Seasonal and solar cycle modulations of Saturn's inner plasma disk

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Planetary Space Weather workshop

2017-10-10

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Saturn's inner plasma disk

- Enceladus (at 3.95 R_S) is the main source of new matter
  - Around 300 kg/s of dust, condensed water, water vapor, and plasma
- Studied region 2.5 to 12 Saturn radii (1 R_S = 60,268 km)
- Dominated by neutrals (H_2O, OH, O, H), density 10 to 100 times n_i
- Impact ionization, photoionization, and transport create the plasma disk
- Dominant ion species: H^+, and water group ions (O^+, OH^+, H_2O^+, and H_3O^+)

Figure 1: Saturn. Image credit: JPL, ESA, NASA.

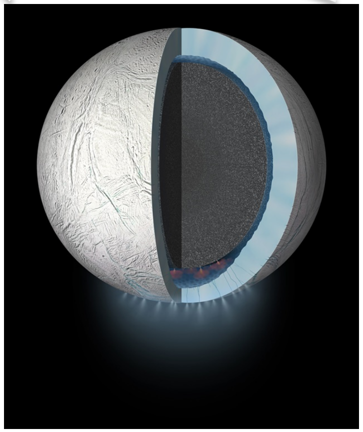


Figure 2: Illustration of the moon Enceladus, its subsurface ocean, and plume. Image credit: JPL, NASA.

The Cassini Langmuir probe

- Cassini main objectives: Study Saturn, its atmosphere, rings, moons (especially Titan), and space environment
- Saturn orbit insertion June 30, 2004
- End of mission September 15, 2017
- Spherical Langmuir probe
- Voltage sweeps (±32 V or ±4 V)
  - Usually every 10 min (occasionally every 24 s)
  - One sweep gives 512 current measurements and takes <0.5 s

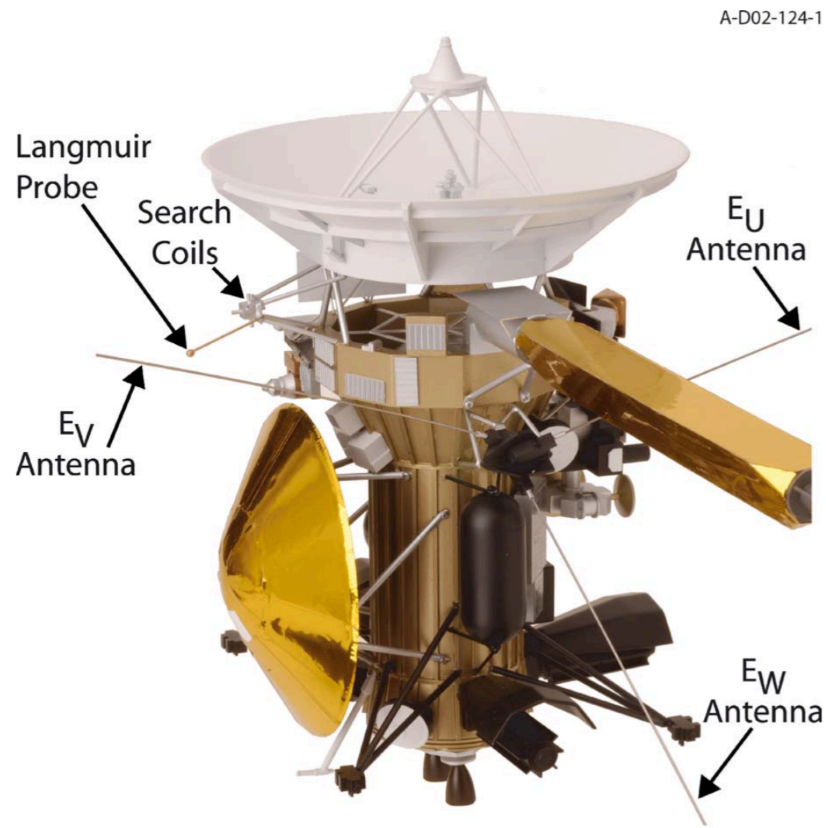


Figure 3: Cassini and the Langmuir probe. Image from Gurnett et al., 2004.

Analysis method

- Ion current (red dashed-dotted line), use <-5 V to avoid electron current (green lines)
  - We fit to $I\_ = b + mU_{bias}$
  - Relate m and b to Fahleson's equations to derive n_i and v_i

$$I_i \approx I_{i0}\left(1 - \frac{q_i(U_1 + U_{bias})}{\frac{m_i v_i^2}{2} + k_B T_i}\right)$$

$$I_{i0} \approx -A_{LP} n_i q_i \sqrt{\frac{v_i^2}{16} + \frac{k_B T_i}{2\pi m_i}}$$

(Fahleson, 1974)

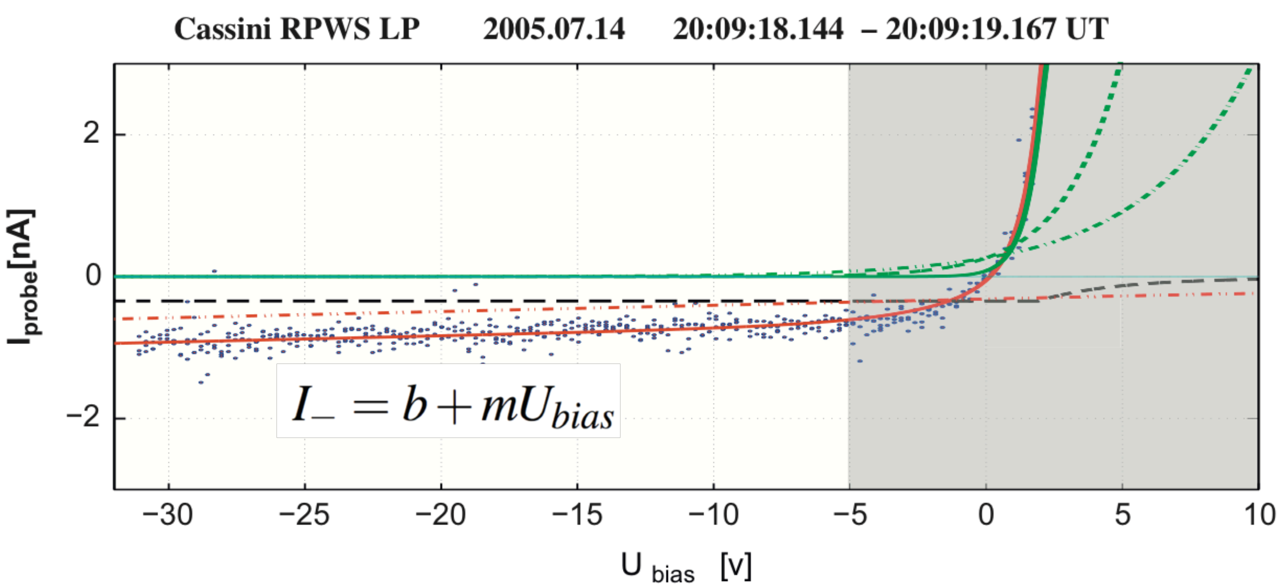


Figure 4. Current-voltage characteristics of a sweep from orbit 11. I_ (red line) are fitted to the LP measurements (blue dots).

A_{LP} – area of the Langmuir probe
n_i – ion number density
q_i – ion charge
v_i – ion velocity relative to the collector
k_B – Boltzmann constant
T_i – ion temperature
m_i – ion mass
U_{bias} – bias voltage to the probe
U_1 – floating potential (the spacecraft potential measured at the probe)

Ion densities

- All LP ion densities measured in between orbit 3 (2005-02-01) and 237 (2016-06-29)
- Plasma disk densities > 20 cm^{-3} in between 2.7 and 8.8 R_S, and about ± 1 R_S in z-direction

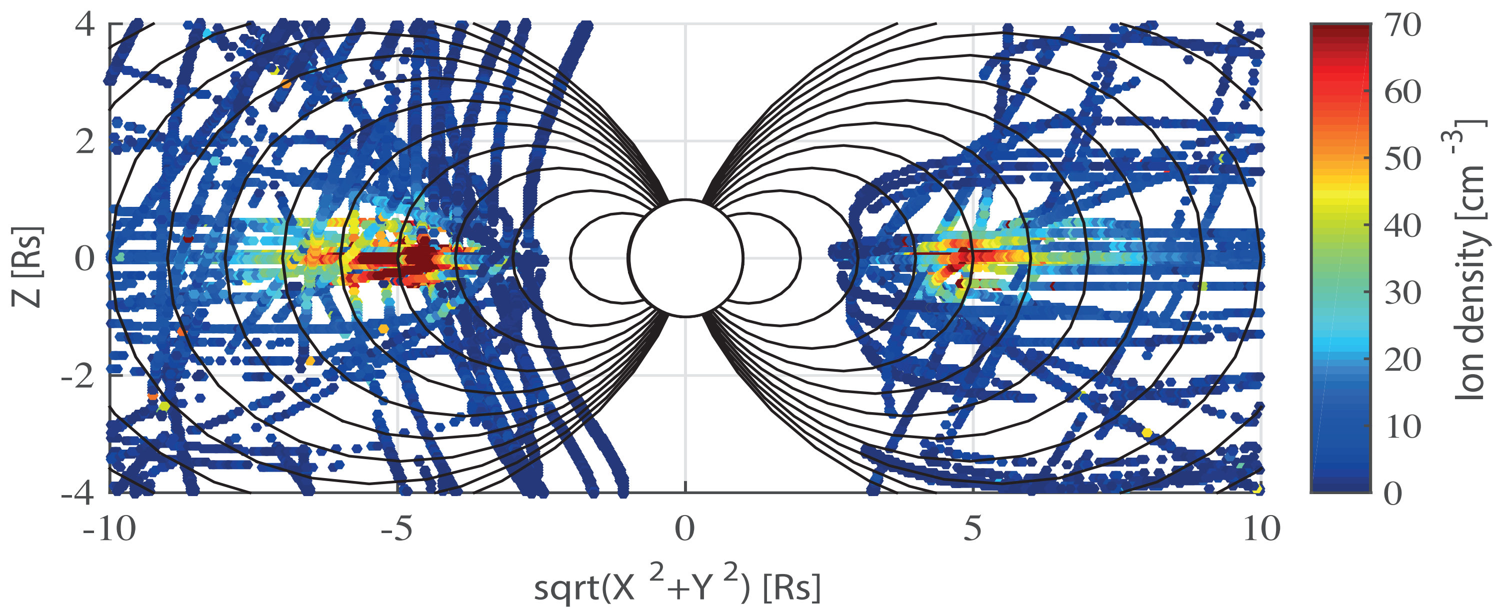


Figure 5: Ion densities derived from Langmuir probe measurements, showing the extension of the inner plasma disk.

Ion densities

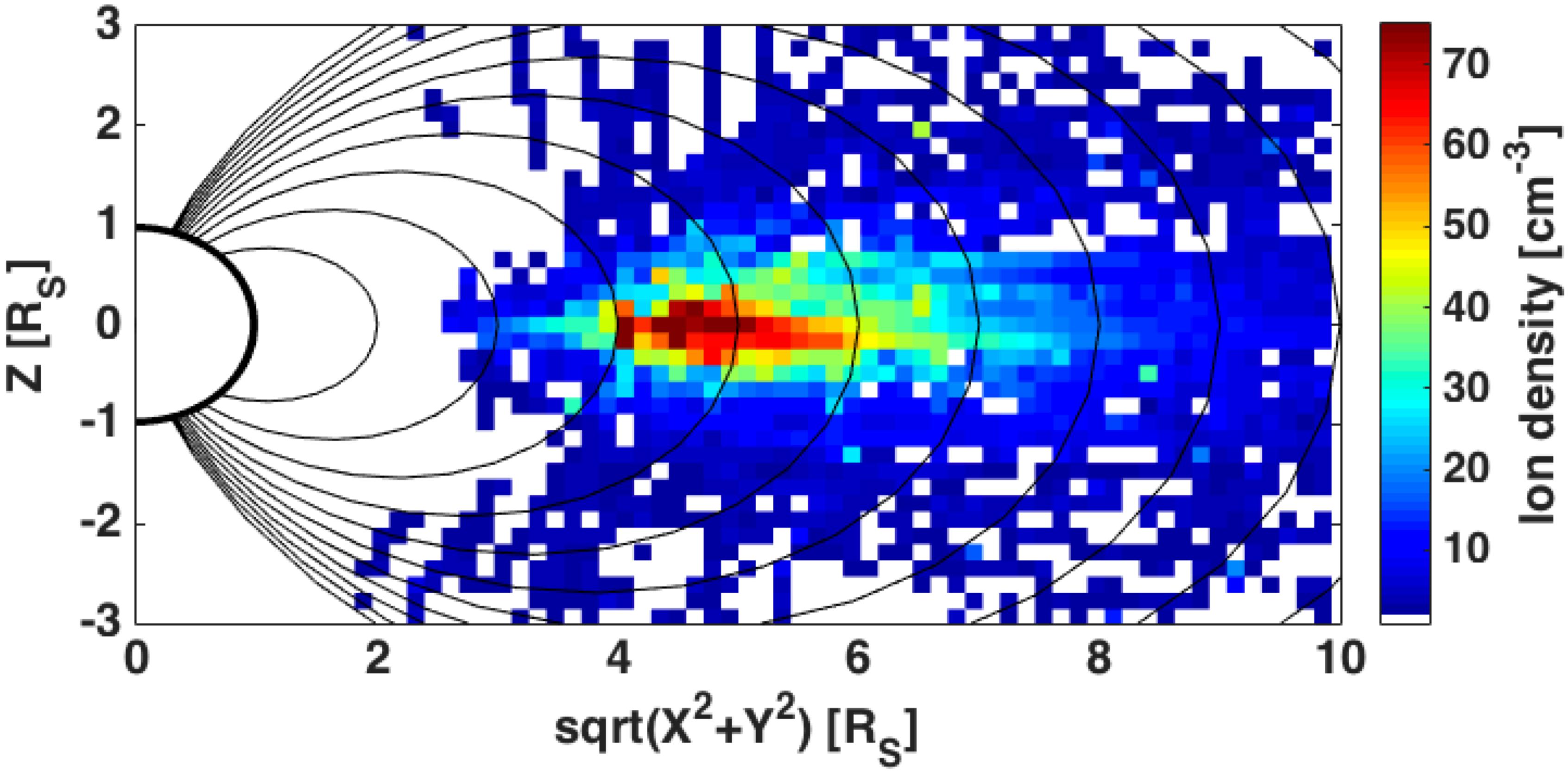
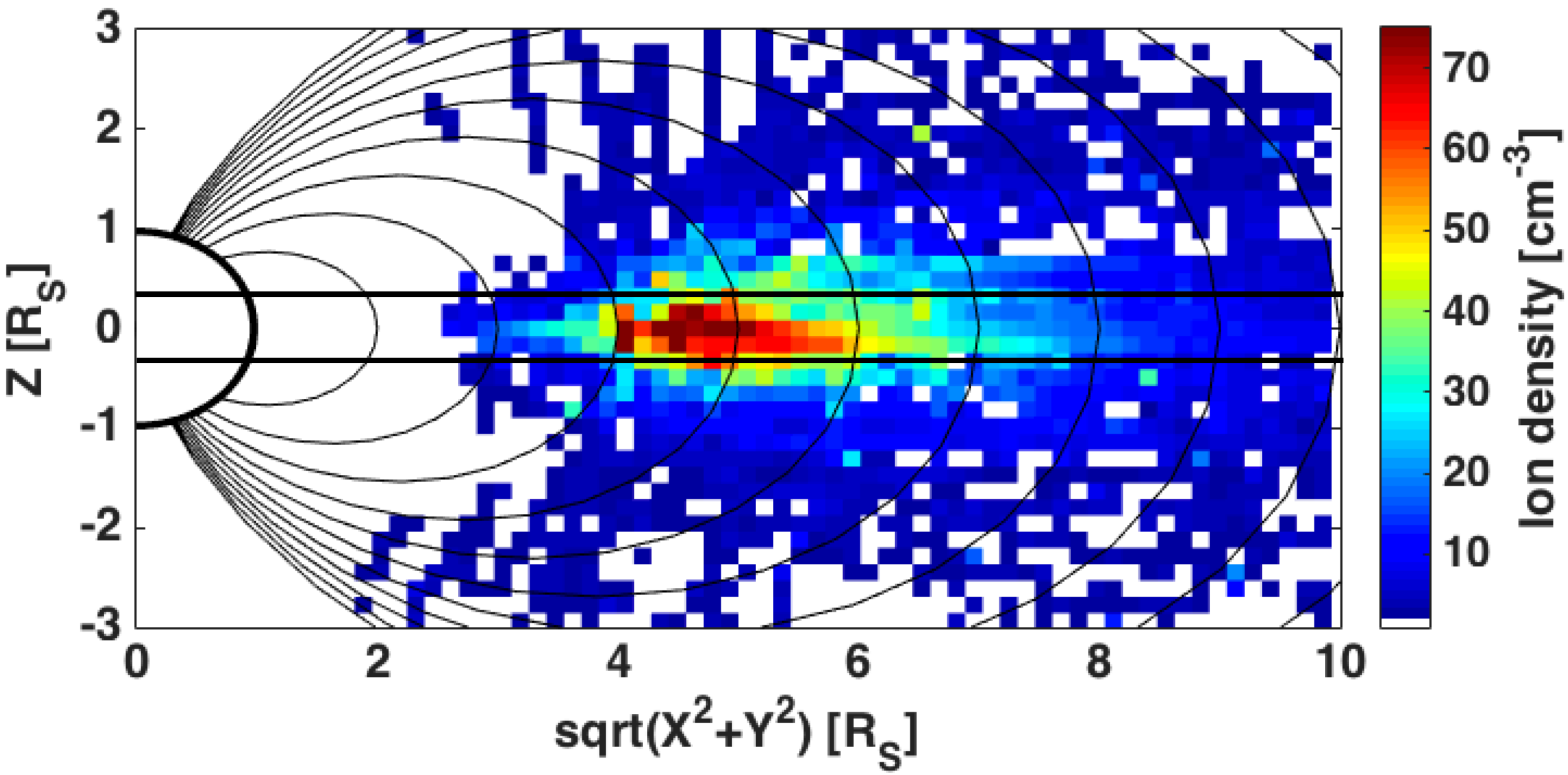


Figure 6. Average of ion density vs. distance from Saturn, magnetic L shells (black lines) 2 to 11. Bin size 0.15 in r and z.

Ion densities



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Equatorial ion densities

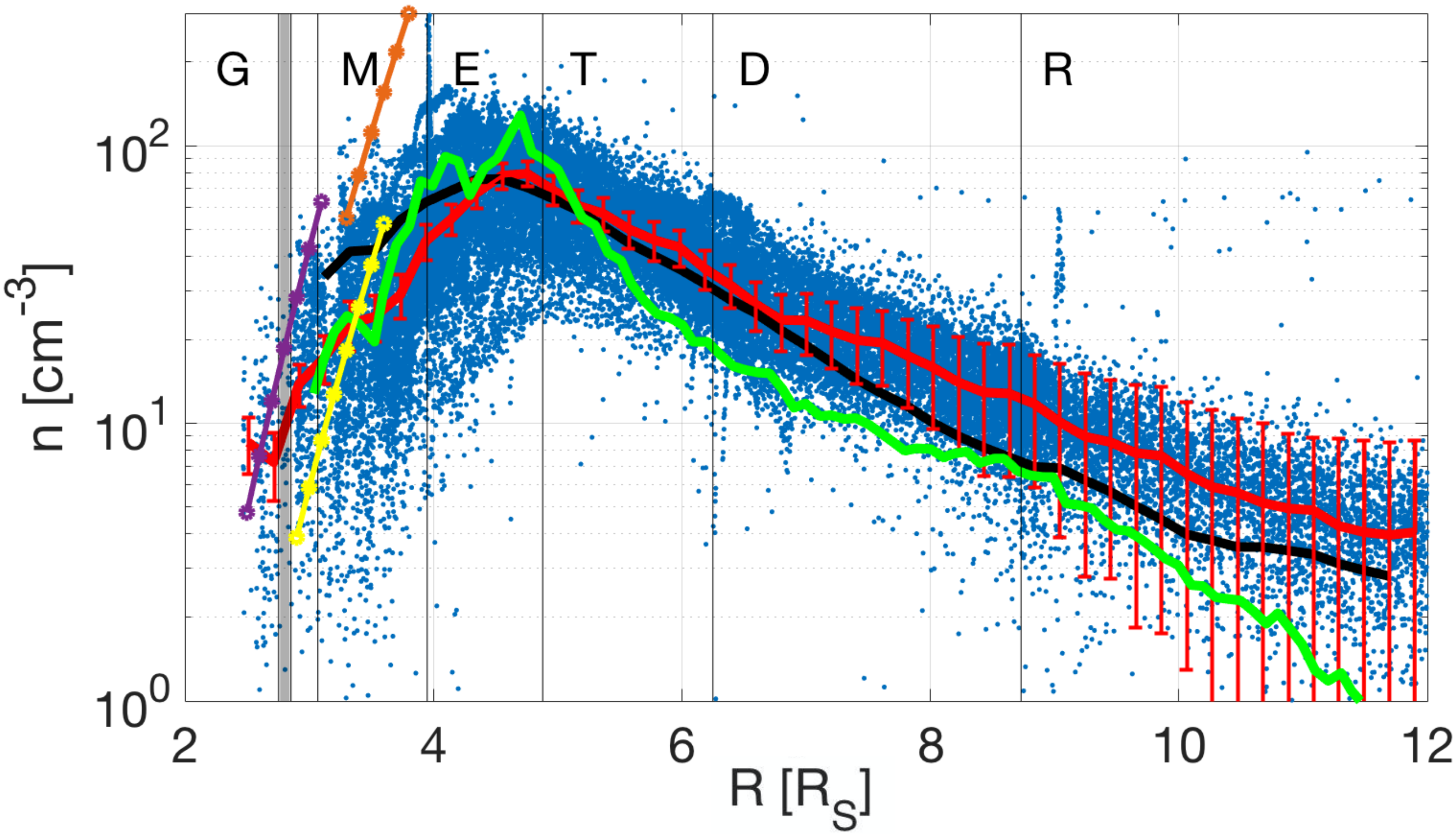


Figure 7. Equatorial, |z| < 0.25 R_S, ion densities (blue dots). Median LP ion density (red) for each 0.2 R_S radial bin, median electron density from upper hybrid resonance (UHR) frequency measurements (black), CAPS ion density (green) (Livi et al., 2014) , CAPS ion density for years 2007 (purple line with circular markers), 2010 (yellow line with markers), and 2012 (orange line with markers) (Elrod et al., 2014)

Seasonal modulation

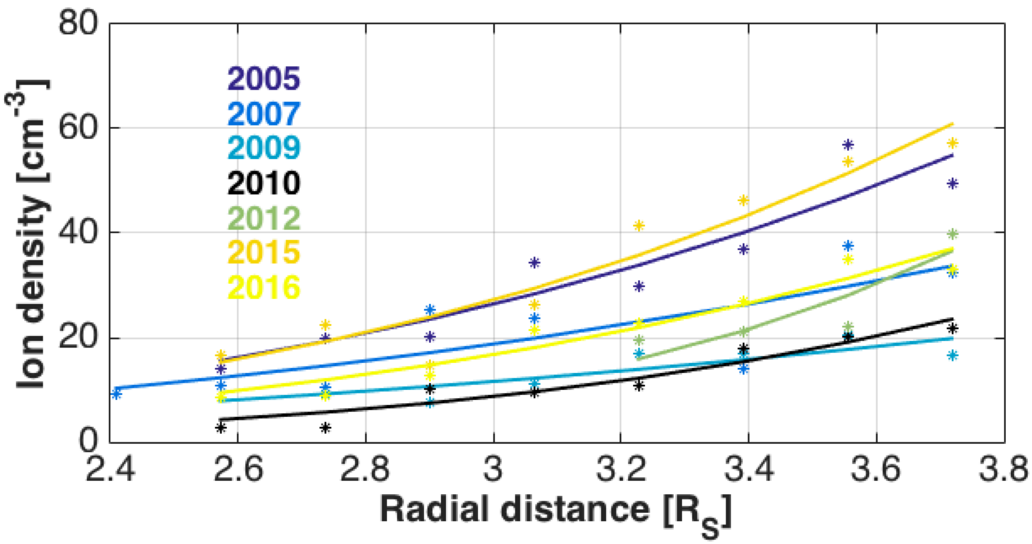


Figure 8. Fit to median equatorial ion density, radial bin size 0.16 R_S, $|z|<0.25\ R_S$

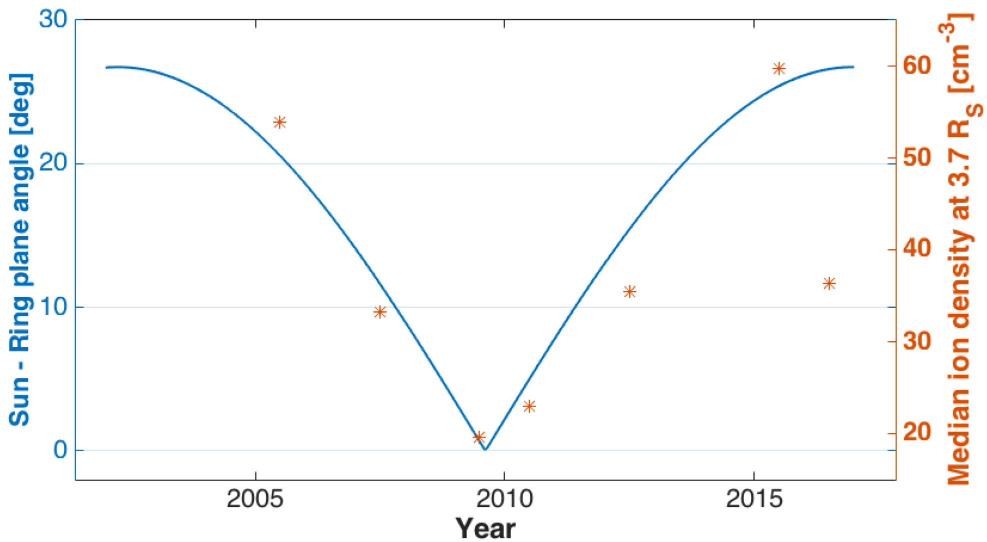
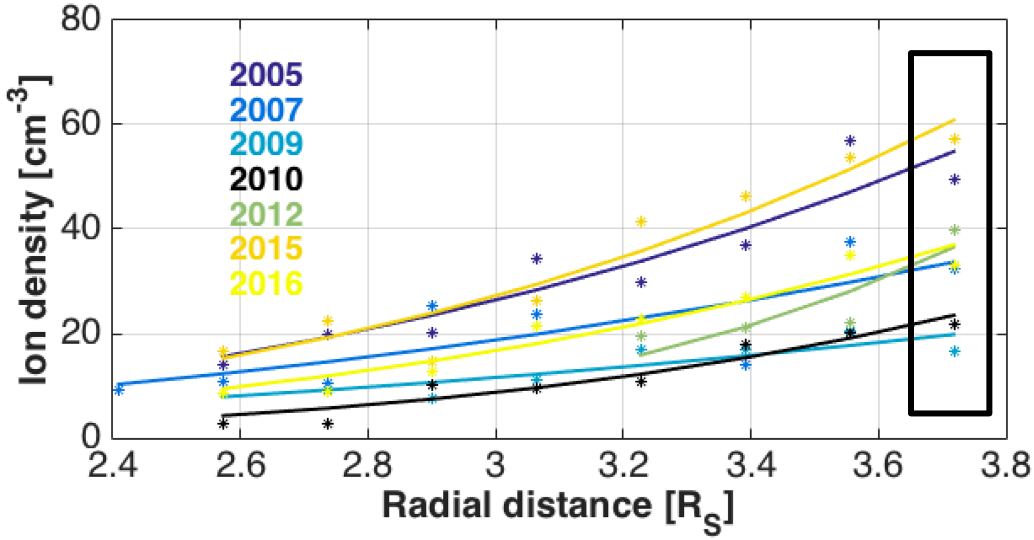


Figure 9. Angle between the ring plane and the Sun (blue), median equatorial ion density at 3.7 R_S (red)

Seasonal modulation



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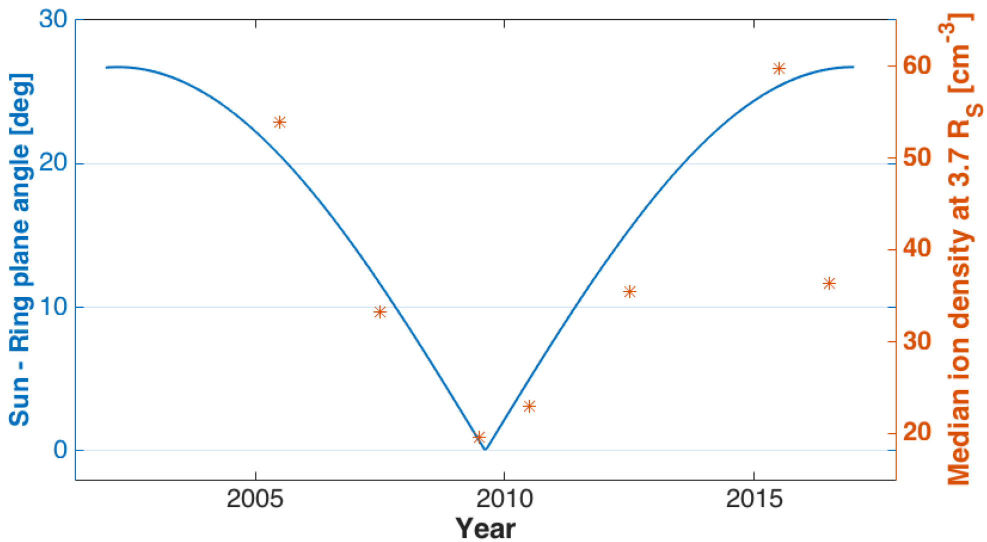

Figure 9. Angle between the ring plane and the Sun (blue), median equatorial ion density at 3.7 R_S (red)

Solar cycle modulation

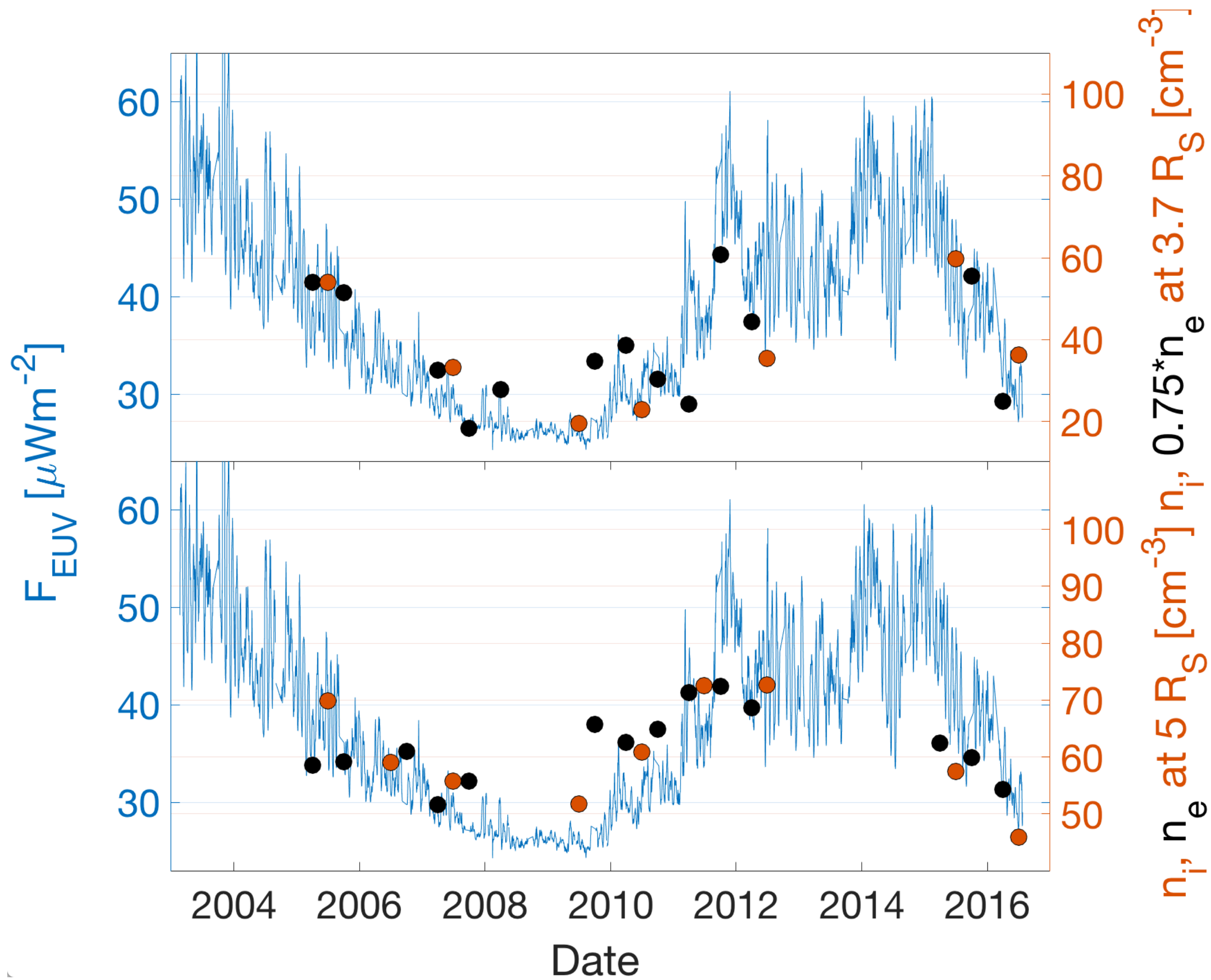

Figure 10. Integrated solar EUV flux (0.5-98.5 nm), F_{EUV}, and median equatorial, $|z| < 0.25\ R_S$, ion densities (red dots) at 3.7 R_S (upper panel) and 5 R_S (lower panel). Average electron density derived from UHR frequency for 6 months time intervals (black dots).

Summary and open questions

- The plasma density of the middle magnetosphere of Saturn shows:
  - A good correlation with season before 2016
  - After 2015, the correlation is better with the solar EUV flux
    - But this cannot be due by photoioniziation only
- Open questions:
  - How are the density and temperature of the hot electrons changing with varying solar EUV flux? Can a modulation in the hot electron impact ionization be a contributing factor?

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Extra slides

Ion densities n_i and velocities v_i

$$I_- = m + bU_{bias},\ m + bU_{bias} - I_{ph} = I_i$$

$$I_i \approx \underbrace{-A_{LP} n_i q_i \sqrt{\frac{v_i^2}{16} + \frac{k_B T_i}{2\pi m_i}}}_{I_{i0} = m - bU_1 - I_{ph}} \left(1 - \frac{q_i(U_1 + U_{bias})}{\frac{m_i v_i^2}{2} + k_B T_i}\right) =$$

$$\underbrace{-A_{LP} n_i q_i \sqrt{\frac{v_i^2}{16} + \frac{k_B T_i}{2\pi m_i}} \left(1 - \frac{q_i U_1}{\frac{m_i v_i^2}{2} + k_B T_i}\right)}_{m - I_{ph}} + \underbrace{A_{LP} n_i q_i \sqrt{\frac{v_i^2}{16} + \frac{k_B T_i}{2\pi m_i}} \left(\frac{q_i}{\frac{m_i v_i^2}{2} + k_B T_i}\right)}_{b} U_{bias}$$

$$-I_{i0} b = \left(-A_{LP} n_i q_i \sqrt{\frac{v_i^2}{16}}\right)^2 \left(\frac{q_i}{\frac{m_i v_i^2}{2}}\right) = (A_{LP} n_i q_i)^2 \left(\frac{q_i}{8 m_i}\right) \propto n_i^2$$

$$-I_{i0}/b = \frac{-I_{i0}}{\frac{-2 I_{i0} q_i}{m_i v_i^2}} = \frac{m_i v_i^2}{2 q_i} \propto v_i^2$$

I_{ph} - photoelectron current
I_{i0} - ion random current
q_i - ion charge
U_1 - floating potential
m_i - ion mass
v_i - ion velocity relative to the collector
k_B - Boltzmann constant
T_i - ion temperature

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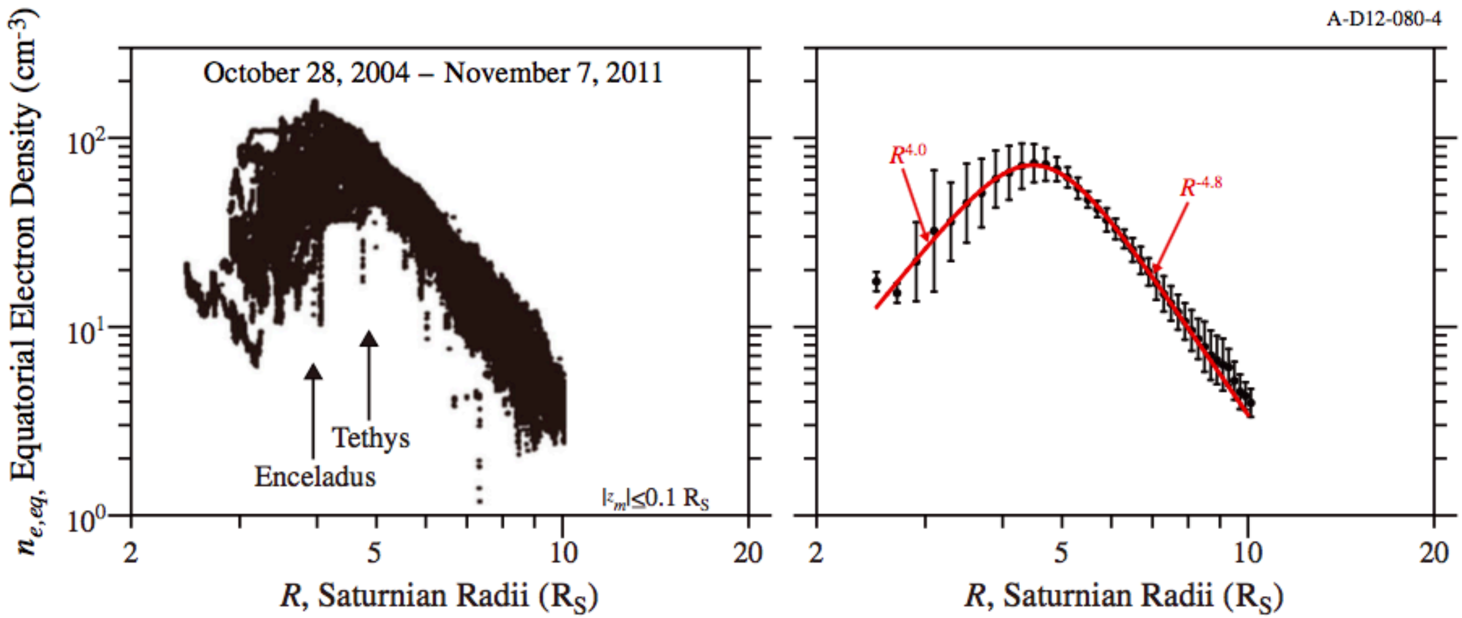
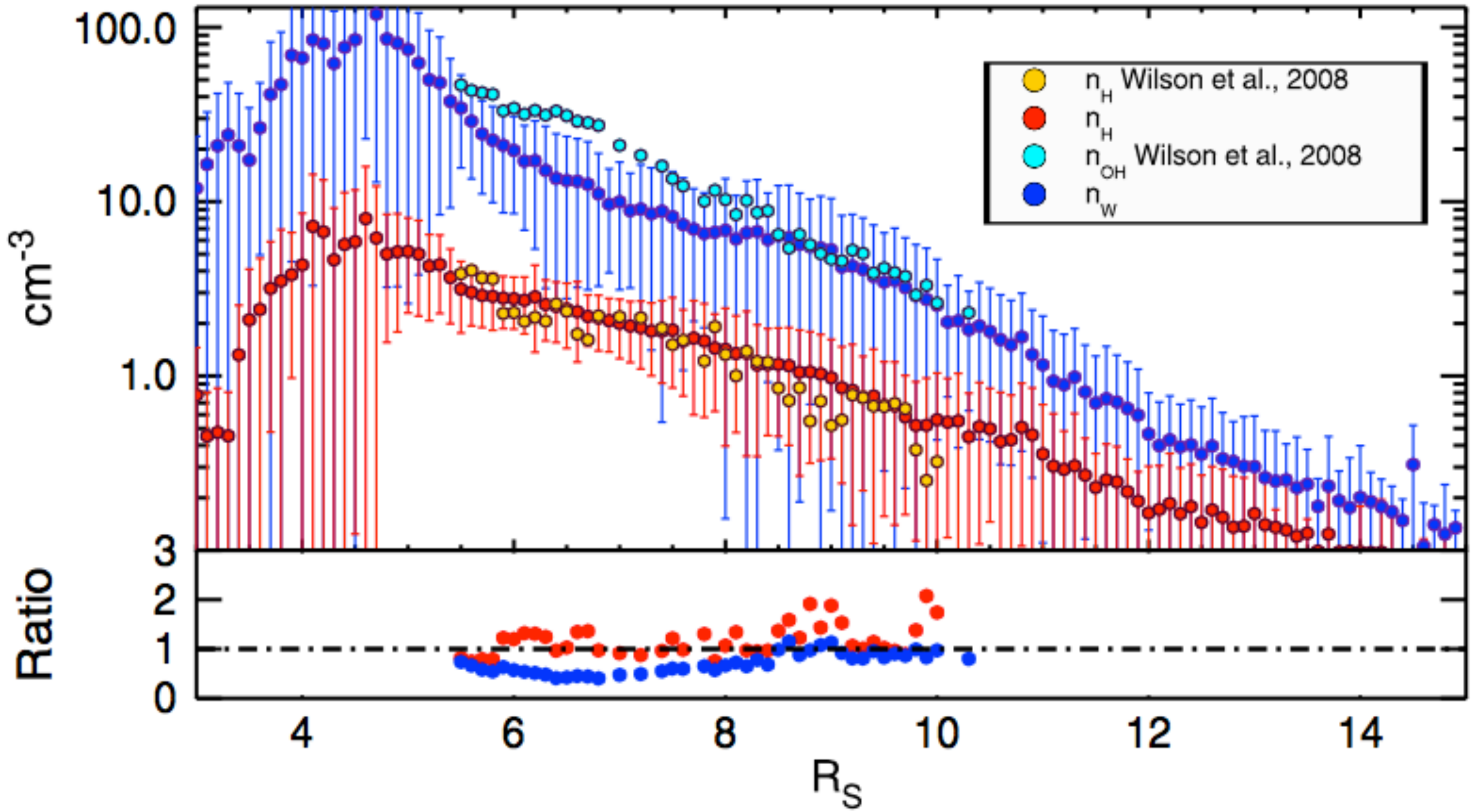


Figure 3. (a) Radial distribution plot of the equatorial densities for $2.6 \leq L \leq 10.0$ R_S over the 7 year period of this study. Low-density excursions at Enceladus are density measurements taken when Cassini passed through the Enceladus plume. Low-density excursions beyond 6 R_S are density measurements taken when Cassini passed through interchanging flux tubes that are depleted of cold plasma. (b) Plot of the equatorial density measurements averaged in non-overlapping L-shell bins of 0.2. The error bars represent one standard deviation on a log scale on either side of the averaged density values. The solid red line shows the model fit to the equatorial densities using equation (2), which gives a peak density of 72 cm^{-3} at 4.6 R_S and shows the densities increasing with increasing radial distance as $R^{4.0}$ inside the orbit of Enceladus and falling off with increasing radial distance as $R^{-4.8}$ outside 5 R_S.

From Persoon et al. 2013



CAPS ion density Livi et al., 2014

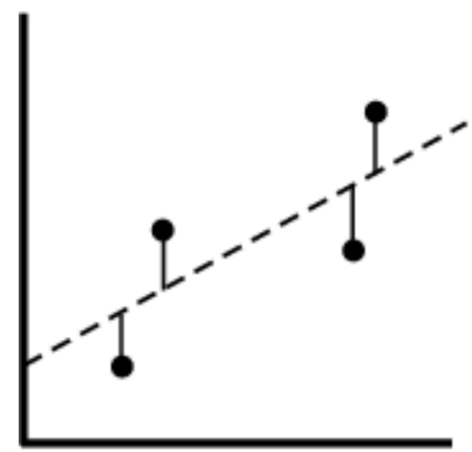
Error estimate m and b

- Regression line, minimize the sum of squared deviations of prediction
- Estimate standard error for the slope

$$Se_b^2 = \frac{1}{\sum(x_i - \bar{x})^2} \frac{\sum(y_i - \hat{y}_i)^2}{n-2}$$

- where y_i, x_i are the measured values, $\hat{y}_i$ is the value from the fit, and x is the mean
- Estimate error of intercept value

$$Se_m^2 = \frac{1}{n} + \frac{\bar{x}^2}{\sum(x_i - \bar{x})^2} \frac{\sum(y_i - \hat{y}_i)^2}{n-2}$$



vertical offsets

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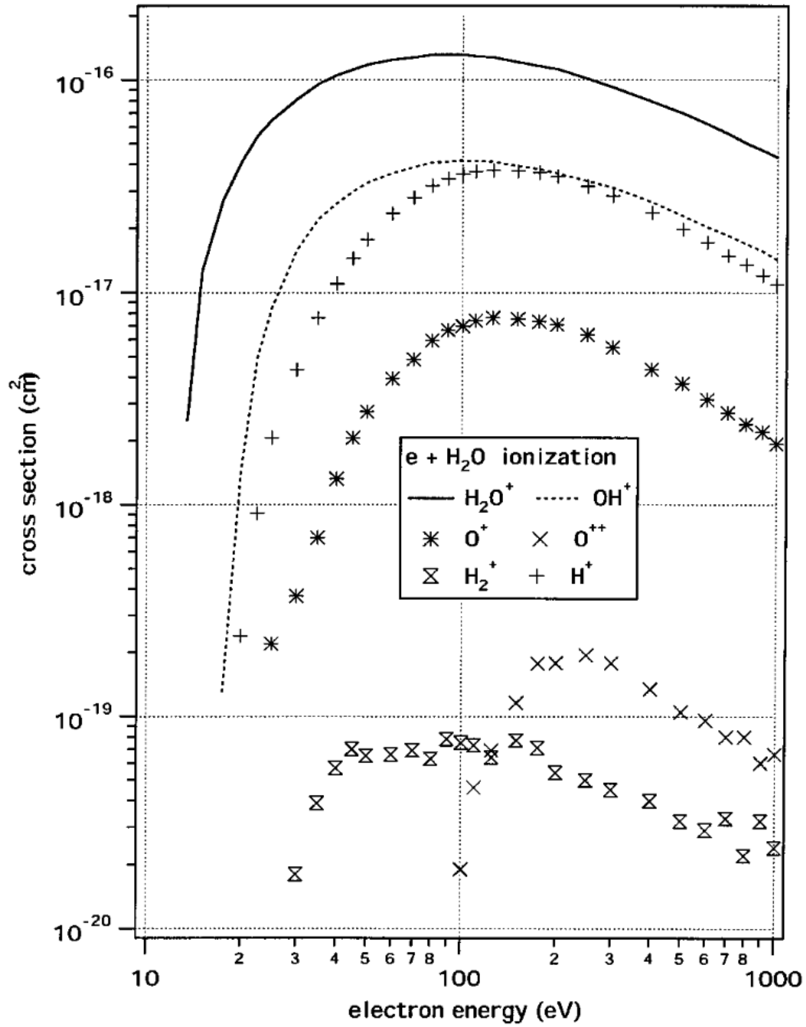

FIG. 11. Recommended values of the partial ionization cross sections of H_2O for the production of H_2O^+, OH^+, O^+, O^{++}, H_2^+, and H^+.

Itikawa and Mason, 2005

Electron density derived from upper hybrid frequency measurement (yellow) and LP (blue)

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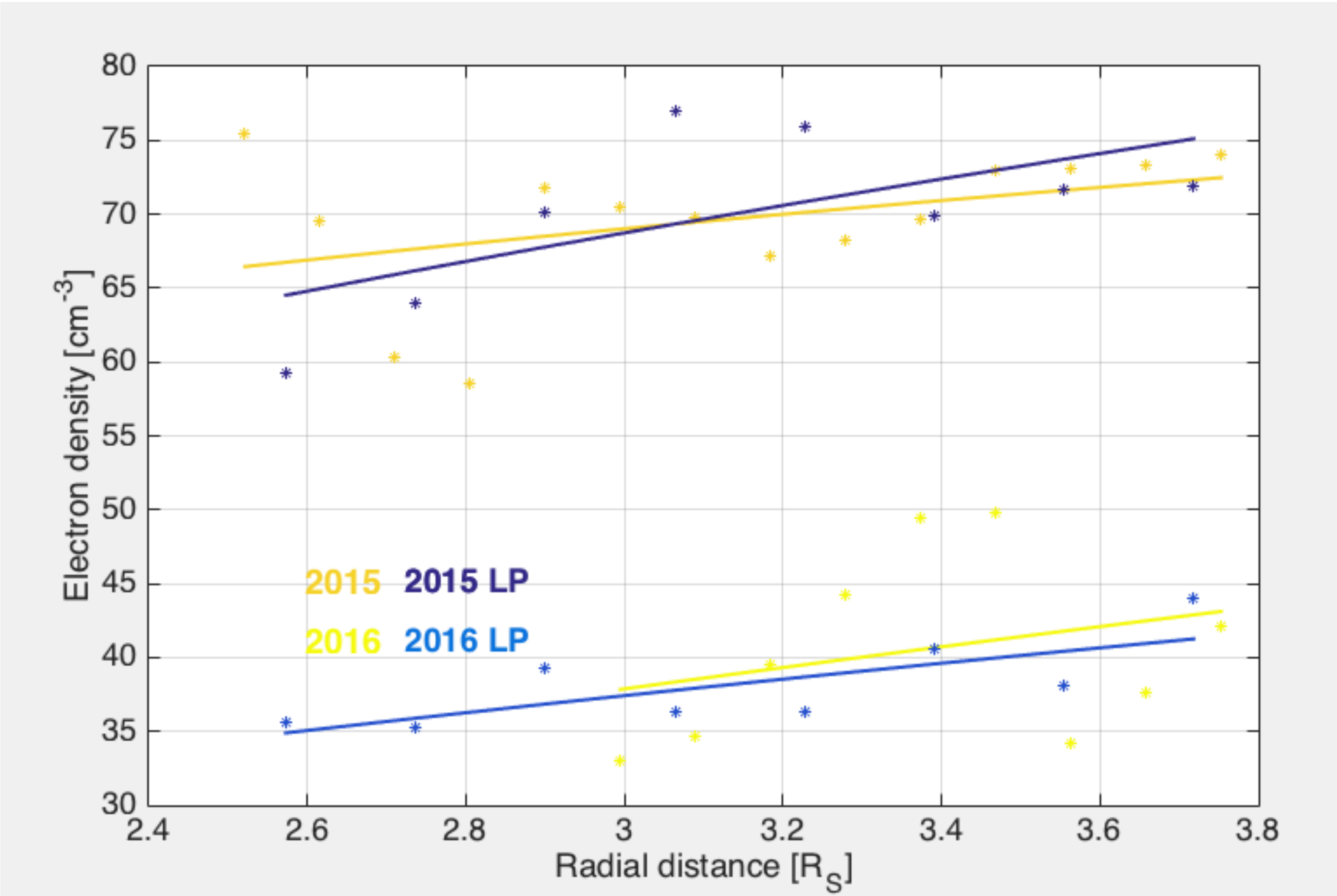

Ion gyroradii

$r_g = mv_{perp}/eB$

Based on ion temperatures measured by CAPS and presented in Thomsen et al. 2010

Assuming dipole field

$m_{W+} = 18$ amu