Charge exchange ion losses in Saturn's magnetosphere

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Abstract

While various source and loss processes have been proposed for ions in Saturn's magnetosphere, it is not yet well understood what role they play in different regions. In this study, we use a physical model of charge exchange to predict how proton and water group ion intensity profiles evolve over time and compare the results to MIMI/CHEMS measurements collected during the Cassini mission. First, we divide the CHEMS data into inbound and outbound half-orbit segments and create intensity profiles for 3-220 keV H+ and W+ ions between 5 and 15 Saturn radii. Then, using the inbound half-orbits as initial conditions, we find qualitative similarities between measured and predicted outbound intensity profiles. This result is important because it provides strong evidence that charge exchange is the dominant loss process for these species in this region. The observed rate of charge exchange also presents information on the density of Saturn's neutral torus. We suggest that data-model discrepancies in the water group ions may be an indication of a significant presence of ions with the water group mass that are multiply charged.

Background

Saturn's inner-to-middle magnetosphere is filled with neutral gases and ions.

- Neutral gases are sourced from Saturn's geologically active moon Enceladus, and are predominantly composed of H_2O, OH, and O (all labeled "W").
- Ions are created when this material is ionized (Delamere et al., 2007) and picked up by the magnetic field.
- Injection processes accelerate ions up to keV energies.
- Charge exchange is the process by which a hot ion strips an electron from a cold neutral. The newly created ion is too cold to be easily detected, so the original ion is effectively lost.

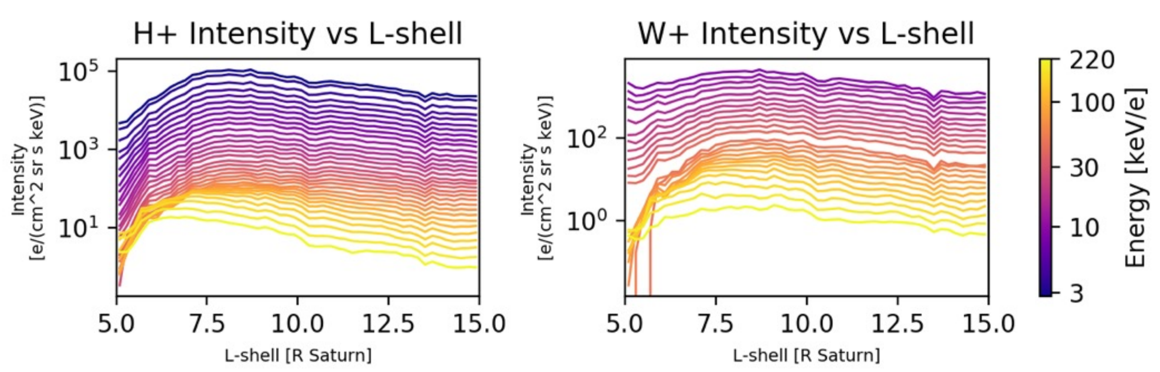

Figure 1: Radial intensity profiles of H+ and W+ ions from ~3 to 220 keV/e.

Our study focuses on the intensities of H^+ and W^+ ions, with energies from 3-220 keV, between 5 and 15 R_S.

- Figure 1 shows the mission-averaged profiles of proton and water group intensities measured by Cassini CHEMS.
- Can charge exchange explain these trends?

Methods

- We divide the CHEMS data into "half-orbit" segments and look at the data from L=5 to 15 R_S. This yields a pair of datasets per orbit: an "inbound" portion (green in Fig. 2), and consecutive "outbound" portion (purple in Fig. 2).

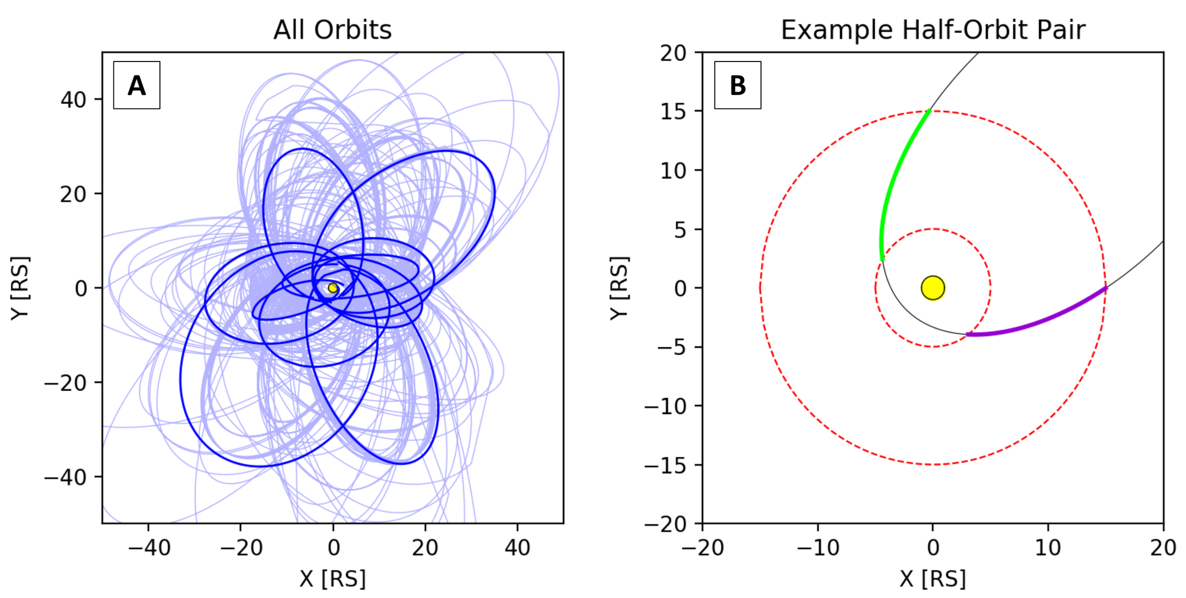

Figure 2: A) Plot of Cassini's complete mission orbital profile mapped onto the equatorial plane. B) One example of a half-orbit pair. The red dashed lines show L=5 and L=15 R_S.

- For each half-orbit, we plot measured ion intensity as a function of L-shell and energy. Examples of such plots are shown in Figure 3.
- We find that most profiles fit into 6 categories (shown in Fig 3), from which we hypothesize that charge exchange is driving losses.

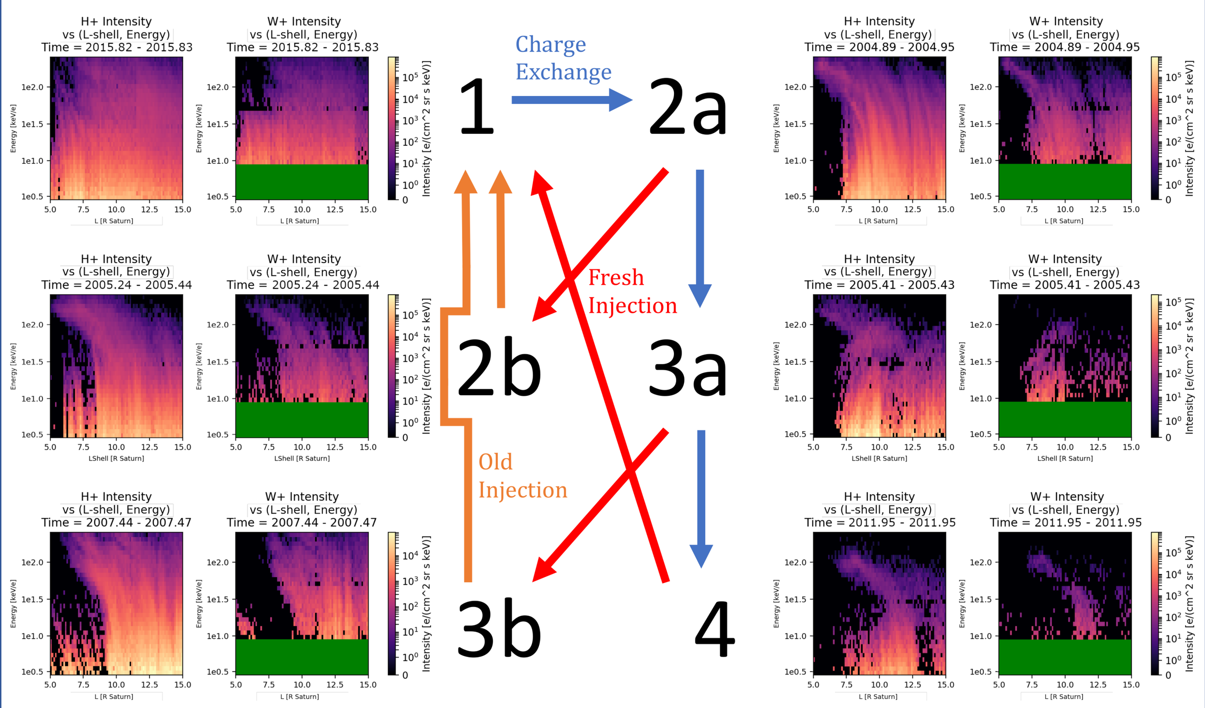

Figure 3: Separation of half-orbit profiles into 6 categories based on qualitative differences in the shapes of the H^+ and W^+ intensities.

- Based on this hypothesis, we develop a physical model of charge exchange, and feed it the inbound intensity profiles as initial conditions.
- The model uses the species' charge exchange cross sections as a function of their energies, as well as the neutral torus density as a function of radial distance.
- Studies vary within a factor of ~10 on the magnitude of this density, so we take a reasonable value and allow it to be fine tuned by a small scaling constant (See Fig. 6).
- We then compare the output of the model to the measured outbound half-orbit intensity profile.

Results

- The predicted intensity profiles match the measured outbound data to a high degree of fidelity! This evidences our claim that charge exchange is the dominant loss process for H^+ and W^+ in this region.

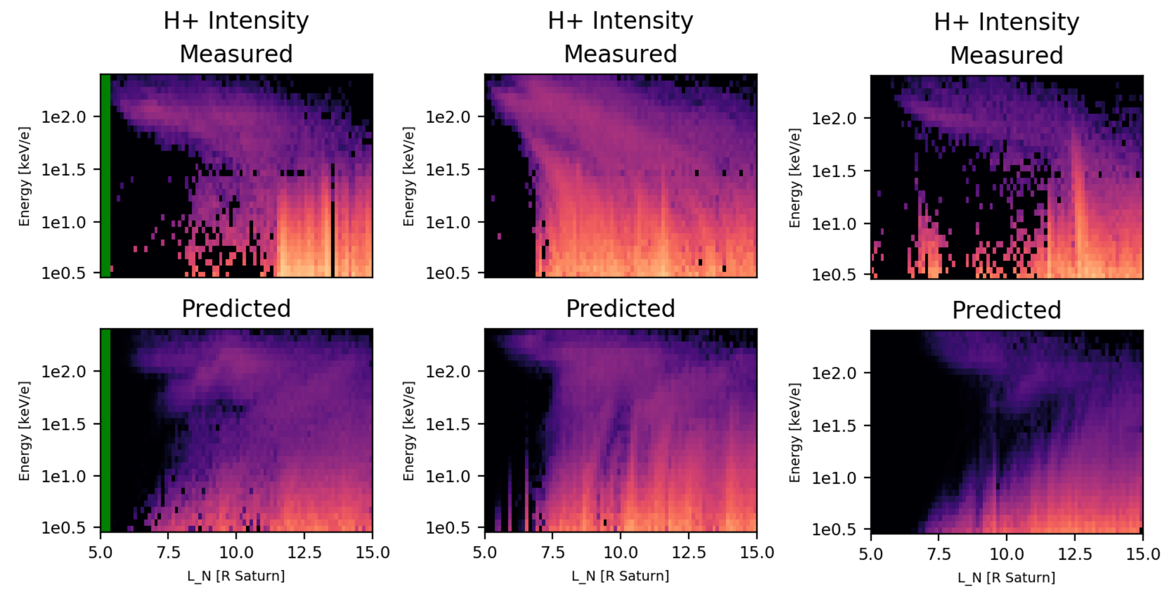

Figure 4: Comparisons of measured outbound data and predicted data for H^+ for 3 different orbits.

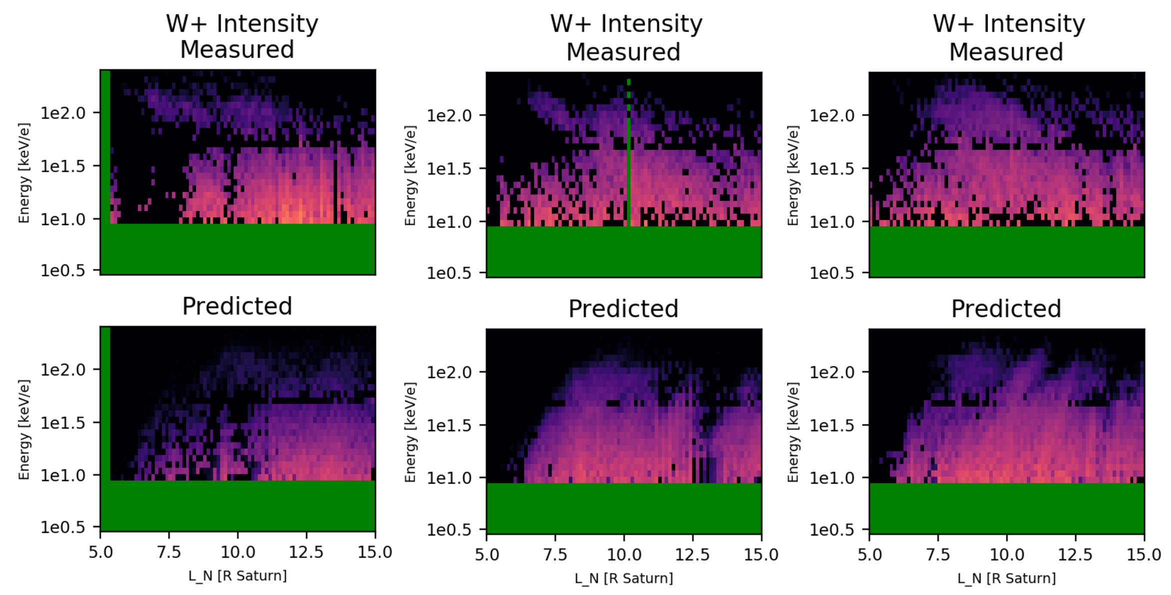

Figure 5: Comparisons of measured outbound data and predicted data for W^+ for 3 different orbits.

- We notice that the model consistently underestimates the W^+ intensity in the low L, high energy region.
- We think this may be the sign of an additional source process for W^+ ions there, and we suggest that W^{2+} charge exchanging into W^+ may be a viable candidate.

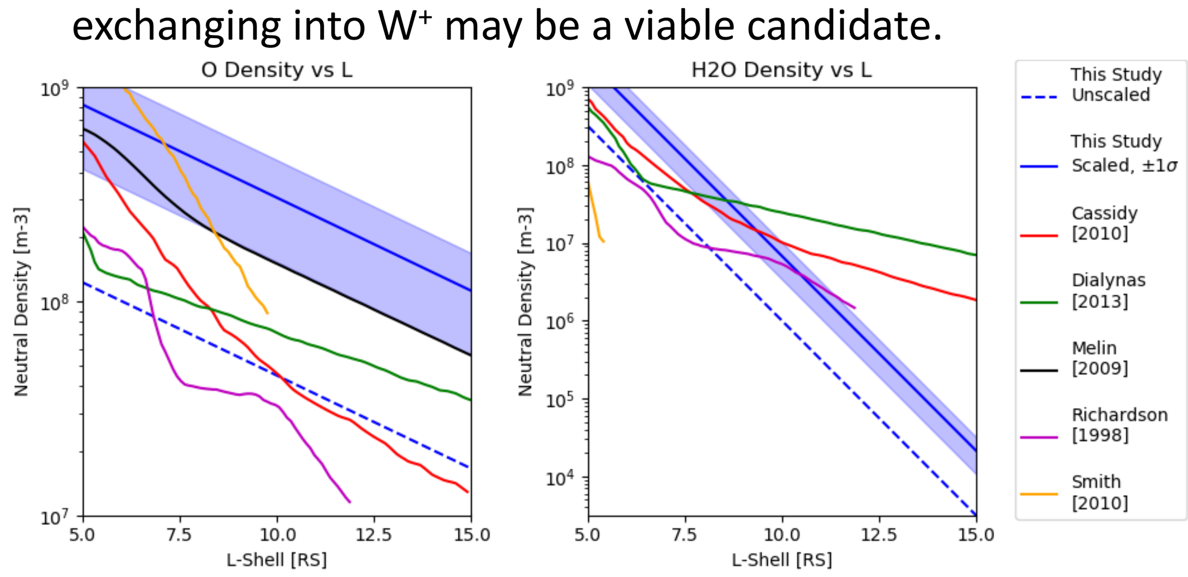

Figure 6: Neutral density radial distributions used by this study and others.

- For every modeled half-orbit pair, we allowed neutral density to be scaled by a small constant. Our original density estimate multiplied by the average of these constants is the solid blue line in Fig. 6. One standard deviation from this average is the blue shaded region.
- This suggests that Saturn's neutral torus may be denser than previous estimates.

Conclusions

1) Orbital intensity profiles of suprathermal proton and water group ions follow distinct qualitative categories, from which we hypothesize charge exchange as the driving loss process.
2) The measured losses between inbound and outbound passes shown by the H^+ intensity profiles are well replicated by the charge exchange model, suggesting that charge exchange is the dominant loss process and driver of the observed variability for 3-220 keV protons between 5 and 15 R_S.
3) By allowing a scale factor for neutral torus density to be a free parameter within the model, we show that the observed rate of charge exchange lends credence to those studies with higher neutral density estimates (Melin et al., 2009; Smith et al., 2010).
4) The measured losses between inbound and outbound passes shown by the W^+ intensity profiles are well replicated by the model in the low energy (10-50 keV/e) region, suggesting that charge exchange is the dominant loss process for 10-50 keV water group ions between 5 and 15 R_S. The model's error in the high energy, low L-shell region tends strongly toward underestimation, suggesting that there may be a gain process for water group ions there.
5) We propose that charge exchange turning W^{2+} into W^+ is a feasible gain process to explain the model's localized underestimation in water group intensity profiles. Further exploration would be needed to see if the intensity and cross sections of multiply charged water group ions could reproduce the observed gains.

References + Acknowledgements

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