Plasma environment at Titan's orbit with Titan present and absent

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Received 18 September 2009; revised 20 October 2009; accepted 23 October 2009; published 3 December 2009.

[1] To understand the possible large scale influence of Titan on its plasma environment, we study the magnetic fields and plasma measurements, both when Cassini flies close to Titan and when Cassini crosses the moon's orbit far from it. Using 98 Cassini passes from 06/2004 to 12/2008, we examine the plasma environments at the orbit of Titan with the moon present and absent. In particular, the presence of Titan appears to affect the magnetopause location. Near noon, the Saturn magnetopause is more frequently inside of Titan's orbit with the moon absent than with it present. Titan's presence near noon appears to locally enhance the total pressure and reduce the magnetosphere compressibility, possibly by mass-loading. Near local midnight, the stretching and sweepback angles for cases with Titan present and absent suggest that the moon enhances the tail reconnection rate, in agreement with previous studies of the moon's influence on the Saturnian magnetosphere.
Citation: Wei, H. Y., C. T. Russell, A. Wellbrock, M. K. Dougherty, and A. J. Coates (2009), Plasma environment at Titan's orbit with Titan present and absent, *Geophys. Res. Lett.*, *36*, L23202, doi:10.1029/2009GL041048.

1. Introduction

[2] The plasma and magnetic fields encountering Titan vary with Saturnian local time (SLT), adding to the complexity of the Titan interaction with its plasma environment. Saturn's magnetopause distance near noon (within 3 hours of local noon) is observed to range from 17 to 29 Saturn radii (Rs) with an averaged distance of 25 Rs [*Arridge et al.*, 2006]. With an orbital distance of 20 Saturn radii (Rs), Titan is mostly in the outer magnetosphere (since an average solar wind dynamic pressure is about 0.03 nPa at Saturn) and interacts with the magnetospheric sub-corotating plasma. But when the solar wind pressure is high and the Saturnian magnetosphere is more compressed, Titan may occasionally enter the magnetosheath, or even enter the solar wind near noon SLT. The variability of Titan's magnetic environment was first studied by *Bertucci et al.* [2009]. They found Titan's magnetic environment is strongly affected by the presence of Saturn's magnetodisk and moves between a "magnetodisk lobe" regime and a "current sheet" regime. Recent study by *Rymer et al.* [2009], using the CAPS and MIMI electron spectrograms, divides the Titan plasma environment into four groups: 1) plasma sheet, 2) lobe-like, 3) magnetosheath, and 4) bimodal.

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0094-8276/09/2009GL041048

[3] In order to further understand the plasma environment interacting with Titan, we study magnetic field measurements from the Cassini magnetometer (MAG) [*Dougherty et al.*, 2004] together with electron spectrograms from the Cassini plasma spectrometer (CAPS) [*Young et al.*, 2004] obtained both when Cassini passes near Titan (i.e. during Titan flybys), and when the spacecraft passes Titan's orbit well away from Titan (i.e. over 2 hours of SLT away). This allows us to statistically estimate the probability of Titan's entry into the magnetosheath and to compare the plasma environments at Titan's orbit with Titan present and absent. We discuss below the implications of these results on the influence of Titan on its plasma environment.

2. Probability of Titan's Orbit in the Magnetosheath of Saturn With Titan Present and Titan Absent

[4] During Titan flybys, the data are generally shown in Titan Interaction System (TIIS) coordinates, in which the x-axis is in the nominal corotation direction, the y-axis points from Titan to Saturn, and the z-axis completes the right-handed coordinate system. Figure 1a shows an example of a Titan-present pass, during T38. The intervals studied in this paper are selected as one-hour approaching and one-hour leaving the strongly-draped-field region close to Titan, shown by shading in Figure 1a. During a Titan-absent pass without the moon nearby (i.e. Cassini is over 2 hours of SLT and more than 11 Rs away from Titan), it is more appropriate to treat the data in Kronocentric Radial-Theta-Phi (KRTP) coordinates which has the r-axis radially outward from Saturn, the phi-axis in direction of the cross product of Saturn's rotation axis and the r-axis, and the theta-axis completing the right-hand coordinate system. Figure 1b shows an example of a Titan-absent pass. We define the region within a vertical distance of 0.5 Rs above or below Titan's orbital plane and within a radial distance between 19 to 21 Rs from Saturn as Titan's orbit for the purposes of this paper. This study includes Cassini orbits Rev. 0 to Rev. 98 over the period of June 2004 to December 2008.

[5] From Figure 1b, we can see from the CAPS electron spectrogram that Cassini crosses the magnetopause around 0800 UT. The magnetopause crossing is identified from both MAG data and CAPS electron spectrograms. The magnetosphere is characterized by hot tenuous plasma [*Rymer et al.*, 2009] and a southward magnetic field while the magnetosheath has cold dense plasma and may have a northward field. During this interval the magnetosheath was observed inside Titan's exact orbit, because the magnetosphere was relaxing from a compressional state and the magnetopause was moving outward faster than Cassini. During this four-hour interval, the fraction of time when Titan's orbit is in the magnetosheath is 50%. We assume

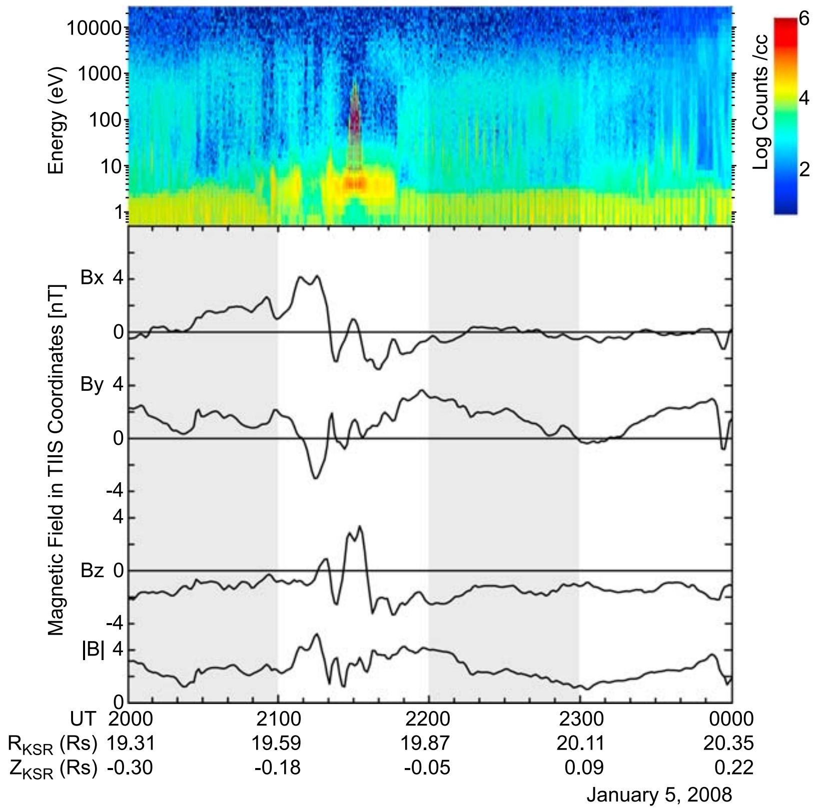

Figure 1a. Electron spectrogram, Bx, By, Bz and B_{total} (field magnitude) in TIIS coordinates versus universal time during a Titan pass T38 near 1130 SLT. Titan's environment field is obtained by averaging over two one-hour intervals inbound and outbound outside the strongly-draped-field region close to Titan. The two intervals are shown by shading.

that magnetopause moves through Titan's orbital region quickly compared to the time interval studied. Therefore, whether Cassini is in the magnetosheath or in the magnetosphere at a particular time is indicative of the entire crossing of the orbital region. We calculate the fraction of time when Titan's orbit (with Titan present or absent) is in the magnetosheath on each pass between 0900 and 1500 SLT. The time window is chosen by looking at the Cassini location and making sure it is within a vertical distance of 0.5 Rs from Titan's orbital plane and at a radial distance between 19 and 21 Rs. The MAG and CAPS data are examined in that interval to determine this fractional in-magnetosheath time.

[6] From 0900 to 1500 SLT, there are 26 Titan-present cases and 37 Titan-absent cases. The fraction of time when Titan's orbital distance was inside the magnetosheath (defined as the in-magnetosheath probability in this paper) is quite different when close to Titan compared to 20 Rs crossings that are away from Titan (3.37% for Titan-present and 10.37% for Titan-absent). The two probabilities are statistically different; for example, if the in-magnetosheath probability were 3.37%, then the chance of observing a 10.37% residence time (as we do in the absence of Titan) would be less than 3%.

[7] Our results indicate that it is more probable for Titan's orbit to be located in Saturn's magnetosheath with Titan absent, than with Titan present. This implies that Titan reduces the compressibility of the local plasma possibly by anchoring the magnetic field, or mass loading either the flux tubes connected to its ionosphere, or the entire near Titan region by the cross-field motion of fast neutrals that later ionize. Field-anchoring can take place at Titan in an analogous manner to field lines in the Earth's magnetosphere in which field lines penetrate a highly conducting region, the ionosphere, crust and core. At Titan the majority of field lines are anchored in the ionosphere but some must also enter the interior of Titan (H. Y. Wei et al., Upper limits of Titan's magnetic moments and implications for its interior, manuscript in preparation, 2009).

3. SLT Variation of the Magnetic Field Near Titan's Orbit

[8] During a Titan pass, the ambient magnetic field near Titan is obtained by averaging over two one-hour intervals inbound and outbound outside the strongly-draped-field region close to Titan, shown shaded in Figure 1a. During a Titan orbit crossing with Titan far away, the observed field is averaged over a four-hour interval closest to Titan's orbit, shown in Figure 1b. Because Titan orbits in the equatorial plane of Saturn, B_y in TIIS coordinates is along $-B_r$ in KRTP coordinates, B_z is along $-B_{theta}$, and B_x is along B_{phi}. Thus we can readily put Titan-present cases and Titan-absent cases in KRTP coordinates and compare them.

[9] Figure 2 shows the SLT variation of B_r, B_{theta}, B_{phi}, stretching angle and sweepback angle. The generally negative B_r shows that Cassini is below the Saturnian magnetospheric current sheet. The stretching angle is defined as $\arctan(B_r/B_{theta})$, so it should be zero when the field is perfectly dipolar and should approach ±90 degrees

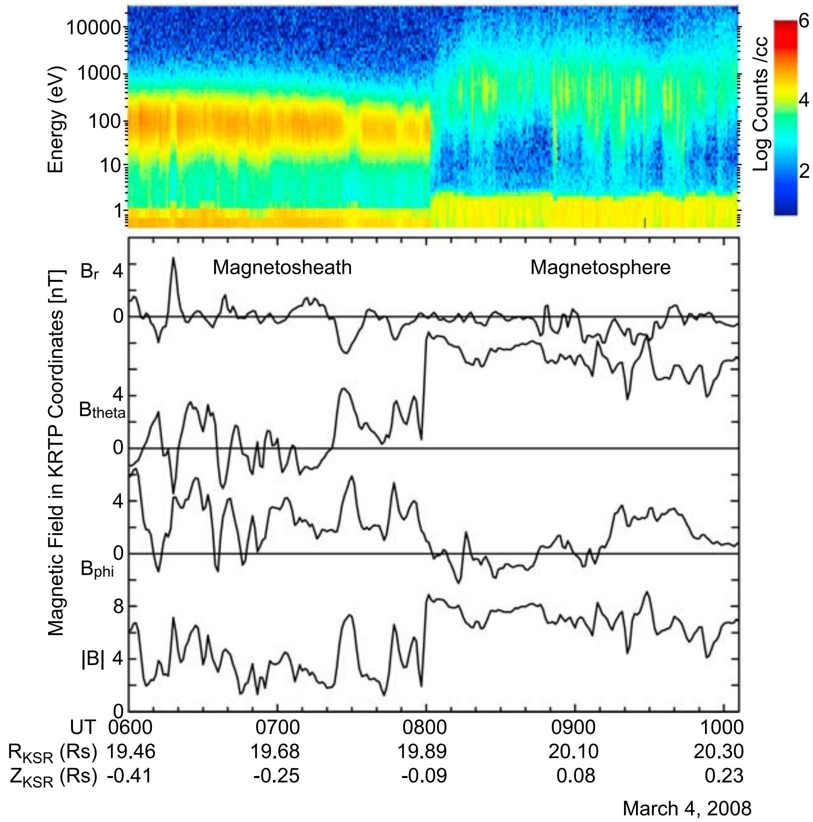

Figure 1b. Electron spectrogram, B_r, B_{theta}, B_{phi} and B_{mag} (field magnitude) in KRTP coordinates versus universal time during a Titan orbit pass with Titan not nearby near 1110 SLT. The field is averaged over a four-hour interval closest to Titan's orbit. They are within a radial distance of 19 to 21 Rs from Saturn and a vertical distance of 0.5 Rs above or below Titan's orbital plane. Near noon SLT Cassini sometimes enters the magnetosheath at Titan's orbit. In this example, Cassini was in the magnetosheath from 0600 to 0800 UT.

when the field is stretched. The sweepback angle is defined as arctan(Bphi/Br), and (when below the current sheet) it should be zero if the plasma is in rigid corotation, negative if sub-corotation and positive if super-corotation. Table 1 shows the mean stretching and sweepback angles and the probable errors of the means for each 3 hours of SLT. Figure 2 and Table 1 show that the stretching angle has stronger SLT variation than the sweepback angle, with the magnetic field being more dipolar near noon and more stretched near mid-night. The generally negative sweepback angle indicates that the flow is mostly sub-corotating except for some cases near noon. The comparison of the Titan-present cases with Titan-absent cases should firstly be focused on the SLT sectors which have relatively large number of samples for both situations.

[10] For SLT from 0000 to 0300, the stretching angles for Titan present are similar to those for Titan absent, except for the three points above −45 degrees. To examine if the stretching-angle distributions with the moon present and absent are statistically different, a t-test [e.g., *Welch*, 1938] is applied using the means and errors in Table 1 for this SLT range. A t-value of 1.35 is obtained, which mean there is only 82% of confidence that the two distributions are statistically different. We define a test that has more than 95% confidence to be statistically significant. The same analysis for the sweepback angles also shows that the two distributions are not statistically different. The three stretching angles above −45 degrees, occurred near 0200 SLT, are −18.5, −26.1 and −34.2 degrees. Assuming the stretching angle distribution for this SLT range has the mean and error in Table 1, a t-test is applied to examine the difference of each of the three values with the distribution and all the three values are significantly different from the mean with over 99% of confidence. The sweepback angles for these three cases are −10.8, 50.0 and −39.5 degrees. Using the mean sweepback angle and error in Table 1, the same analysis shows that only the second sweepback angle is significantly different from the mean with confidence of 99%. This extraordinary case (stretching angle of −26.1 and sweepback angle of 50.0) has both stretching and sweepback angles significantly different from the mean.

[11] Why the field is more dipolar and has positive sweepback angle (an indication of super-corotation) during this case can be explained by the fact that Cassini is on Saturnward moving flux tubes just after they were reconnected in Saturn's tail. Titan being near midnight may facilitate tail reconnection by mass-loading the flux tube, making it even more stretched or easier to break. Another possible explanation is that Cassini is passing the tail current sheet, as argued by *Bertucci et al.* [2009] that "the stretch angle provides a good estimate of the distance between Cassini and the magnetodisk's central current sheet." To examine whether a stretching angle approaching zero is due to returning flux tube or due to current sheet

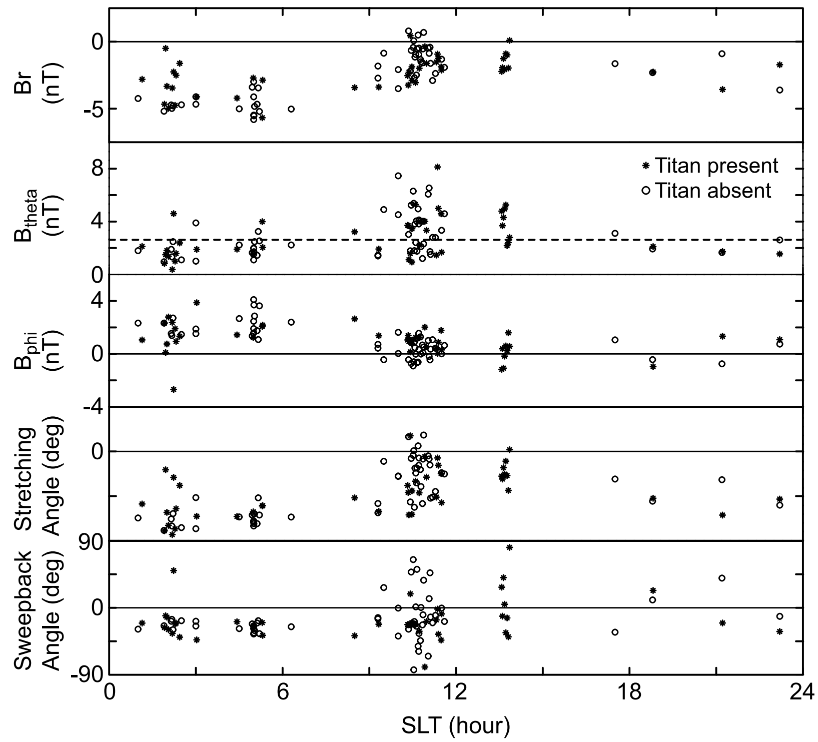

Figure 2. SLT variation of B_r, B_{theta}, and B_{phi}, stretching angle, and sweepback angle. The Titan-present cases (43 cases) are shown with asterisks and the Titan-absent cases (55 cases) are shown with circles, both having the in-magnetosheath cases excluded. The dashed line in the second panel shows expected strength of B_{theta} due to Saturn's dipole moment.

crossing, the magnetic field data in a two-day interval around this case were examined. If it was due to current sheet crossing, there would be a strong decrease in the field magnitude accompanying the decrease of the radial field magnitude. However, there is no decrease of field magnitude when the radial field weakens. Thus the more dipolar field in this case does not appear to due to approaching the current sheet but probably due to flux returned after tail reconnection. The positive sweepback angle also agrees with the returned flux scenario, because the inward moving flux tube would speed up to conserve angular momentum.

[12] *Menietti et al.* [2007] studied the Saturnian Kilometric Radiation (SKR) and found that when Titan is near midnight SLT there is a significant increase in the occurrence probability of SKR and a diminution of SKR when Titan is near local noon and afternoon. They argued that it was possibly due to Titan enhancing the reconnection rate near midnight and decreasing it near noon. If Titan's presence near midnight enhances the reconnection rate in Saturn's tail, we should be able to see more cases of dipolar-like fields with Titan present than with Titan absent. Because after reconnection which is at a greater distance than Titan's orbit, the flux tubes move Saturnward and become more dipolar near the orbit of Titan, we have a greater chance to see the dipolar-like field structure when the reconnection rate is enhanced. *Russell et al.* [2008] studied tail reconnection observations and found that when Titan is near midnight the field is weak and stretched and substorms were more frequent. They suggested that the extra mass added by Titan may trigger substorms. Thus,

Table 1. Mean Stretching and Sweepback Angles and the Probable Errors of the Means for Each 3 Hours of SLT

	Saturnian Local Time							
	0000 to 0300	0300 to 0600	0600 to 0900	0900 to 1200	1200 to 1500	1500 to 1800	1800 to 2100	2100 to 2400
				Titan Present				
Stretching angle								
Number of cases	11	4	1	16	8	0	1	2
Mean	−57.5	−58.9	−46.8	−33.2	−20.4	n/a	−47.1	−56.0
Error of the mean	6.8	2.7	n/a	5.7	4.4	n/a	n/a	8.1
Sweepback angle								
Mean	−19.0	−25.1	−37.6	−23.2	7.0	n/a	23.2	−26.2
Error of the mean	7.6	4.2	n/a	5.1	14.4	n/a	n/a	5.7
				Titan Absent				
Stretching angle								
Number of cases	8	11	1	31	0	1	1	2
Mean	−69.2	−66.2	−66.1	−21.9	n/a	−27.8	−50.1	−41.3
Error of the mean	3.9	2.4	n/a	3.8	n/a	n/a	n/a	12.9
Sweepback angle								
Mean	−22.0	−27.2	−25.5	−10.5	n/a	−32.9	10.5	14.1
Error of the mean	1.9	1.8	n/a	6.3	n/a	n/a	n/a	25.7

the previous studies of SKR and tail reconnection and our study agree on the influence of Titan on the Saturnian magnetosphere near midnight in three independent aspects.

[13] For SLT from 0300 to 0600, there are smaller variations for both the stretching and sweepback angles, compared with those for SLT from 0000 to 0300. The mean values in Table 1 show that the fields for the Titan absent cases are slightly less stretched than those closer to midnight during 0000 to 0300 SLT. For SLT from 0600 to 0900, there is only one case in either category so it is hard to compare them statistically.

[14] For SLT from 0900 to 1200, the cases are near local noon, so the solar wind pressure and magnetopause reconnection may affect the stretching and sweepback angles. From Table 1, the Titan absent cases have slightly more dipolar fields and sweepback angles closer to zero that those of the Titan present cases. However, these differences are not statistically significant according to the t-test. A t-value of 1.69 shows that there is a confidence of 91% for the two means to be statistically different. This does not meet our criterion of statistical significance which requires a confidence over 95%. In Figure 2, the sweepback angles have several positive values, especially for the Titan absent cases. Some of these cases have small positive B_r and positive B_{phi}, which indicates they may be slightly above the current sheet and the plasma is still sub-corotating. Others have negative B_r but negative B_{phi}, which indicates they are below the current sheet and the positive sweepback angles in these cases could be caused by the solar wind pushing the magnetopause towards Saturn so that the plasma in the inward-moving flux tubes speeds up and becomes temporarily super-corotating.

[15] For SLT from 1200 to 1500, there are only Titan present cases but four out of eight cases have positive sweepback angles. Only the one with the largest sweepback angle is due to a small positive B_r, while the others are due to positive B_{phi}. It is possible that the largest one is because it is above the current sheet and the other three are caused by solar wind compressing the magnetosphere. However, the Titan present cases in 0900 to 1200 SLT do not have so many positive sweepback angles. We need more Titan-present cases and Titan-absent cases to understand this difference and whether it is caused by Titan.

[16] For SLT from 1500 to 2400, there are very few cases so it is hard to compare them. *Bertucci et al.* [2009] has more samples in these SLT because their study region has larger ranges in the radial and vertical directions. They found that the stretching and sweepback angles are more variable at these SLTs. When Cassini obtains more measurements in these SLT in the future, there will be a large sample size to study and compare the statistical properties of the Titan present and absent cases in the afternoon to midnight SLT.

4. Concluding Remarks

[17] In summary, by comparing the magnetic field and plasma measurements near Titan's orbit with the moon present and absent, we find that Titan does have large-scale effects on its plasma environment. The main points are as follows.

[18] (1) Near noon SLT, Titan's orbit is more frequently inside the magnetosheath with Titan absent than with Titan present. The in-magnetosheath probabilities are 10.37% and 3.37% respectively (for SLT from 0900 to 1500). We suggest that this indicates that Titan reduces the compressibility of the local plasma possibly by anchoring the magnetic field to the Titan ionosphere, by mass loading the flux tube or from fast neutrals crossing field lines and transferring momentum from the subsonic magnetospheric plasma as seen at Io [*Russell et al.*, 2001].

[19] (2) Generally, the field is more dipolar near noon SLT and more stretched near midnight, but the sweepback angles do not have a strong SLT variation as do the stretching angles. The stretching angles and sweepback angles for the Titan present and absent cases are not significantly different. However, near 0200 SLT, there is one extraordinary case with a more dipolar field and a positive sweepback angle, statistically different from the mean values for 0000 to 0300 SLT. It appears to be due to Cassini being on a recently reconnected Saturnward moving flux tube. Titan's presence near midnight may facilitate tail reconnection by mass-loading the flux tube, making it even more stretched or easier to break. This conclusion agrees with previous studies of Titan enhancing the reconnection rate near midnight [*Menietti et al.*, 2007; *Russell et al.*, 2008].

[20] **Acknowledgments.** This work was supported by the National Aeronautics and Space Administration through contract JPL1236948 administered by the Jet Propulsion Laboratory. The authors want to thanks Chris Arridge, Geraint Jones and Abi Rymer for useful discussions.

References

Arridge, C. S., N. Achilleos, M. K. Dougherty, K. K. Khurana, and C. T. Russell (2006), Modeling the size and shape of Saturn's magnetopause with variable dynamic pressure, *J. Geophys. Res.*, *111*, A11227, doi:10.1029/2005JA011574.

Bertucci, C., et al. (2009), The variability of Titan's magnetic environment, *Planet. Space Sci.*, doi:10.1016/j.pss.2009.02.009, in press.

Dougherty, M. K., et al. (2004), The Cassini magnetic field investigation, *Space Sci. Rev.*, *114*, 331–383, doi:10.1007/s11214-004-1432-2.

Menietti, J. D., B. Groene, T. F. Averkamp, G. B. Hospodarsky, W. S. Kurth, D. A. Gurnett, and P. Zarka (2007), Influence of Saturnian moons on Saturn kilometric radiation, *J. Geophys. Res.*, *112*, A08211, doi:10.1029/2007JA012331.

Russell, C. T., Y. L. Wang, X. Blanco-Cano, and R. J. Strangeway (2001), The Io mass-loading disk: Constraints provided by the ion cyclotron wave observations, *J. Geophys. Res.*, *106*, 26,233–26,242, doi:10.1029/2001JA900029.

Russell, C. T., C. M. Jackman, H. Y. Wei, C. Bertucci, and M. K. Dougherty (2008), Titan's influence on Saturnian substorm occurrence, *Geophys. Res. Lett.*, *35*, L12105, doi:10.1029/2008GL034080.

Rymer, A. M., H. T. Smith, A. Wellbrock, A. J. Coates, and D. T. Young (2009), Discrete classification and electron energy spectra of Titan's varied magnetospheric environment, *Geophys. Res. Lett.*, *36*, L15109, doi:10.1029/2009GL039427.

Welch, B. L. (1938), The significance of the difference between two means when the population variances are unequal, *Biometrika*, *29*, 350–362.

Young, D. T., et al. (2004), Cassini Plasma Spectrometer investigation, *Space Sci. Rev.*, *114*, 1–112, doi:10.1007/s11214-004-1406-4.

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