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Key Points:
- Density properties of the ionosphere diminish with decreasing latitude
- This diminution starts over the main rings and is maximum inside the D ring
- This confirms transport of water from the tings

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The ionosphere of Saturn as observed by the Cassini Radio Science System

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Abstract Fifty-nine ionsopheric radio occultation observations of the vertical electron density profile in the Saturn ionosphere have been made since the Cassini spacecraft was inserted in orbit around Saturn in 2004. Significant orbit to orbit variations were observed, but the general trend noted in earlier orbits, namely, increasing electron densities with increasing latitude was reconfirmed and bolstered with this extended data base. This trend is likely to be due to some combination of increasing ionization rates and decreasing water influx with latitude.

1. Introduction

Our current, very limited, understanding of the ionosphere of Saturn is based on a few electron density profiles from Pioneer, Voyager, and Cassini radio occultation profiles. Saturn electrostatic discharge (SED) observations from Voyager and Cassini missions provide an indication of the diurnal variation of the peak electron densities [cf. *Moore et al*., 2012]. A number of models of the structure and composition of the ionosphere have been published to date, which have provided some context to these observations [e.g., *Majeed and McConnell*, 1996; *Moses and Bass*, 2000; *Moore et al*., 2010]. In this paper we present the results from 59 ionospheric radio occultations obtained by the Cassini Radio Science System (RSS) from orbital insertion to 2013. These observations include the ones presented by *Nagy et al*. [2006] and *Kliore et al*. [2009]. There are only a very few occultation opportunities left (only one more is planned before the end of the Cassini mission in 2017), so it seems appropriate to present all the available results and discuss what was learned so far about Saturn's ionosphere from these occultations. Radio occultation observations of ionospheric electron densities is a well-established and classical technique, which has been widely used during the last 50 years [cf. *Kliore et al*., 1980; *Lindal et al*., 1985]. *Nagy et al*. [2006] described in quite some detail the Cassini data acquisition and analysis approach being used, so it will not be repeated and discussed here.

2. Results

Table 1 lists the 59 ionospheric radio occultations obtained since the Saturn orbit insertion of the Cassini spacecraft. The N and X symbols next to the orbit number denote entry and exit observations. The second column, listed as peak altitude, indicates the kronographic altitude of the electron density peak relative to the 1 bar pressure level in the atmosphere. Column 8 gives the Earth-Probe-Sun (EPS) angle. It is desirable that this angle be relatively large in order to keep the radio propagation path as far as possible from the solar plasma and hence keep the noise level in the signal low. The "ionopause height" given in column 9 is the altitude at which the electron density drops to below 200 cm^{-3}. Column 10 gives the total vertical electron content (TEC). Finally, column 11 shows if the ionosphere probed was magnetically connected to a specific ring or gap.

Figure 1a shows the peak electron densities as a function of absolute latitude of all the 59 occultations. As can be seen, there is a great deal of variability from orbit to orbit, but the general trend of increasing peak densities with increasing latitudes is quite clear. Another way to see the general trend is shown in Figure 1b, which shows the vertical total electron content (TEC) for each observation, and Figure 1c, in which the observed behavior of the ionopause height with latitude is displayed. Finally, Figure 1d shows the altitude of the main peak, which also drops toward the equatorial latitudes. Figure 2 shows a surface fit of all electron density data as a function of latitude and altitude. This plot was generated by fitting all data points from all of the observations (some 60,000 in number) with a bivariate fifth degree Chebyshev polynomial surface using Systat Table Curve 3-D software. This plot also clearly shows the depletion trend toward the equator.

Table 1. Summary of Cassini Radio Science Results on the Saturn Ionosphere

Orbit ID	Year and Day	Peak Altitude (km)	Peak Electron Density (cm^{-3})	SZA (deg)	Latitude (deg)	L Shell (RS)	EPS Angle (deg)	Ionopause Height (km)	TEC (cm^{-2})	Ring Connection
7N	2005 123	1326.3	6693.5	84.4	−4.9	1.0074	75	6512	8.356E+11	—
7X	2005 123	2472	2215.7	95.9	−9.0	1.0251	75	4808	2.751E+11	—
8N	2005 141	1312	9469.1	85.2	−3.1	1.0029	58	6320	1.013E+12	—
8X	2005 141	1792	1339.4	95.1	−8.3	1.0213	58	5344	2.526E+11	—
9X	2005 159	1168	1688.6	93.8	−7.5	1.0173	41	4728	1.092E+11	—
10N	2005 177	1913.4	7736.1	87.7	1.6	1.0008	25	3640	6.785E+11	—
10X	2005 177	2409.6	1481.3	92.4	−6.1	1.0114	25	5232	3.628E+11	—
11X	2005 196	2528	4287.6	90.8	−4.5	1.0062	8	4096	1.121E+12	—
12N	2005 214	1379.4	10783.9	90.9	7.5	1.0173	9	3144	8.649E+11	—
12X	2005 214	1326	546.1	89.1	−2.6	1.0021	9	2160	2.993E+11	—
13X	2005 232	2921.9	925.5	87.6	−0.5	1.0001	26	5072	2.131E+11	—
14N	2005 248	1712	12606.9	93.3	−8.4	1.0218	41	3280	7.428E+11	—
28N	2006 260	1360	7965.9	93	−4.3	1.0049	36	3408	1.013E+12	—
44N	2007 130	3032	19028.2	80.4	72.0	10.4721	96	7888	2.806E+12	—
44X	2007 130	1664	757.4	95.5	3.5	1.0037	96	3400	8.343E+10	—
46N	2007 162	2274	11671.2	85.2	−4.1	1.0051	65	7888	4.823E+11	—
47X	2007 179	2637.2	12217.5	94.4	−35.4	1.5050	51	9840	1.964E+12	C
51N	2007 297	2264	2719.8	92.4	−28.4	1.2924	60	6728	9.953E+11	C
51X	2007 297	2916	9466.7	85	−37.9	1.6060	60	9136	1.428E+12	B
54N	2007 353	1456	9615.3	94.3	−14.5	1.0669	114	3160	8.662E+11	—
54X	2007 353	2382	21567.7	85.5	−65.6	5.8598	114	9952	5.073E+12	E
56X	2008 15	2178.4	18436.9	89.6	−68.9	7.7162	141	9920	2.868E+12	E
58X	2008 39	1656	20864.5	89.9	−70.6	9.0636	165	9808	3.573E+12	—
68N	2008 138	1960	8071.5	83.8	23.3	1.1855	101	6552	1.837E+12	D
68X	2008 138	2376	11098.3	90.1	−60.8	4.2016	101	11960	3.037E+12	E
70N	2008 153	2376	2733.5	83.9	37.0	1.5678	86	5144	8.707E+11	B
70X	2008 153	2346.1	10769.6	90.4	−65.1	5.6411	86	10600	1.645E+12	E
72N	2008 168	1672	4803.6	84.2	35.3	1.5013	74	7616	9.005E+11	C
72X	2008 168	2400	14289.4	90.1	−62.9	4.8188	74	9760	2.444E+12	E
73X	2008 175	2472	26192.9	89.9	−61.5	4.3921	67	7328	3.215E+12	E
75N	2008 189	1128	11635.6	85.3	30.0	1.3333	54	9392	1.275E+12	C
75X	2008 189	2184	13083.4	89.5	−57.7	3.5022	54	11336	1.797E+12	E
120N	2009 305	2328	7510.8	93.8	28.5	1.2948	43	5368	1.227E+12	C
120X	2009 305	3216	5140.5	87.6	20.8	1.1443	43	9560	1.391E+12	D
121X	2009 324	2796.1	7090.8	87.1	25.2	1.2214	86	6056	5.138E+11	D
122N	2009 343	2460	5145.2	95.6	41.4	1.7773	80	6648	6.857E+11	B
122X	2009 343	1810.6	16447.2	86.9	29.7	1.3253	80	5488	2.175E+12	C
123X	2009 360	2076.8	4984.6	84.8	1.5	1.0007	96	5256	4.491E+11	—
125N	2010 26	1477.6	5994.6	94.5	−1.4	1.0006	127	8024	2.178E+12	—
125X	2010 26	1888	1540.4	85.5	2.1	1.0013	127	5432	9.119E+11	—
130N	2010 117	1594	10034.2	86.3	17.2	1.0958	145	9920	1.128E+12	—
130X	2010 117	1498.7	24059.9	92.7	12.7	1.0508	145	8344	7.776E+11	—
133N	2020 170	1835.4	6772.3	84.6	−0.4	1.0000	97	4640	5.960E+11	—
133X	2020 170	1309.3	752.3	95.4	0.3	1.0000	96	1464	2.074E+11	—
135N	2010 205	1685.9	14783.4	86	−13.5	1.0576	64	4856	6.295E+11	—
137N	2010 245	1640	6069.6	87.6	3.8	1.0044	27	4112	6.920E+11	—
151N	2011 213	1624	5571.8	86.5	48.3	2.2597	69	8024	9.328E+11	A
151X	2011 213	2288	6003.3	93.5	40.3	1.7192	69	6176	8.879E+11	B
167N	2012 157	1492.7	7161.7	85.6	4.7	1.0068	133	3888	9.214E+11	—
170N	2012 225	2248	6594.0	89.7	−60.4	4.0987	70	4648	1.803E+12	E
170X	2012 225	1384.9	330.4	95	−1.0	1.0003	70	1896	1.833E+10	—
171N	2012 246	2048	6061.0	88.4	−44.6	1.9725	50	6446	1.546E+12	C. Div.
178X	2013 5	2368	4876.5	89.2	56.1	3.2146	70	6360	2.265E+12	E
180X	2013 31	2344	21488.9	90.4	66.1	6.0924	96	6456	3.774E+12	E
182X	2013 56	2256.8	24509.0	89.5	61.0	4.2546	121	6480	4.526E+12	E
189N	2013 130	2328	10294.0	90.8	−71.9	10.3606	168	6056	2.262E+12	—
190N	2013 140	2584	6246.8	91.3	−70.5	8.9745	159	8552	6.058E+12	—
191N	2013 151	2512	4940.6	93	−44.6	1.9725	149	3640	1.015E+12	C. Div.
191X	2013 151	1314.8	561.1	93.2	−10.1	1.0317	149	1968	2.960E+10	—

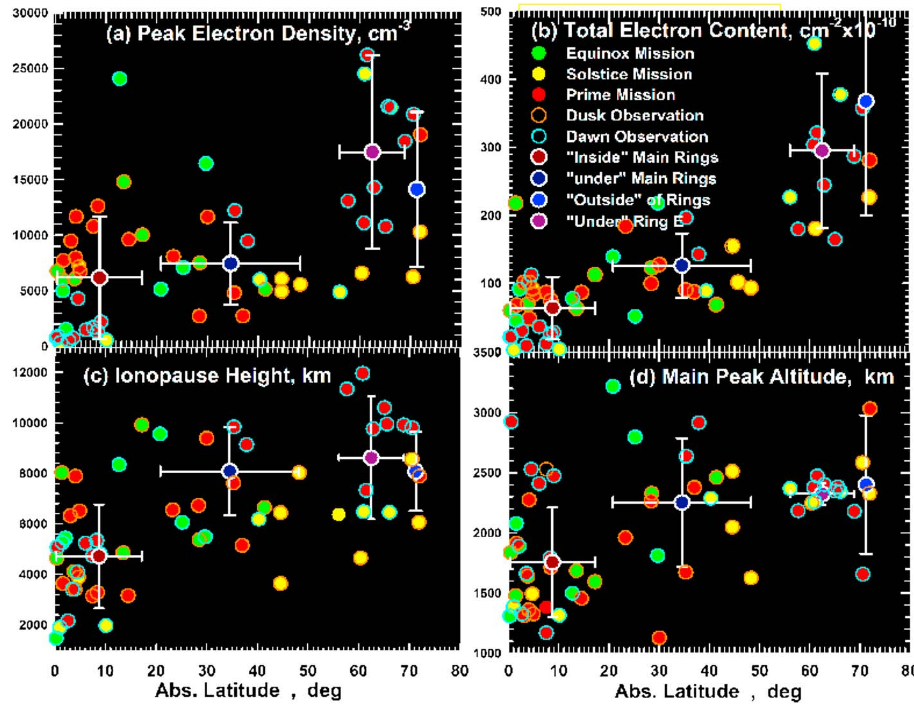

Figure 1. The variation of the (a) peak electron density, (b) the total vertical electron content (TEC), (c) "ionopause" height, and (d) the altitude of the main peak as a function of the absolute latitude. In all panels, the symbols represent the averages of data from the four regions relative to the magnetic connection to the rings, namely, from left to right, "inside" the D ring (dark red), "under" the A, B, C, and D rings (dark blue), "under" the E ring (dark pink), and "beyond" the E ring (blue). The vertical error bars show the standard deviation of the average, while the horizontal ones simply demarcate the latitude range of data for each category.

3. Discussion

The more limited database, presented in *Nagy et al*. [2006] and *Kliore et al*. [2009], already indicated that the observed electron densities increase, in general, with latitude. This general trend is reconfirmed here where we present the results from 59 ionospheric occultations. The original idea to explain this trend was that ionization sources (e.g., plasma precipitation) may be increasing with latitude and thus be responsible for this observed variation [*Kliore et al*., 2009]. This explanation may still hold, but there are no relevant observations to confirm or reject this idea. However, an alternate and/or supplemental explanation may be that ion loss processes are greater near the equator. Water is very efficient in turning the long-lived atomic ion, H^+, into a molecular ion that can rapidly dissociatively recombine and thus lead to lower electron densities [*Connerney and Waite*, 1984]. *Moore et al*. [2010] successfully fitted the observed latitude variation from the early Cassini results by assuming an ad hoc, but not unreasonable, water influx into the ionosphere, which peaked at the equator at about 5×10^6 cm^{-2} s^{-1} and decreased with latitude. There are no

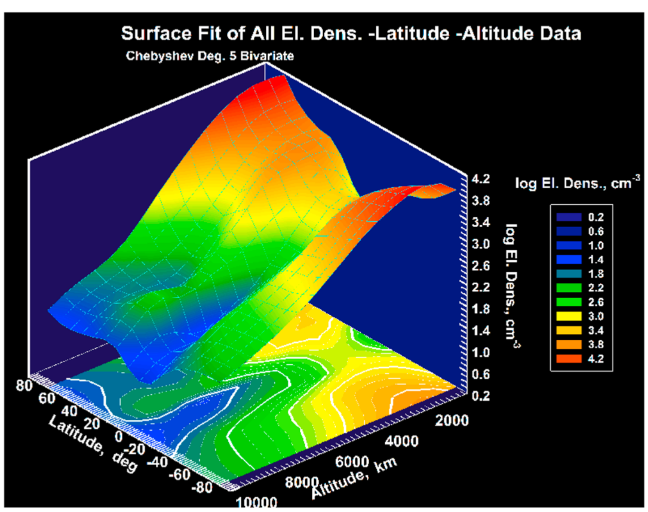

Figure 2. Surface plot of $\log_{10}$ electron density versus altitude and latitude derived from all Cassini RSS Saturn occultation data (approximately 60,000 data points). The upper plot is a 3-D representation of electron density, and the lower graphic is the corresponding contour plot.

relevant published results on H_2O fluxes at Saturn to confirm or contradict these assumptions, but there are indications from the Cassini Composite Infrared Spectrometer (CIRS) data [*Bjoraker et al*., 2010] that while the observed stratospheric water column densities are variable, they are, in general, greater at low than at high latitudes, thus providing some credibility to this possibility. More recent water observations [*Bjoraker*, 2013] show that these stratospheric water column densities were increased by about a factor of 2.5 after the December 2010 storm near 40°N and stayed elevated for over a year. Unfortunately, the number of occultations available to examine these implications is extremely limited and has very little statistical strength. Nevertheless, we find that the average of the peak electron densities measured during the entry and exit occultations on 10 August 2011 (orbit 151) is 7690 cm^{-3}, while the next three middle to high northern latitude occultations (178X, 180X, and 182X), which took place between 4 January and 25 February 2013, well after the observed increases in water abated, showed an increased peak electron density of 26,818 cm^{-3}. If one is allowed to draw any conclusions from such a meager database, it does indicate that the enhanced water densities are associated with decreased electron densities.

O'Donoghue et al. [2013] used the W. M. Keck Telescope to observe two bright H_3^+ rotational-vibrational infrared emission lines of Saturn. There are no measurements on the ion composition in the ionosphere, but the model results [cf. *Nagy et al*., 2009] indicate that H_3^+ is expected to dominate up to the electron density peak. Thus, these H_3^+ observations should provide a good indication of the ionospheric electron densities below the peak. As mentioned above, the presence of water, originating from the rings, is likely to lead decreased electron densities, or in other words, the observations by *O'Donoghue et al*. [2013] should show increased intensities at locations where the ionosphere is magnetically connected to a gap between the rings. Indeed, these measurements indicate some features along this line. Thus, we tried to see if we could find a similar signature in our data. As indicated in Table 1, there were only two occultations corresponding to the Cassini Division, and the average observed peak electron densities of these two falls well within the spread in the 16 occultations corresponding to rings A, B, C, and D, which had highly variable peak densities. Given that our data base is not sufficiently large, especially in the regions of interest, and/or the fact that all our observations are near-terminator ones, it is still somewhat surprising that our measurements, while not contradicting, do not show support for the "ring rain" hypothesis of *O'Donoghue et al*. [2013].

In summary, here we presented the results from all but one ionospheric occultation from Cassini; because of open-ring interference, there will most likely be only one other low-latitude occultation in 2016. The data presented here reconfirmed previous indications of increasing electron densities with latitude. We suggest that this trend may be a combination of increasing ionization and decreasing water inflow with latitude. The only insight we have on the ion composition comes from the models mentioned earlier, which, in general, predict that H_3^+ is the dominant ion below the peak, and H^+ is the dominant one above the peak. There have been no self-consistent calculations of the plasma temperature for the main ionospheric region. There is some chance that the Cassini Ion Neutral Mass Spectrometer Instrument will be able to provide certain clues about these unknowns during some of the final close proximal orbits. Also, we still have no answer to the large diurnal variations in the peak electron densities indicated by the SED measurements [*Moore et al*., 2012]. No model has been put forward that can account for these variations. Thus, while we obtained some insights into the nature of Saturn's ionosphere, a great deal is still unknown.

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References

Bjoraker, G. (2013), Oxygen compounds in Saturn's stratosphere during the 2010 Northern storm, AGU Meeting, San Francisco, Calif.

Bjoraker, G., R. K. Achterberg, A. A. Simon-Miller, and D. E. Jennings (2010), Cassini CIRS observations of water vapor in Saturn's stratosphere, EPSC Meeting, Rome, Italy.

Connerney, J. A. P., and J. H. Waite (1984), New model of Saturn's ionosphere with an influx of water from the rings, *Nature*, *312*, 136–138.

Kliore, A. J., I. R. Patel, G. F. Lindal, D. N. Sweetnam, H. B. Hotz, J. H. Waite Jr., and T. R. McDonough (1980), Structure of the ionosphere and atmosphere of Saturn from Pioneer 11 Saturn radio occultation, *J. Geophys. Res.*, *85*, 5857–5870, doi:10.1029/JA085iA11p05857.

Kliore, A. J., A. F. Nagy, E. A. Marouf, A. Anabtawi, E. Barbinis, D. U. Fleischman, and D. S. Kahan (2009), Midlatitude and high-latitude electron density profiles in the ionosphere of Saturn obtained by Cassini radio occultation observations, *J. Geophys. Res.*, *114*, A04315, doi:10.1029/2008JA013900.

Lindal, G. F., D. N. Sweetnam, and V. R. Eshleman (1985), The atmosphere of Saturn: An analysis of the Voyager radio occultation measurements, *Astron. J.*, *90*, 1136–1146.

Majeed, T., and J. McConnell (1996), Voyager electron density measurements on Saturn: Analysis with a time dependent ionospheric model, *J. Geophys. Res.*, *101*, 7589–7598, doi:10.1029/96JE00115.

Moore, L., I. Mueller-Wodarg, M. Galand, A. Kliore, and M. Mendillo (2010), Latitudinal variations in Saturn's ionosphere: Cassini measurements and model comparisons, *J. Geophys. Res.*, *115*, A11317, doi:10.1029/2010JA015692.

Moore, L., G. Fischer, I. Müller-Wodarg, M. Galand, and M. Mendillo (2012), Diurnal variation of electron density in Saturn's ionosphere: Model comparisons with Saturn Electrostatic Discharges (SED) observations, *Icarus*, *221*, 508–516, doi:10.1016/j.icarus.2012.08.010.

Moses, J., and S. Bass (2000), The effects of external material on the chemistry and structure of Saturn's ionosphere, *J. Geophys. Res.*, *105*, 7013–7052, doi:10.1029/1999JE001172.

Nagy, A. F., et al. (2006), First results from the ionospheric radio occultations of Saturn by the Cassini spacecraft, *J. Geophys. Res.*, *111*, A06310, doi:10.1029/2005JA011519.

Nagy, A. F., A. J. Kliore, M. Mendillo, S. Miller, L. Moore, J. I. Moses, I. Müller-Wodarg, and D. Shemansky (2009), Upper atmosphere and ionosphere of Saturn, in *Saturn From Cassini-Huygens*, edited by M. K. Dougherty, L. W. Esposito, and S. M. Krimigis, pp. 181–201, Springer, Houten, Netherlands.

O'Donoghue, J., T. S. Stallard, H. Melin, G. H. Jones, S. W. Cowley, S. Miller, K. H. Baines, and J. S. Blake (2013), The domination of Saturn's low-latitude ionosphere by ring "rain", *Nature*, *496*, 193–195, doi:10.1038/nature12049.