Saturn's Ionosphere

Ring Rain and Other Drivers

Luke Moore, Marina Galand, Arv Kliore, Andy Nagy, James O'Donoghue

BOSTON UNIVERSITY

Imperial College London

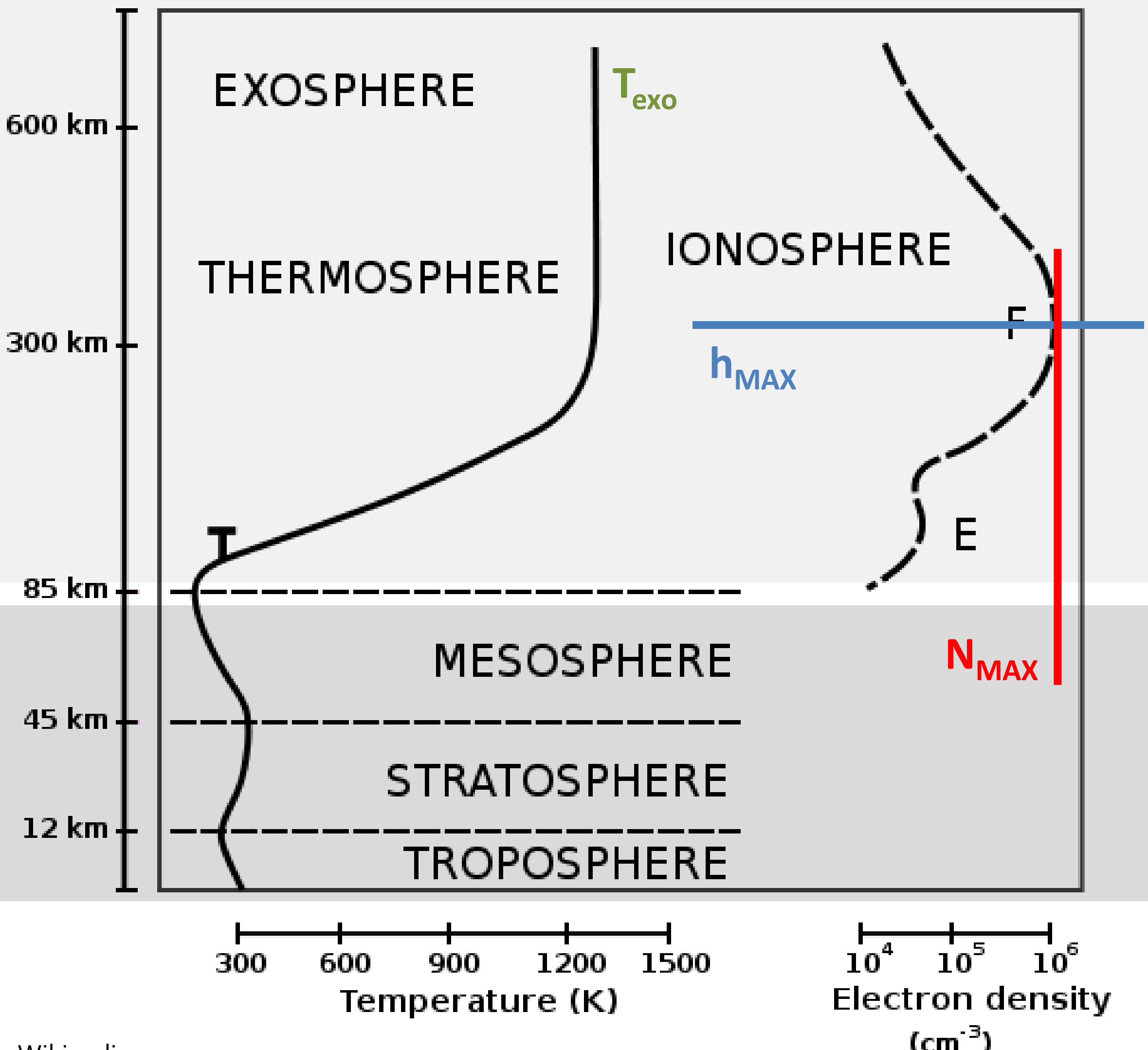
JPL

MICHIGAN

Outline

- Introduction to Saturn's ionosphere
  - Basic properties and theory
- Observations: what do we know?
  - Radio occultations: **$N_e(h)$**
  - Saturn Electrostatic Discharges: **$N_{MAX}(SLT)$**
  - Ring rain: **$H_3^+(12\ SLT)$**
- Theory/Models: what do we think we know?
  - Comparisons with observations
- Summary
  - Remaining uncertainties, future observations

Atmospheric Layers



Wikipedia

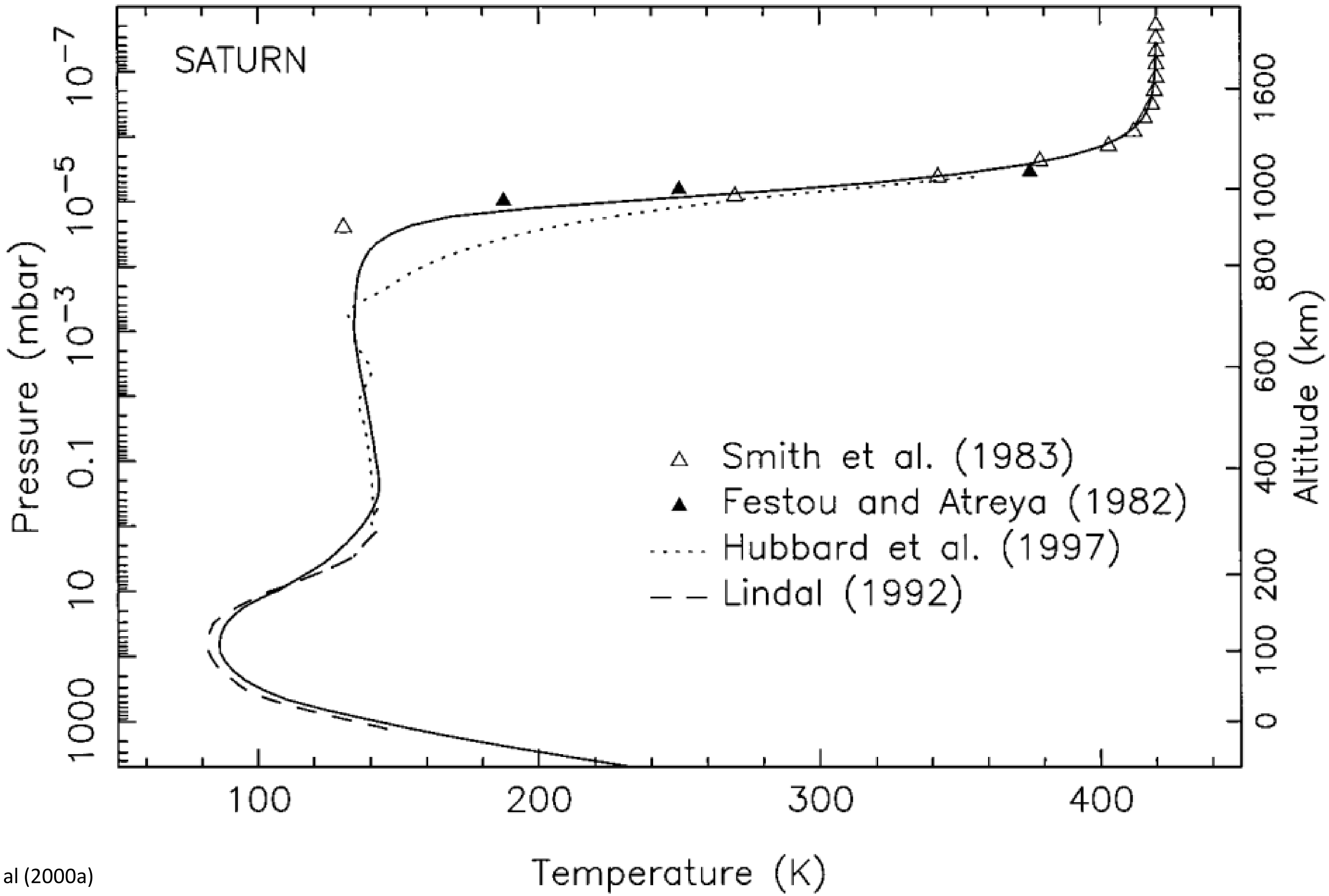
Upper atmosphere (aeronomy)

- **Key transition region** between lower atmosphere and magnetosphere
- **Energy and momentum sources:**
  - EUV/FUV solar radiation
  - Energetic particles
  - Forcing from below (e.g., gravity waves)

Lower atmosphere (meteorology)

Vertical Temperature Profile

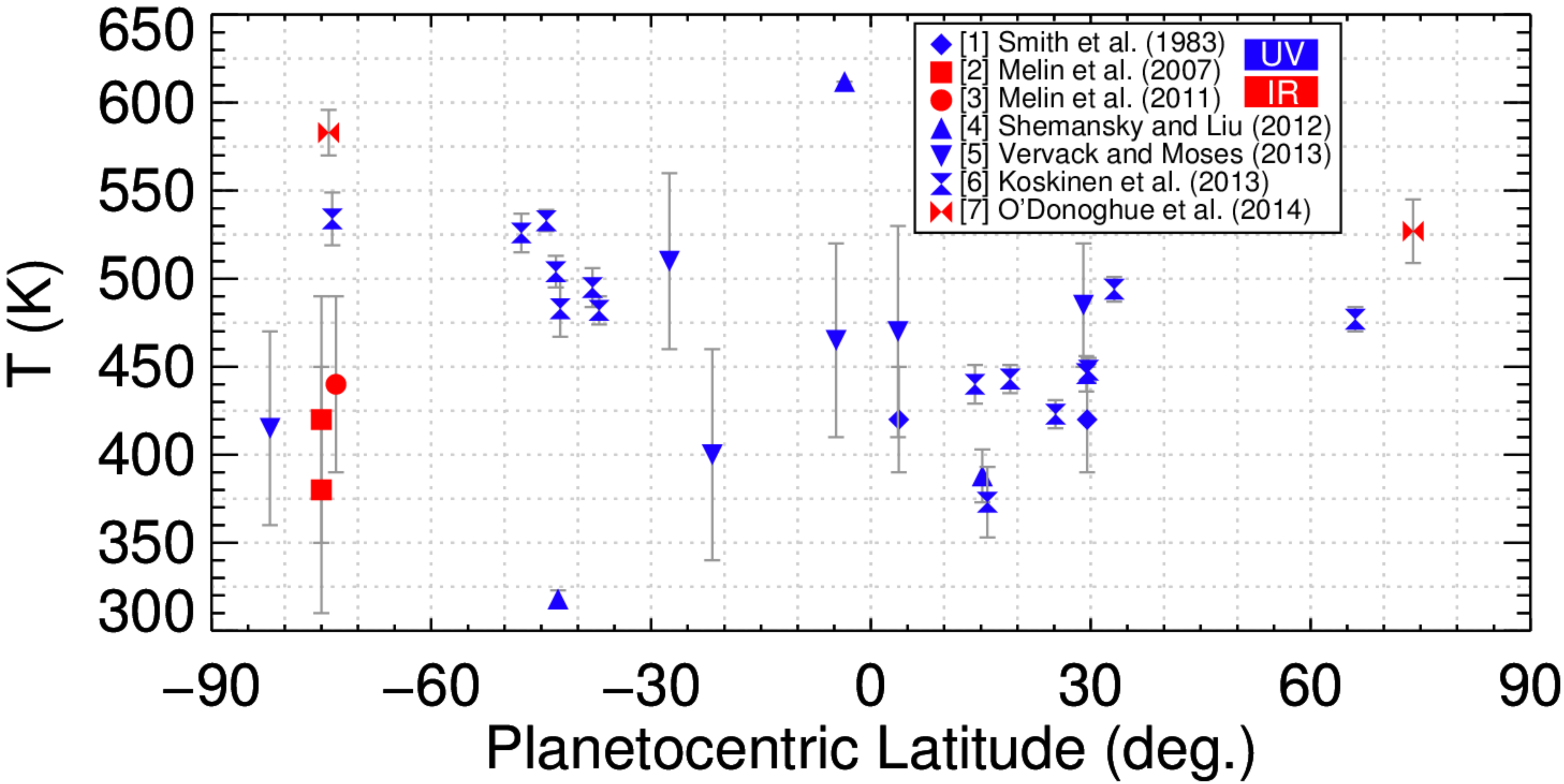
Reference altitude (0 km) = 1 bar level



Moses et al (2000a)

Latitudinal Temperature Behavior

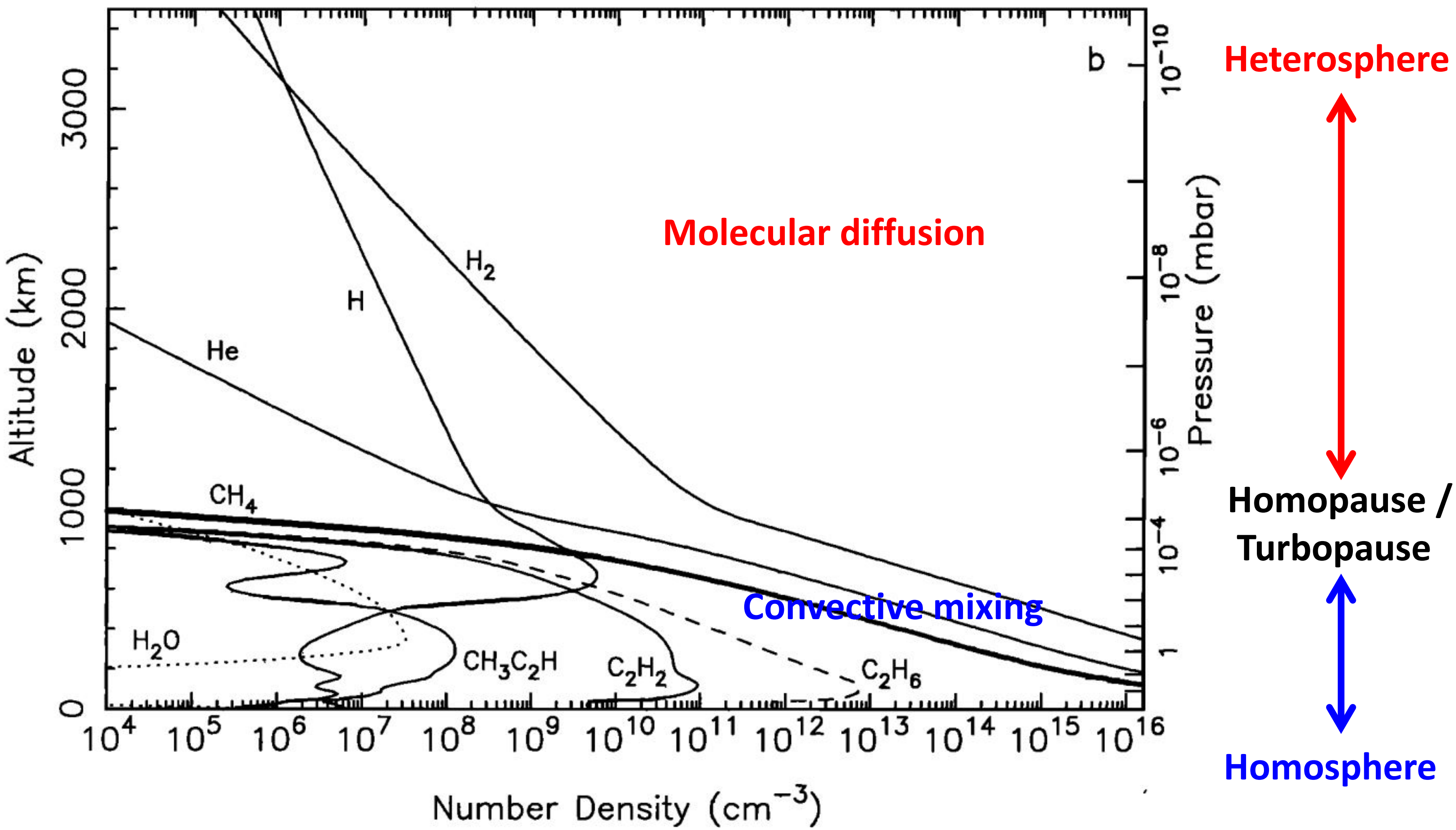
UV: from solar and stellar occultations, represent T_{exo}
IR: from H_3^+ emissions, represent effective column temperature



Moore et al (2014)

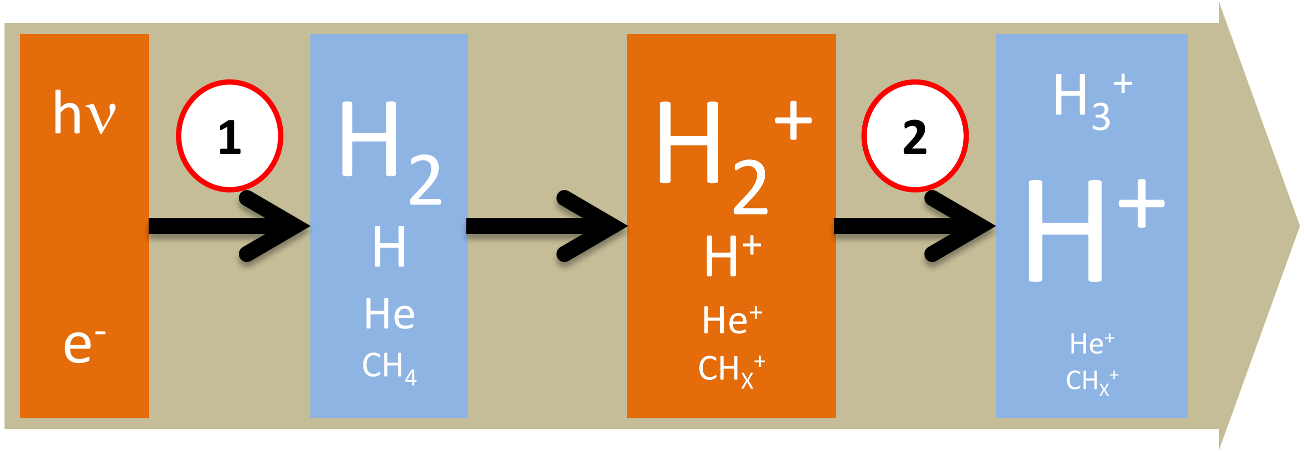
Thermosphere of Saturn

Reference altitude (0 km) = 1 bar level

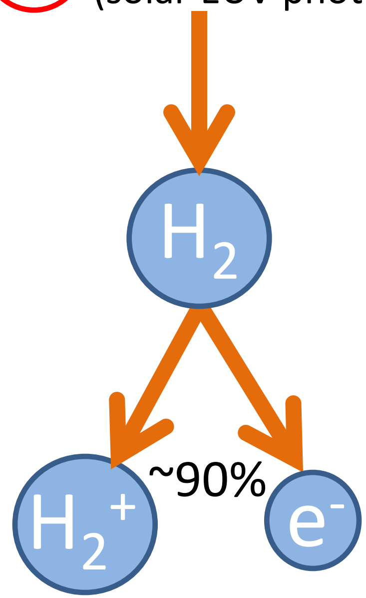


Moses and Bass (2000)

Initial Theory: Saturn's Ionosphere



1 Photoionization (solar EUV photons)



2 Charge-exchange and recombination

$$H_2^+ + H_2 \rightarrow H_3^+ + H$$ **FAST**

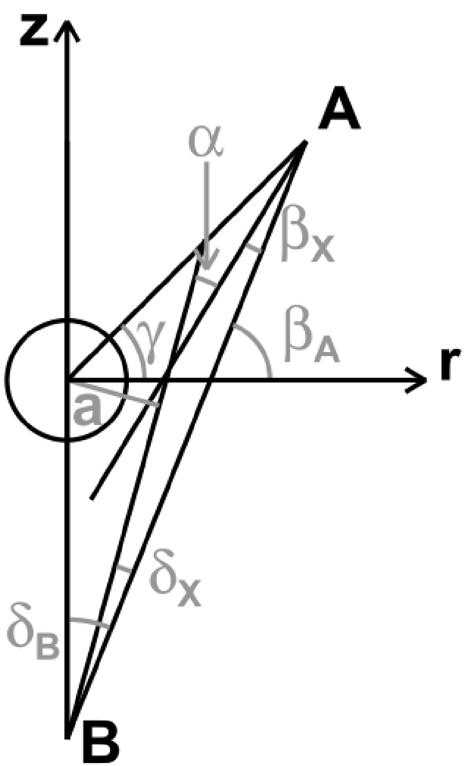
$$H_3^+ + e^- \rightarrow H_2O + H$$
$$\rightarrow OH + 2H$$ **FAST**

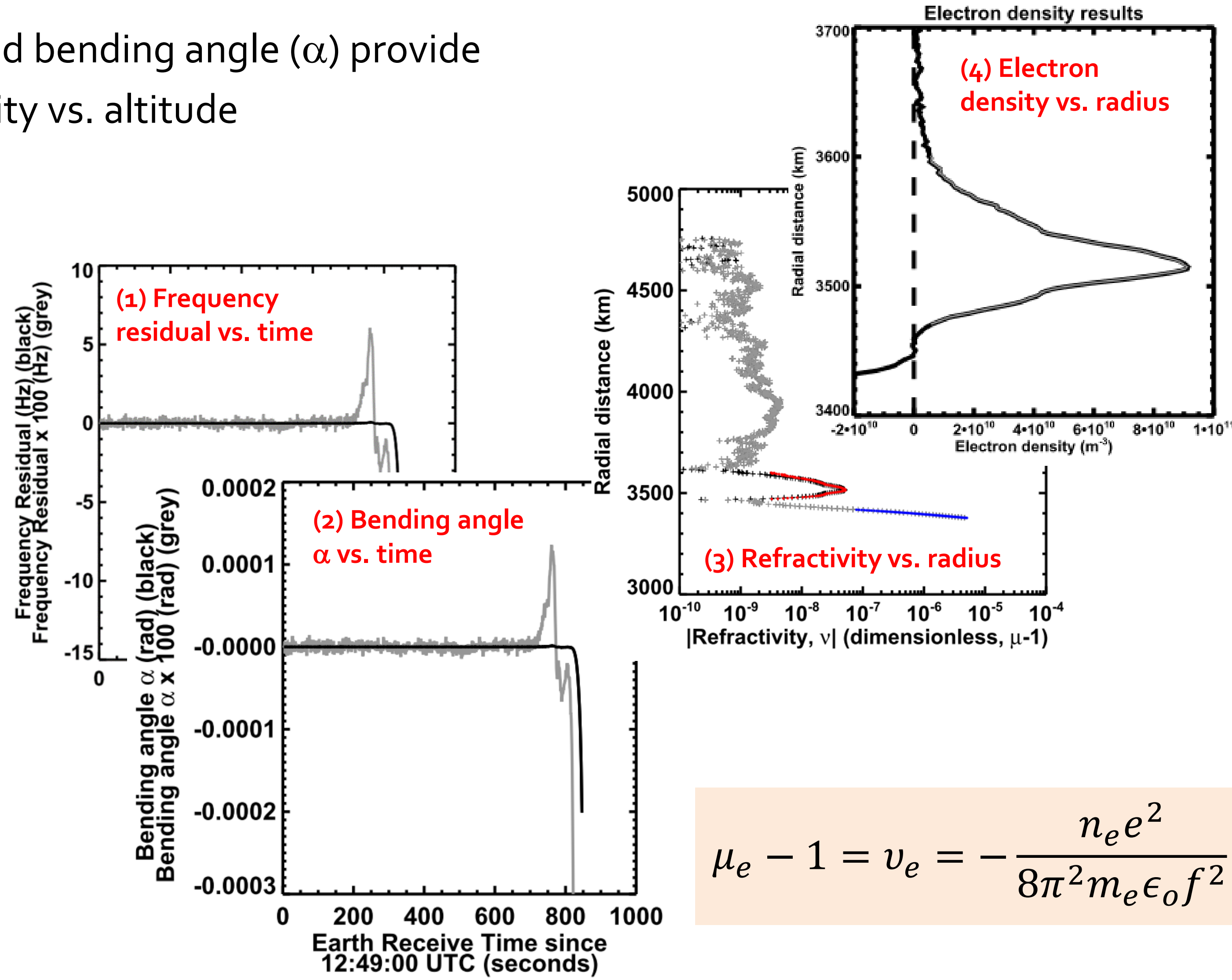
$$H^+ + e^- \rightarrow H$$ **SLOW**

Observations

Radio Occultations

- Time delay and bending angle (α) provide electron density vs. altitude

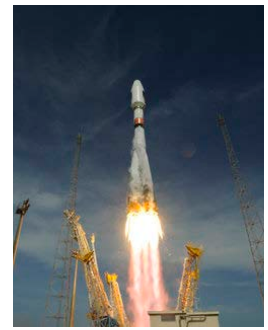
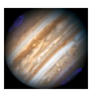
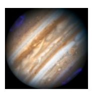
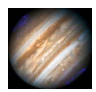
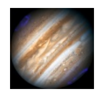
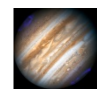
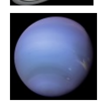
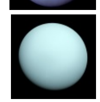




$$\mu_e - 1 = \upsilon_e = -\frac{n_e e^2}{8\pi^2 m_e \epsilon_o f^2}$$

Withers et al (2014)

Summary of Outer Planet Radio Occultations

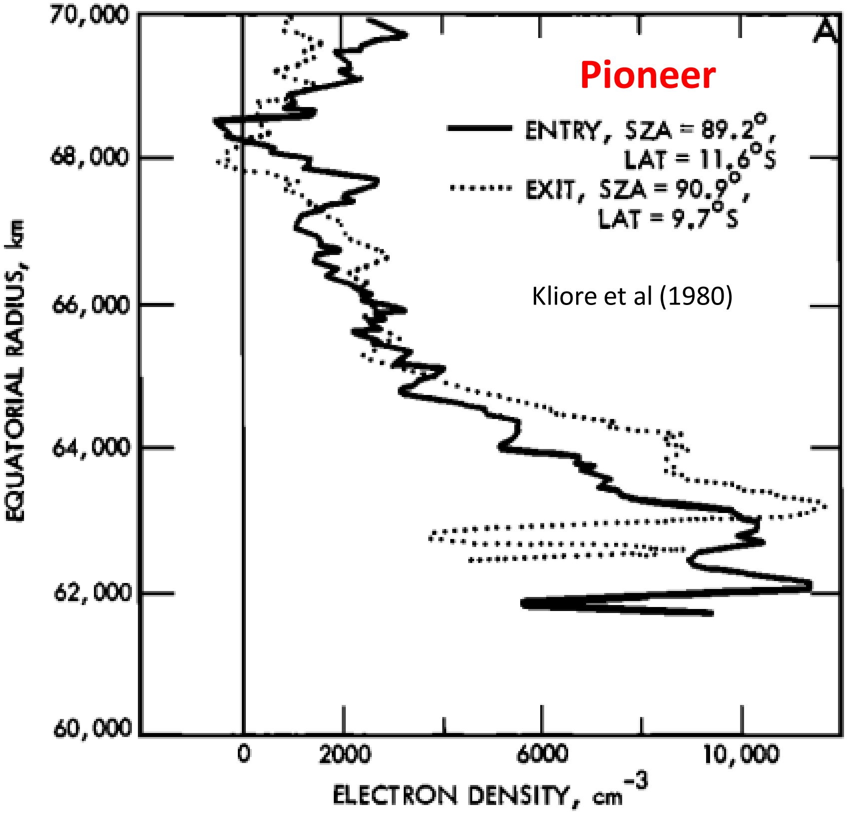
Pioneer 10	Pioneer 11	Voyager 1	Voyager 2	Galileo	Cassini	
						
3 Mar 1972	6 Apr 1973	5 Sep 1977	20 Aug 1977	18 Oct 1989	15 Oct 1997	
 x 2	 x 2	 x 2	 x 2	 x 5*		= 13
	 x 2	 x 2	 x 2		 x 59**	= 65
			 x 2			= 2
			 x 2			= 2

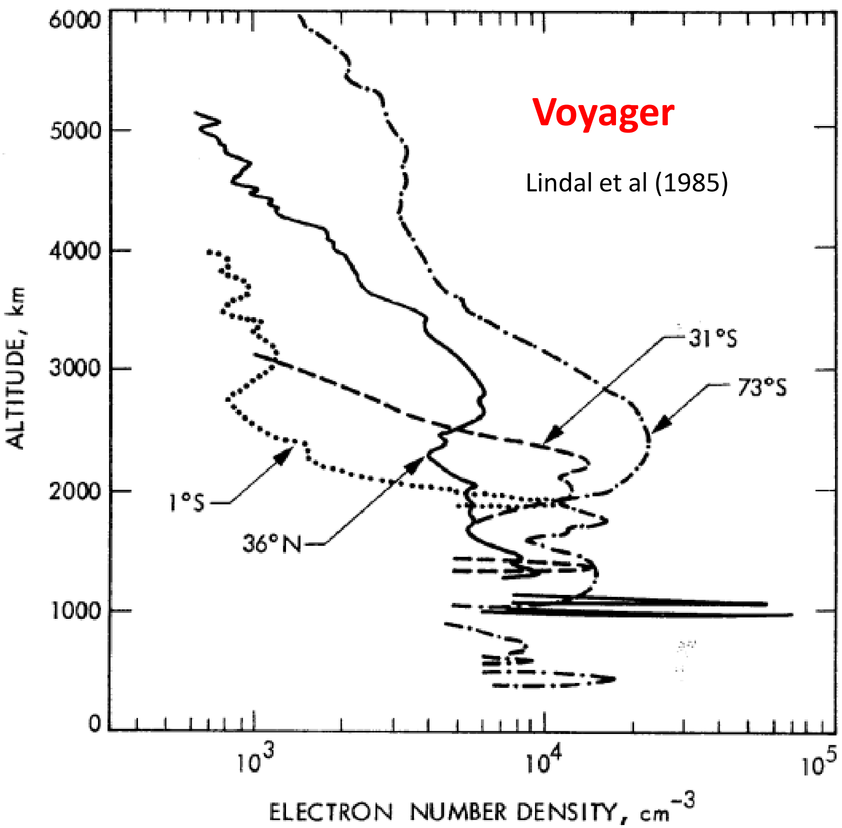
ingress (N) and egress (X) — Pioneer 10, Pioneer 11, Voyager 1, Voyager 2

orbiters — Galileo, Cassini

* analyzed; ** taken to-date

Pre-Cassini Saturn Radio Occultations



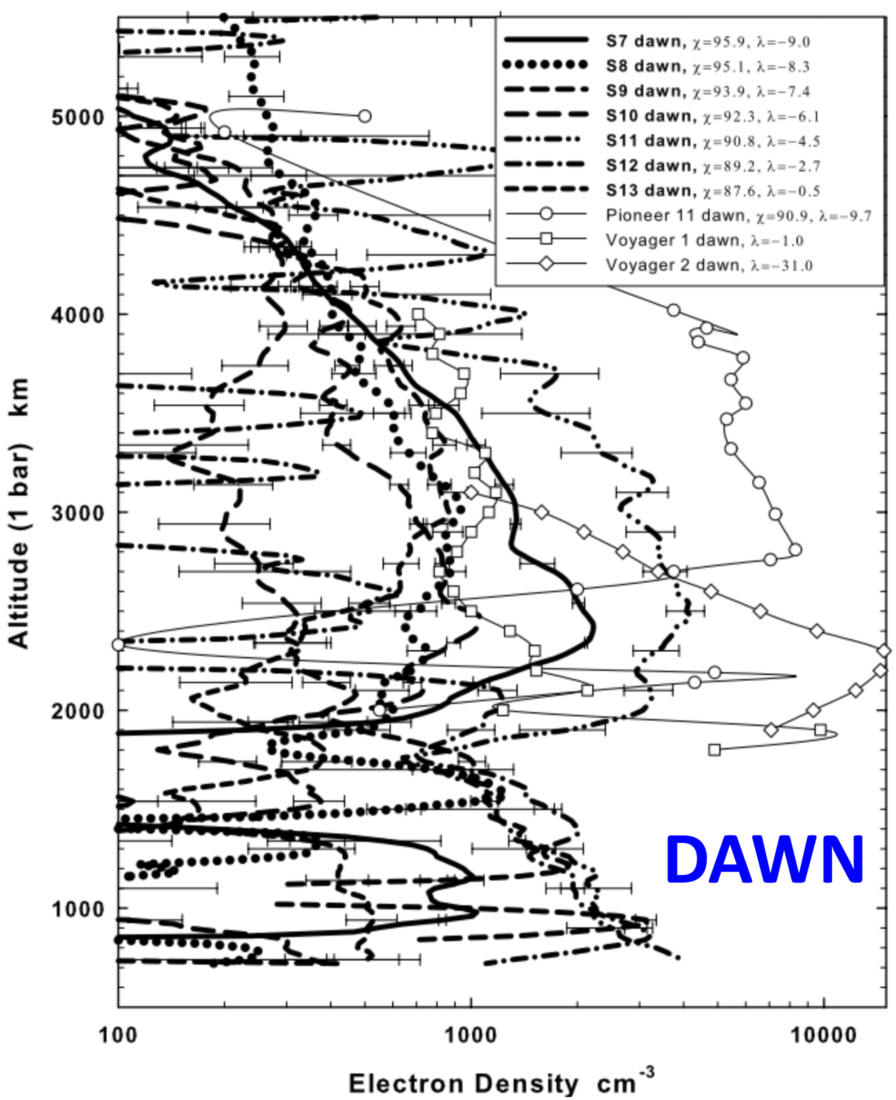


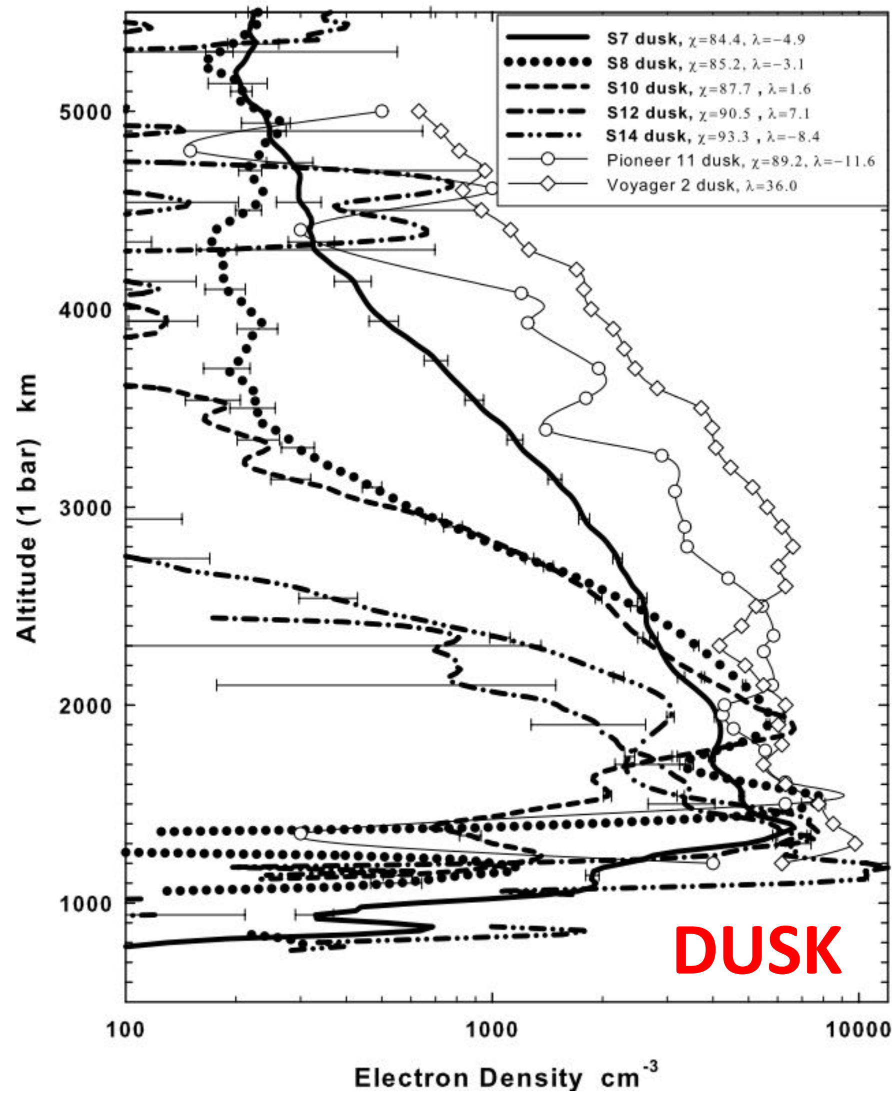
Narrow low-altitude layers of N_e

N_{MAX} ~ 10^4 cm^{-3}

h_{MAX} ~ 1000-2500 km

Cassini Equatorial Radio Occultations



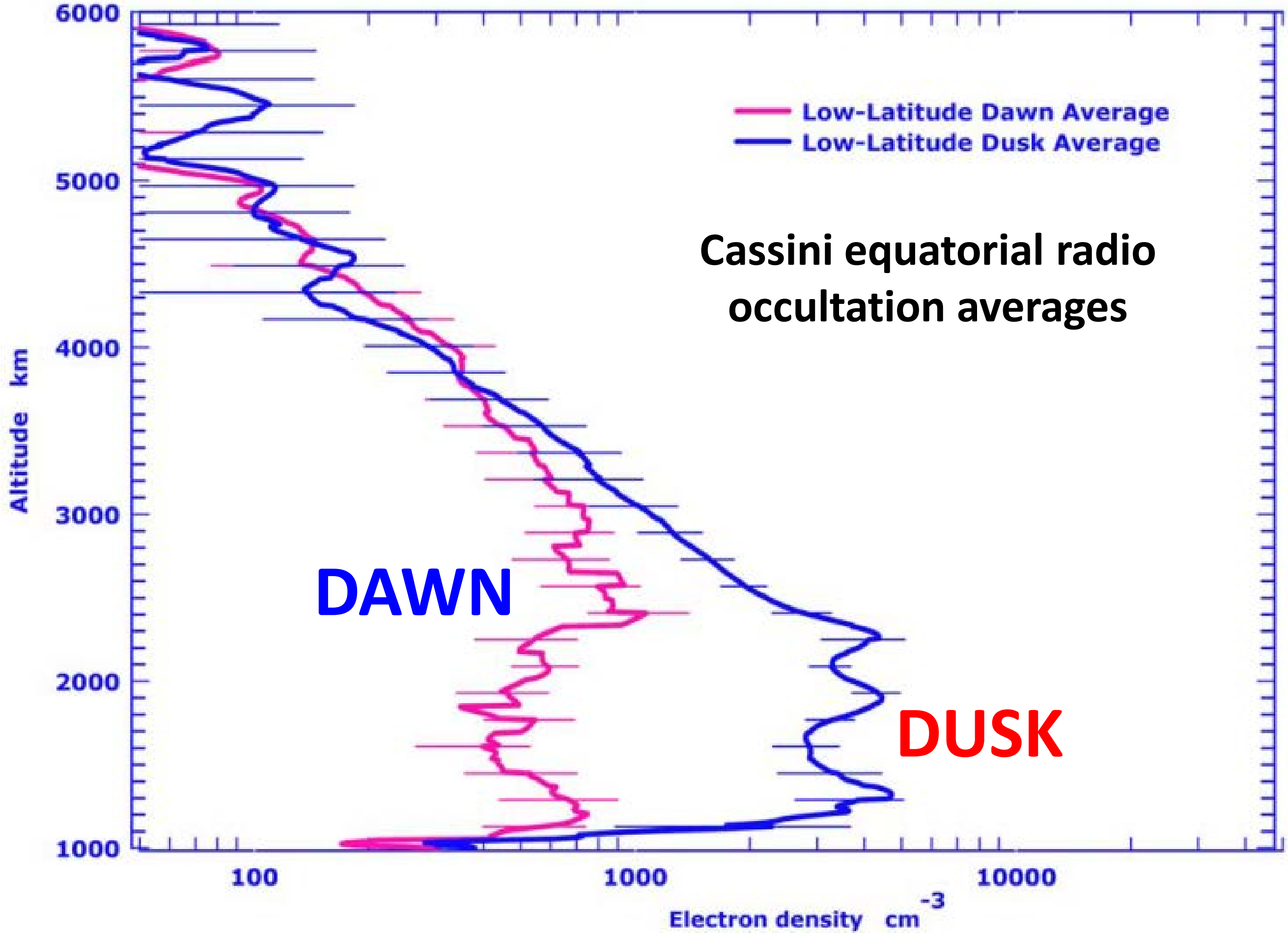


Nagy et al (2006)

Cassini Equatorial Dawn/Dusk Asymmetry

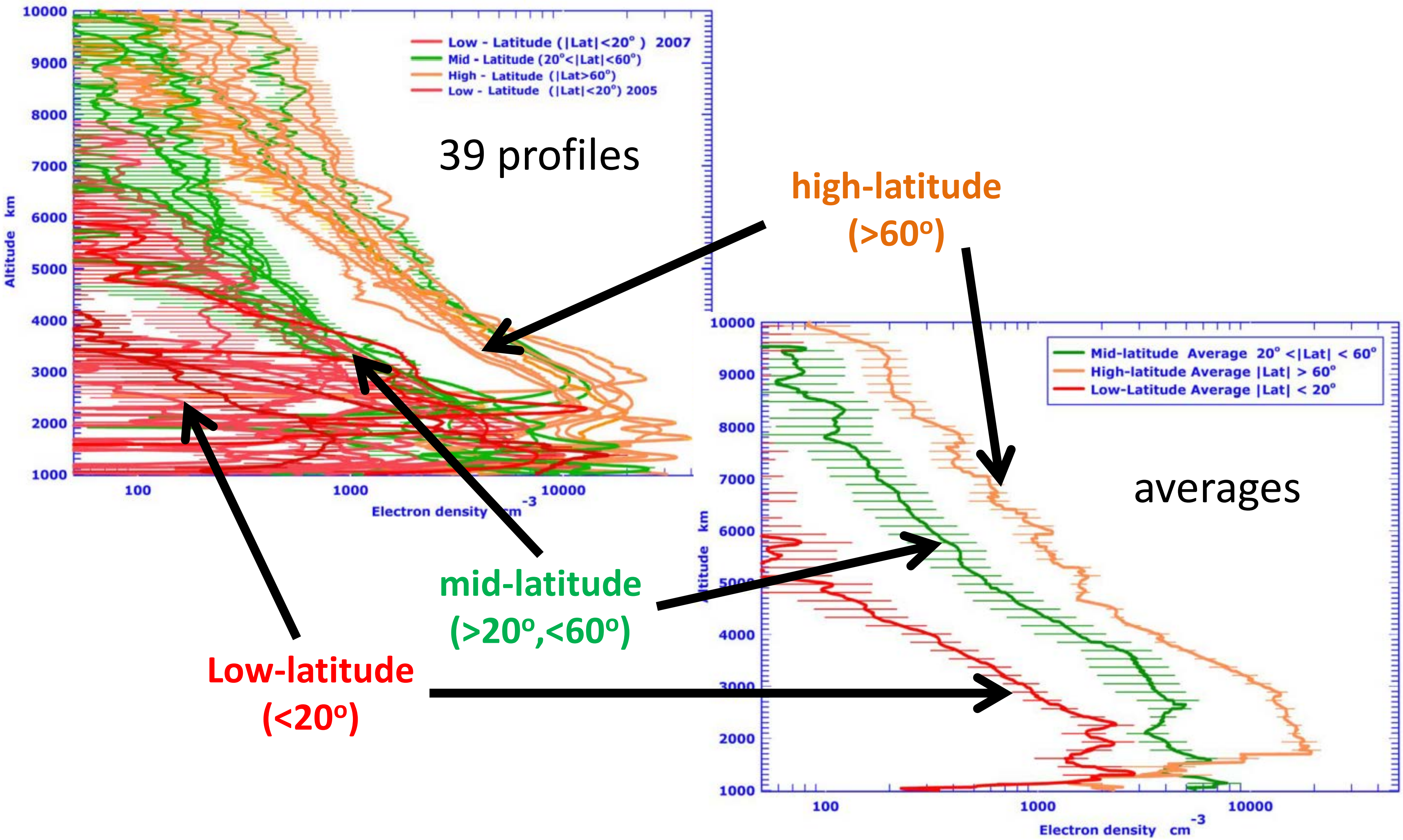
DAWN N_{MAX} < DUSK N_{MAX}

DAWN h_{MAX} > DUSK h_{MAX}



Kliore et al (2009)

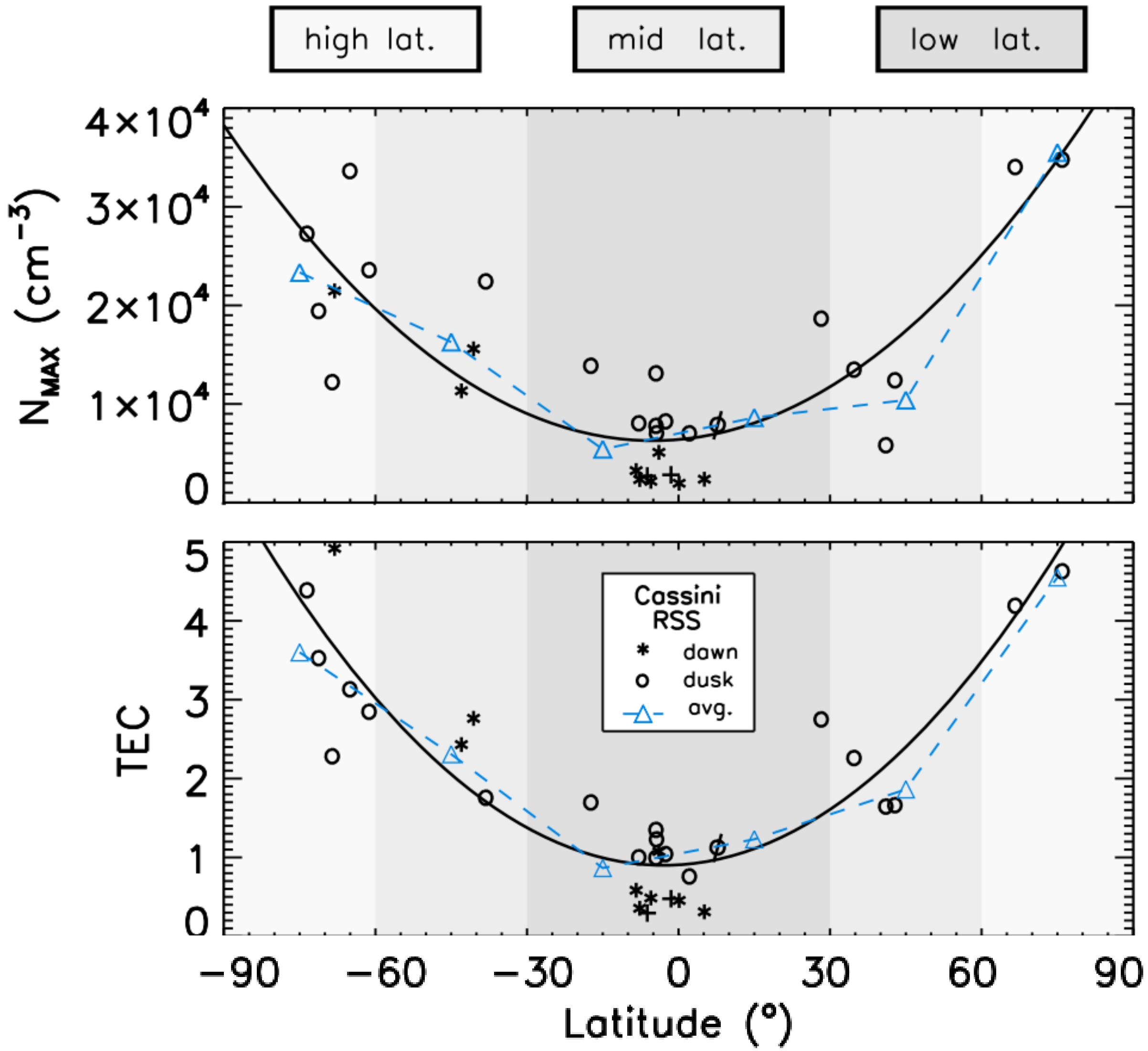
Cassini Latitudinal Trend in N_e



Kliore et al (2009)

Cassini Latitudinal Trend in N_e

Minimum N_{MAX} at equator; N_{MAX} increases with latitude

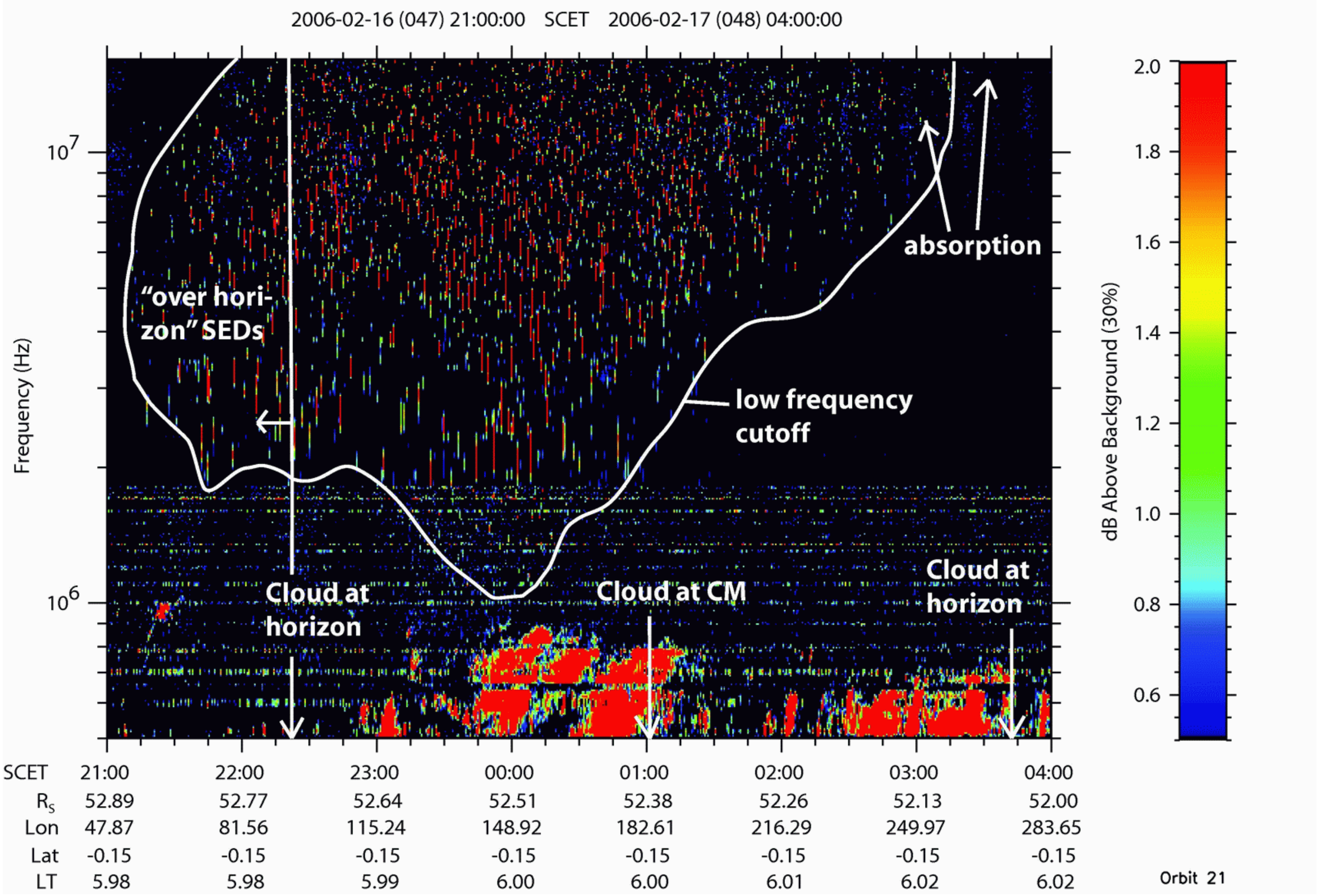


Moore et al (2010)

Saturn Electrostatic Discharges (SEDs)

- Broadband, short-lived, impulsive radio emission, ~10 hr periodicity
  - Initially thought to originate in Saturn's rings, later shown to be associated with powerful lightning storms in Saturn's lower atmosphere
  - Detected by Voyager and Cassini (~9 SED storms to-date, each lasting weeks-months)
- Observed low-frequency cutoff can be used to derive **N_{MAX}(SLT)**
- Specific latitudes (primarily -35°), single storm locations
- Powerful lightning also observed at Jupiter, but no "JEDs"
  - Perhaps due to attenuation of radio waves by Jupiter's ionosphere

N_{MAX}(SLT) from SEDs



LT of storm from images, angle of incidence α calculated from storm location and Cassini position

$$f_{cutoff} = \frac{f_{pe,\max}}{\cos(\alpha)}$$

$$N_e = f_{pe,\max}^2 / 81$$

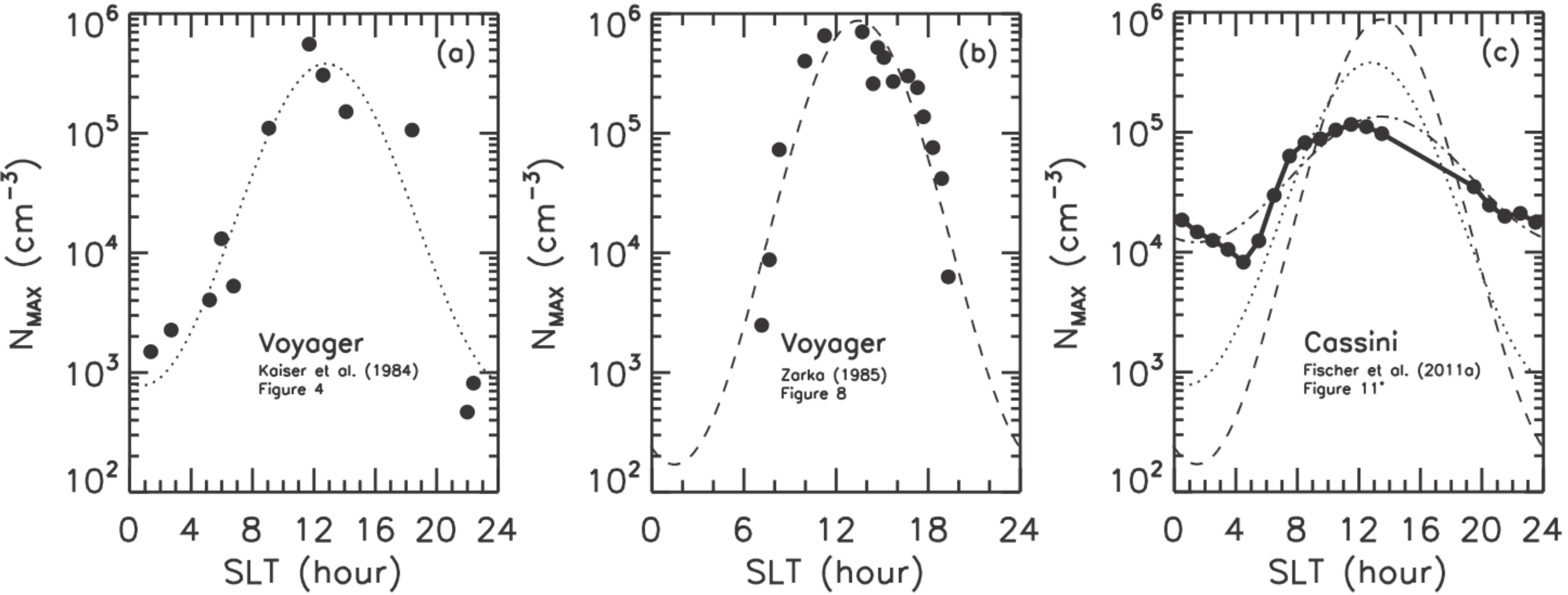
Fischer et al (2011)

N_{MAX}(SLT) from SEDs

Strong diurnal variation in N_{MAX}

N_{MAX}(noon) ~ 10^5 cm^{-3}

N_{MAX}(midnight) ~ 10^{3-4} cm^{-3}



$$\log N_e = A - B \cos(LT - \phi)$$

Moore et al (2012)

Protonated Molecular Hydrogen: H_3^+

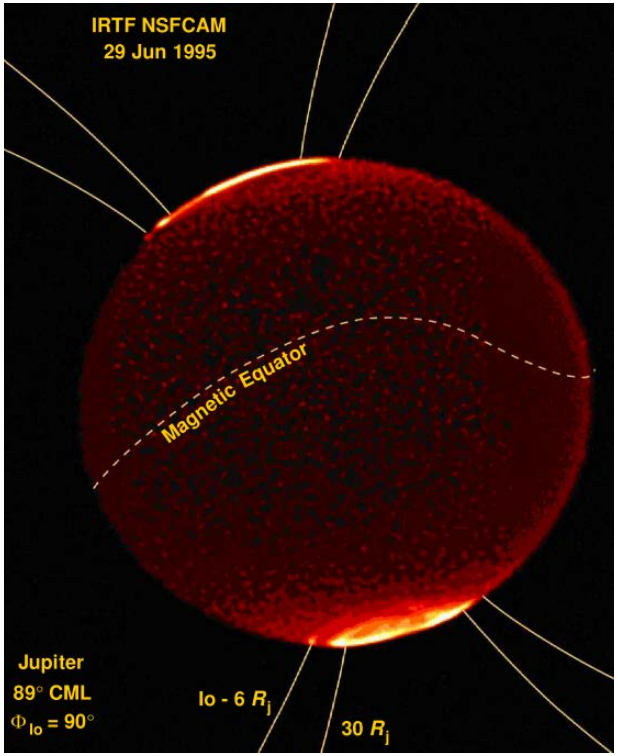
- First astronomical spectroscopic detection in the universe at Jupiter
  - Auroral IR measurements with CFHT (Drossart et al., 1989)

- Bright emission lines in K-band (2-2.5 mm) and L-band (3-4 mm) atmospheric windows
  - Strong methane absorption in the L-band
    - Therefore, at the giant planets (where H_3^+ is above the homopause), H_3^+ appears as bright emission above a dark background

- Highly temperature dependent

- Can be used to derive ion temperatures, densities, and velocities

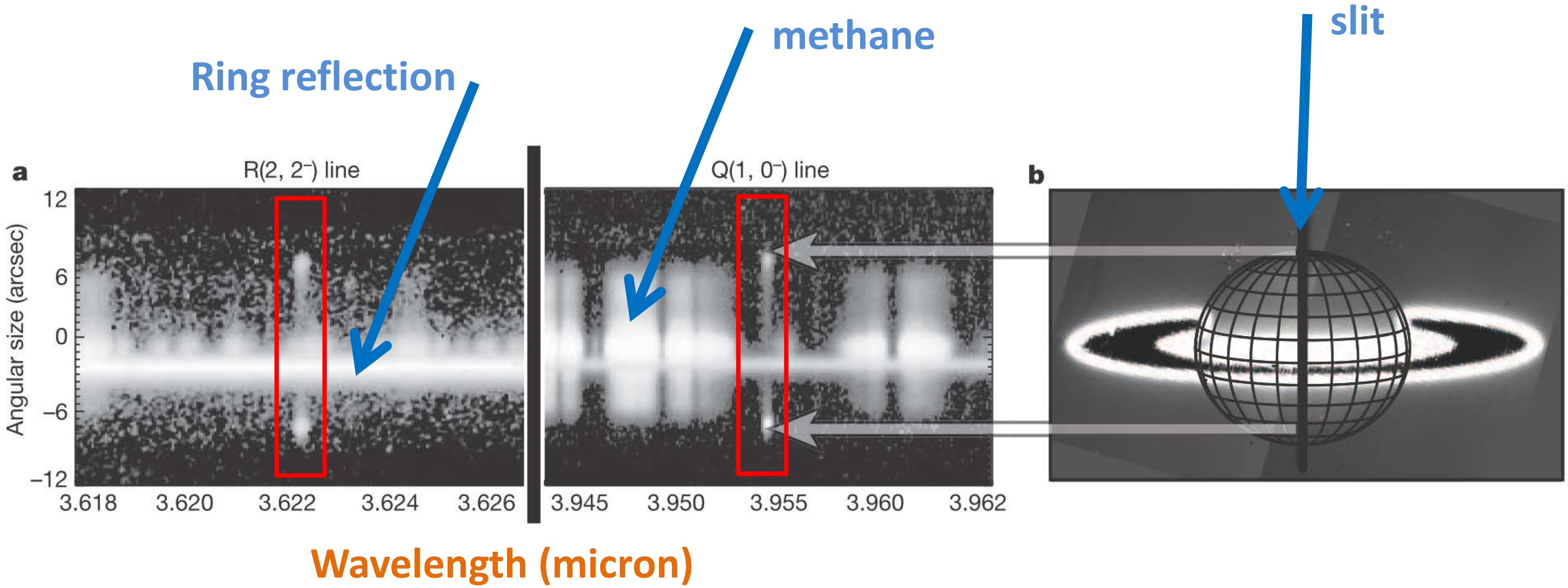
- Important as a coolant, e.g.:
  - Efficient thermostat at Jupiter
  - Hot exoplanets with dissociated H_2 lose a key cooling mechanism



Connerney and Satoh (2000)

First Low-Latitude Measurements of H_3^+

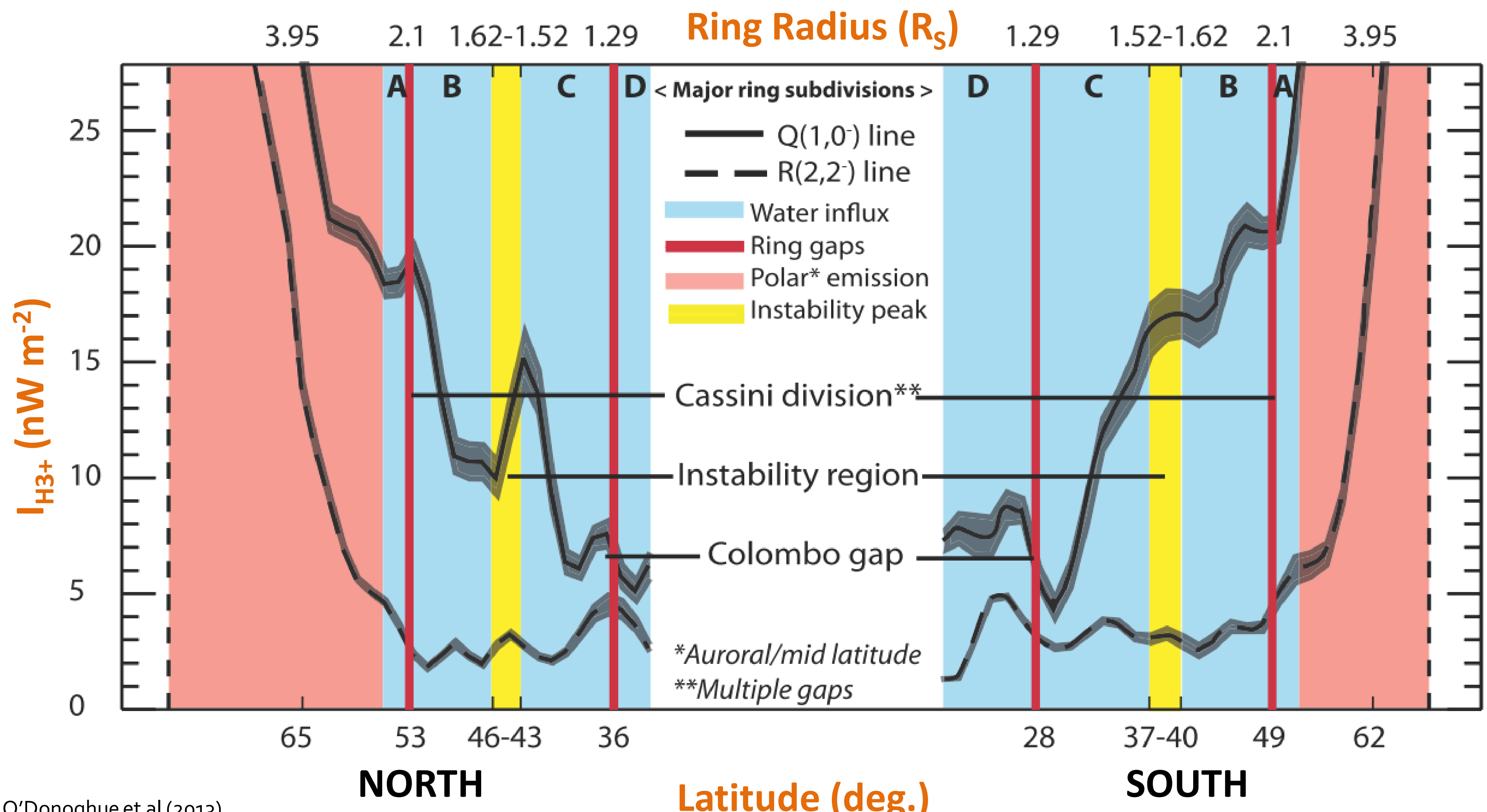
- H_3^+ frequently used as a diagnostic of outer planet ionospheres (Jupiter, Saturn, Uranus), BUT:
- H_3^+ only detected in Saturn's auroral regions until 17 April 2011 Keck NIRSPEC observations



O'Donoghue et al (2013)

Latitudinal Variations in H_3^+ Emission

- local extrema mirrored at magnetically conjugate latitudes, and also map to structures in the rings



O'Donoghue et al (2013)

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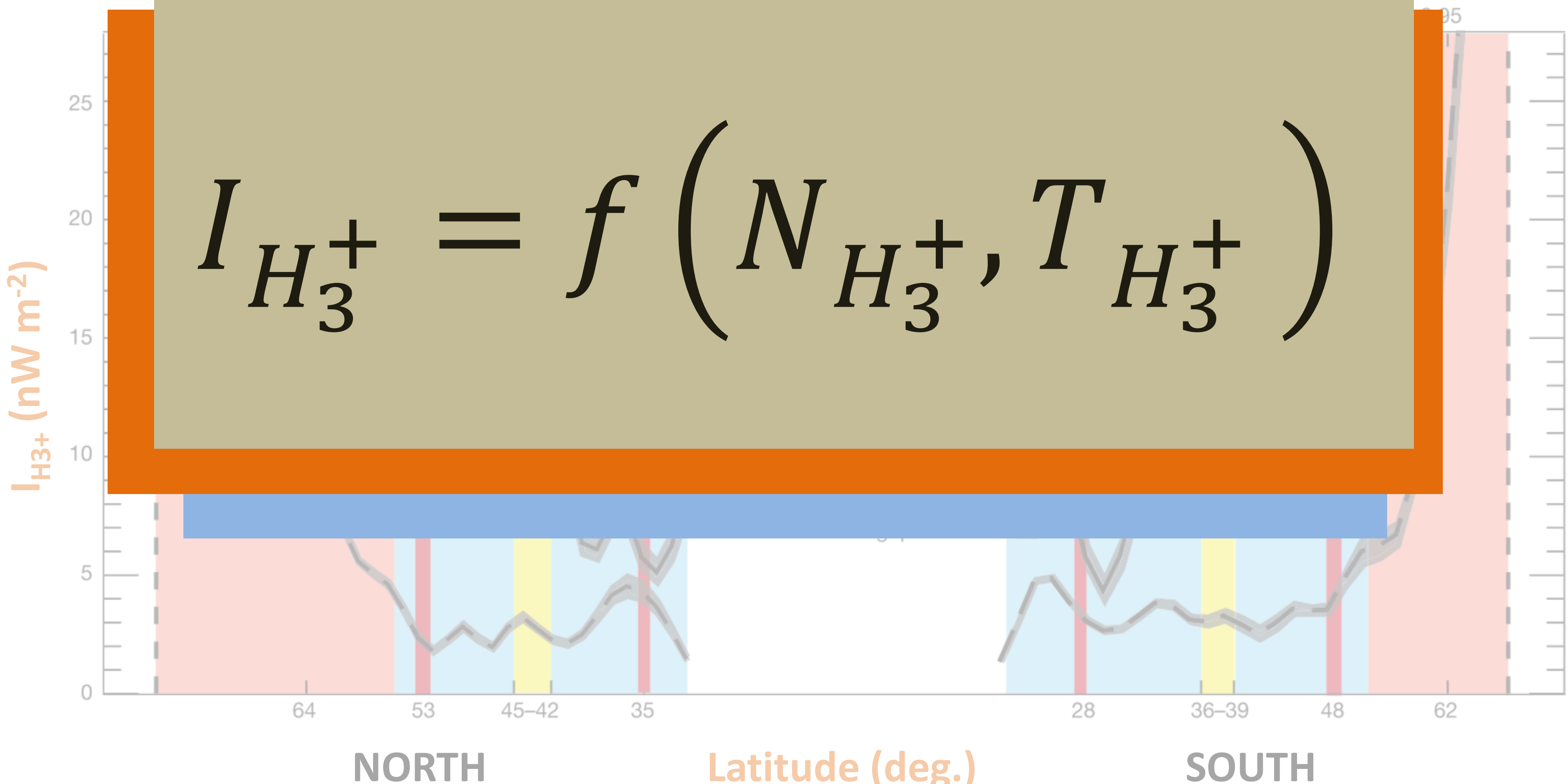
$$I_{H_3^+} = f\left(N_{H_3^+}, T_{H_3^+}\right)$$

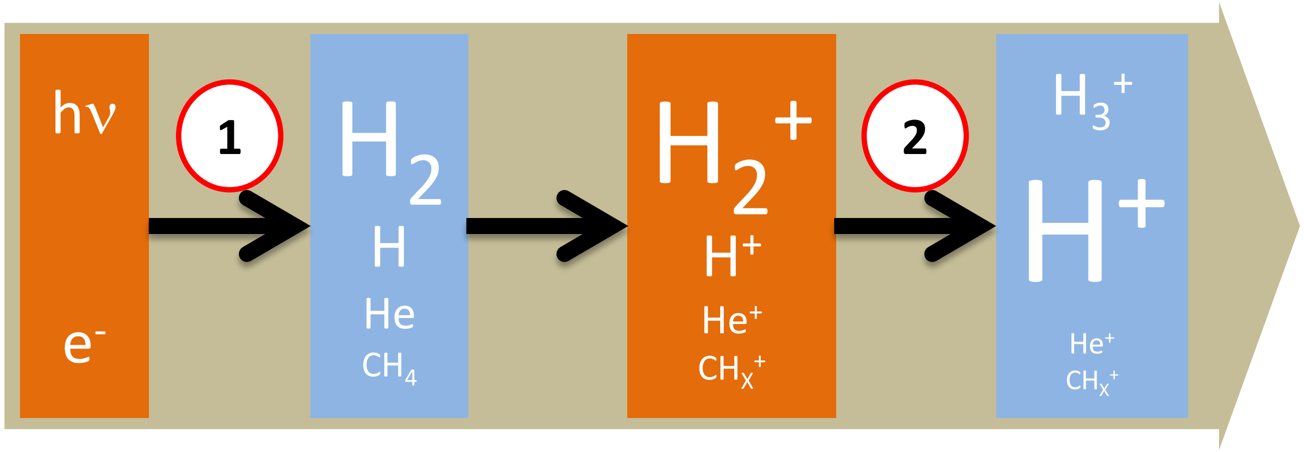


Summary of Observational Constraints

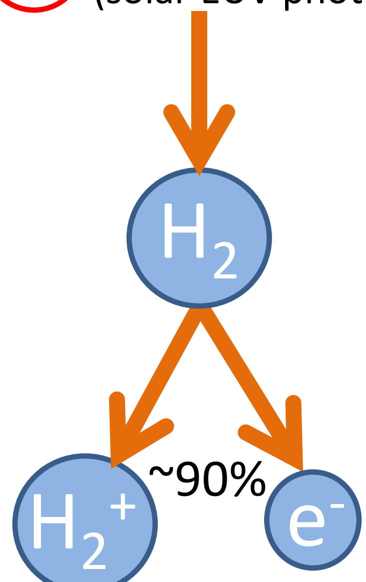
- Radio occultations
  - Unusual vertical structure: Narrow low-altitude layers of N_e
  - Average peak values: $N_{MAX} \sim 10^4$ cm^{-3} | $h_{MAX} \sim 1000$-2500 km
  - Dawn/dusk asymmetry: DAWN N_{MAX} < DUSK N_{MAX} | DAWN h_{MAX} > DUSK h_{MAX}
  - Latitudinal variation: Minimum N_{MAX} at equator; N_{MAX} increases with latitude
- Saturn Electrostatic Discharges (SEDs)
  - Strong diurnal variation: 1-2 order of magnitude variation in N_{MAX}
  - Noon and midnight values: N_{MAX}(noon) ~ 10^5 cm^{-3} | N_{MAX}(midnight) ~ 10^{3-4} cm^{-3}
- "Ring Rain"
  - Latitudinal structure in H_3^+: Non-solar structure in H_3^+ emission; coupling to rings
  - Mid- and low-latitude temperatures and densities?

Theory

Overview of Saturn's Main Ionosphere



1 Photoionization (solar EUV photons)



2 Charge-exchange and recombination

$$H_2^+ + H_2 \rightarrow H_3^+ + H$$ **FAST**

$$H_3^+ + e^- \rightarrow H_2O + H$$
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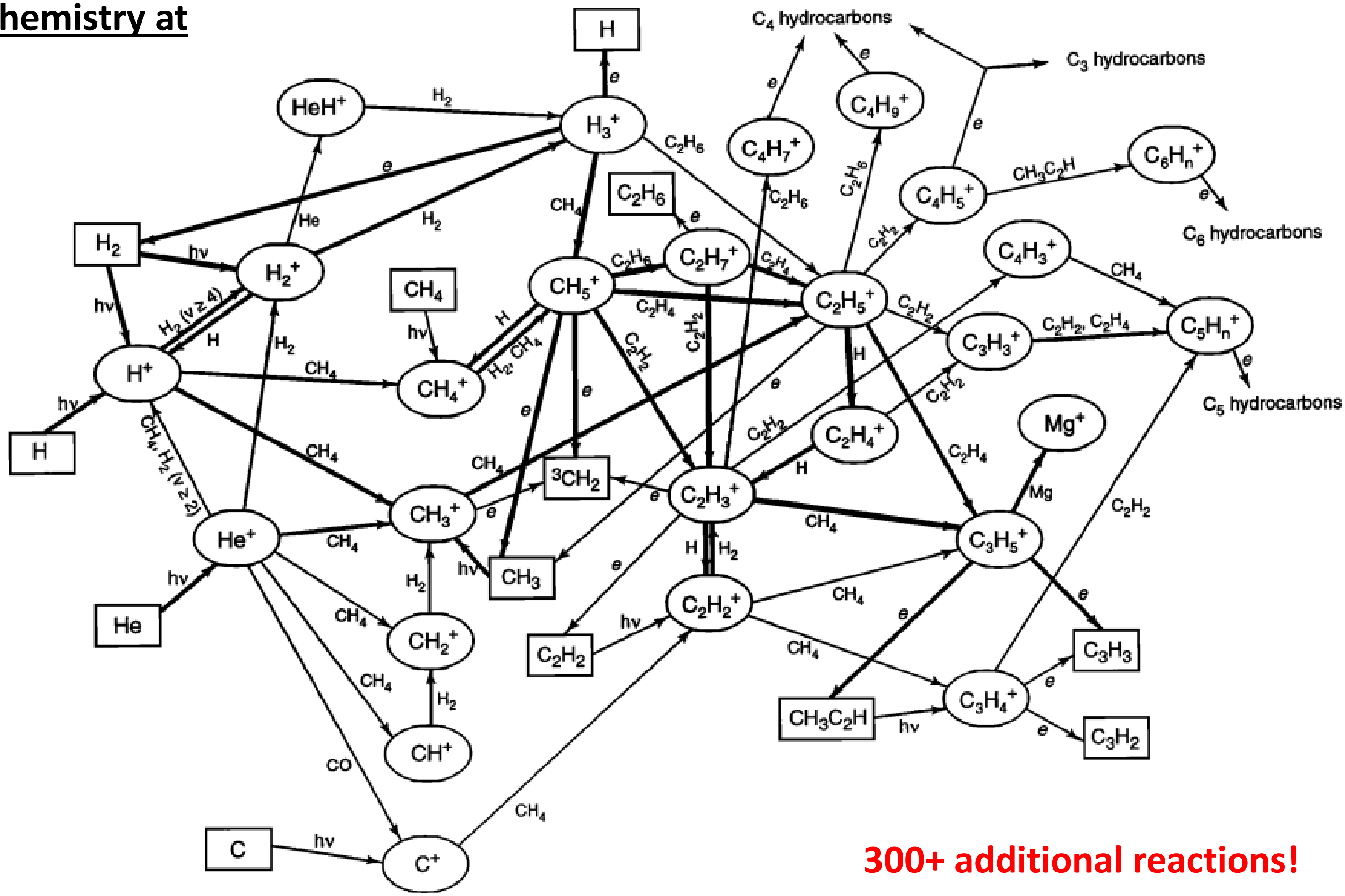
$$H^+ + e^- \rightarrow H$$ **SLOW**

Hydrocarbon photochemistry

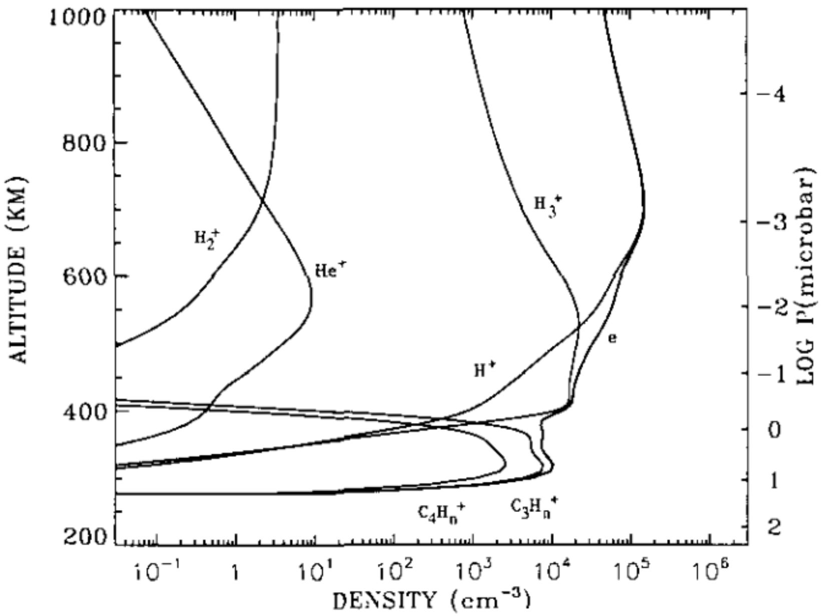
Simplified Schematic of Hydrocarbon Photochemistry at Saturn



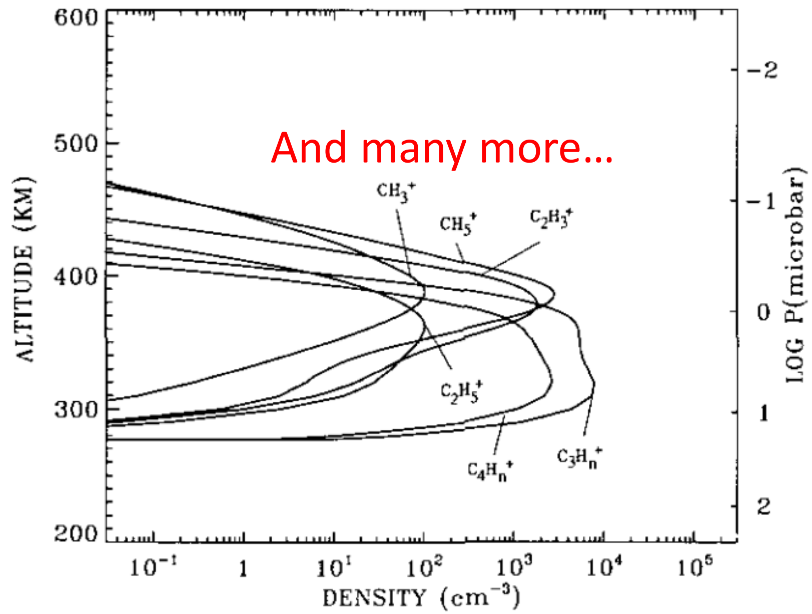
300+ additional reactions!

Moses and Bass (2000)

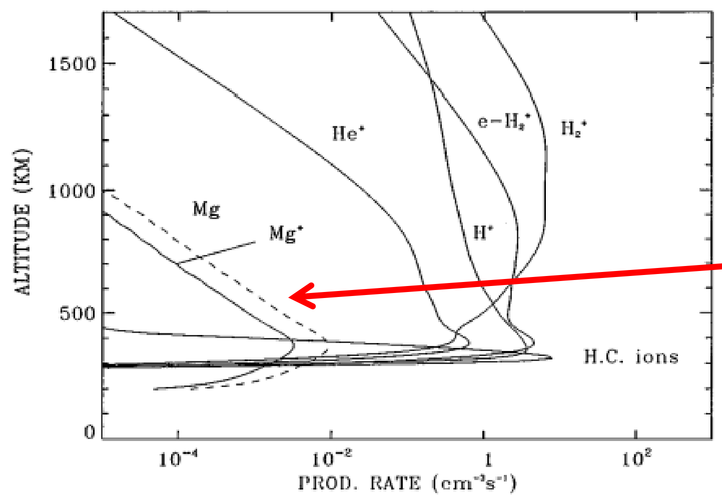
Hydrocarbon/metallic ion ledge



Kim and Fox (1994)



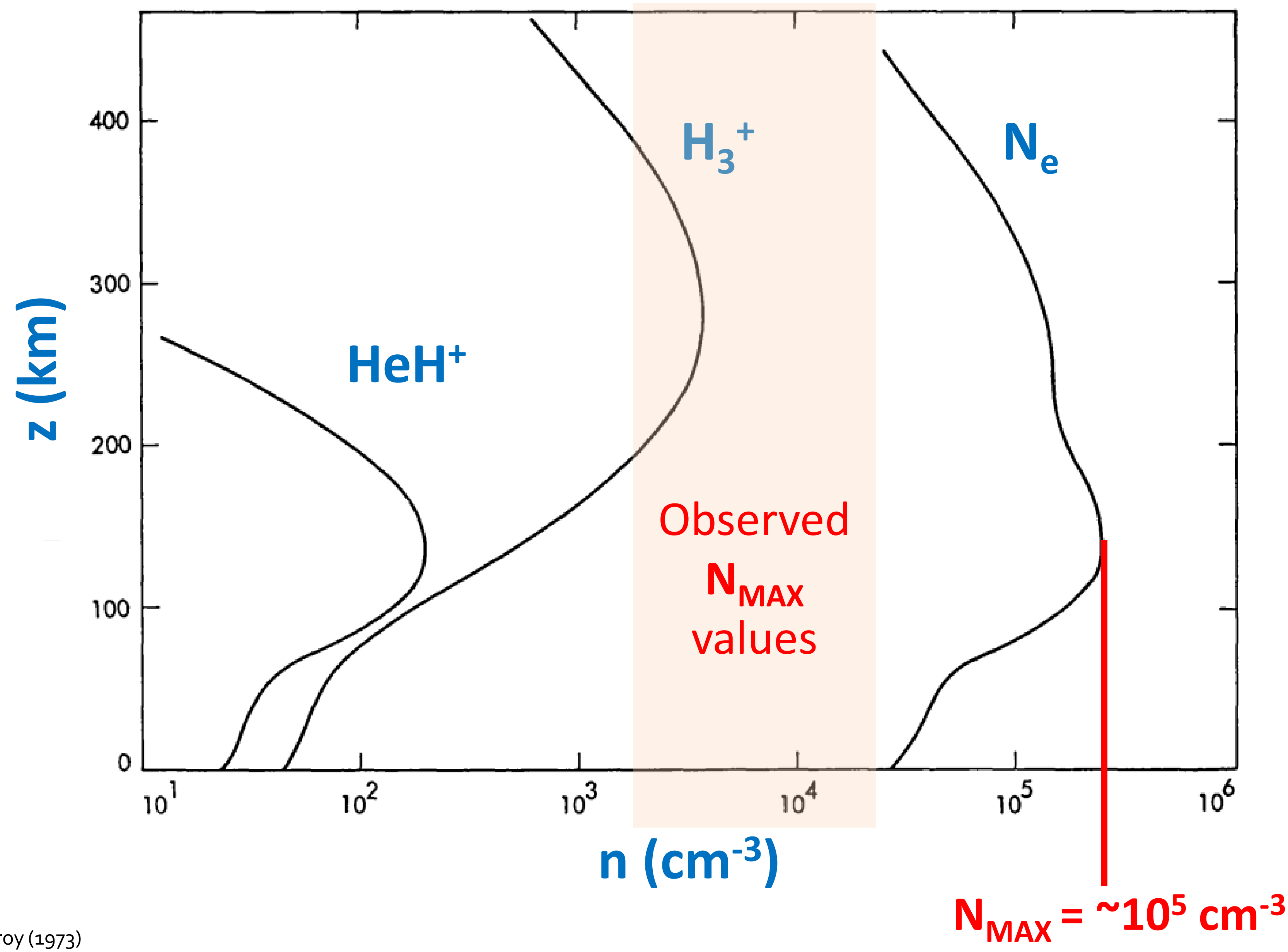
And many more…



Meteoroid ablation deposition leads to Mg/Mg^+, Fe/Fe^+, Si/Si^+, O/O^+, S/S^+, C/C^+, etc.

Kim and Fox (2001)

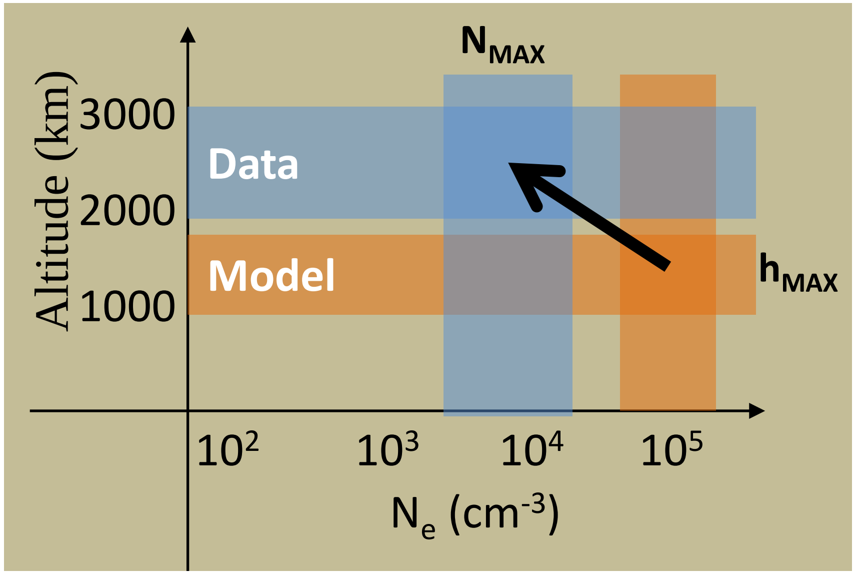
Predicted Ionospheric Densities



McElroy (1973)

Radio Occultation Constraints:

N_{MAX} ~ 10^4 cm^{-3} | h_{MAX} ~ 1000-2500 km

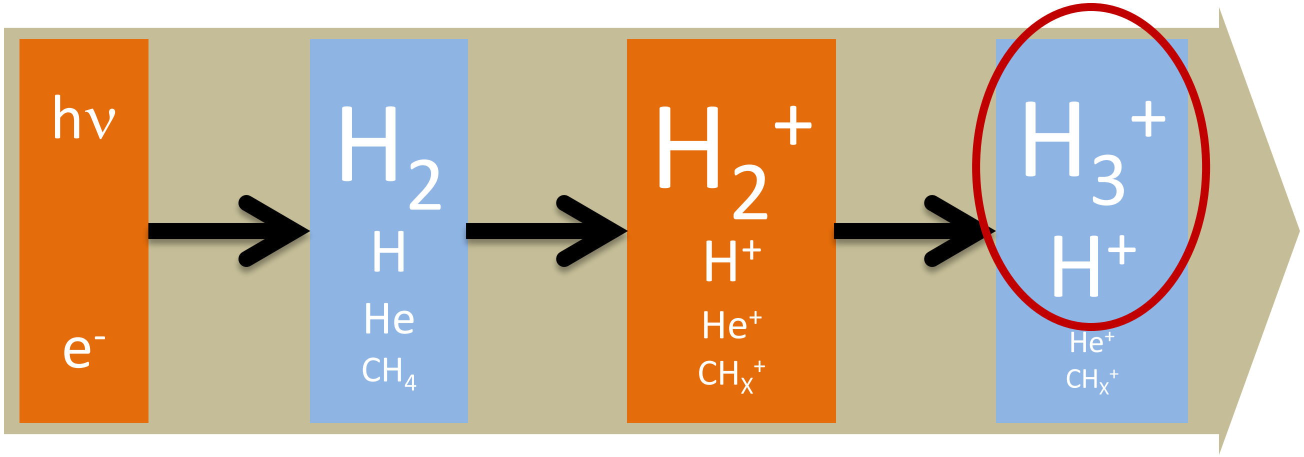


Water

$H^+ + H_2O$	→	$H_2O^+ + H$
$H_2O^+ + H_2$	→	$H_3O^+ + H$
$H_3O^+ + e$	→	$H_2O + H$ $OH + 2H$

Vibrationally Excited H_2

$H^+ + H_2(\nu \geq 4)$	→	$H_2^+ + H$
$H_2^+ + H_2$	→	$H_3^+ + H$
$H_3^+ + e$	→	$3H$ $H_2 + H$



Radio Occultation Constraints:

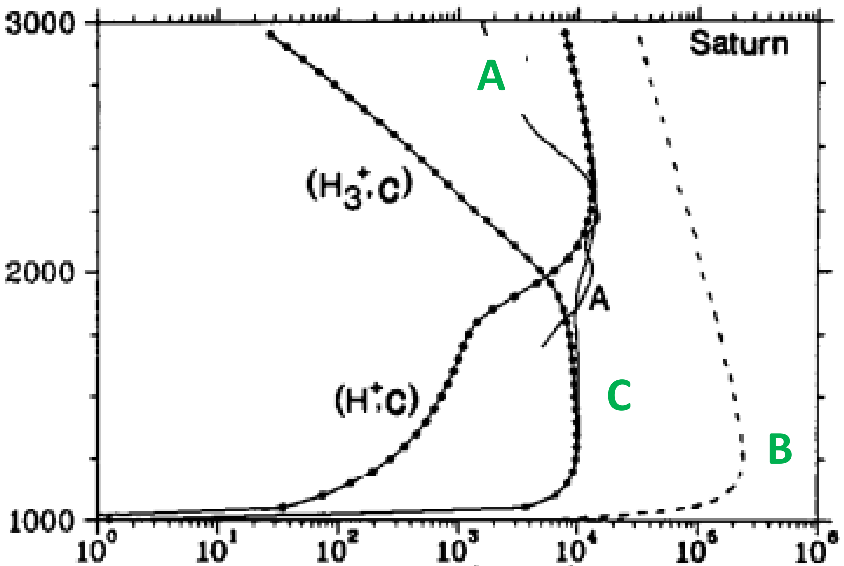
$N_{MAX} \sim 10^4\ cm^{-3}$ | $h_{MAX} \sim 1000\text{-}2500$ km

Forced vertical drift (↑h_{MAX})

Enhanced $H_2(\nu \geq 4)$ population(↓N_{MAX})

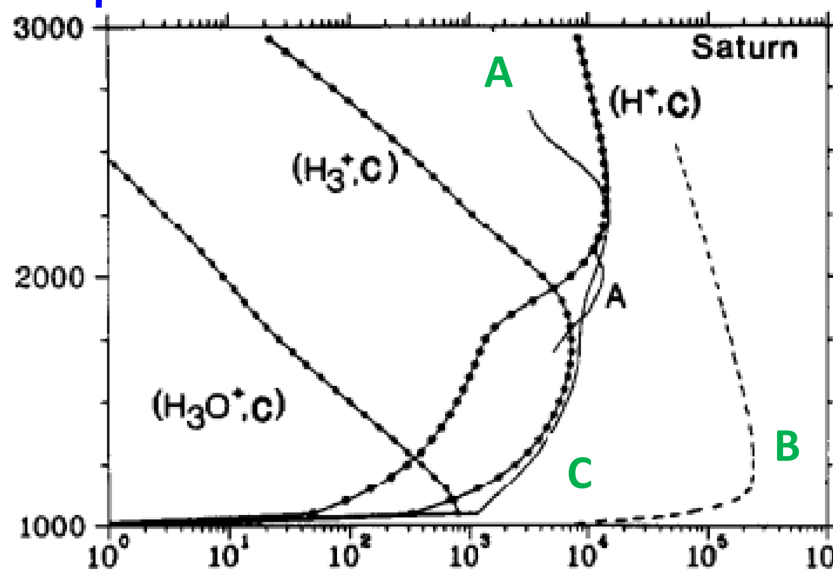
Topside H_2O influx (↓N_{MAX})

z (km)



n (cm⁻³)

z (km)



n (cm^{-3})

A – observations

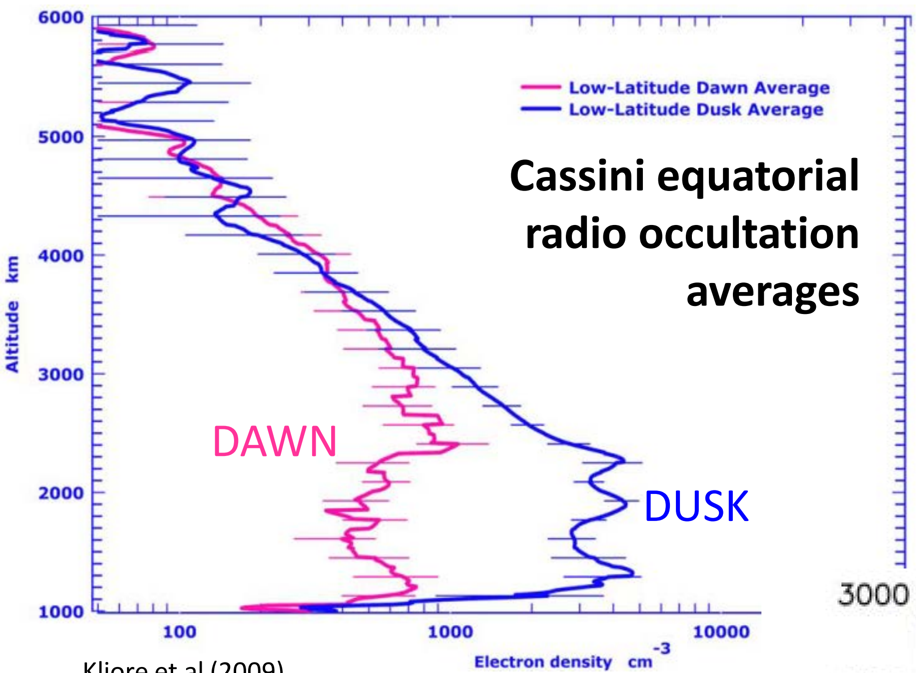
B – nominal model

C – model fit

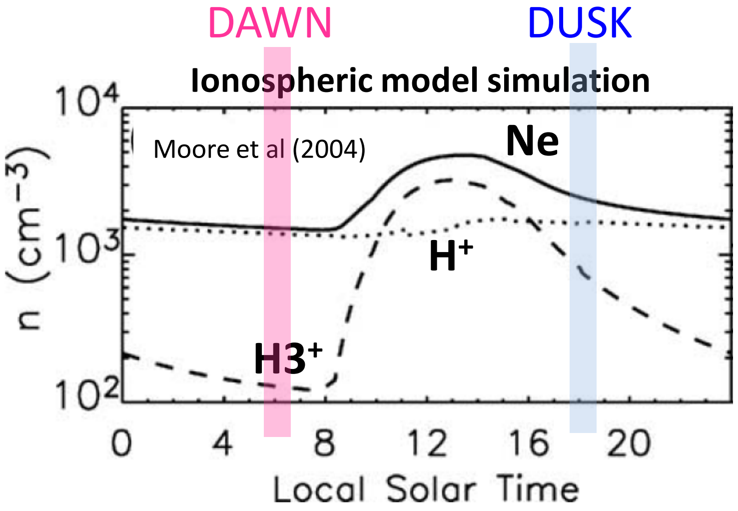
Majeed and McConnell (1991)

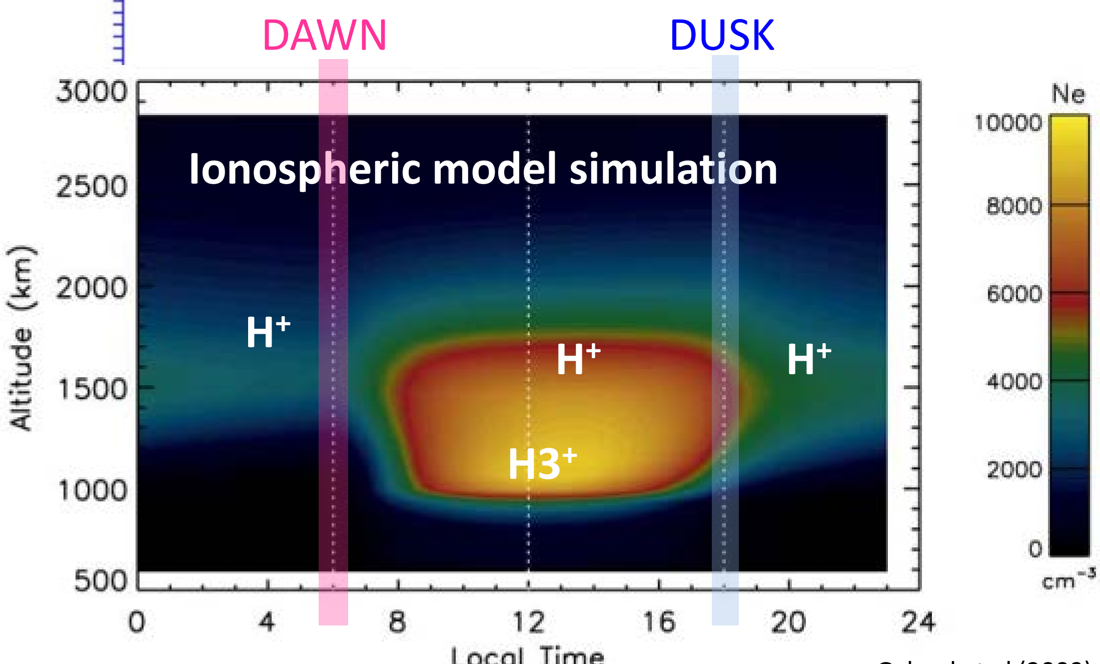
Radio Occultation Constraints

DAWN N_{MAX} < DUSK N_{MAX} DAWN h_{MAX} > DUSK h_{MAX}



Kliore et al (2009)





Galand et al (2009)

At Saturn's equator:

$N_{MAX} \sim 10^3\ cm^{-3}$

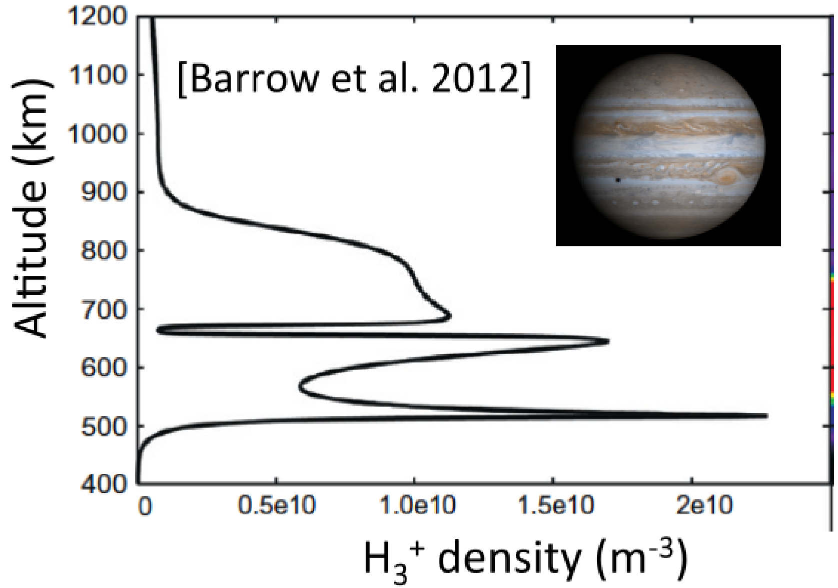
$h_{MAX} \sim 1200\text{-}2800$ km

Radio Occultation Constraints:

Narrow low-altitude layers of N_e

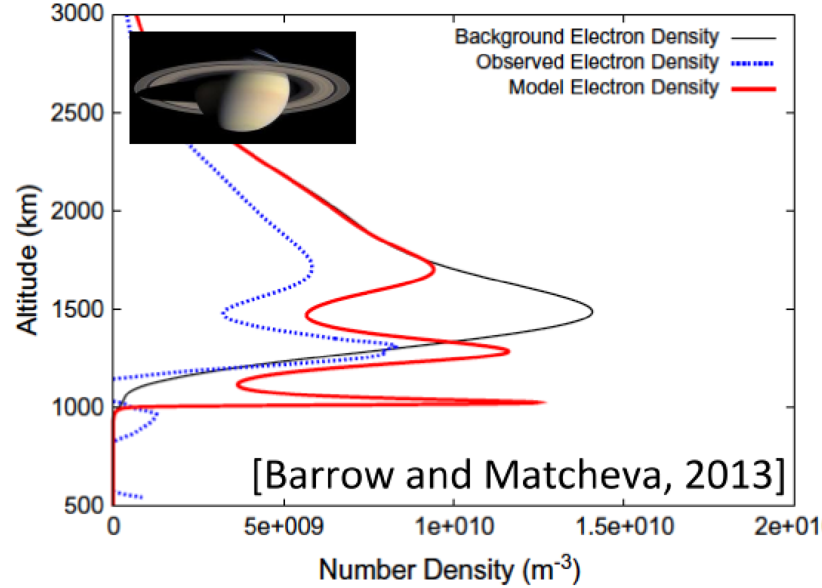
- Structure driven by vertical wind shear interactions with magnetic field. Such shears could result from gravity wave breaking.

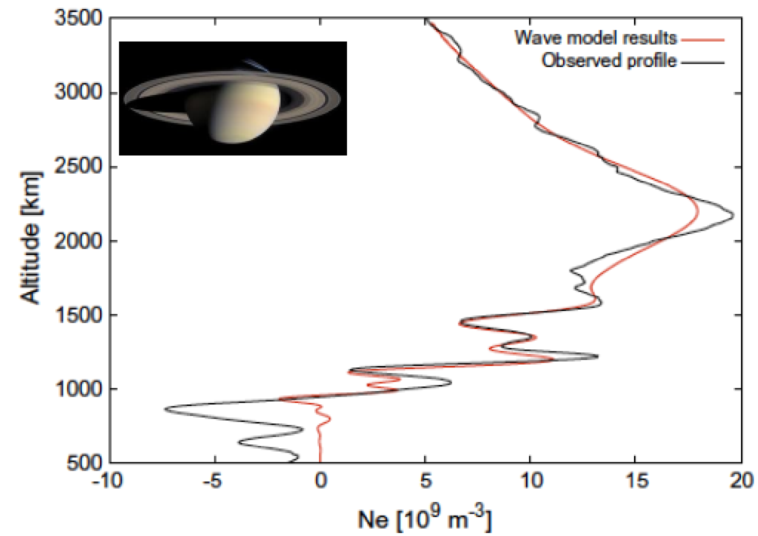
Simulations



- Other sources remain possible, such as meteoric layers.

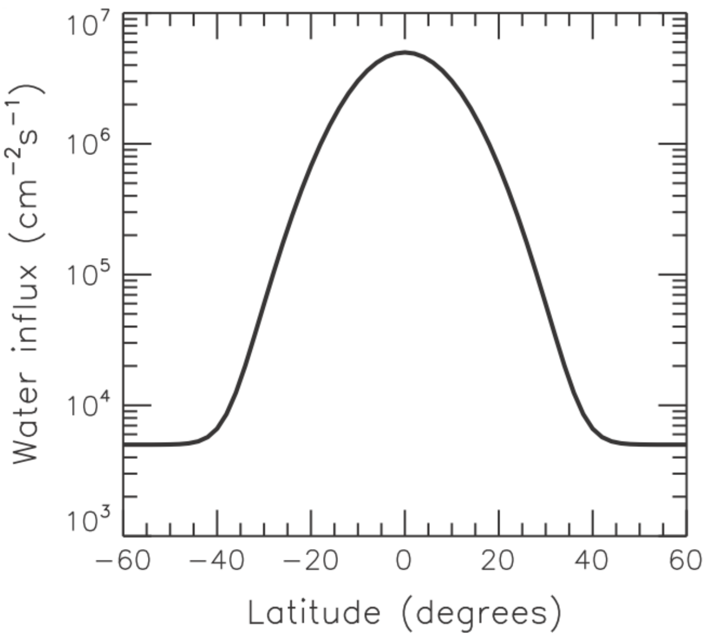
Simulations

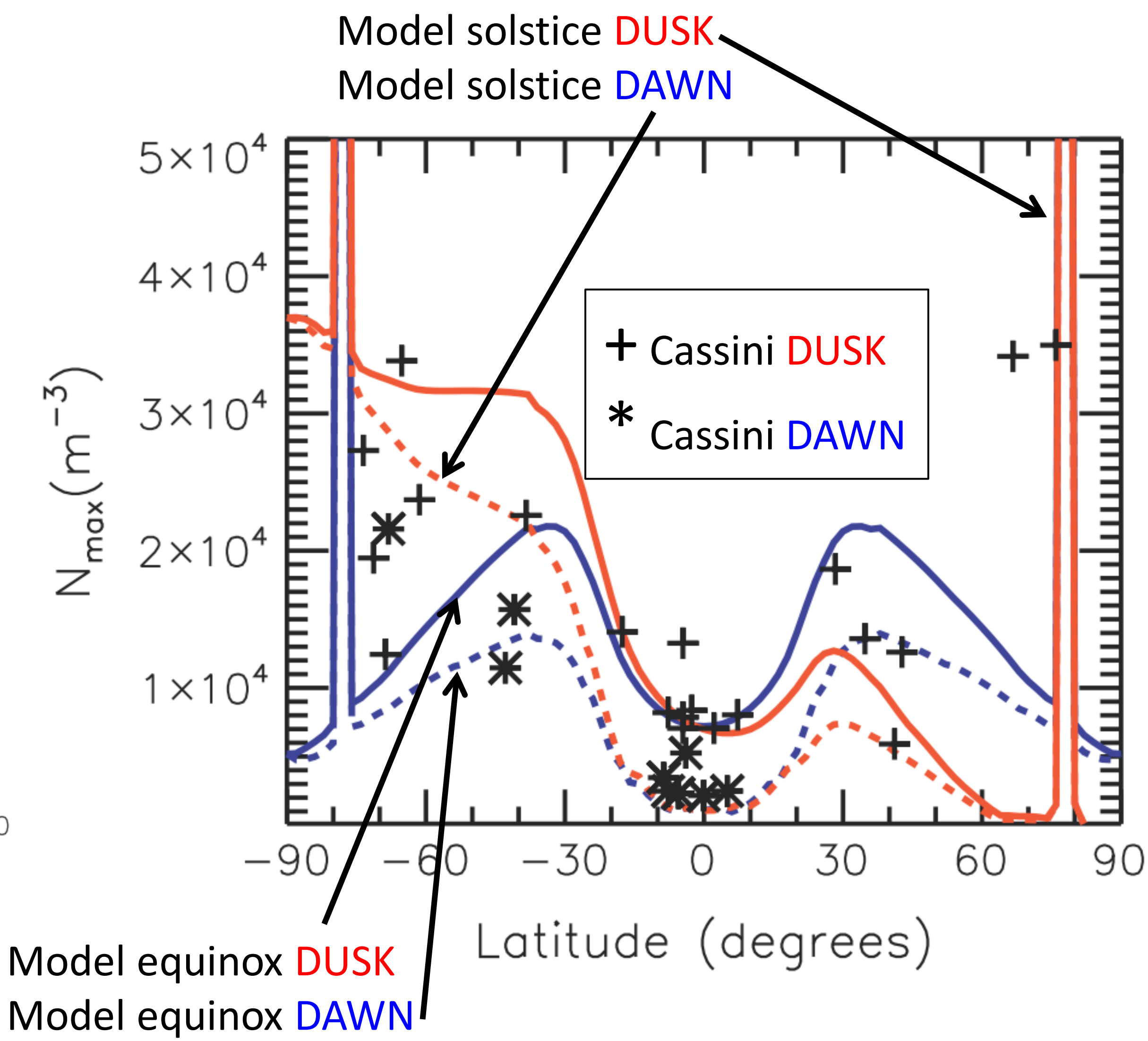




Radio Occultation Constraints: Minimum N_{MAX} at equator; N_{MAX} increases with latitude

Topside H_2O influx (derived)

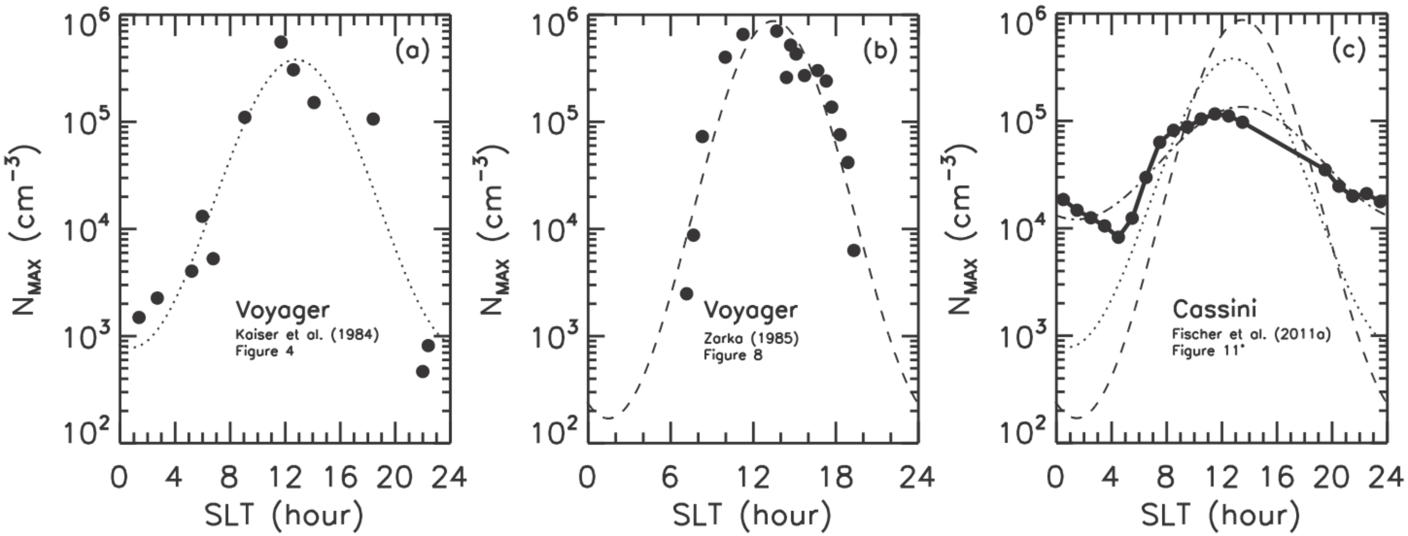




Mueller-Wodarg et al (2012)

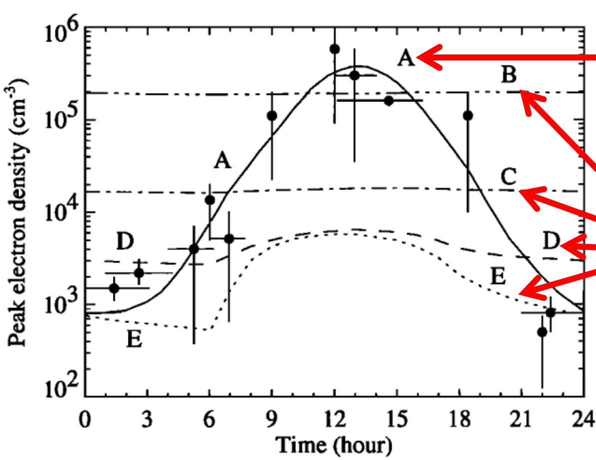
SED constraints:

1-2 order of magnitude variation in N_{MAX}



Moore et al (2012)

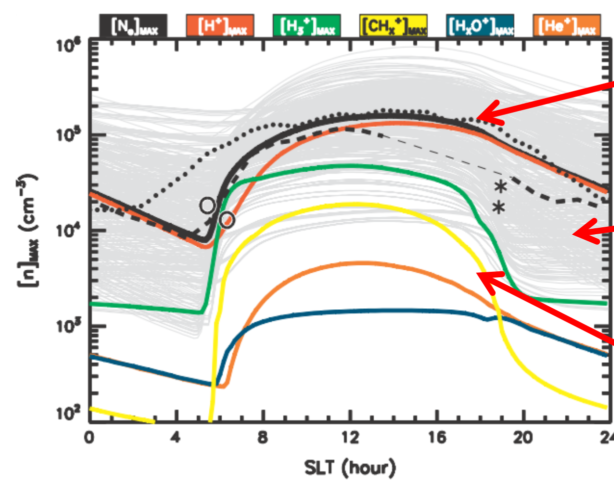
- Significant ionization enhancements required to match dawn-noon rise
- Drastic losses required to match nighttime decline
- Non-photochemical solution? Low altitude ion layers?



Voyager result (A)

Various attempted model fits (B-E)

Majeed and McConnell (1996)



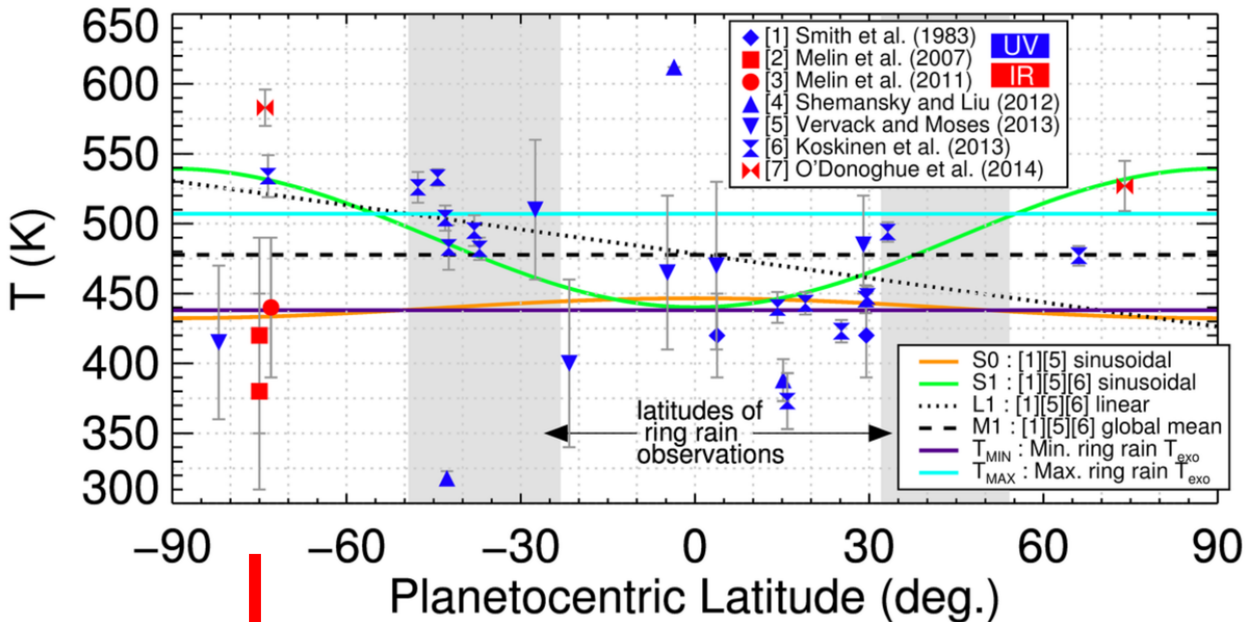
Cassini results (dotted and dashed)

Various attempted model fits (grey)

Best model fit (solid lines)

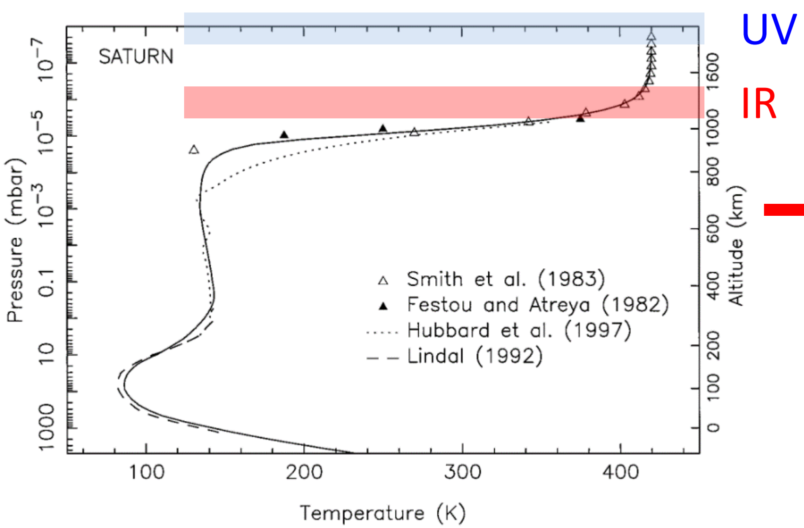
Moore et al (2012)

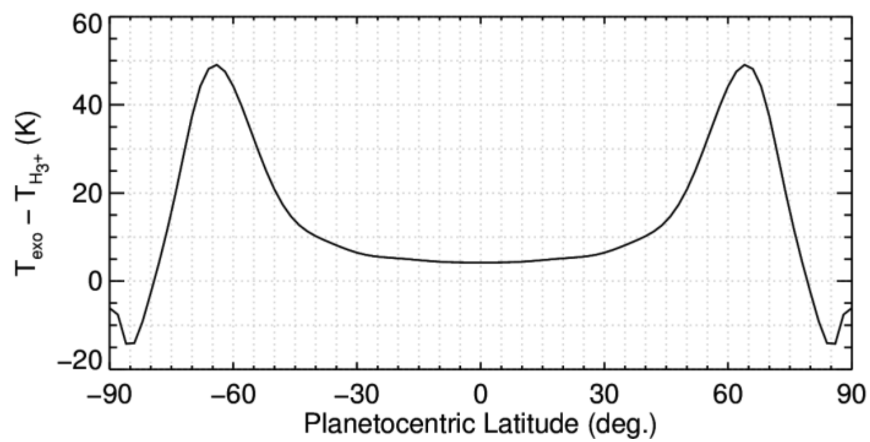
Ring rain constraints: Non-solar structure in H_3^+ emission; coupling to rings



$$N_{H_3^+} = f\left(I_{H_3^+}, T_{H_3^+}\right)$$

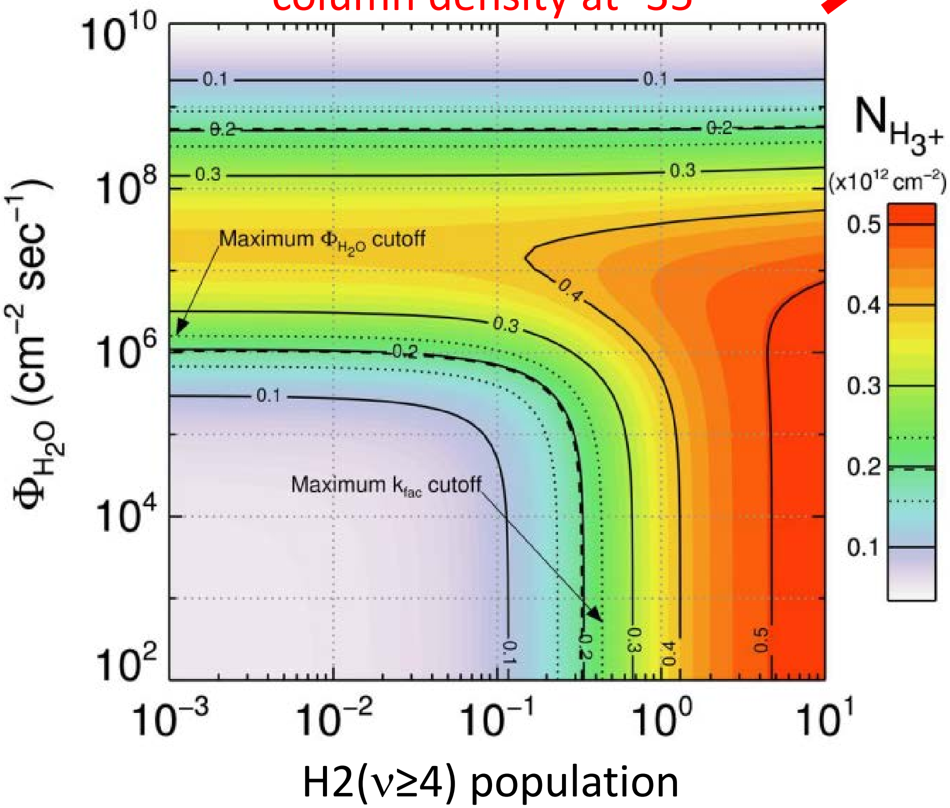
$$T_{H_3^+} = f(\phi_{pc})$$



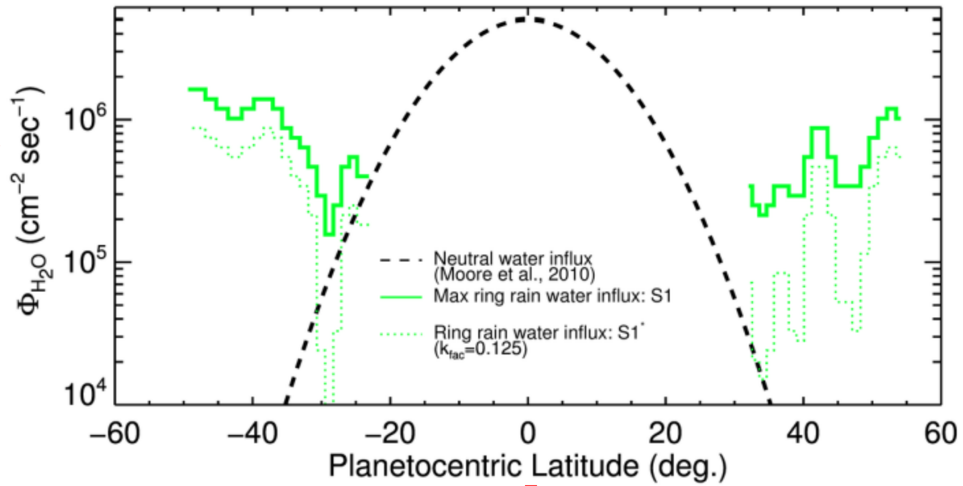


Ring rain constraints: Non-solar structure in H_3^+ emission; coupling to rings

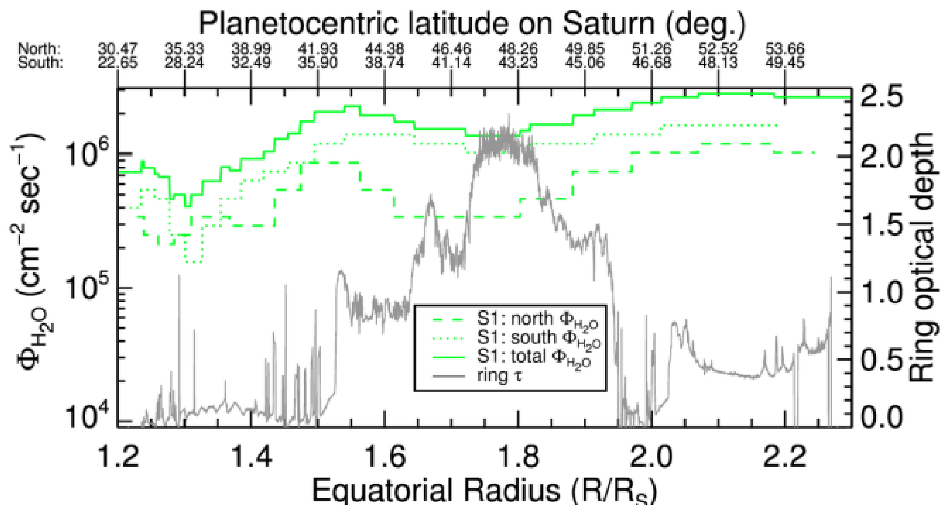
Family of solutions matching ring rain H_3^+ column density at -35^0



Global water influx at Saturn

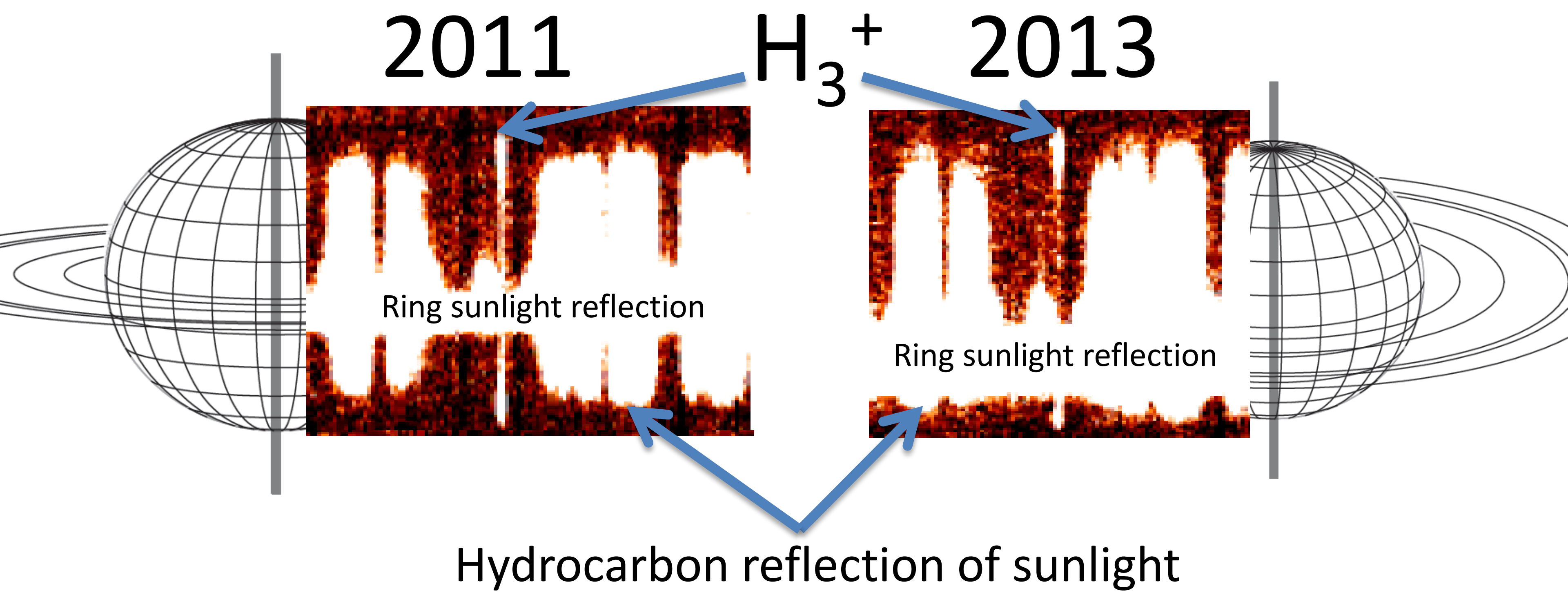


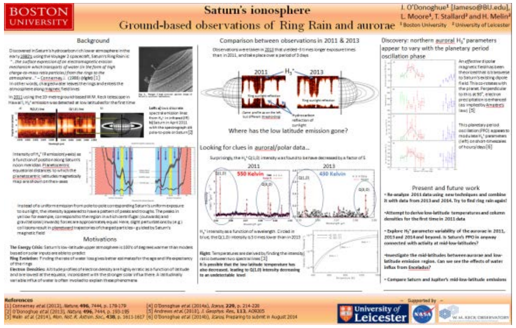
Water influx mapped to ring plane



Moore et al (2014)

Ring rain: where is it?





See poster by James O'Donoghue

Summary of Model Data Comparisons

- Radio occultations
  - ✓ Unusual vertical structure:
    - Narrow low-altitude layers of N_e
    - Gravity waves. (Meteors?)
  - ✓ Average peak values:
    - $N_{MAX} \sim 10^4$ cm^{-3}
    - $h_{MAX} \sim$ 1000-2500 km
  - Dawn/dusk asymmetry:
    - DAWN N_{MAX} < DUSK N_{MAX}
    - DAWN h_{MAX} > DUSK h_{MAX}
    - Water influx and/or $H_2(\nu \geq 4)$ enhancements.
  - ✓ Latitudinal variation:
    - Minimum N_{MAX} at equator; N_{MAX} increases with latitude
    - Latitudinal variation in water influx.
- Saturn Electrostatic Discharges (SEDs)
  - X Strong diurnal variation:
    - 1-2 order of magnitude variation in N_{MAX}
  - Noon and midnight values:
    - N_{MAX}(noon) $\sim 10^5$ cm^{-3}
    - N_{MAX}(midnight) $\sim 10^{3\text{-}4}$ cm^{-3}
    - Require extreme ionization enhancement process. Low altitude layers?
- "Ring Rain"
  - ✓ Latitudinal structure in H_3^+:
    - Non-solar structure in H_3^+ emission; coupling to rings
    - Latitudinal variation in water influx and/or heating?

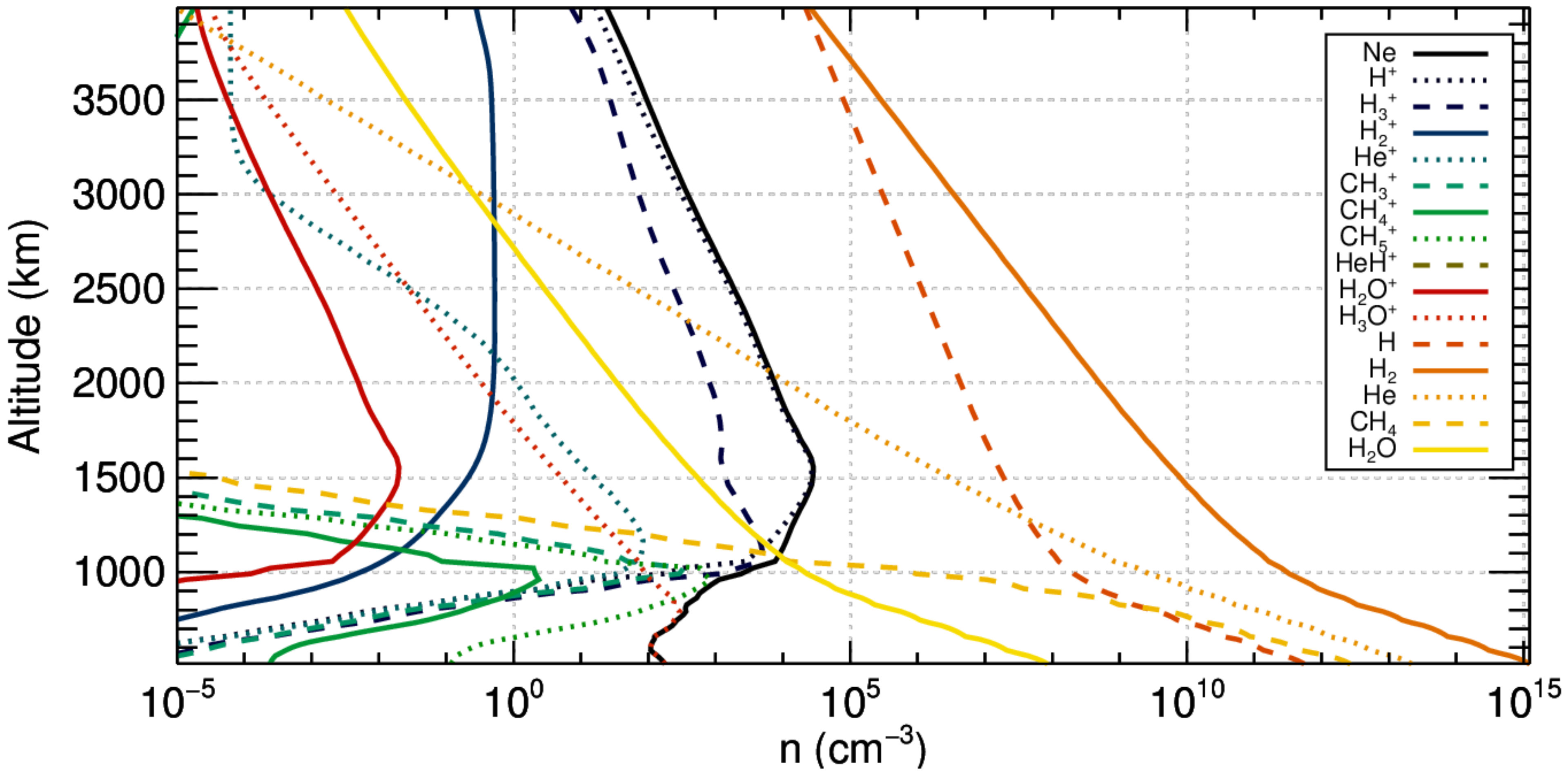
A look towards the future

- Radio occultations
  - Further mid- and high-latitude occultations to help solidify the trend in N_{MAX} there
- Proximal orbits
  - Ion densities? Electron densities?
  - SEDs? (attenuation varies with frequency, so Cassini SED measurements close to Saturn may alter derived N_{MAX} trend)
- "Ring Rain" observations
  - Self-consistent H_3^+ temperatures and densities (H^+ densities)
- Water measurements
  - Help reinforce influxes derived from Ionospheric model-data comparisons

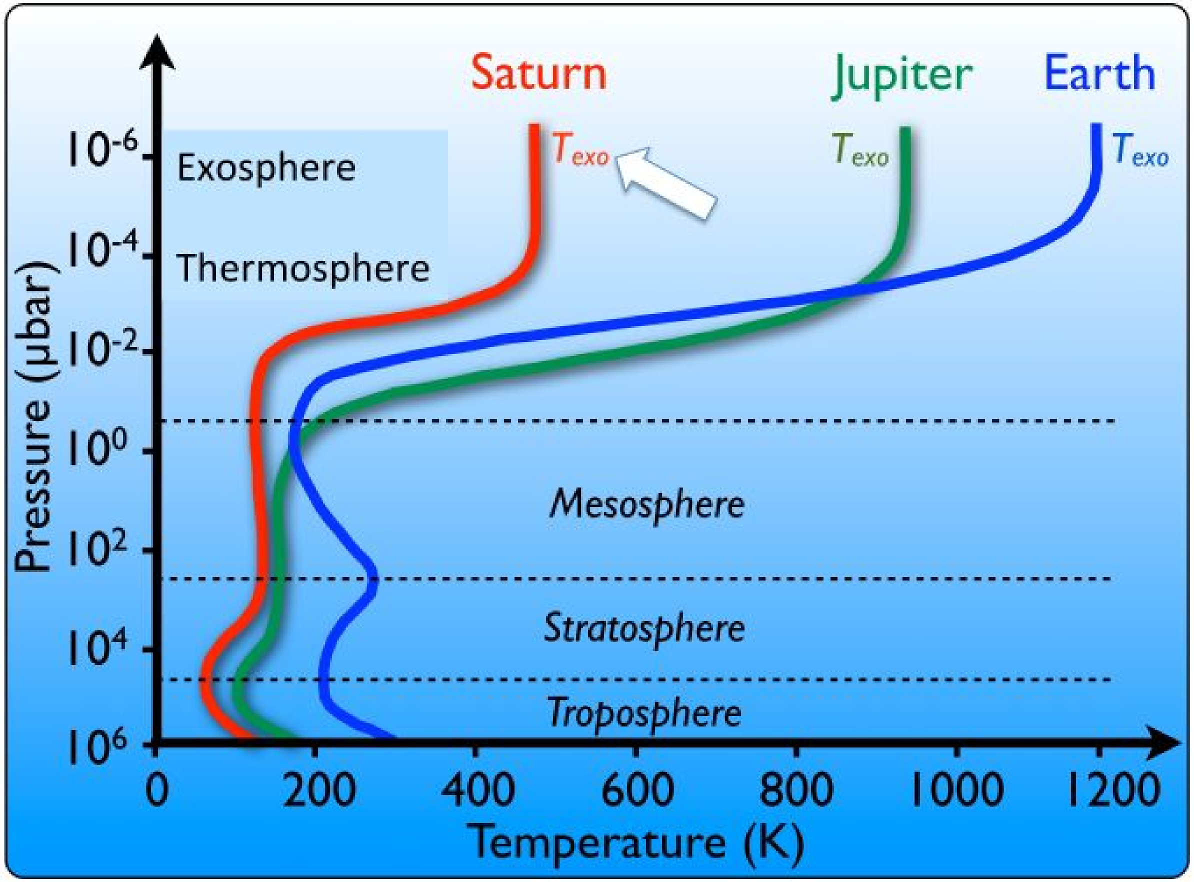
X

Representative Ionospheric Structure

- Basic Ionospheric structure
  - Basic



Thermal Profile Comparisons



I. Müller-Wodarg

Thermosphere:

- Positive temperature gradient
- Collective (fluid) behavior

Exosphere:

- Constant temperature ("exospheric temperature")
- Infrequent collisions → kinetic particle behavior and escape