June 2014 INMS White Paper

CASSINI INMS EXPLORATION OF THE UPPER ATMOSPHERE AND IONOSPHERE OF SATURN AND RINGS

Introduction

The proximal orbits represent a unique opportunity for the *in situ* exploration of the upper atmosphere and ionosphere of Saturn and of the ring atmosphere - ionosphere. The Cassini INMS and other instruments (e.g., RPWS/LP) will measure plasma and neutral densities, temperatures, and composition in a very interesting region of the thermosphere, exosphere and ionosphere linking Saturn's atmosphere with the rings. Our current knowledge of the atmospheres and ionospheres of the outer planets has entirely, with one exception, been derived from remote observations made across the electromagnetic spectrum from radio waves to x-rays. The only in situ data has been the atmospheric profiles returned by the Galileo probe at Jupiter's equatorial region (e.g., *Seiff et al.,* 1997). *In situ* atmospheric data returned from Cassini will provide a different perspective on atmospheric phenomena and allow the remote observations to be put into context (i.e., "ground-truth").

Brief Overview of the Ring Atmosphere and Ionosphere of Saturn

As the Cassini Orbiter passed over the rings, at a distance of a few thousand km above the A-ring, during SOI in July 2004, instruments detected a ring "ionosphere". Both CAPS and INMS detected H^+, O^+, and O_2^+ ions, which evidently had traveled up from the rings to the spacecraft (*Tokar et al*., 2005; *Waite et al*., 2005). This plasma indicated the existence of a ring atmosphere associated with water-related species (particularly O_2) photolytically produced from icy ring particles (*Ip*, 1995). The ring ionosphere forms when this neutral "atmosphere" is ionized (*Luhmann et al*., 2006). Oxygen-containing ions formed in the ring atmosphere according to models populate the local magnetosphere and, depending on where they are formed, can either precipitate back onto the ring particles, scatter by charge exchange into the magnetosphere beyond the main rings (*Martens et al*., 2008), or precipitate directly into Saturn's atmosphere (*Luhmann et al*., 2006; *Bouhram et al*., 2006; *Tseng et al*., 2010; *Johnson et al*., 2006). It has also been suggested that ring ion precipitation into Saturn's atmosphere is hemispherically asymmetric due to the axial offset of Saturn's dipole field (*Luhmann et al*., 2006). This could have consequences that also show up as differences in the two sides of the ring atmosphere/ionosphere.

The rings also interfere with the formation of a classical exosphere and plasmasphere at Saturn (e.g. *Luhmann and Walker*, 1981). According to models they absorb some of Saturn's ballistic exospheric neutral particles and prevent the occupation of Saturn-orbiting particles. In addition they absorb trapped plasmaspheric electrons and ions undergoing interhemispheric flow. Spatial and dynamical evidence and plasma physical phenomena related to these 'holes' carved out of the related distribution functions (and perhaps occupied instead with ring-originating counterparts) may be observable during the proximal or F-ring orbital phases of Cassini. The consequences may include the introduction of anomalous processes including enhanced diffusion or wave generation that affect the inner magnetosphere as a whole and are yet to be investigated.

During the proximal orbits Cassini explores the regions near the rings, and between the rings and Saturn, allowing *in situ* measurements to be made that promise to greatly improve our understanding of the rings and their interaction with Saturn. Some of the questions that need answering include:

- What is the neutral and ion composition of the ring atmosphere and ionosphere at different locations? (The relative abundances of O_2 and H_2O give insight into the photolytic processes generating the gas from the ice particles.)
- What are the fluxes of neutral and ionized species along the magnetic field lines linking the rings to Saturn and how does this vary with latitude (i.e., ring location)? How much of this precipitation of water products from the rings reach Saturn's upper atmosphere?
- How important are the rings as a source of material for Saturn's magnetosphere (as opposed to Enceladus or Titan for example)? What is the ultimate fate of this ring material, for example in determining the composition of the plasma interacting with Enceladus?

Brief Overview of the Saturn's Upper Atmosphere and Ionosphere

The chapter, "Upper Atmosphere and Ionosphere of Saturn" by *Nagy et al (2009)*, provides a good review of this topic, including information gathered by the Cassini mission up to 2009. The exospheric temperature, determined by ultraviolet stellar occultation measurement made by the Cassini UVIS instrument (and earlier Voyager data) vary from ~360 K to ~540 K with lower temperatures at lower latitudes (*Koskinen et al* 2013). The high temperatures in the Saturn thermosphere are not understood. Models predict a thermospheric temperature rise of tens of kelvins rather than the hundreds of kelvins observed (*Mueller-Wodarg et al*. 2006). The latitudinal temperature gradient revealed in the UVIS occultation data (*Koskinen et al.* 2013) suggest an energy source in the polar regions; however, meridional transport of energy is inhibited by the Coriolis effect and models based on auroral heating processes are unable to explain the equatorial temperatures (*Smith et al.* 2007, *Muller-Wodarg et al.* 2012, *Koskinen et al.* 2013). INMS observations may lead to progress on this problem because, in addition to temperature, INMS will simultaneously constrain the ionospheric densities and the densities of minor neutral species.

The main atmospheric constituents are molecular hydrogen and helium, with atomic hydrogen becoming more important at higher altitudes. Chemically long-lived atmospheric species are well-mixed below the homopause, thought to be located near 800-900 km (pressure of 10^{-5} mbar). Below the homopause the mixing ratios of methane and other hydrocarbon species are less than ≈ .005, but nonetheless play an important role in the atmospheric photochemistry.

In situ confirmation, for low latitudes, of thermospheric temperatures and composition, up to now acquired remotely, are needed. Information from *in situ* measurements should include the scale height (i.e., neutral temperature), the relative abundances of HD and He, which provide information on the homopause altitude (and eddy diffusion coefficient) and on the D/H ratio and, with some modeling, the He to H_2 ratio in the lower atmosphere. See Figure 1.

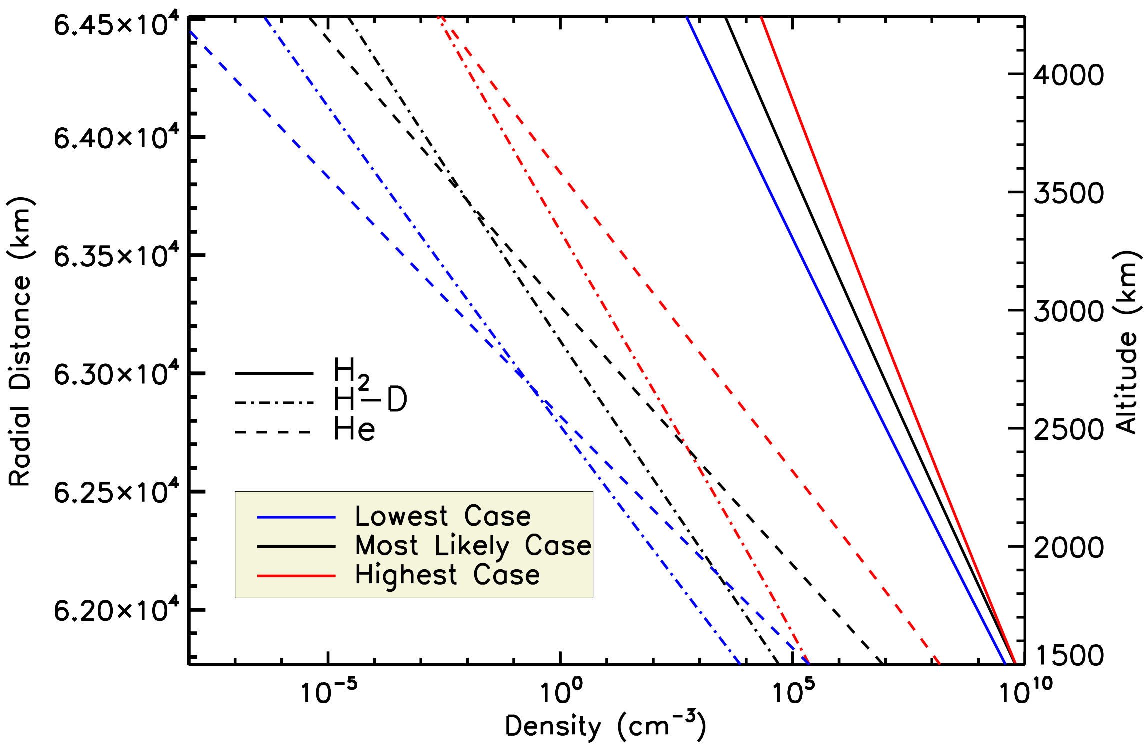

Figure 1: *Model calculations by Jared Bell for this document showing the expected range of densities for major neutrals in Saturn's upper atmosphere. Vertical (Radial) density profiles for H_2 (solid), HD (dot-dashed), and He (dashed) indicate that INMS can measure with significant signal-to-noise ratio all major constituents during much of the Proximal Orbit Campaign (POC). For reference, the INMS sensitivity allows determination of densities of > 5×10^2 cm^{-3} and the radial distance of the POC extends from 61,500 km to 64,000 km.*

Ionospheres are produced when solar radiation or precipitation of energetic particles from the external environment (e.g., magnetospheres or solar wind) ionizes the neutral atmosphere constituents. The major ion species produced at the outer planets is H_2^+ but some 10% or so H^+ is also produced. Hydrocarbon ions are also produced in the lower ionosphere (*Moore et al*., 2006), much below altitudes the Cassini spacecraft will encounter. See Figure 2. H_2^+ ions quickly react with H_2 to produce H_3^+ ions. Information on the ionospheres of the outer planets mainly comes from (1) radio occultation measurements of the electron density (i.e., which equals the sum of the densities of all ion species) made by several spacecraft, including Cassini, for Saturn (Nagy et al. 2009), (2) from H_3^+ column densities derived from Earth-based IR measurements (*Stallard et al*., 1999), and (3) from Saturn Electrostatic discharge (SED) measurements of peak electron densities made by the Cassini RPWS experiment (Fischer et al., 2011). Radio occultation observations from Pioneer, Voyager, and Cassini have all shown a factor-of-three variability in electron densities at Saturn (*Waite*, 1981; *Connerney and Waite*, 1985; *Nagy et al*., 2006, 2009), including a significant diurnal variation.

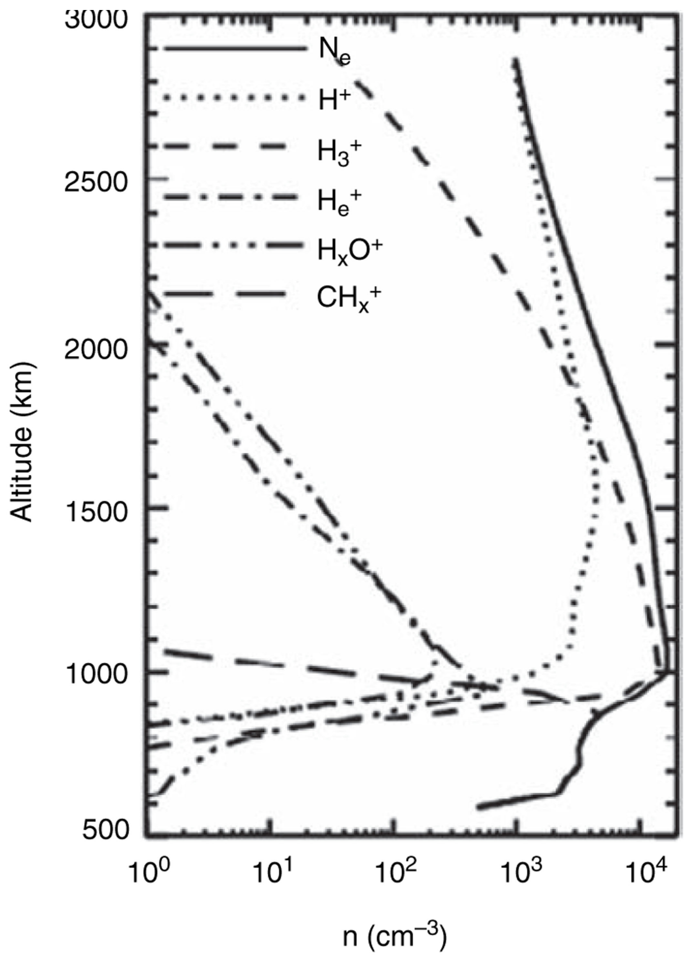

Figure 2: *Ionospheric profile from Moore et al. (2006). INMS sensitivity extends down to 10^{-2} cm^{-3}. H^+ may be difficult, but H_3^+ will provide excellent spatial and latitudinal resolution. H_2^+ and He^+ are less dense, but will be fully characterized. The measured H_2^+ density can be used to determine ionizing energy deposition in the ionosphere. High speeds would nominally limit the mass range near closest approach to ion species with mass numbers below 12 amu, however, velocity phase space sampling will put some higher-mass ions within the energy range of INMS.*

One of the key problems over many decades with theoretical models of outer planets ionospheres is that the predicted electron densities exceed the measured electron densities by large factors, due to very high H^+ densities. The models "solved" this problem by introducing loss processes for H^+ other than the very slow radiative recombination process. For example, reaction of H^+ with vibrationally excited H_2 has been a popular choice (c.f. *Nagy et al*, 2009). For Saturn, *Connerney and Waite* (1984) suggested that an influx of water from the rings could reduce the H^+ density, and thus the electron density. Proton reaction with water (or with O or OH) produces water group ions that rapidly undergo dissociative recombination. In the Cassini era this mechanism was further studied by *Moore et al*. (2006).

Recent dramatic evidence for the effects of water products from the rings on Saturn's ionosphere ("ring rain" as it was called) was published by *O'Donogohue et al.* (2013). H_3^+ observed in the IR (i.e., ≈ 4 microns) showed latitudinal patterns corresponding to ring structure (e.g., lower intensities at latitudes mapping along the magnetic field to ring gaps). This is evidence for influx of water group ions from the rings into the atmosphere. The Cassini proximal orbits are well-positioned for Cassini to make *in situ* measurements of plasma properties in the topside ionosphere and in the region between the ionosphere and rings that could help explain the processes linking the two regions.

These ionospheric issues are linked to the problems with our understanding of the thermal structure because H_3^+ is an important coolant for the thermosphere of Saturn.

Questions that should be addressed in this region using data from INMS, the RPWS/LP, MIMI, and other instruments include:

- How does the total plasma density vary with altitude and latitude (i.e, mapping to different locations at the rings)?
- How do the relative abundances of H_3^+, H_2^+, and H^+ (measured *in situ* by INMS) vary with altitude and latitude and is there correspondance to any variations in the neutral densities?
- Are these measurements consistent with remote observations and with models?
- How do the electron and neutral temperatures vary along the spacecraft track and do these variations show any correlation with ion composition?
- How do the energetic particle fluxes measured by MIMI vary along the spacecraft track and is there any correlation with the densities measured by INMS or RPWS/LP?

The Role of INMS During the Proximal Orbits.

In this section we address the role of the Cassini Ion and Neutral Mass Spectrometer during the proximal orbits. Quadrupole mass spectrometers such as INMS are designed to measure relatively cold and slow-moving neutral gas (in the closed or open source neutral modes) and ionized gas (in the open source ion mode) in planetary atmospheres. In this respect, INMS was expected to, and has, characterized the composition of the upper atmosphere and ionosphere of Titan and of the icy satellites.

But INMS has also been used to successfully make measurements of neutral and ionized gases in the Saturn system in ways far exceeding the original design expectations. For example, INMS has mapped out the neutral density and composition of the plume of Enceladus (*Waite et al.* 2009) as well as ice grain composition (*Magee et al.,* 2014). INMS in its ion mode also measured the ion composition of the plume ionosphere (mainly H_3O^+ and not H_2O^+) (*Cravens et al.*, 2009) and the A-ring ionosphere during SOI (mainly O_2^+) (*Waite et al.,* 2005). In this case, due to the limited field-of-view of the INMS in its open source mode, absolute ion densities were not obtained, but in a limited region of phase space phase space densities were determined that agreed with CAPS data. Nonetheless, the relatively high mass resolution ion composition measurements make an important contribution to our knowledge of these regions. Similarly difficult measurements of the neutral and ion composition are being made by INMS in the inner magnetosphere (*Perry et al*., 2010; *Perry et al.,* 2012).

Measurements of neutrals and low-mass ions in Saturn's exosphere are expected to be rather "standard" with the caveat that high-mass ions will not be detectable due to the high spacecraft speed with respect to the atmosphere (i.e., ≈ 34 km/) and we must be concerned about impact dissociation of the closed source neutrals. On the other hand, measurements made near the rings will be more difficult to carry out although techniques honed during SOI, Enceladus flybys, and in the inner magnetosphere will be applied.

INMS Measurement Strategy

Although the orbits of the proximal mission occur only near noon, local time, they cover several longitudes and the entire altitude range from Saturn's upper atmosphere to near the inner edge of the D-ring. Using a judicious choice of only nine orbits, INMS can sample both the neutral and ions of this region, as depicted in Figure 3. In addition, INMS observations during other orbits will expand the survey of ion velocity phase space. The INMS observing strategy includes observations that aid in sorting temporal and spatial variations.

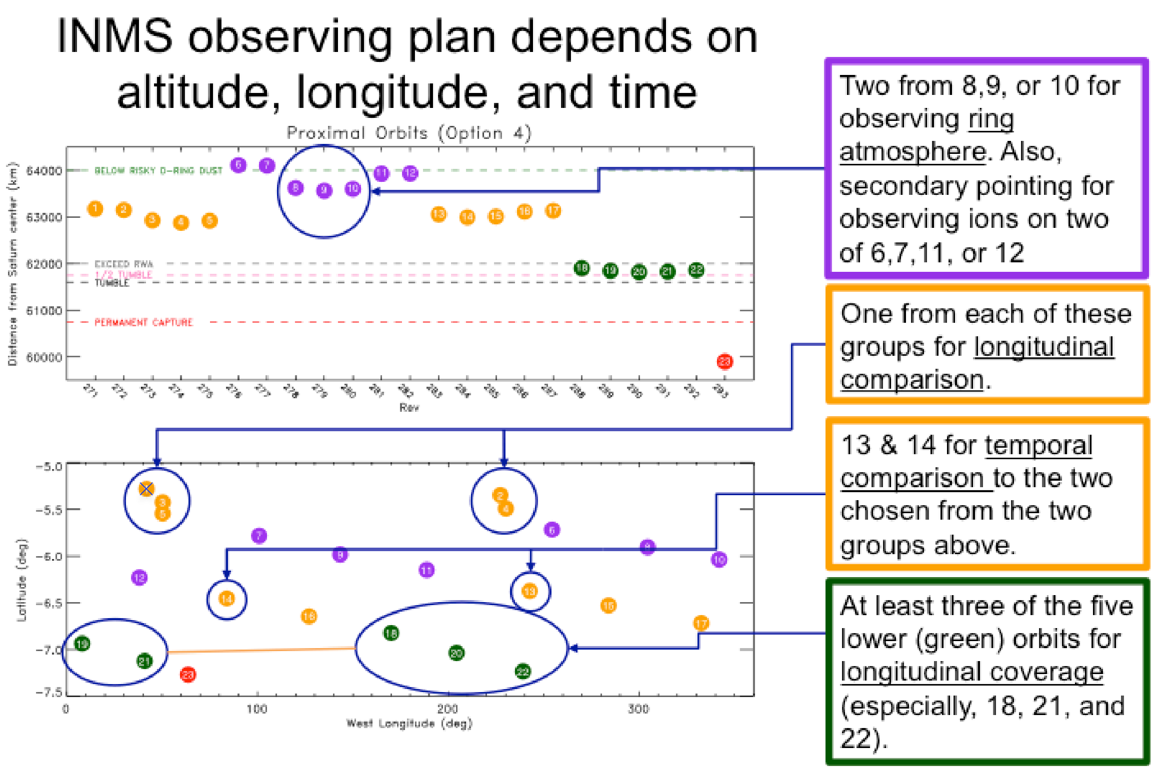

Figure 3: *The INMS observing plan was developed based on temporal, altitude, and longitudinal coverage.*

Summary

In summary, the INMS *in situ* measurements will provide the long-awaited ground-truth necessary to calibrate and verify models of the ring rain, electron density variations, and the ionospheric chemistry at Saturn. INMS will be able to measure densities of H_2, HD, and He in the neutral exospheres of Saturn and the rings, and perhaps oxygen-bearing species depending on their densities. INMS will be able to map the very important ion species, H_3^+, in Saturn's topside ionosphere with 100-km resolution along Cassini's trajectory. H_2^+ and other species are expected to have lower densities than H_3^+ (*Nagy et al.*, 2009), and will be characterized with coarser resolution. Out in the rings INMS be able to measure ions such as O_2^+ created on the surface of the rings and transported along field lines to other locations. See Figure 4.

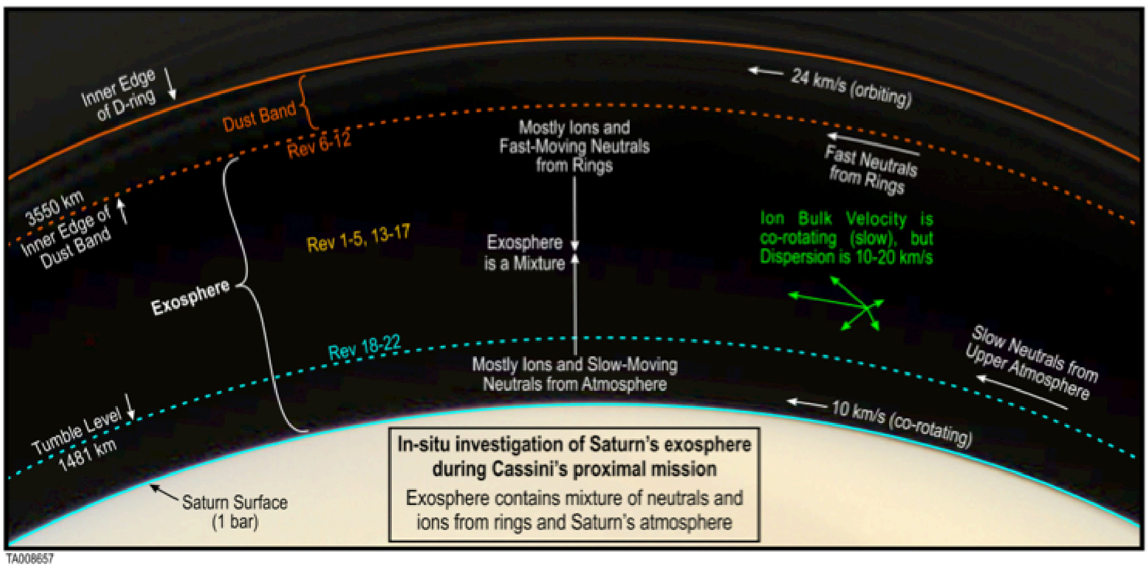

Figure 4: *Saturn's exosphere contains a mix of ions and neutrals derived from the rings and from Saturn. Comprehensive measurements of these particles reveal the processes affecting the rings, Saturn's atmosphere, and the region between.*

References

Bouhram, M, R.E. Johnson, J.-J. Berthelier, J.-M. Illiano, R.L. Tokar, D.T. Young, and F.J. Crary, "A test-particle model of the atmosphere/ionosphere system of Saturn's main rings", *Geophys. Res. Lett.*, 33, 2006.

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

Cravens, T.E., R. L. McNutt Jr., J. H. Waite Jr., I. P. Robertson, J. G. Luhmann, W. Kasprzak, and W.-H. Ip, The plume ionosphere of Enceladus as seen by the Cassini Ion and Neutral Mass Spectrometer *Geophys. Res. Lett.*, **36**, L08106, doi:10.1029/2009GL037811, 2009.

Fischer, G., D. A. Gurnett, P. Zarka, L. Moore, U. A. Dyudina, Peak electron densities in Saturn's ionosphere derived from the low-frequency cutoff of Saturn lightning, J.Geophys. Res. DOI:10.1029/2010JA016187, 2011

Ip, W.-H. Exospheric systems of Saturn's rings. Icarus 115, 295–303. 1995.

Ip, W.-H. An update on the ring exosphere and plasma disc of Saturn. Geophys. Res. Lett. 32, doi:10.1029/2004GL022217. L13204, 2005.

Johnson, R. E., J. G. Luhmann, R. L. Tokar, M. Bouhram, J. J. Berthelier, E. C. Sittler, J. F. Cooper, T. W. Hill, H. T. Smith, M. Michael, M. Liu, F. J. Crary, D.T. Young (2006) Produc- tion, ionization and redistribution of O_2 Saturn's ring atmosphere. Icarus180, 393–402.

Koskinen, T. T. et al., The density and temperature near the exobase of Saturn from UVIS solar occultation, Icarus, 226(2), 1318, 2013.

Luhmann J. G., and R. J. Walker, Model exospheres of the ringed planets *Geophys. Res. Lett.*, **8**, 107, 1981.

Luhmann, J. G., R. E. Johnson, R. L. Tokar, S. A. Ledvina, T. E. Cravens, A model of the ionosphere of Saturn's rings and its implications, *Icarus*, **181(2)**, 465-474, 2006.

Magee et al., The Enceladus Plume Composition, in preparation, 2014.

Martens, H. R., Reisenfeld, D. B., Williams, J. D., Johnson, R.E., Smith H. T., "Observations of molecular oxygen ions in Saturn's inner magnetosphere", Geophy. Res. Lett. , 2009.

Melin, H., Miller, S., Stallard, T., Trafton, L.M., Geballe, T.R., Variability in the Hþ3 emission of Saturn: Consequences for ionization rate and temperature. Icarus 186, 234–241, 2007

Melin, H. et al., 2011. Simultaneous Cassini VIMS and UVIS observations of Saturn's southern aurora: Comparing emissions from H, H2, and Hþ3 at a high spatial resolution. Geophys. Res. Lett. 38, L15203.

Moore, L., A. F. Nagy, A. J. Kliore, I. Müller-Wodarg, J. D. Richardson and M. Mendillo, Cassini radio occultations of Saturn's ionosphere: Model comparisons using a constant water flux, *Geophys. Res. Lett., 33*, L22202, 2006.

Müller-Wodarg, I. C. F., M. Mendillo, R. V. Yelle, and A. D. Aylward, A global circulation model of Saturn's thermosphere, *Icarus, 180*, 147–160, 2006.

Müller-Wodarg, I.C.F., Moore, L., Galand, M., Miller, S., Mendillo, M., Magnetosphere–

atmosphere coupling at Saturn: 1 – Response of thermosphere and ionosphere to steady state polar forcing. Icarus 221, 481– 494, 2012

Nagy, A. F., A. J. Kliore, E. Marouf, R. French, M. Flasar, N. Rappa- port, A. Anabtawi, S. W. Asmar, D. Johnston, E. Barbinis, and 2 coauthors, First results from the ionospheric radio occultations of Saturn by the Cassini spacecraft, *J. Geophys. Res., 111*, A06310, 2006.

Nagy et al., in M.K. Dougherty et al. (eds.), Saturn from Cassini-Huygens, DOI 10.1007/978-1-4020-9217-6_8,_c Springer Science+Business Media B.V. 2009.

O'Donogohue et al. The domination of Saturn's low-latitude ionosphere by ring 'rain', *Nature,* **496**, 193–195 , doi:10.1038/nature12049 (11 April 2013) .

Perry, M. E., B. Teolis, H. T. Smith, R. L. McNutt, G. Fletcher, W. Kasprzak, B. A. Magee, D. G. Mitchell, and J. H. Waite Jr., Cassini INMS observations of neutral molecules in Saturn's E-Ring, J. Geophys. Res., 115, A10206, doi:10.1029/2010JA015248, 2010.

Perry, M. E., Cravens, T.E., Mandt, K.E., Teolis, B.D., Tokar, R.L., Smith, H.T., McNutt, R.L. Jr., Waite, J.H., Jr., Cassini INMS Observations of Ions and Neutrals in Saturn's Inner Magnetosphere, AGU, SM51A-2283, 2012.

Seiff, A., et al. (1997), Thermal structure of Jupiter 's upper atmosphere derived from the Galileo probe, Science, 276, 102–104, doi:10.1126/ science.276.5309.102.

Shemansky, D.E., Liu, X., 2012. Saturn upper atmospheric structure from Cassini EUV and FUV occultations. Can. J. Phys. 90, 817–831.

Smith C. G. A., A. D. Aylward, G. H. Millwrad, S. Miller and L. Moore, An unexpected cooling effect in Saturn's upper atmosphere, *Nature, 445*, 399–401, 2007.

Stallard T., S. Miller, G. E. Ballester, D. Rego, R. D. Joseph, and L. M. Trafton, The H_3^C latitudinal profile of Saturn, Astrophys. *J. Lett., 521*, L149–L152, 1999.

Tokar, R.L., and 12 colleagues, "Cassini Observations of the Thermal Plasma in the Vicinity of Saturn's Main Rings and the F and G Rings." Geophys. Res. Lett. 32, 2005.

Tseng, W-.L., W.-H. Ip, R.E. Johnson, T.A. Cassidy, and M.K. Elrod, "The Structure and Time Variability of the Ring atmosphere and ionosphere", Icarus, 2010.

Waite, J. H., S. K. Atreya, and A. F. Nagy, The ionosphere of Sat- urn – Predictions for Pioneer 11, *Geophys. Res. Lett., 6*, 723–726, 1979.

Waite, J.H., *The ionosphere of Saturn*, PhD Thesis, Univ. of Mich., Ann Arbor, 1981.

Waite Jr., J.H., T. E. Cravens, W.-H. Ip, W. T. Kasprzak, J. G. Luhmann, R. L. McNutt, H. B. Niemann, R. B. Yelle, I. Meuller-Wodarg, S. A. Ledvina, and S. Scherer, Oxygen ions observed near Saturn's A-ring, *Science*, **307**, 1260, doi: 10.1126/science.1105734, 2005.

Waite, J. H., Jr., W. S. Lewis, B. A. Magee, J. I. Lunine, W. B. McKinnon, C. R. Glein, O. Mousis, D. T. Young, T. Brockwell, J. Westlake, M.-J. Nguyen, B. D. Teolis H. B. Niemann, R. L. McNutt, M. Perry, W.-H. Ip, Liquid water on Enceladus from observations of ammonia and 40Ar in the plume, Nature, 460, 487-490, 2009.