field to project the acquired high-latitude hot plasma pressure onto the equatorial plane of the nightside magnetosphere of Saturn. Thus, we project along shells of field lines produced by a centered dipole internal field plus a realistic magnetodisk/ring current distribution.

3. Results

The resulting L-shell profile for hot plasma pressure is presented in Figure 2, as a scatter plot (Figure 2a) and as a probability distribution map (Figure 2b). Note that the "L shell" parameter referred to for the abscissa represents the equatorial crossing distance of the relevant field line and can deviate up to a factor of 2 from the dipole L shell, depending on the magnetic latitude. The hot plasma pressure data exhibit a scatter of nearly one order of magnitude, and a clear drop with L shell between L ~ 10 and L ~ 16, in agreement to the presently established picture of the equatorial hot plasma distribution from direct observations (Sergis et al., 2017). Measurements that correspond to intervals during which Cassini is located in the magnetic lobes (i.e., those regions magnetically conjugate to polar shells relatively devoid of plasma) can be easily identified and are marked (Figure 2a), although they do not seem to affect the overall distribution (Figure 2b).

Figure 3 shows the corresponding L-shell profiles (scatter and probability map) for the hot plasma beta, computed using the coincident, in situ magnetic field measurements. The hot plasma beta increases with L shell, reaching $\beta \sim 1$ near L = 16 and generally appears quite similar to the direct equatorial beta profile derived by

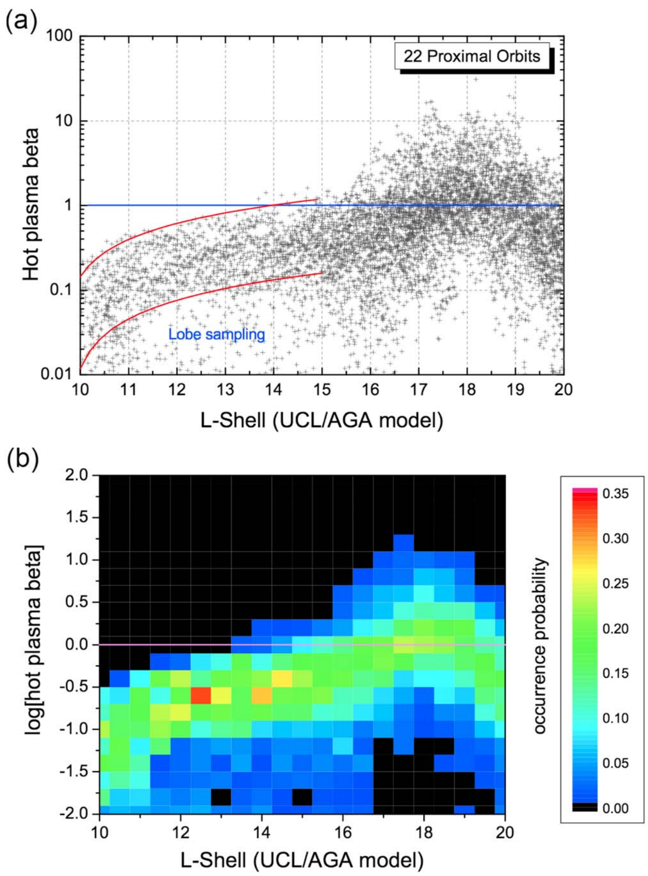

Figure 3. Similar to Figure 2 but for the hot plasma beta distribution. UCL/AGA = University College London/Achilleos-Guio-Arridge.

Sergis et al., 2007, using data from 11 equatorial orbits of Cassini. Beyond L = 16, both profiles (hot plasma pressure and hot beta) become significantly more variable.

At this point, we should note that the geometry of the proximal orbits, although beneficial for the study of the plasma sheet dynamics, imposes a systematic error due to the inevitable incomplete pitch angle coverage with changing spacecraft latitude, as Cassini cannot measure ions that mirror equatorward of its position. Beyond L = 16, Cassini travels closer to the equatorial plane and can thus capture almost the full range of the quasi-isotropic pitch angle distribution of ions. Therefore, both the hot pressure and hot beta L-shell profiles of Figures 2 and 3 should be viewed as lower limits for $L < 16$, until a more detailed pitch angle analysis can be carried out and the appropriate correction is applied. These lower limits are nevertheless in agreement with the direct equatorial profiles within the displayed uncertainties.

An additional error in our equatorial projection is imposed by the fact that the UCL/AGA model does not predict an azimuthal component of the magnetic field. This component is generally known from previous studies that have empirically modeled this component using its observed relation with the poloidal field (e.g., Achilleos et al., 2014; Arridge et al., 2011; Connerney et al., 1983) but can also be locally measured when Cassini crosses the equatorial plane. However, the presence of a nonzero azimuthal field component cannot affect significantly the mapping process or the produced L-Shell profiles (i.e., in such a degree that the equatorial foot point of a model field line would correspond to a different local time sector compared to the real crossing point of the field line).

Despite the small systematic underestimation in the pressure (of the order of 10–30% as discussed later), two states of the ring current can be unambiguously identified in both profiles, similar to those introduced by Sergis et al. (2007) and later modeled by Achilleos, Guio, Arridge, Sergis, et al. (2010b): A "quiescent" and a "disturbed" ring current, with a corresponding strength ratio in the range ~5 to ~8, as reflected in the energetic particle pressure and the corresponding plasma beta. In addition, Krupp et al. (2018) report that, during the proximal orbits, the disturbed ring current is correlated with low-latitude energetic neutral atom (ENA) emissions, as energetic neutrals, produced at the ring current region, reach Saturn's atmosphere and are backscattered (planet-wards) to Cassini.

Figure 4a summarizes the hot plasma pressure conditions in the nightside magnetosphere of Saturn during the Cassini proximal orbits (median pressure values per radial bins of 1 R_S, solid line). This profile is compared to the long-term (2004–2013) measured radial hot plasma pressure (dashed line) for roughly the same local time sector (Sergis et al., 2017). The very good agreement between the two profiles is indicative of how well the UCL/AGA model reproduces the disk-like magnetic field and projects the high-latitude measurements to the equatorial plane. The relatively small systematic difference in the pressure values is below 30% for L shells between ~10 and ~16 (Figure 4b) and is attributed to the incomplete pitch angle sampling described earlier. Note that the average 2004–2013 profile was obtained from measurements strictly close to the center of the plasma sheet, thus demonstrating that the more energetic ions (>3 keV) are not subject to significant confinement toward the equator, in terms of their overall pressure.

The error bars in the profile of Figure 4 correspond to the interquartile range (Q_1–Q_3) and are thus indicative of the dynamic behavior of the plasma sheet, which appears comparable to the typical range associated with the local time asymmetry that characterizes the averaged conditions in the ring current region (Krimigis et al., 2007; Sergis et al., 2017).

An uncertainty in the overall mapping process is also introduced by the selection of the magnetopause standoff distance, as this distance can vary on time scales as small as a few hours or even less (Achilleos

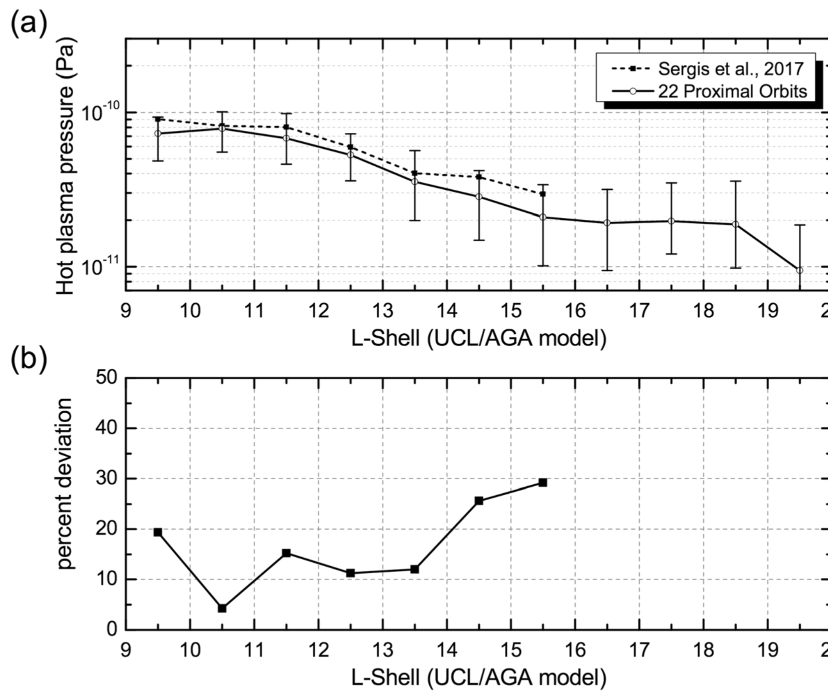

Figure 4. (a) Average L-shell profile of the hot plasma pressure for the 22 proximal orbits of Cassini (solid line). Pressure medians are given for each bin of 1 R_S, while the error bar brackets the interquartile range (Q_1 to Q_3). For comparison, the corresponding pressure profile from a larger part of the mission (2004–2013) and for roughly the same local time range (2100–0300 hr) is shown (dashed line). (b) Percent deviation between the two profiles as a function of L shell. UCL/AGA = University College London/Achilleos-Guio-Arridge.

et al., 2008; Kanani et al., 2010; Pilkington et al., 2015a; Pilkington et al., 2015b; Ramer et al., 2016), due to both external and internal influences (Sorba et al., 2017). Since there is no dedicated upstream monitor at Saturn in addition to Cassini, it is not possible to have a continuous, accurate estimate of magnetopause size as a function of time. During the execution of the proximal orbits Saturn was under the influence of recurrent corotating interaction regions, and likely interacted with periodically varying solar wind flows, as well as enhanced and rarefied interplanetary magnetic field (Roussos et al., 2018). In addition, the same study reports that Saturn was exposed to two transients of solar energetic particles that are expected to have increased the interplanetary magnetic field in the region, causing a magnetospheric compression, for at least the few-day duration of each event's peak. We should point out, however, that the observed difference is considered a relatively small influence, given the much higher range associated with the solar wind dynamic pressure.

4. Summary and Conclusions

We analyzed Cassini/MIMI and MAG data obtained during the final (proximal) obits of the Cassini mission. These 22 orbits had a very similar geometry with a period of 6.5 days and are therefore ideal to examine the hot ion plasma variability on this time scale, since all spatial dependencies are minimized due to the repeatable orbital coverage.

Using the UCL/AGA magnetodisk model, we modeled the global geometry of the planetary field and projected the computed hot plasma pressure onto the equatorial plane. We constructed the corresponding L-shell profiles for the suprathermal pressure and the corresponding plasma beta, and we compared those to the average radial profiles directly observed for the same local time sector from previous, more extended parts of the mission.

The main conclusions of this study can be summarized as follows:

1. The L-shell profile of the hot plasma pressure produced by mapping the data to the equatorial plane with the UCL/AGA magnetodisk model is in very good quantitative and qualitative agreement with the

corresponding (and directly observed) average, long-term profiles presented in Sergis et al., 2017. This similarity indicates that the model describes very well the distorted or "stretched" magnetic field configuration of the Saturnian magnetodisk, when an appropriate magnetopause standoff distance is selected. The systematic deviation, attributed mostly to the incomplete pitch angle sampling, appears to be below ~30%.

2. The two states of the Saturnian ring current (quiescent and disturbed) that have been reported since the early stages of the Cassini mission are also identified herein on the 6.5-day time scale, indicating that the temporal (few-day time scale) variability in the nightside magnetosphere is at least comparable to the documented systematic spatial variation with local time. The partial (hot) plasma beta appears to increase with L shell at least up to L ~ 18, revealing the increasing contribution of the hot plasma component to the dynamics of the system. It is important to note that at L ~ 17, the hot plasma beta attains a median value of ~1, suggesting that the energetic (E $>$ 3 keV) particle pressure alone can locally balance the magnetic pressure.

The successful application of the UCL/AGA model to project measurements from the proximal orbits indicates that, if the described issues concerning pitch angle sampling and the variability of the magnetopause location are successfully addressed, we would, in principle, be able to expand this magnetic mapping method to data from the entire mission.

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References

Achilleos, N., Arridge, C. S., Bertucci, C., Guio, P., Romanelli, N., & Sergis, N. (2014). A combined model of pressure variations in Titan's plasma environment. *Geophysical Research Letters*, *41*, 8730–8735. https://doi.org/10.1002/2014GL061747

Achilleos, N., Arridge, C. S., Bertucci, C., Jackman, C. M., Dougherty, M. K., Khurana, K. K., & Russell, C. T. (2008). Large-scale dynamics of Saturn's magnetopause: Observations by Cassini. *Journal of Geophysical Research*, *113*, A11209. https://doi.org/10.1029/2008JA013265

Achilleos, N., Guio, P., & Arridge, C. S. (2010a). A model of force balance in Saturn's magnetodisc. *Monthly Notices of the Royal Astronomical Society*, *401*(4), 2349–2371. https://doi.org/10.1111/j.1365-2966.2009.15865.x

Achilleos, N., Guio, P., Arridge, C. S., Sergis, N., Wilson, R. J., Thomsen, M. F., & Coates, A. J. (2010b). Influence of hot plasma pressure on the global structure of Saturn's magnetodisk. *Geophysical Research Letters*, *37*, L20201. https://doi.org/10.1029/2010GL045159

Arridge, C. S., André, N., Khurana, K. K., Russell, C. T., Cowley, S. W. H., Provan, G., et al. (2011). Periodic motion of Saturn's nightside plasma sheet. *Journal of Geophysical Research*, *116*, A11205. https://doi.org/10.1029/2011JA016827

Carbary, J. F., Sergis, N., Mitchell, D. G., & Krupp, N. (2015). Saturn's hinge parameter from Cassini magnetotail passes in 2013–2014. *Journal of Geophysical Research: Space Physics*, *120*, 4438–4445. https://doi.org/10.1002/2015JA021152

Caudal, G. (1986). A self-consistent model of Jupiter's magnetodisc including the effects of centrifugal force and pressure. *Journal of Geophysical Research*, *91*(A4), 4201–4221. https://doi.org/10.1029/JA091iA04p04201

Connerney, J. E. P., Acuña, M. H., & Ness, N. F. (1983). Currents in Saturn's magnetosphere. *Journal of Geophysical Research*, *88*, 8779–8789. https://doi.org/10.1029/JA088iA11p08779

Cowley, S. W. H., & Provan, G. (2017). Planetary period modulations of Saturn's magnetotail current sheet during northern spring: Observations and modeling. *Journal of Geophysical Research: Space Physics*, *122*, 6049–6077. https://doi.org/10.1002/2017JA023993

Dougherty, M. K., Kellock, S., Southwood, D. J., Balogh, A., Smith, E. J., Tsurutani, B. T., et al. (2004). The Cassini magnetic field investigation. *Space Science Reviews*, *114*(1-4), 331–383. https://doi.org/10.1007/s11214-004-1432-2

Jia, X., & Kivelson, M. G. (2012). Driving Saturn's magnetospheric periodicities from the upper atmosphere/ionosphere: Magnetotail response to dual sources. *Journal of Geophysical Research*, *117*, A11219. https://doi.org/10.1029/2012JA018183

Kanani, S. J., Arridge, C. S., Jones, G. H., Fazakerley, A. N., McAndrews, H. J., Sergis, N., et al. (2010). A new form of Saturns magnetopause using a dynamic pressure balance model, based on in situ, multi-instrument Cassini measurements. *Journal of Geophysical Research*, *115*, A06207. https://doi.org/10.1029/2009JA014262

Kellett, S., Arridge, C. S., Bunce, E. J., Coates, A. J., Cowley, S. W. H., Dougherty, M. K., et al. (2011). Saturn's ring current: Local time dependence and temporal variability. *Journal of Geophysical Research*, *116*, A05220. https://doi.org/10.1029/2010JA016216

Krimigis, S., Mitchell, D. G., Hamilton, D. C., Livi, S., Dandouras, J., Jaskulek, S., et al. (2004). Magnetosphere Imaging Instrument (MIMI) on the Cassini mission to Saturn/Titan. *Space Science Reviews*, *114*(1-4), 233–329. https://doi.org/10.1007/s11214-004-1410-8

Krimigis, S. M., Sergis, N., Mitchell, D. G., Hamilton, D. C., & Krupp, N. (2007). A dynamic, rotating ring current around Saturn. *Nature*, *450*(7172), 1050–1053. https://doi.org/10.1038/nature06425

Krupp, N., Roussos, E., Kollmann, P., Mitchell, D. G., Paranicas, C. P., Krimigis, S. M., et al. (2018). Overview of neutral and energetic charged particle measurements in the inner Saturnian magnetosphere during the grand finale orbits of Cassini 2016/2017. *Geophysical Research Letters*, *45*. https://doi.org/10.1029/2018GL078096

Krupp, N., Roussos, E., Lagg, A., Woch, J., ·ller, A. L. M., Krimigis, S. M., et al. (2009). Energetic particles in Saturn's magnetosphere during the Cassini nominal mission (July 2004-July 2008). *Planetary and Space Science*, *57*(14-15), 1754–1768. https://doi.org/10.1016/j.pss.2009.06.010

Nemeth, Z., Szego, K., Foldy, L., Kivelson, M. G., Jia, X., Ramer, K. M., et al. (2015). The latitudinal structure of the nightside outer magnetosphere of Saturn as revealed by velocity moments of thermal ions. *Annales Geophysicae*, *33*(9), 1195–1202. https://doi.org/10.5194/angeo-33-1195-2015

Pilkington, N. M., Achilleos, N., Arridge, C. S., Guio, P., Masters, A., Ray, L. C., et al. (2015a). Internally driven large-scale changes in the size of Saturn's magnetosphere. *Journal of Geophysical Research: Space Physics*, *120*, 7289–7306. https://doi.org/10.1002/2015JA021290

Pilkington, N. M., Achilleos, N., Arridge, C. S., Guio, P., Masters, A., Ray, L. C., et al. (2015b). Asymmetries observed in Saturn's magnetopause geometry. *Geophysical Research Letters*, *42*, 6890–6898. https://doi.org/10.1002/2015GL065477

Ramer, K. M., Kivelson, M. G., Sergis, N., Khurana, K. K., & Jia, X. (2016). Spinning, breathing, and flapping: Periodicities in Saturn's middle magnetosphere. *Journal of Geophysical Research: Space Physics*, *122*, 393–416. https://doi.org/10.1002/2016JA023126

Roussos, E., Krupp, N., Paranicas, C., Mitchell, P. K. D., Krimigis, S., Palmaerts, B., et al. (2018). Heliospheric conditions at Saturn during Cassini's ring grazing and proximal orbits. *Geophysical Research Letters*, *45*. https://doi.org/10.1029/2018GL078093

Sergis, N., Arridge, C. S., Krimigis, S. M., Mitchell, D. G., Rymer, A. M., Hamilton, D. C., et al. (2011). Dynamics and seasonal variations in Saturn's magnetospheric plasma sheet, as measured by Cassini. *Journal of Geophysical Research*, *116*, A04203. https://doi.org/10.1029/2010JA016180

Sergis, N., Jackman, C. M., Thomsen, M. F., Krimigis, S. M., Mitchell, D. G., Hamilton, D. C., et al. (2017). Radial and local time structure of the Saturnian ring current, revealed by Cassini. *Journal of Geophysical Research: Space Physics*, *122*, 1803–1815. https://doi.org/10.1002/2016JA023742

Sergis, N., Krimigis, S. M., Mitchell, D. G., Hamilton, D. C., Krupp, N., Mauk, B. H., et al. (2009). Energetic particle pressure in Saturn's magnetosphere measured with the Magnetospheric Imaging Instrument on Cassini. *Journal of Geophysical Research*, *114*, A02214. https://doi.org/10.1029/2008JA013774

Sergis, N., Krimigis, S. M., Mitchell, D. G., Hamilton, D. C., Krupp, N., Mauk, B. M., et al. (2007). Ring current at Saturn: Energetic particle pressure in Saturn's equatorial magnetosphere measured with Cassini/MIMI. *Geophysical Research Letters*, *34*, L09102. https://doi.org/10.1029/2006GL029223

Sorba, A. M., Achilleos, N. A., Guio, P., Arridge, C. S., Pilkington, N. M., Masters, A., et al. (2017). Modeling the compressibility of Saturn's magnetosphere in response to internal and external influences. *Journal of Geophysical Research: Space Physics*, *122*, 1572–1589. https://doi.org/10.1002/2016JA023544

Thomsen, M. F., Jackman, C. M., Cowley, S. W. H., Jia, X., Kivelson, M. G., & Provan, G. (2017). Evidence for periodic variations in the thickness of Saturn's nightside plasma sheet. *Journal of Geophysical Research: Space Physics*, *122*, 280–292. https://doi.org/10.1002/2016JA023368

Wilson, R. J., Bagenal, F., Cassidy, T., Fleshman, B. L., & Crary, F. (2015). The relative proportions of water group ions in Saturn's inner magnetosphere: A preliminary study. *Journal of Geophysical Research: Space Physics*, *120*, 6624–6632. https://doi.org/10.1002/2014JA020557

Wilson, R. J., Bagenal, F., & Persoon, A. M. (2017). Survey of thermal plasma ions in Saturn's magnetosphere utilizing a forward model. *Journal of Geophysical Research: Space Physics*, *122*, 7256–7278. https://doi.org/10.1002/2017JA024117