Charge Exchange-Driven Soft X-Ray Emission from Outer Planetary Magnetosheaths

Space & Planetary Physics | Lancaster University

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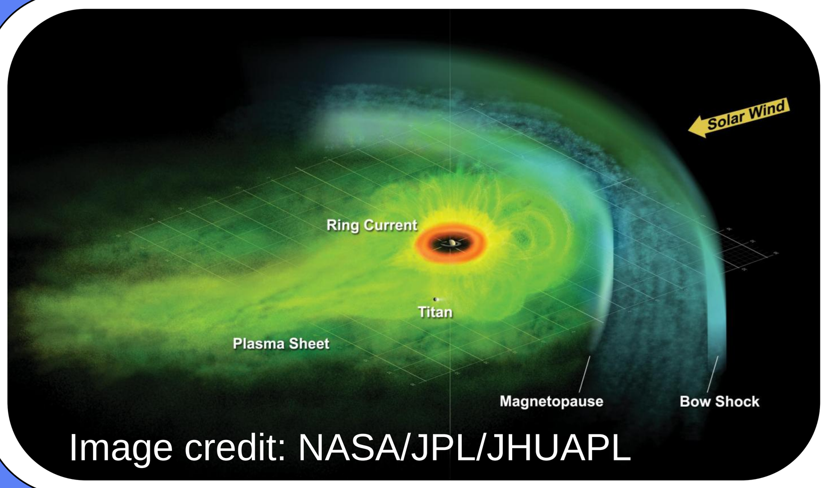

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Can X-Ray Emission be Detected from Planetary Magnetosheaths?

When magnetospheres are filled with neutral particles from moons and other sources, they can undergo charge exchange with heavily stripped solar wind ions within the magnetosheath. This leads to soft x-ray emission. Imaging the soft x-rays can give a global view of the magnetopause, bow shock and cusps. We apply a simple model to simulate charge exchange rates within the sheath, exploring volumetric emission and testing the viability of a SMILE-like SXI in imaging both the Saturnian and Uranian systems. We then explore how solar wind variations drive changes in emission structure and rate.

Volumetric Emission Rate (VER), ρ

$$\rho = \Sigma_n n_n n_q v_{\text{rel}} \sigma_{sqn} b_{sqj}$$

$$v_{\text{rel}} \sim \left(v_{\text{bulk}}^2 + v_{\text{therm}}^2\right)^{1/2}$$

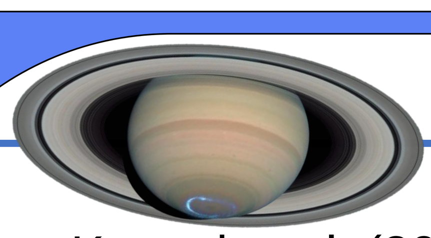
$\boldsymbol{\sigma_{sqn}}$ = Cross Section $\boldsymbol{b_{sqj}}$ = Branching Ratio $\boldsymbol{n_n}$ = Neutral Density
$\boldsymbol{n_q}$ = Ion Density $\boldsymbol{v_{\text{rel}}}$ = Collision Velocity

Saturn model assumes H-like cross sections for all species (Bodewits et al., 2007). Uranus model uses H-like and H_2O-like cross sections (Schwadron & Cravens, 2000)

Solar Wind Variations

- Saturn model: magnetosheath density fixed at 0.1 cm^{-3} (Sergis et al., 2013)
- 400 km s^{-1} and 800 km s^{-1} solar wind speed with dynamic pressure given by $P_{\text{dyn}} = n_p m_p v_{\text{SW}}^2$
- Uranus model: Tóth et al. (2004) Voyager 2 measurements of solar wind data, also scales ACE data to test how high speed and density affect emission.
- Both use O^{7+} abundances from Whittaker and Sembay (2016).

SATURN MODEL



Magnetopause Location

- Use Kanani at al. (2010) magnetopause model based on Cassini data:

$$r_{\text{MP}} = r_0 \left(\frac{2}{1+\cos\theta}\right)^K$$

a_1	10.3
a_2	0.2
a_3	0.73
a_4	0.4

r_0 magnetopause nose distance, P_{dyn} dynamic pressure,
$r_0 = a_1 P_{\text{dyn}}^{-a_2}$, $K = a_3 + a_4 P_{\text{dyn}}$

Bow Shock Surface

Semi-empirical bow shock surface from Went et al. (2011)

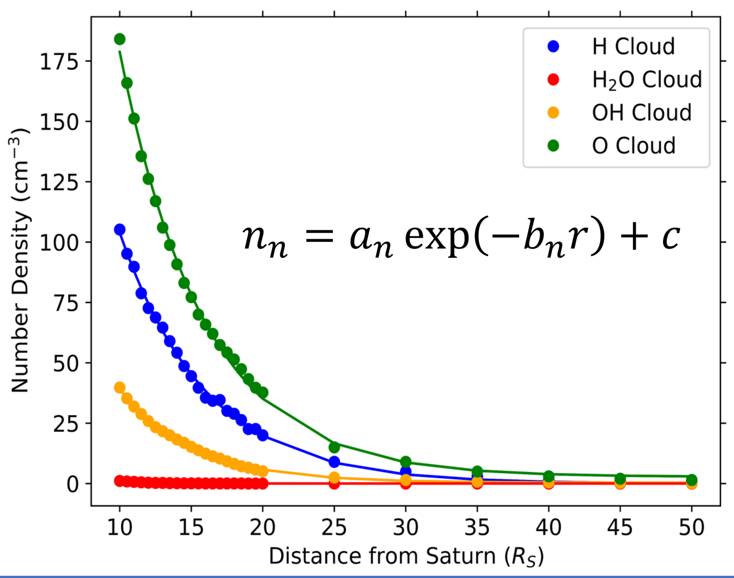
$$r_{\text{BS}}(\theta) = \frac{(1+\epsilon) c_1 P_{\text{dyn}}^{-1/c_2}}{1+\epsilon\cos\theta}$$

c_1	10.3
c_2	0.2
ϵ	0.73

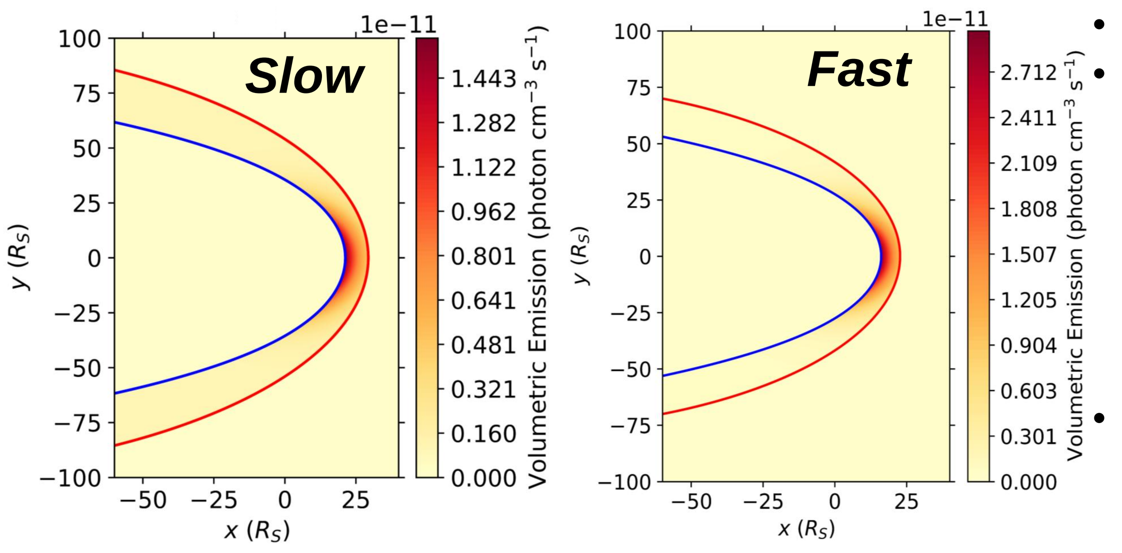
ϵ is eccentricity (bluntness) of the surface of the shock

Neutral Density

- Enceladus sources neutral H_2O
- Disassociates into OH, O, and H; forms extended clouds
- Density extrapolated from Cassini-based models (Smith & Richardson, 2021)
- Other sources of neutrals neglected



VER Results

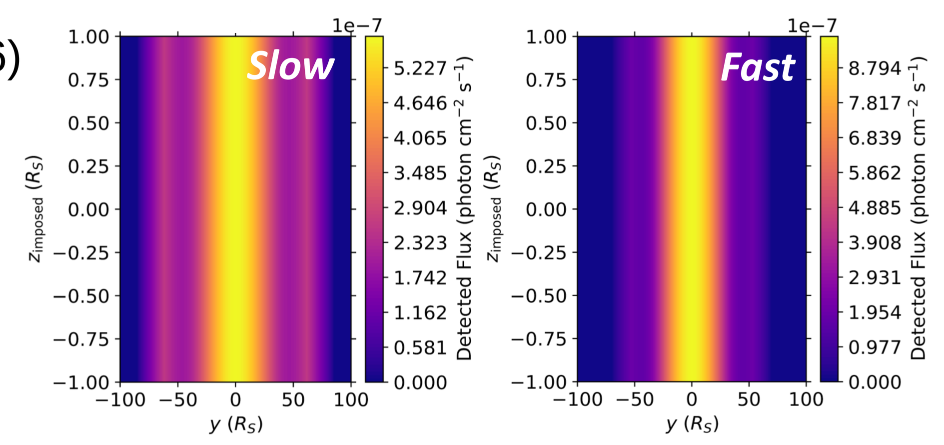


- VER ~10^{-11} photon cm^{-3} s^{-1}
- VER peaks at nose
- Fast wind VER ~twice that of slow wind
  - Compressed magnetosphere: more neutral material within sheath
  - Emission more concentrated spatially
- Neutral density variations govern VER

Imaging the Region with SMILE-like SXI

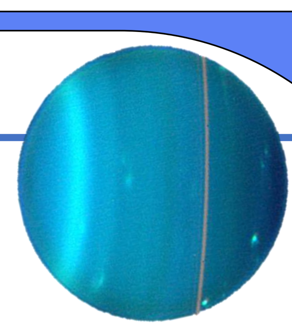
- FOV: 15.5° × 26.5° (Sembay et al., 2016)
- Different SXI configurations tested:
  1. SXI at 303 R_S – image whole sheath
  2. Move SXI to ~178 R_S - central region
  3. 'Future' SXI - double FOV
- Integration times:

Configuration	Slow (h)	Fast (h)
~303 R_S	55.3	35.2
~178 R_S	16.3	10.9
Double FOV	5.21	3.62



Closer or double FOV detector has integration times on order of one Saturnian rotation – able to probe magnetospheric dynamics!

URANUS MODEL



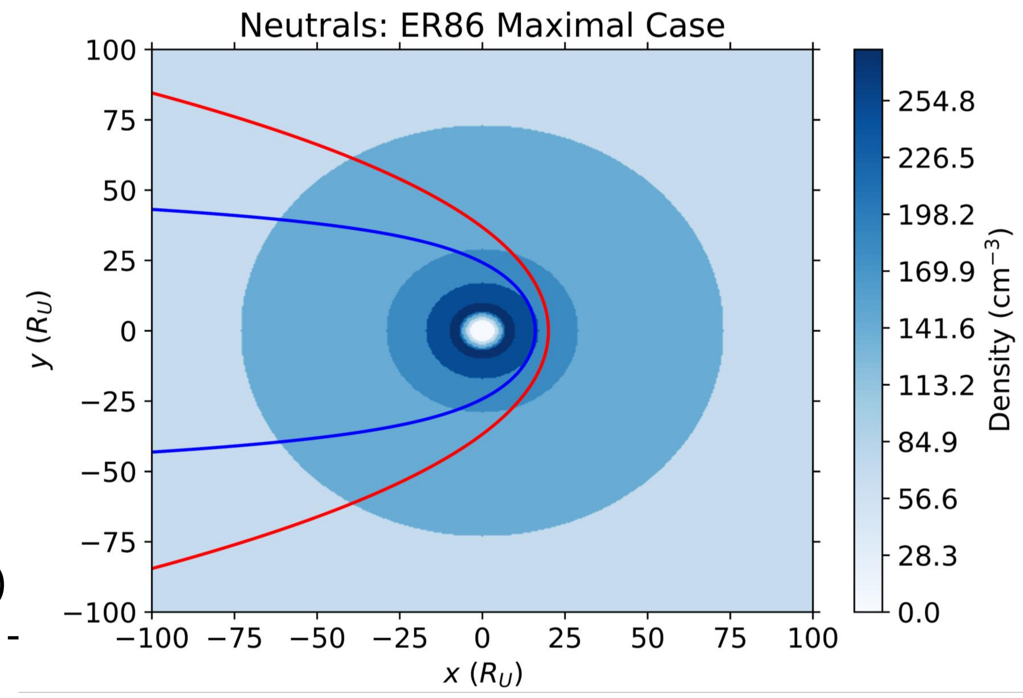
Magnetopause and Bow Shock Locations

- Impose Shue et al. (1997) magnetopause
- Standoff distance modified by P_{dyn}
- Bow shock estimated using Richardson et al. (1990) & Shue et al. (1997) model
- Very simplified representation of the complicated Uranian magnetosphere

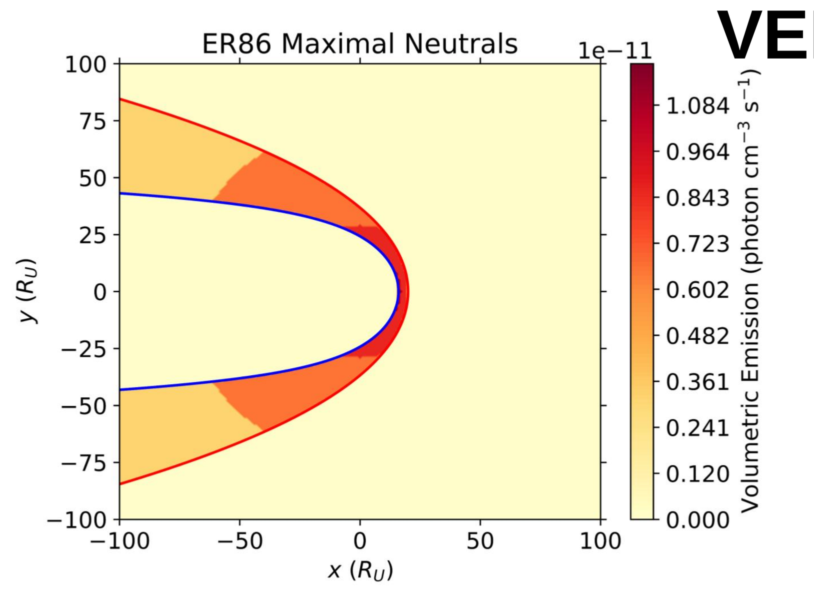
	K	R_{SS} (R_U)
MP	0.6	16
BS	0.88	20

Neutral Density

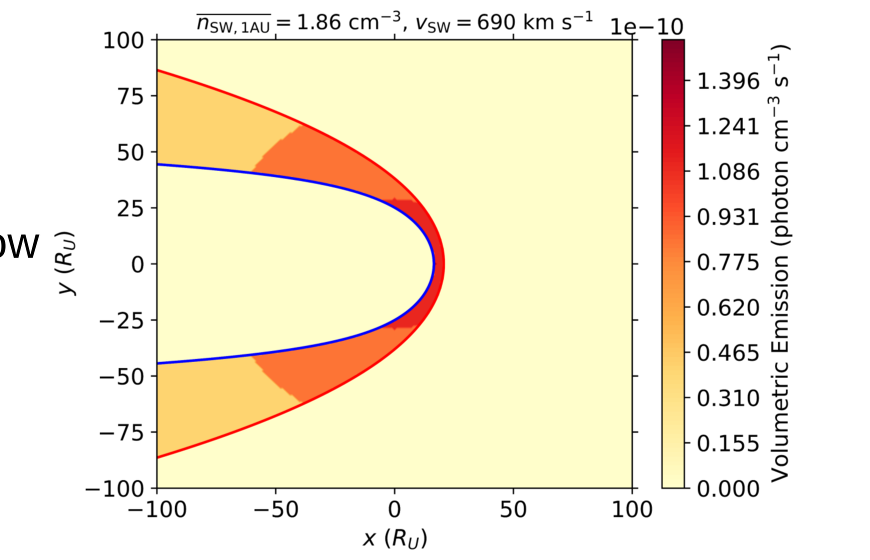
- Herbert et al. (1977) exosphere included
- Moon neutral densities not well understood
- Consider Miranda, Ariel, Umbriel, Titania, Oberon
- Discrete tori defined using models:
  - Pre-Voyager min/max limits w/ Saturn-like moons (Eviator and Richardson, 1986)
  - Post Voyager inferred neutrals from plasma data (Cheng, 1987)
- Cheng neutrals likely underestimate - Jasinksi et al. (2024)



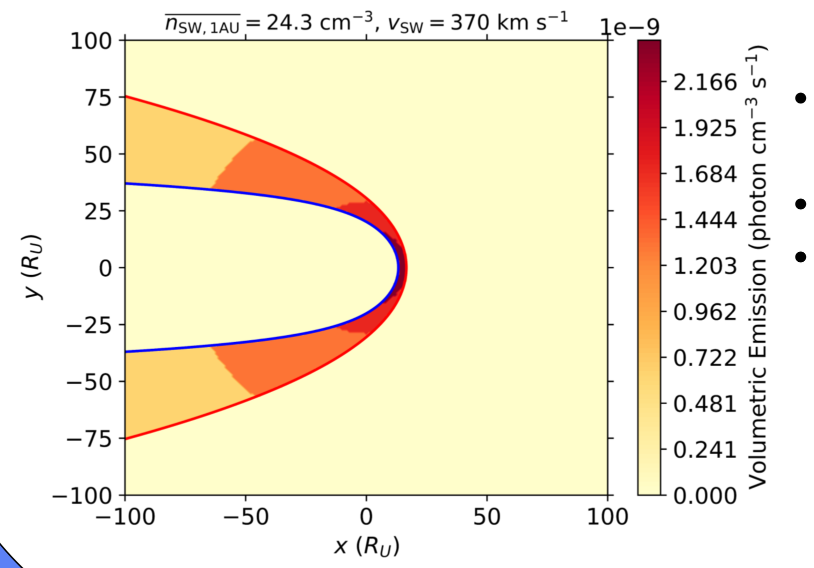
VER Results



- Same order of magnitude as Saturn when using ER86's maximal neutral densities
- Peaks at the nose
- Oxygen-like cross sections are higher than hydrogen-like so increase VER



- Scaled ACE data – high v_{SW}
- VER one order of magnitude higher than slow
- Preliminary integration time estimate of 206 s/photon
- Not as much of an effect as high solar wind density - more investigation needed



- High solar wind density significantly drives up emission
- Integration time estimate is 13.2 s/photon
- Imaging would be potentially possible within magnetospheric timescales

VER similar to or higher than Saturn - integration times well within system timescales!

Conclusions

- At both planets, significant emission region likely exists
- VER higher for fast solar wind - comparable at Saturn, one order greater at Uranus
- Modifications to current generation of SXIs required for giant-planet suitability
- At Saturn, VER likely underestimate due to non-Enceladus neutrals not included
- Uranus model is highly simplified – much more development to take place

Where Next?

- Uranus model is currently being developed into 3D
- After, a more complicated magnetopause surface, including cusps, will be developed
- Upcoming work: developing the neutral tori – scale heights, non-constant densities etc.