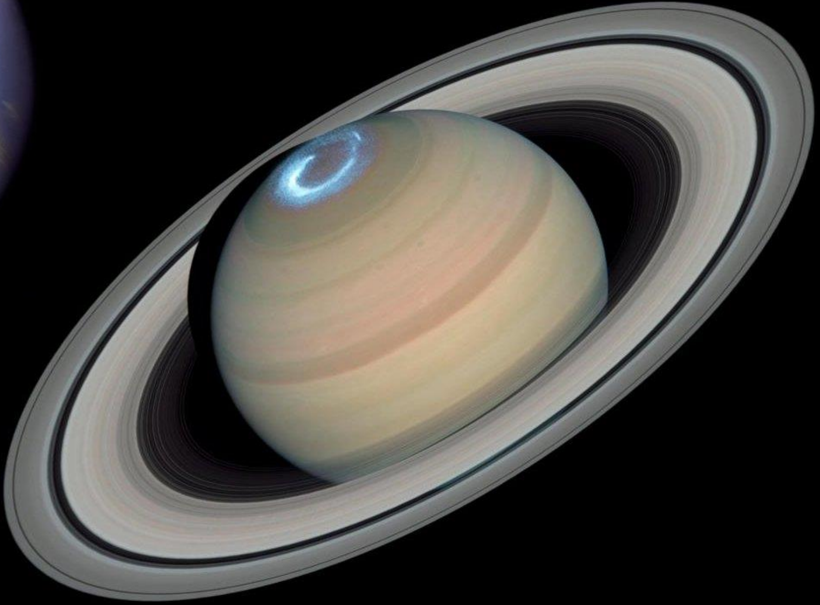
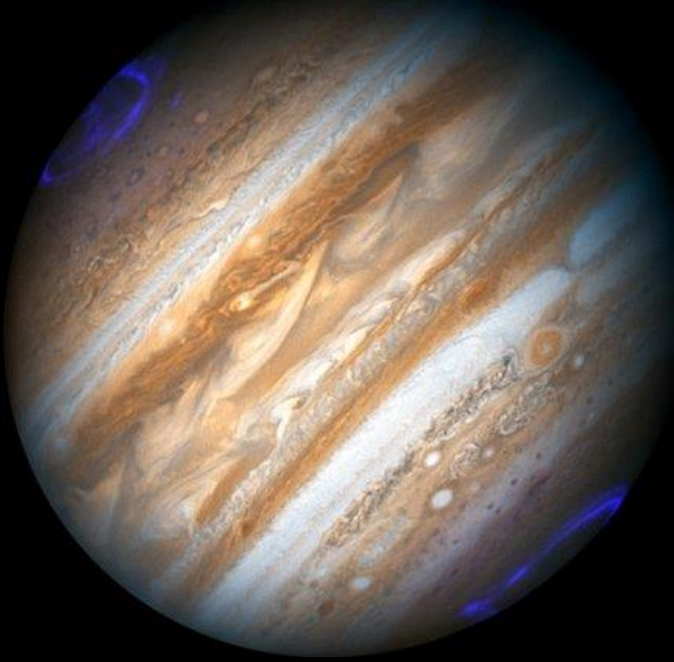





Upper atmospheres of the giant planets

Interfaces between atmospheres and magnetospheres

Luke Moore, Boston University
Marina Galand, Imperial College London

Part I

Giant planet upper atmospheric physics, observations, and theory

Outline, Part I

- Upper atmosphere "basics"
  - Thermosphere, ionosphere, exosphere, homopause…
- Generation of an ionosphere
  - Photon absorption, particle precipitation
  - Ion production and loss
- Remote ionospheric diagnostics
  - Giant planet observations
- Model-data comparisons
  - Outstanding issues

Astrophysicists beware:

"H-two" = $H_2 \neq$ HII

"H-plus" = H^+ = HII

Atmospheres everywhere

Dense Atmospheres

N_2 atmospheres

- Earth
- Titan
- Triton
- Pluto

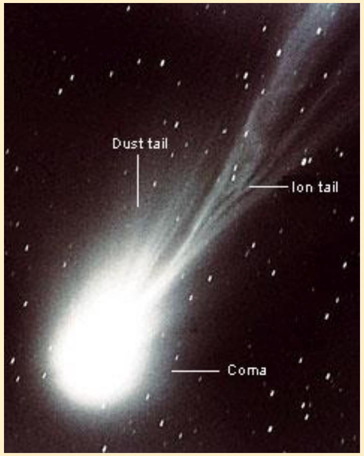
CO_2 atmospheres

- Venus
- Mars
- Pluto

H_2/H/He atmospheres

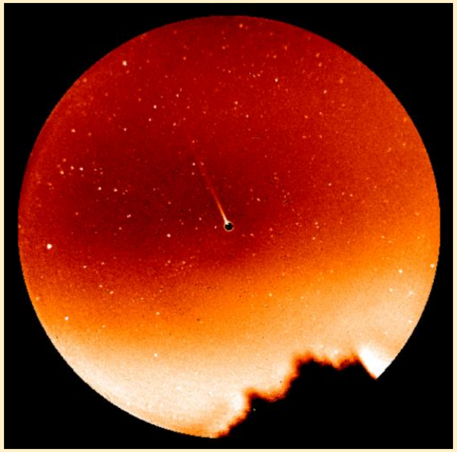
- Jupiter (P10/P11/V1/V2/Ulysses/Cassini/New Horizons, **Galileo**)
- Saturn (P11/V1/V2, **Cassini**)
- Uranus (V2)
- Neptune (V2)

Coma

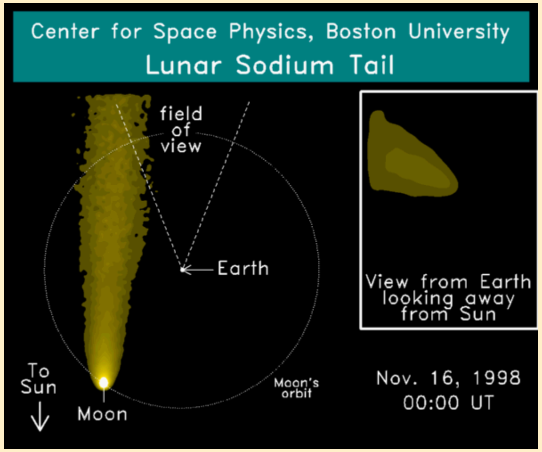


Lick Observatory

Surface-bound Exospheres



Baumgarder et al. (2008)

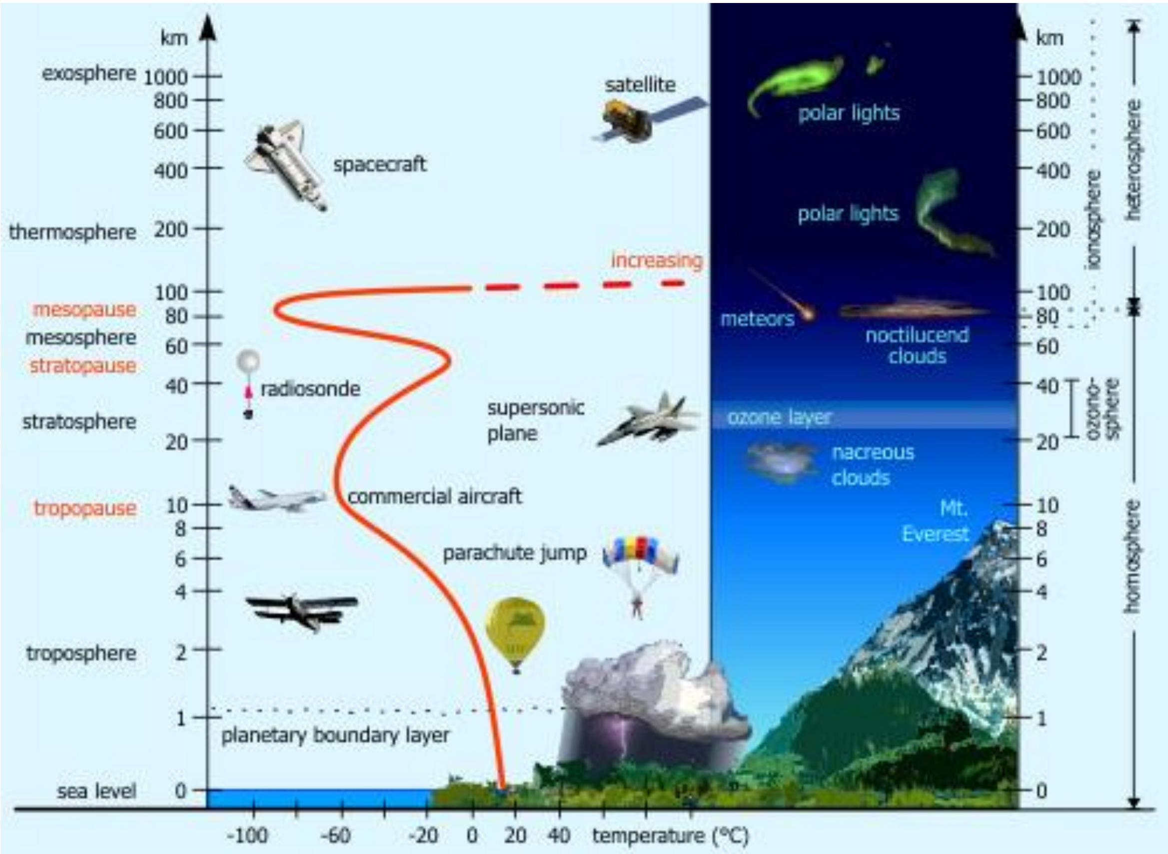


J. Wilson

And more…

- Enceladus
- Io
- Europa
- Ganymede
- Callisto

Atmospheric regimes

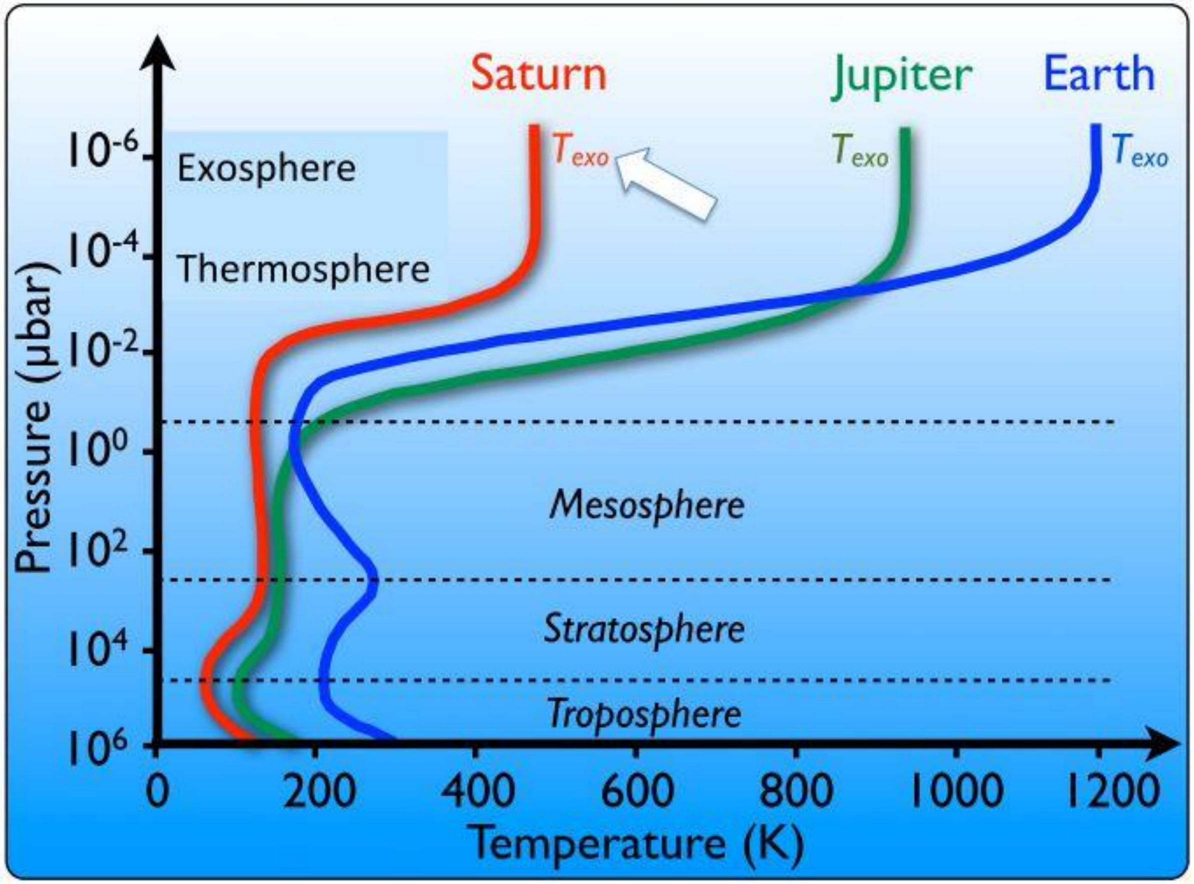


Upper atmosphere (aeronomy)

- **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)

Thermal profiles

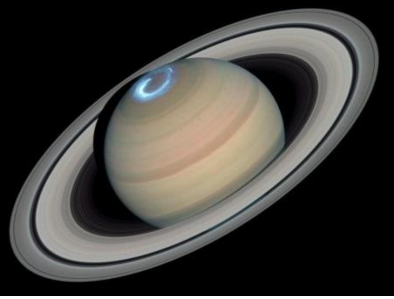


I. Müller-Wodarg

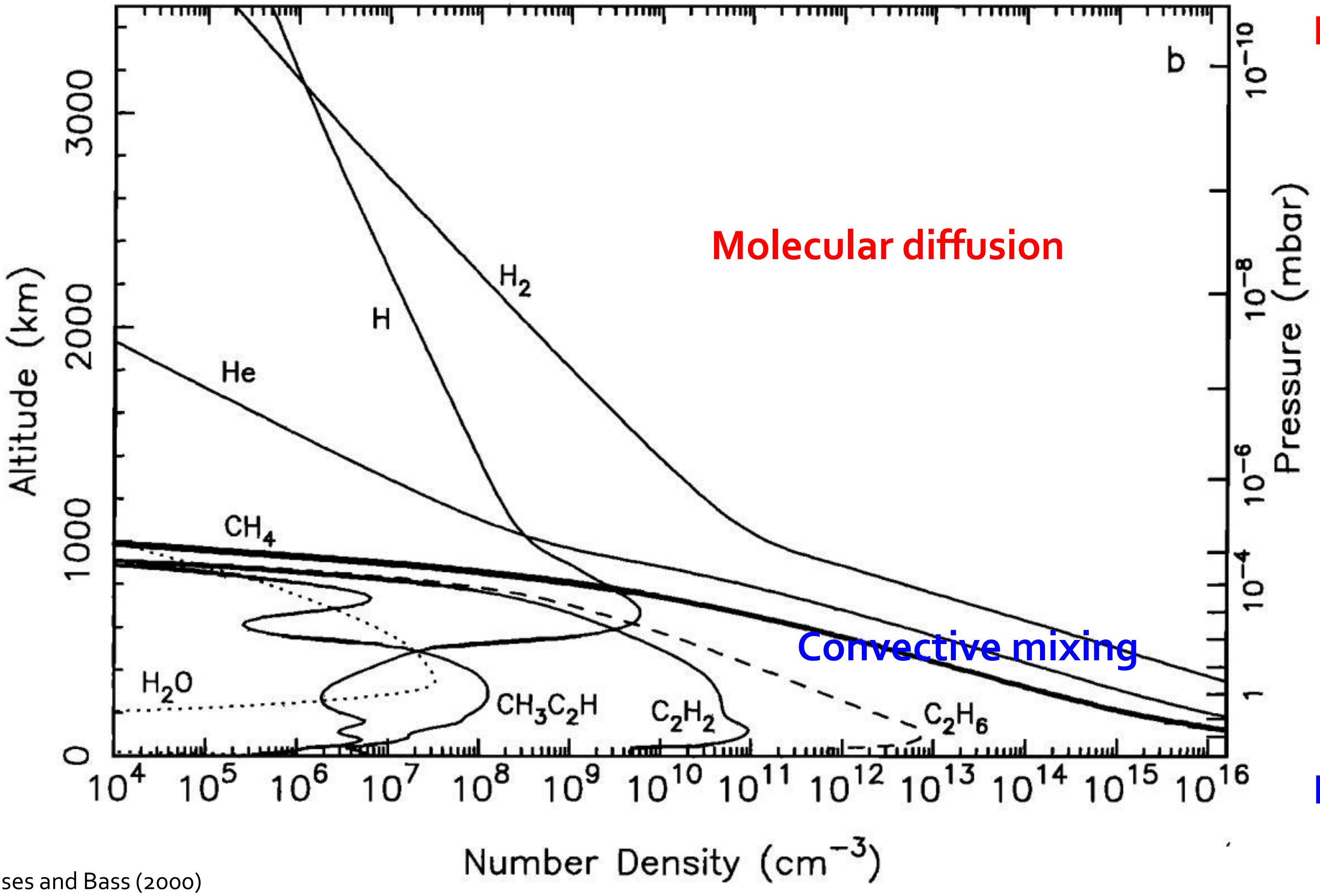
Thermosphere:
- Positive temperature gradient
- Collective (fluid) behavior

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

Thermosphere of Saturn



Reference altitude (0 km) = 1 bar level



Heterosphere

Homopause / Turbopause

Homosphere

Moses and Bass (2000)

Ionosphere

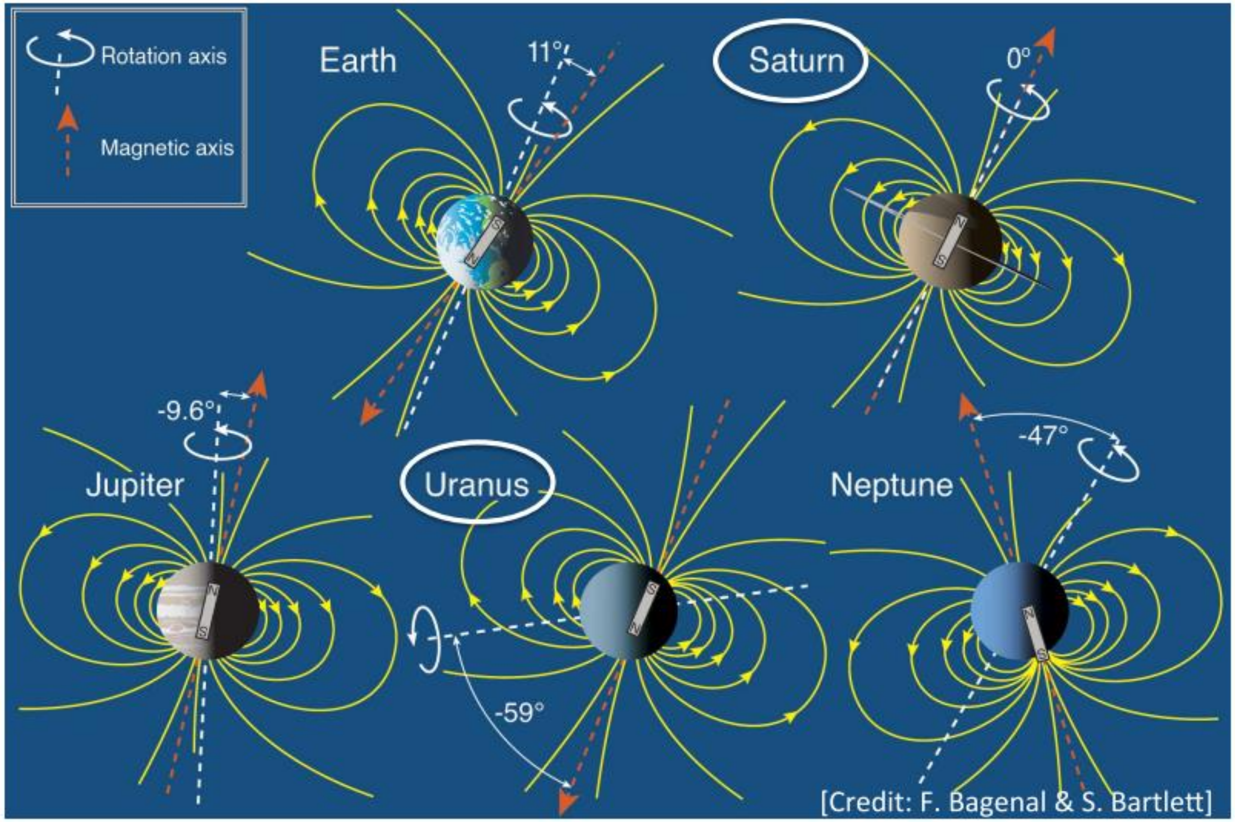
- Ionized part of upper atmosphere
  - Typically coincident with thermosphere, but
  - Present at any object with an atmosphere *
- Ion densities << neutral densities
- Key layer for coupling between the upper atmosphere and the magnetosphere
  - Closure of the magnetospheric current system
- Conducting layer
  - Key source of heating of the high latitude upper atmosphere

Some outer planet properties

- Dominated by hydrogen:
- Distant: ~5.2, 9.5, 19, 30 and AU
  - (reduced solar insolation)

	Jupiter	Saturn	Uranus	Neptune
H_2	89.8%	96.3%	82.5%	80.0%
He	10.2%	3.25%	15.2%	18.5%
CH_4	1000 ppm	4500 ppm	2.3%	1.5%

- Fast rotators: ~9.925, 10.656, 17.24, and 16.11 hours/day
- Widely varying dipole alignments:



[Credit: F. Bagenal & S. Bartlett]

Generation of an ionosphere: ionization sources

- Ionization thresholds:
  - H_2: 15.43 eV (80 nm)
  - H: 13.60 eV (91 nm)
  - CH_4: 12.55 eV (99 nm)

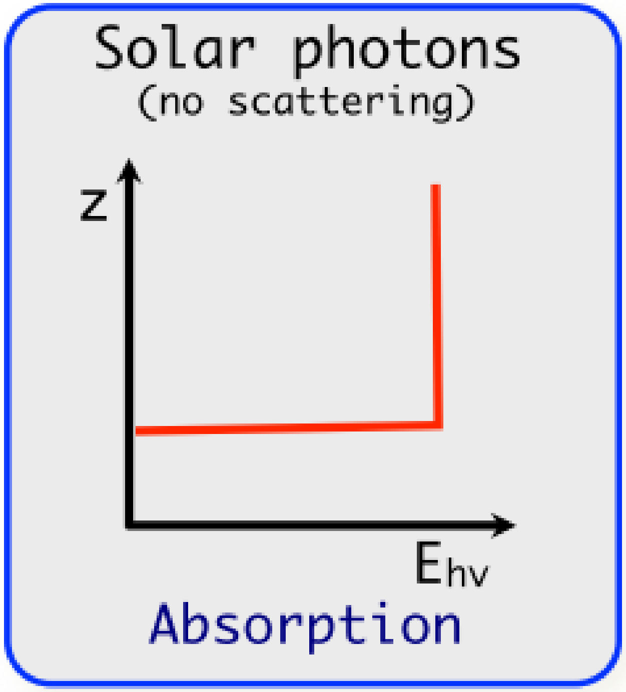
13 eV ≈ 100 nm

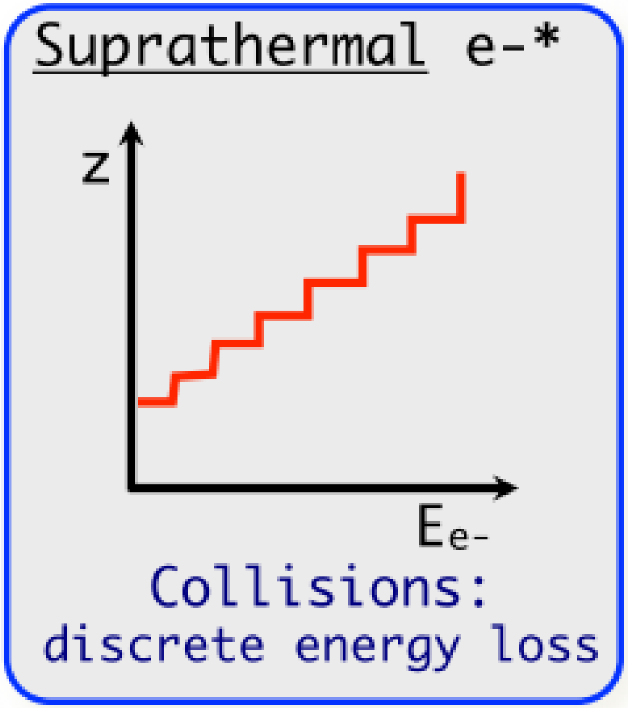
- Solar EUV and X-ray (<10 nm) radiation:
  - Solar photon flux / (Sun-planet distance)^2
- Energetic particles from the space environment:
  - A few keV to a few 100s keV

Question #1

- True or False?
  - The higher the energy of **a photon**, the lower in altitude it will be absorbed.
  - The higher the energy of **an electron**, the lower in altitude it will be absorbed.

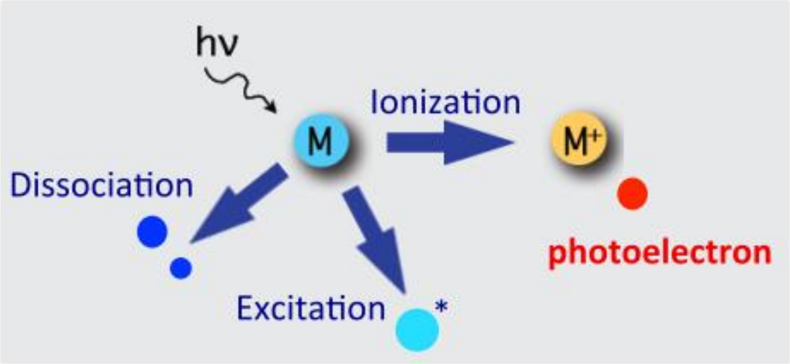
Energy deposition





* Suprathermal electrons can be photoelectrons, auroral electrons, and/or secondary electrons

Absorption of photons in an atmosphere



Attenuated photon flux at wavelength λ and at altitude **z**:

solar zenith angle

$$I_\lambda = I_\lambda^{TOP}\, exp\left(\underbrace{\sum_n \sigma_\lambda^{abs}(\lambda) \int_z^\infty n_n(z')\sec(\chi)\, dz'}_{\text{Optical depth } \tau}\right)$$

Neutral number density of constituent **n**

Solar flux at top of atmosphere

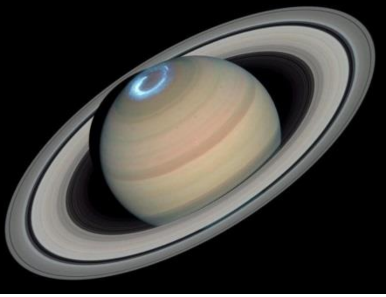
Photoabsorption cross section

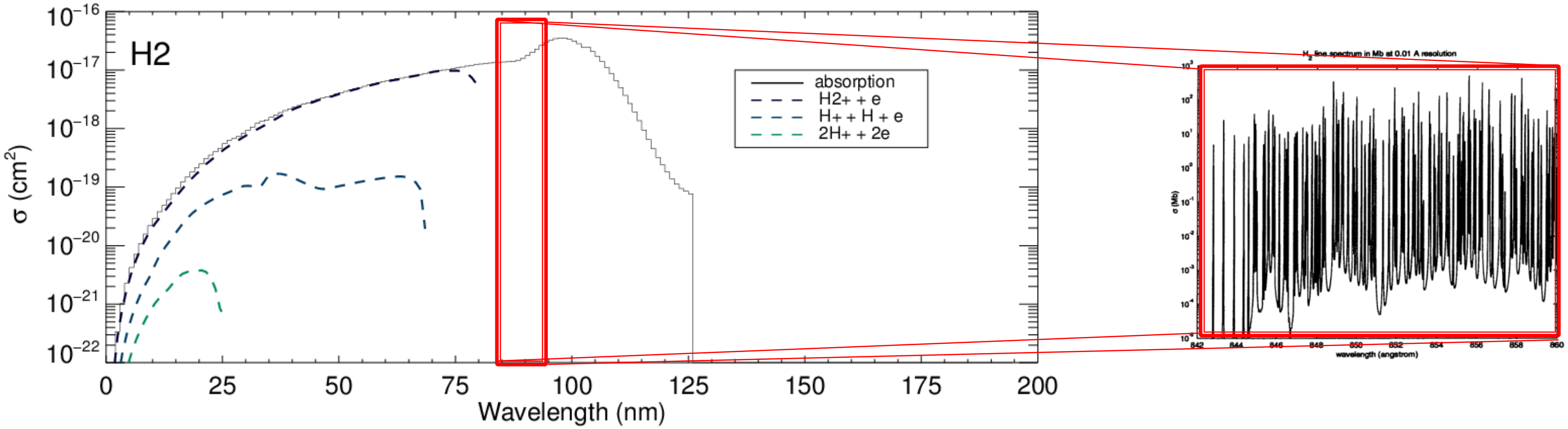
Ion (and photoelectron) production rate at wavelength λ and at altitude **z**:

$$P_\lambda(z) = \sum_n \sigma_n^{ionization}(\lambda) n_n(z) I_\lambda(z) \propto I_\lambda^{TOP} \propto \frac{1}{\left(d_{sun\rightarrow planet}\right)^2}$$

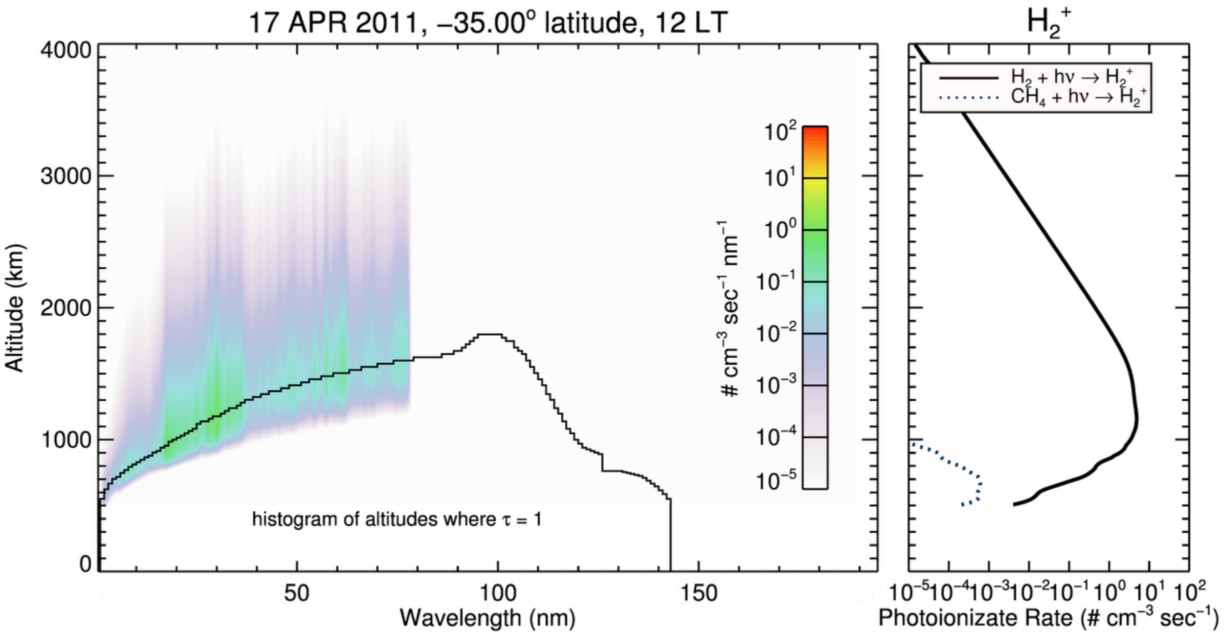
Photoionization rates (cm^{-3} s^{-1}):

$$h\nu + M \rightarrow M^{+} + e^{-}$$



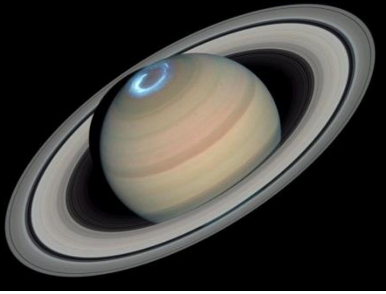


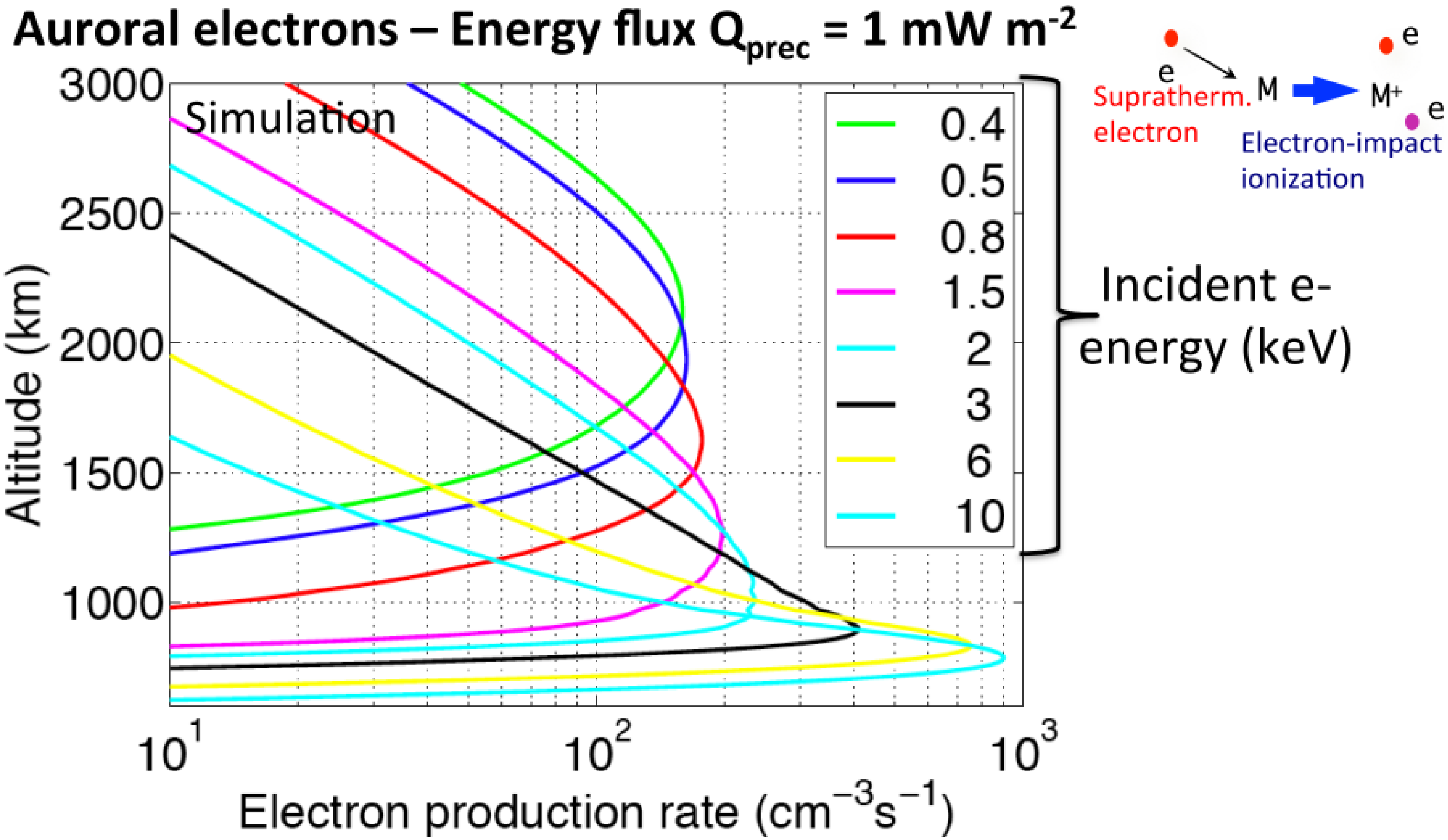
1 Mb = 10^{-18} cm^2



Deposition of auroral electrons:

$e^- + M \rightarrow e^- + M^+ + e^-$



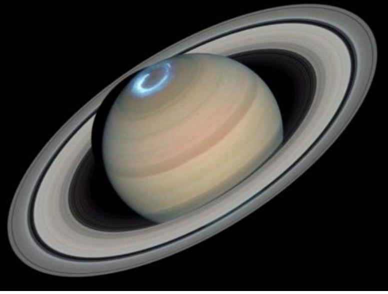


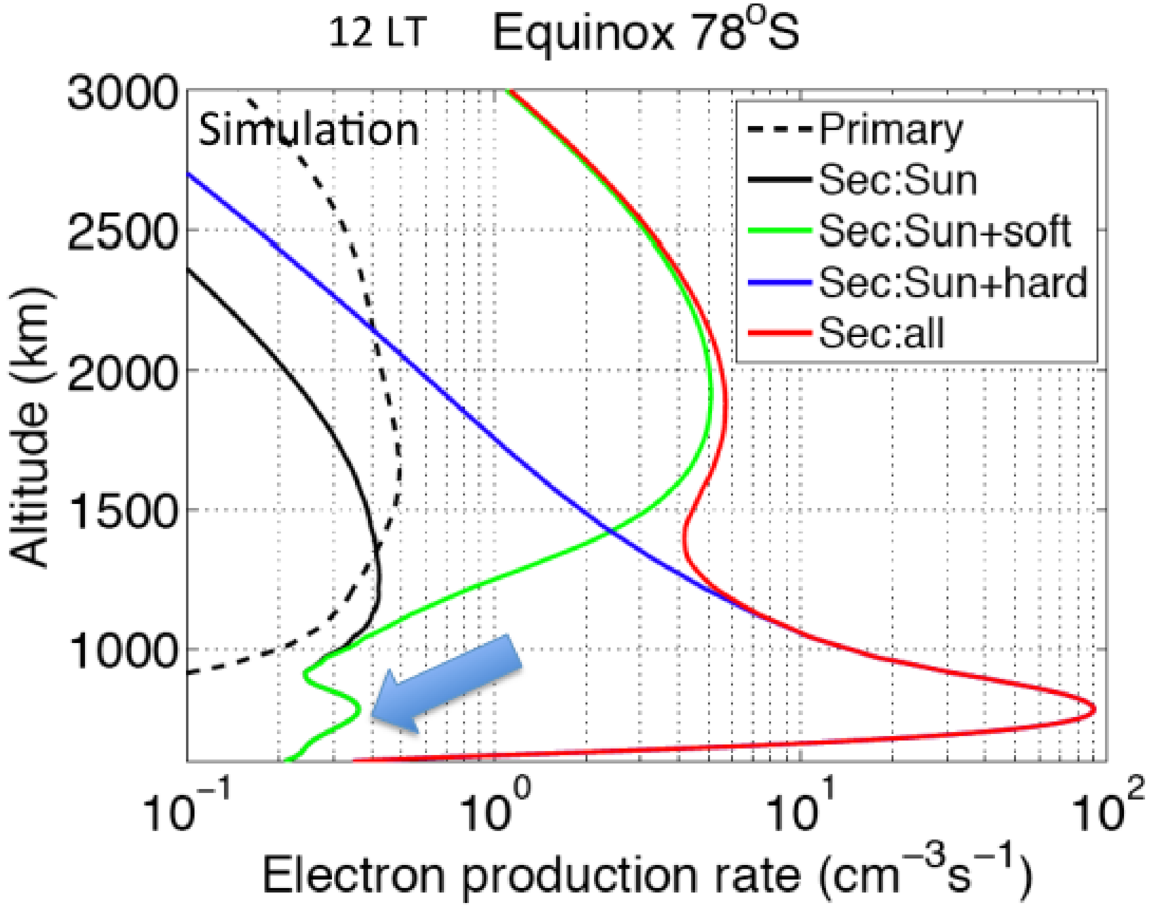
Auroral electrons – Energy flux Q_{prec} = 1 mW m^{-2}

$$P_e(z) = 4\pi \sum_n n_n(z) \int_{E_{min}}^{E_{Max}} I_e(E,z)\,\sigma_n^{ioni}(E)\,dE \propto Q_{prec}$$

M. Galand

Solar vs. particle ionization





- **Soft component: 500 eV, 0.03 $mW.m^{-2}$**

- **Hard component: 10 keV, 0.1 $mW.m^{-2}$**

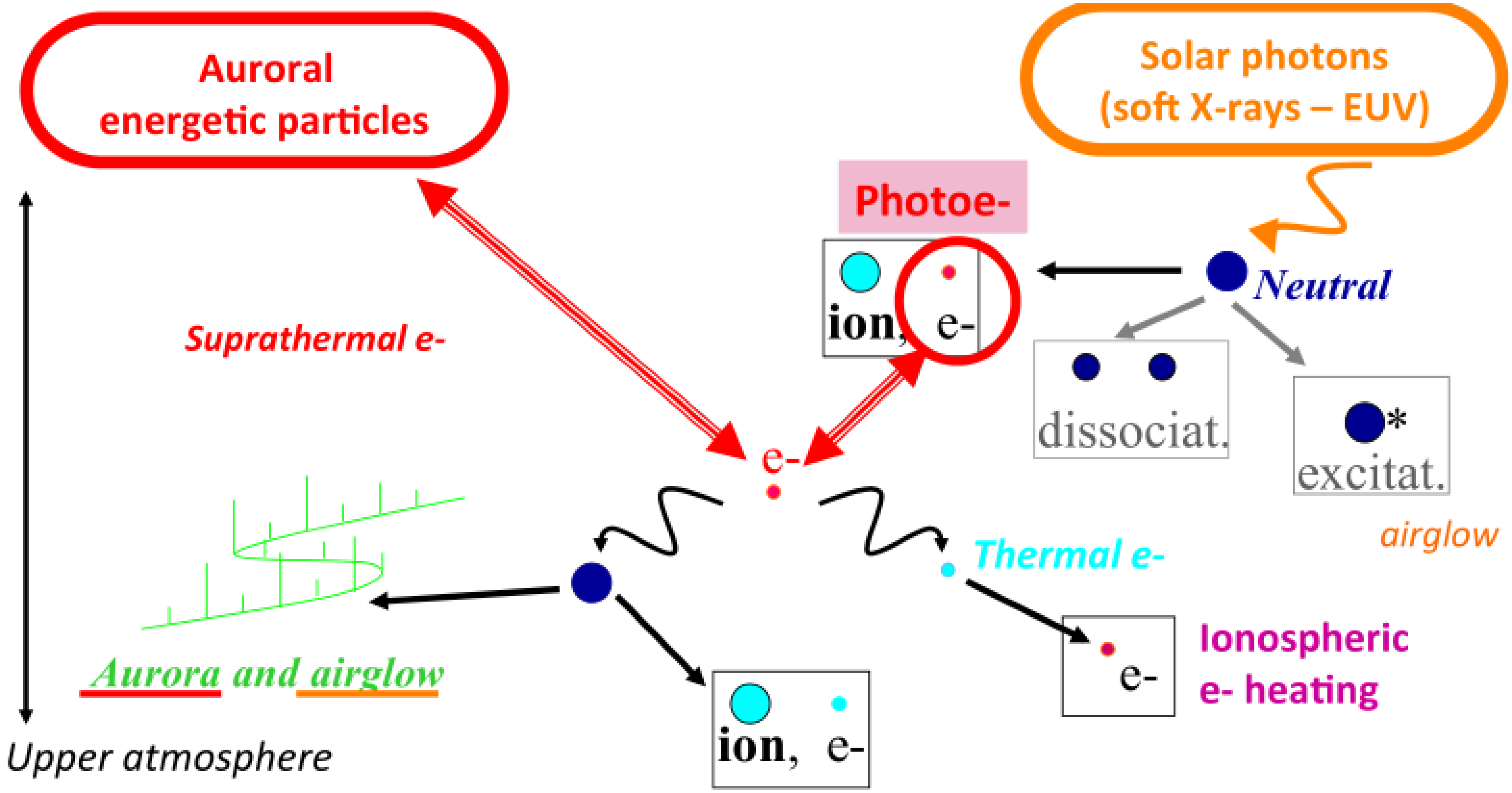
- **Soft + Hard component**

M. Galand

Question #2

- We’ve talked a lot about solar photons as sources of ionization. Why not stellar photons?

Two populations of electrons



* Suprathermal electrons can be photoelectrons, auroral electrons, and/or secondary electrons

M. Galand

Ion and electron densities

- Thermal ion continuity equation

$$\frac{\partial n_i}{\partial t} = \overset{\text{Production}}{P_i} - \underset{\text{Loss}}{L_i} - \overset{\text{Transport}}{\nabla \cdot (n_i \underset{\text{bulk velocity}}{\vec{u}})}$$

- Photochemical equilibrium
  - When chemical processes dominate over transport (typically in lower ionosphere; e.g., terrestrial E region)

$$\boxed{P_i = L_i}$$

Chemical loss processes (cm^{-3} s^{-1})

- Radiative recombination (RR; atomic ions)

$$X^+ + e^- \rightarrow X + h\nu$$

SLOW

$$L^{RR}_{X^+} = \alpha^{RR}_{X^+} n_{X^+} n_e$$

- Charge exchange

$$X^+ + Y \rightarrow X + Y^+$$

FAST (typically)

$$L^{CE}_{X^+,Y} = \alpha^{CE}_{X^+,Y} n_{X^+} n_Y$$

- Dissociative Recombination (DR; molecular ions)

$$XY^+ + e^- \rightarrow X + Y$$

FAST

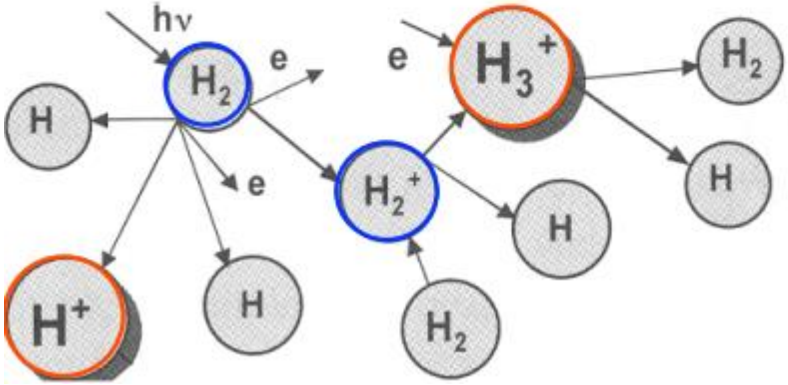
$$L^{DR}_{XY^+} = \alpha^{DR}_{XY^+} n_{XY^+} n_e \boxed{\approx \alpha^{DR}_{XY^+} n_e^2}$$

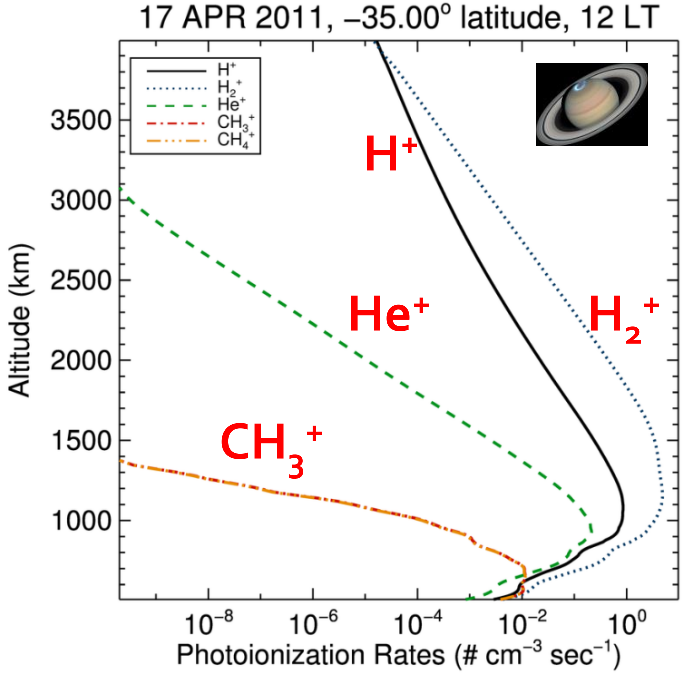
→ If XY$^+$ is dominant ion

Protonated molecular hydrogen

- What is it?

Photochemistry in H2 atmospheres





- $H2^+$ accounts for ~90% of initial ion production
  - **$H2^+ + H2 \rightarrow H3^+ + H$** R1

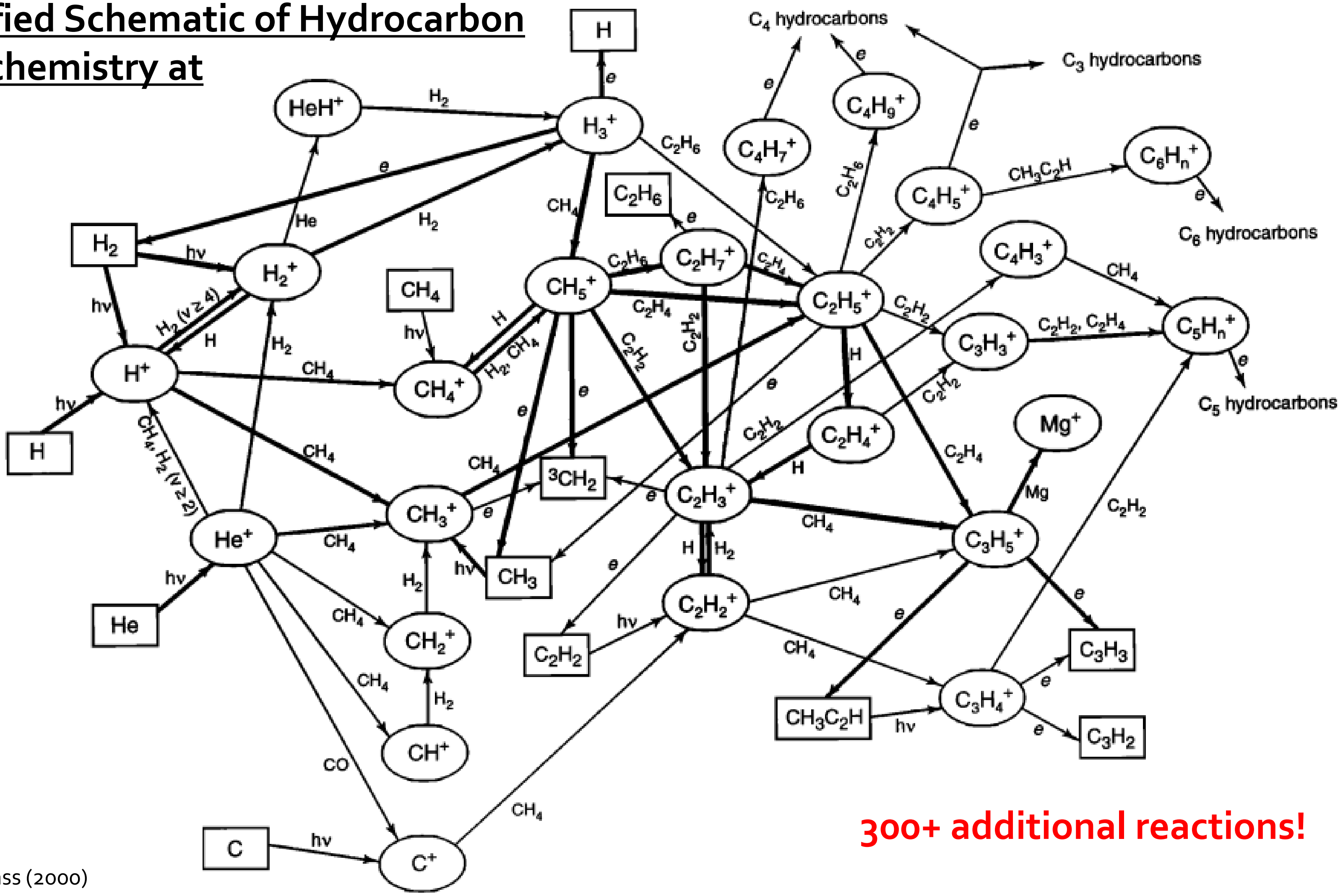
    $k1 = 2.0\text{x}10^{-9}\ cm^3\ s^{-1}$
- $H2^+$ rapidly converted to $H3^+$
  - **$H3^+ + e^- \rightarrow$ neutrals** R2

    $k2 \approx 8.6\text{x}10^{-7}\ T^{-0.5}\ cm^3\ s^{-1}$
- H^+ becomes dominant due to slow RR loss and short day (rapid rotation)
  - **$H^+ + e^- \rightarrow H + h\nu$** R3

    $\alpha 3 \approx 2\text{x}10^{-10}\ T^{-0.7}\ cm^3\ s^{-1}$
- Initial theory therefore predicts:
  - Predominantly H^+ ionosphere with little diurnal variation

Hydrocarbon photochemistry

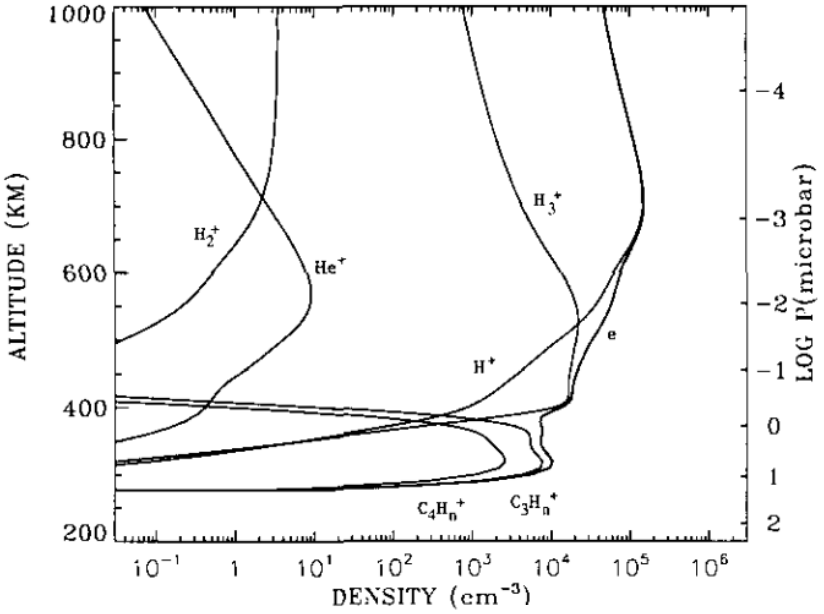
Simplified Schematic of Hydrocarbon Photochemistry at Saturn



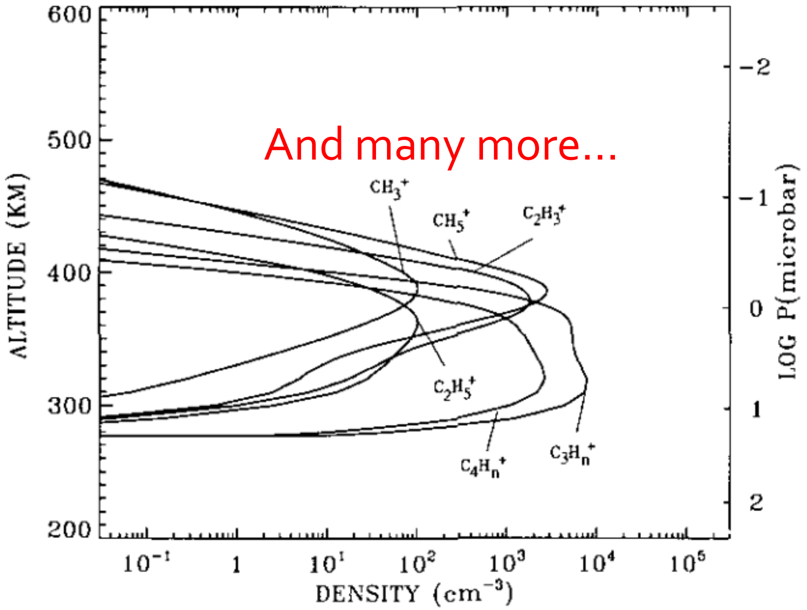
Moses and Bass (2000)

300+ additional reactions!

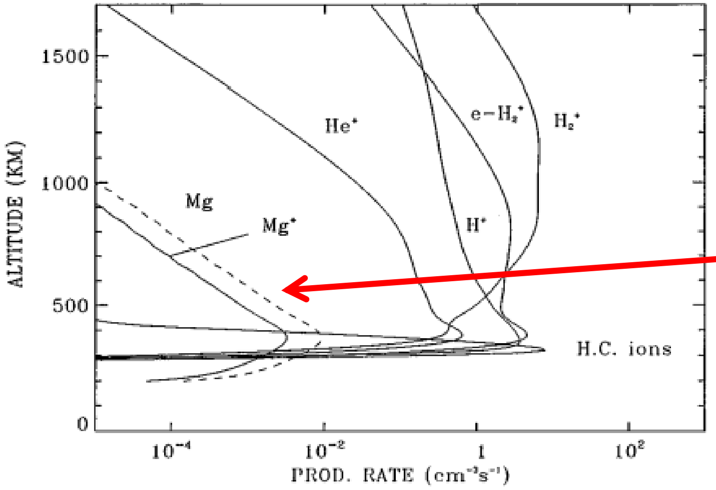
Hydrocarbon/metallic ion ledge



Kim and Fox (1994)



And many more…

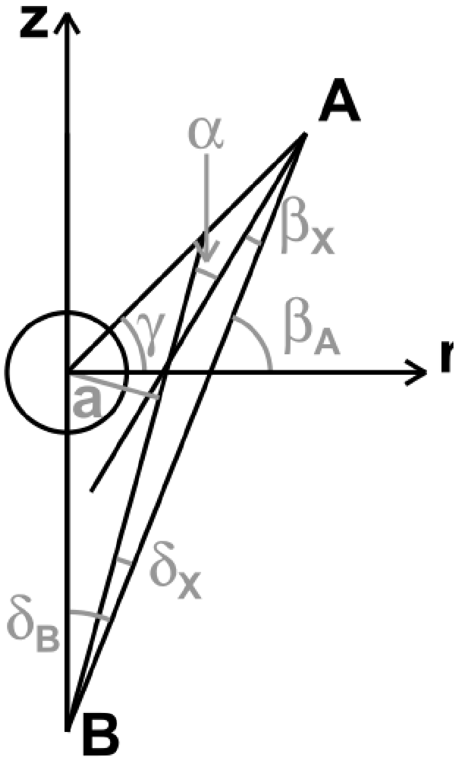


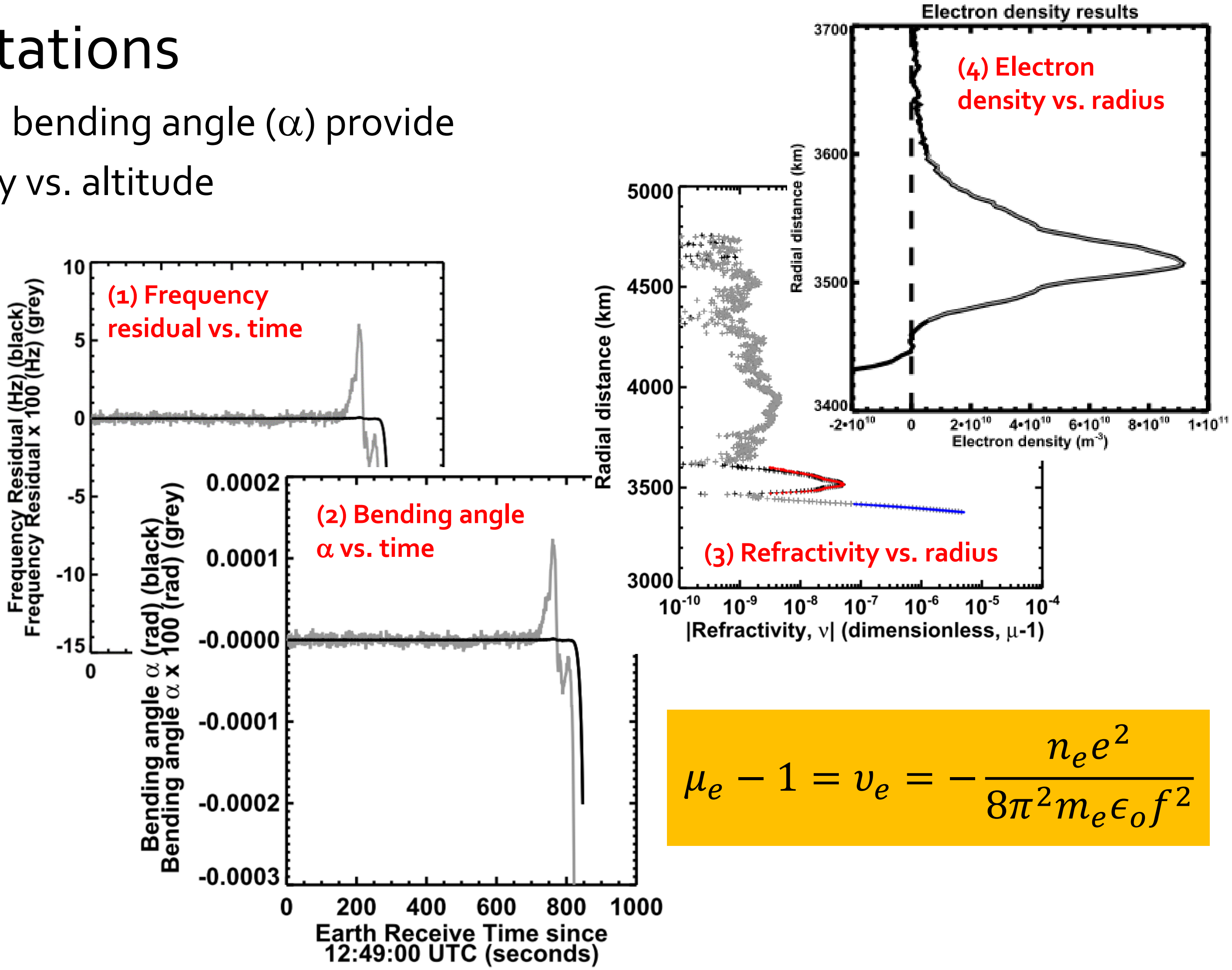
Meteoroid ablation deposition leads to Mg/Mg^+, Fe/Fe^+, Si/Si^+, O/O^+, S/S^+, C/C^+, etc.

Kim and Fox (2001)

Remote observation techniques

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





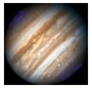
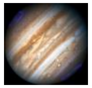
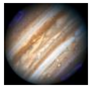
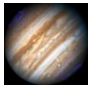
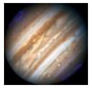
$$\mu_e - 1 = \upsilon_e = -\frac{n_e e^2}{8\pi^2 m_e \epsilon_o f^2}$$

Withers et al (2014)

Remote observation techniques

- 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 (~6 SED storms to-date, lasting weeks-months)
  - Observed low-frequency cutoff can be used to derive **$N_{MAX}(t)$**
  - Powerful lightning also observed at Jupiter, but no "JEDs"
    - Perhaps due to attenuation of radio waves by Jupiter's ionosphere
- H_3^+ observations
  - Predicted to be a major ion in outer planet ionospheres
  - Plethora of H_3^+ emission lines available in IR, particularly through K-band (2-2.5 μm) and L-band (3-4 μm) atmospheric windows
  - To be continued in Part II…

Radio occultation observations

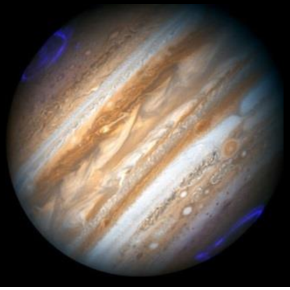
Pioneer 10	Pioneer 11	Voyager 1	Voyager 2	Galileo	Cassini	
						
3 Mar 1972	6 Apr 1973	5 Sep 1977	20 Aug 1977	18 Oct 1989	15 Oct 1997	
 x 2	 x 2	 x 2	 x 2	 x 5*		= 13
	 x 2	 x 2	 x 2		 x 59**	= 65
			 x 2			= 2
			 x 2			= 2

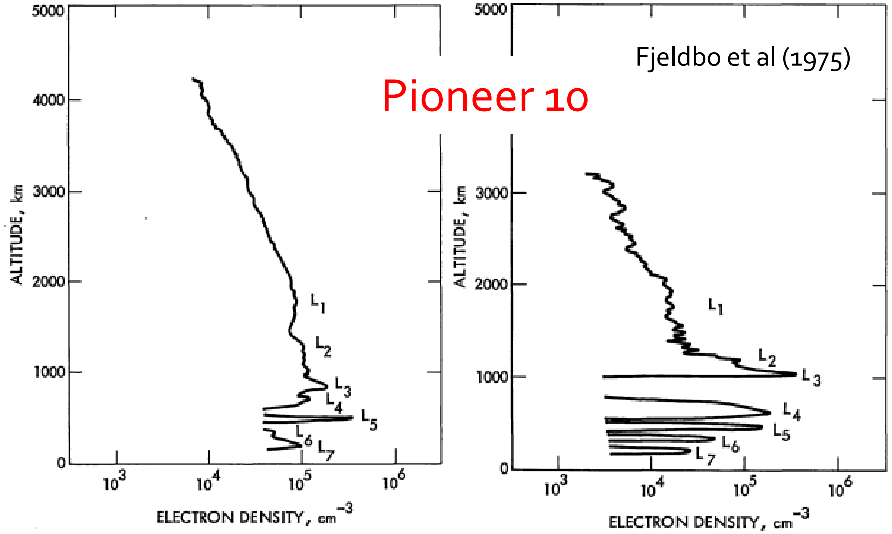
ingress (N) and egress (X)

orbiters

* analyzed; ** taken to-date

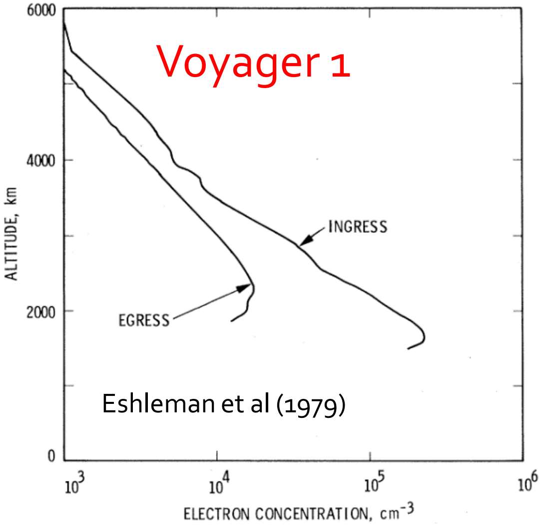
Radio occultation observations





Pioneer 10

Fjeldbo et al (1975)



Voyager 1

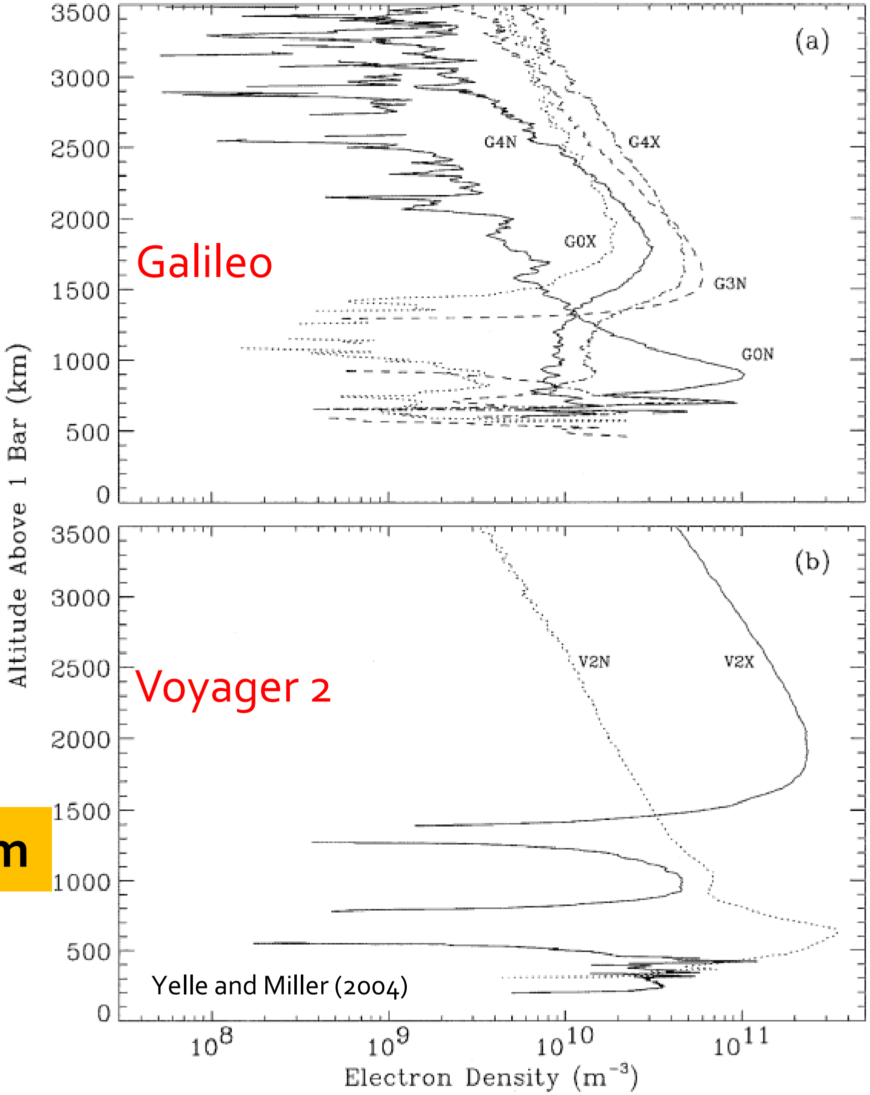
Eshleman et al (1979)

N_{MAX} ~ 10^5 cm^{-3}

= peak electron density

h_{MAX} ~ 600-2000 km

= altitude of N_{MAX}

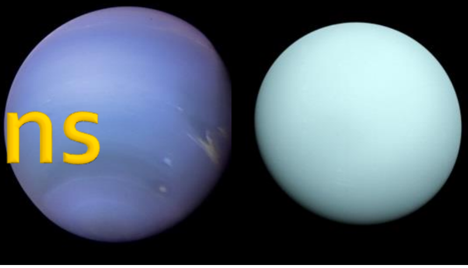


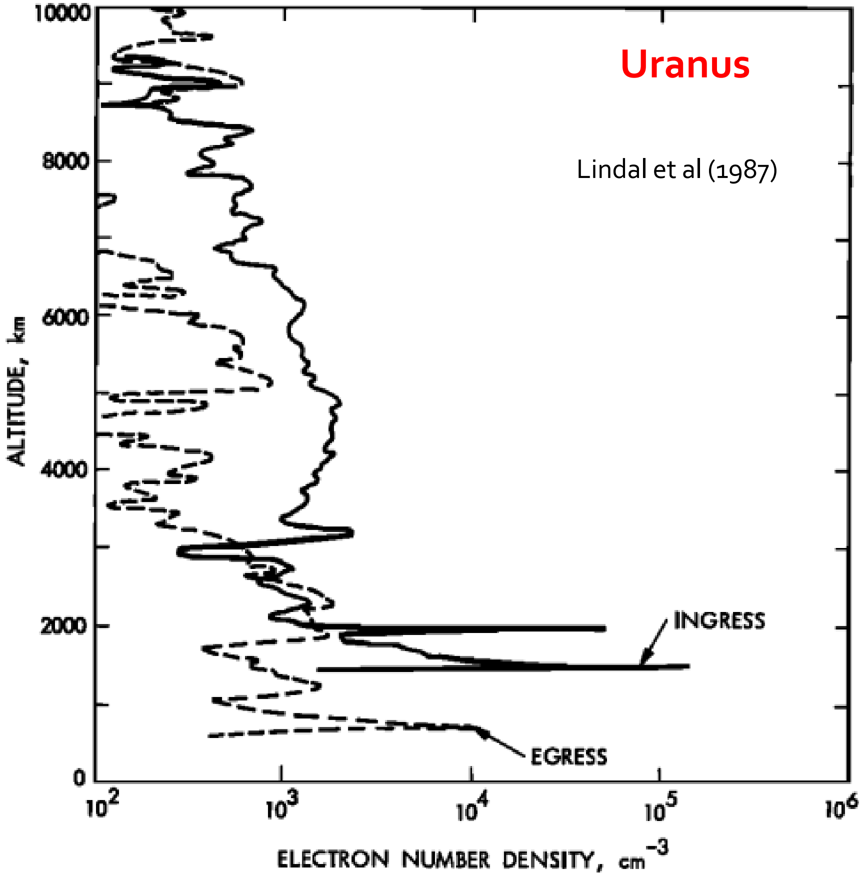
Galileo

Voyager 2

Yelle and Miller (2004)

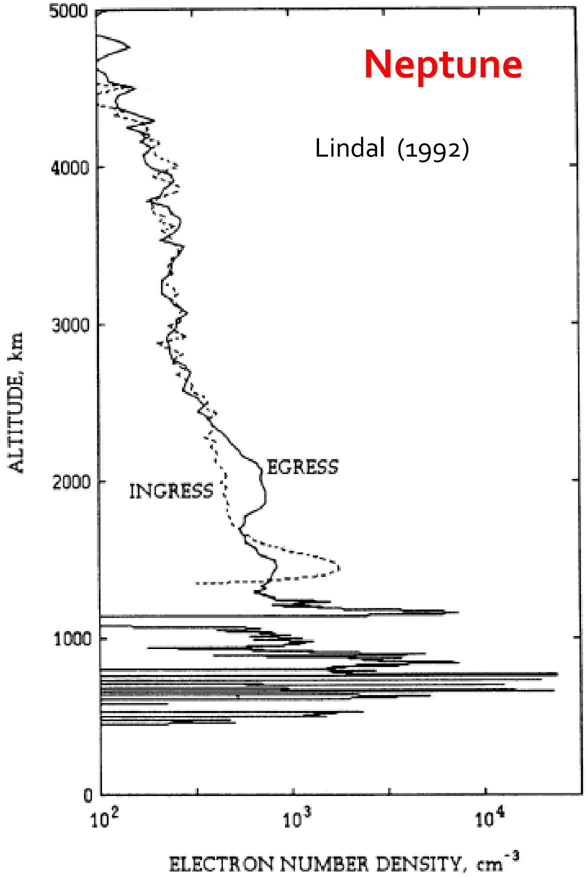
Radio occultation observations





$N_{MAX} \sim 10^4\ cm^{-3}$

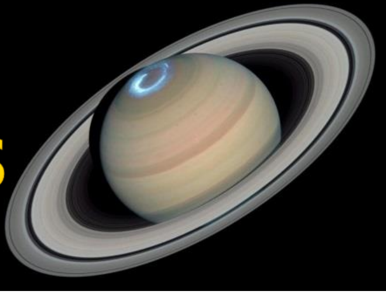
$h_{MAX} \sim 1000\text{-}2000$ km

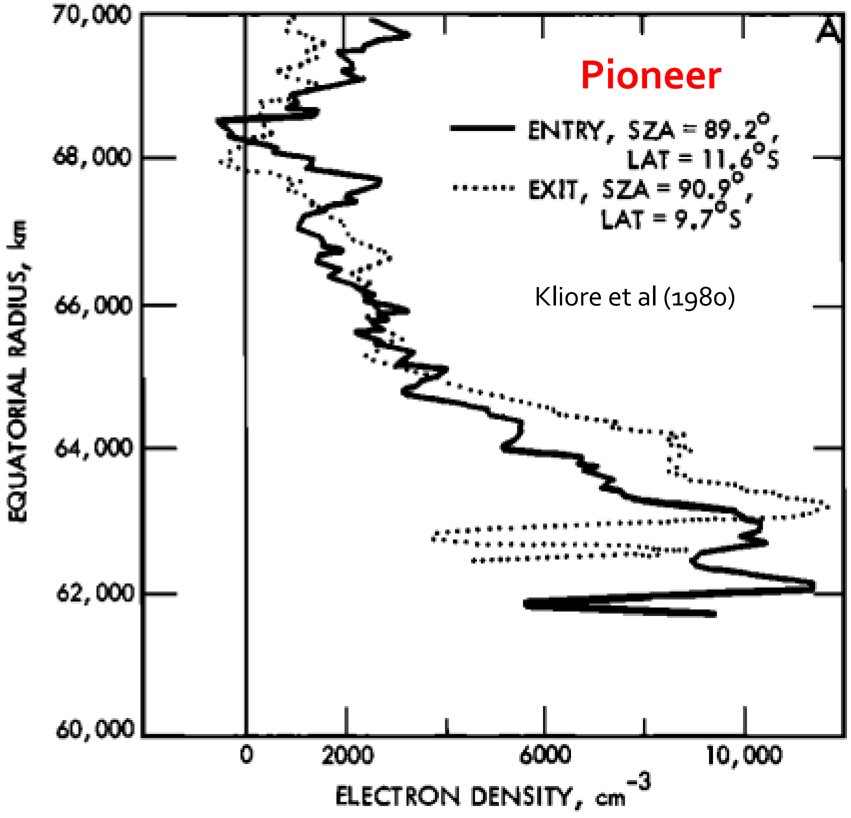


$N_{MAX} \sim 10^3\text{-}10^4\ cm^{-3}$

$h_{MAX} \sim 800\text{-}1500$ km

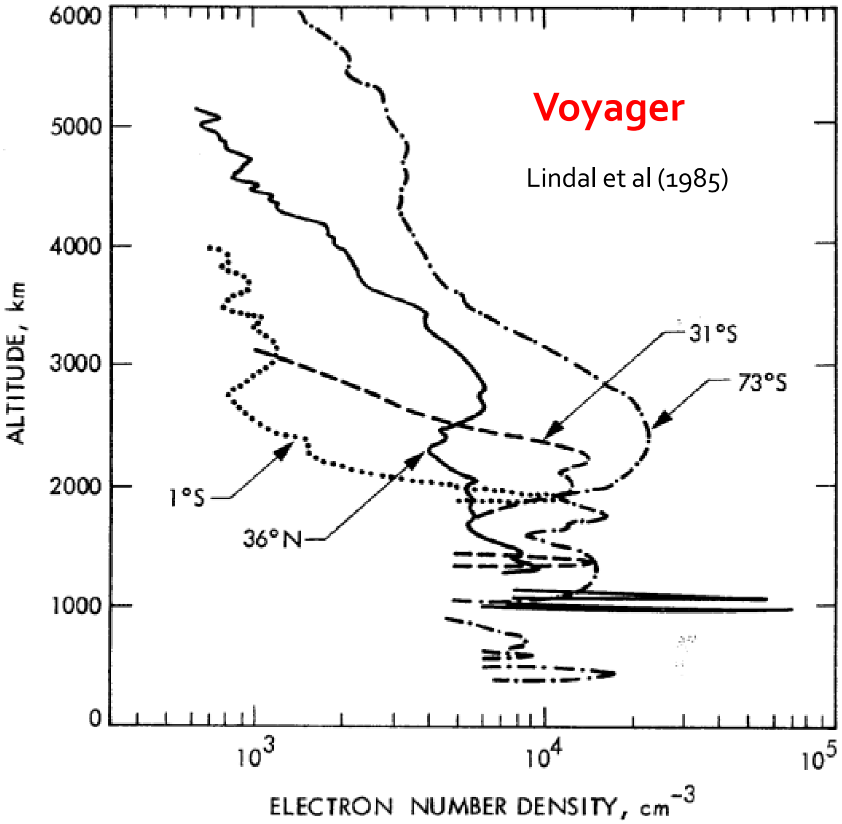
Radio occultation observations





Pioneer

Kliore et al (1980)



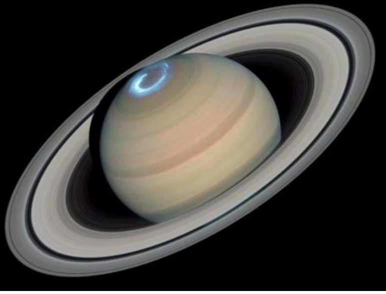
Voyager

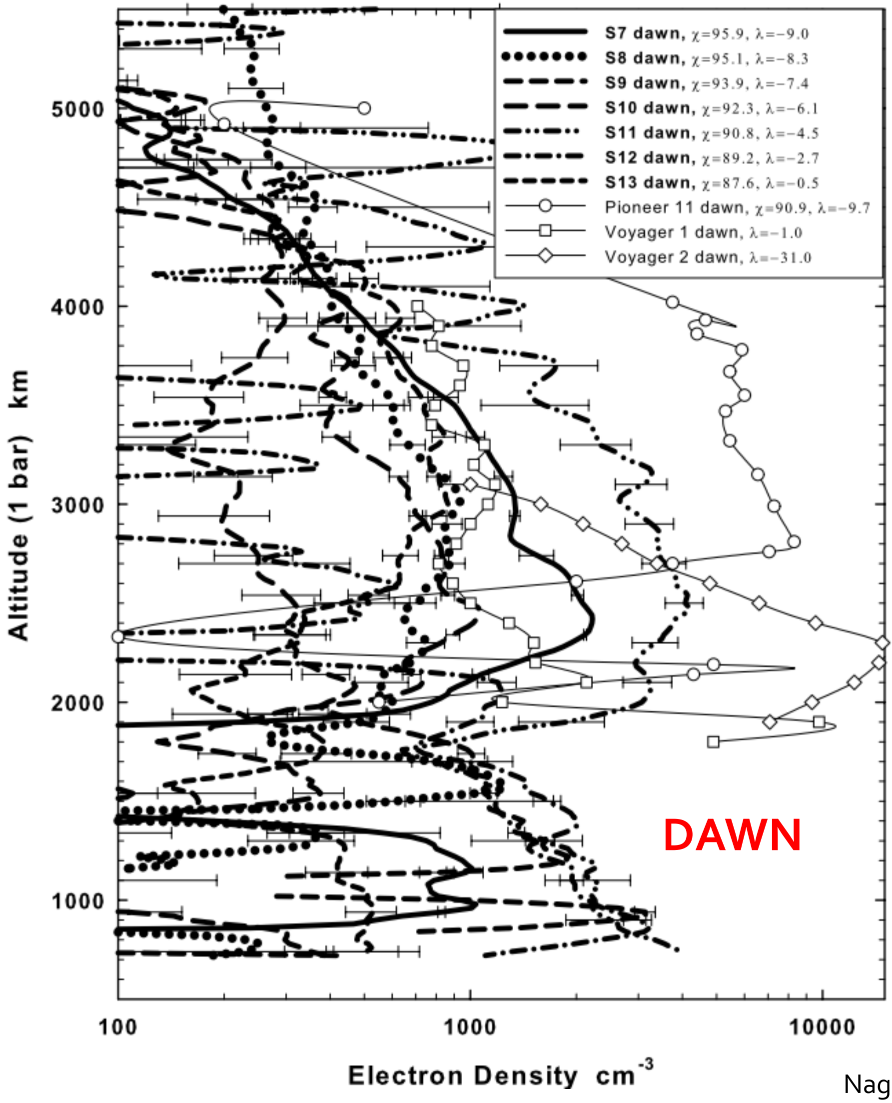
Lindal et al (1985)

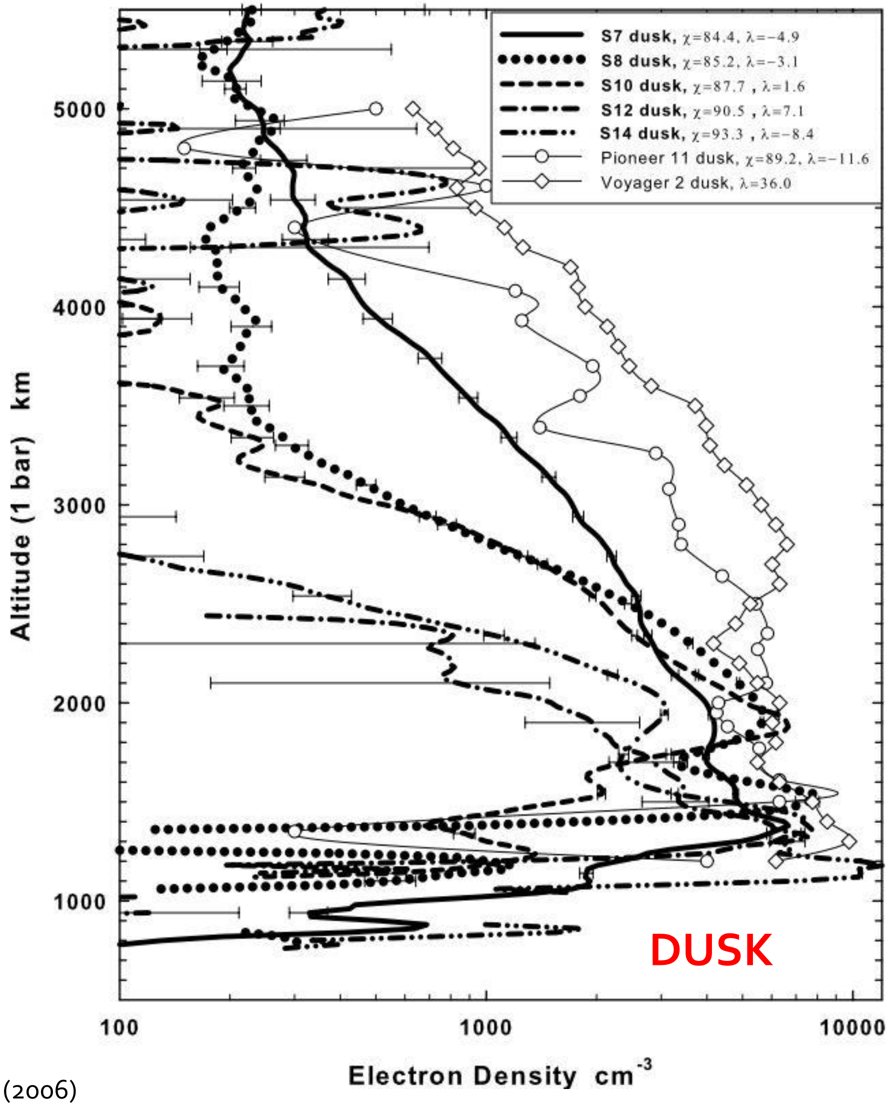
N_{MAX} ~ 10^4 cm^{-3}

h_{MAX} ~ 1000-2500 km

Cassini radio occultations

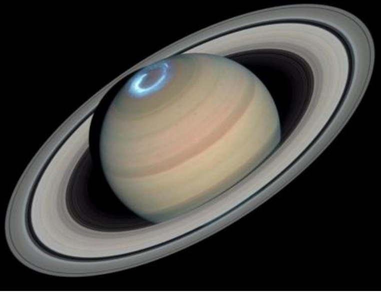


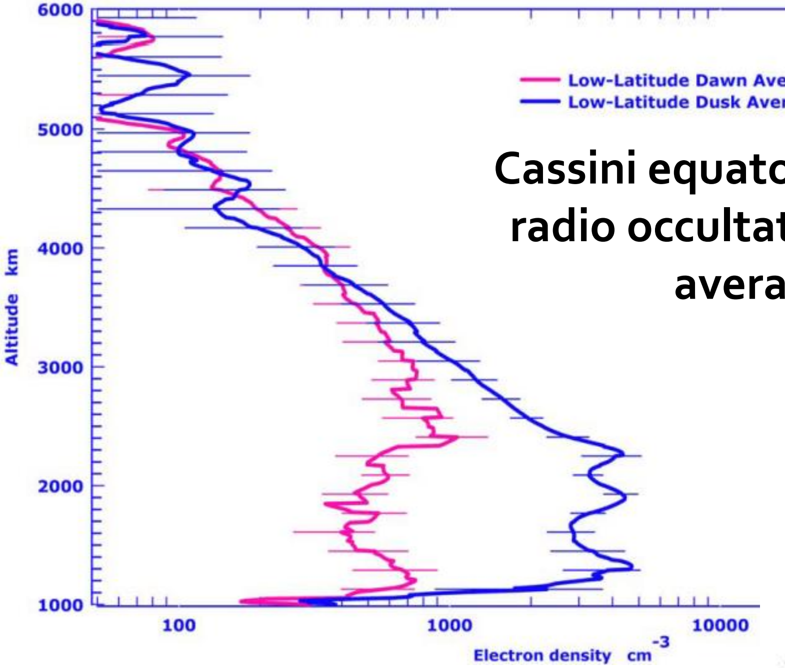




Nagy et al (2006)

Dawn/Dusk asymmetry

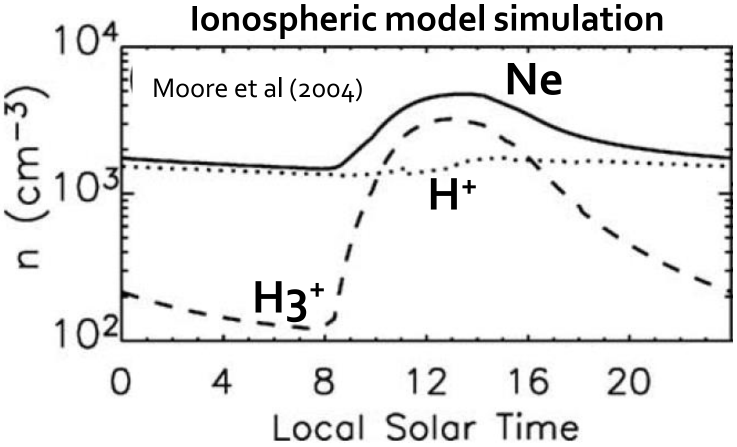




Cassini equatorial radio occultation averages

Nagy et al (2006)

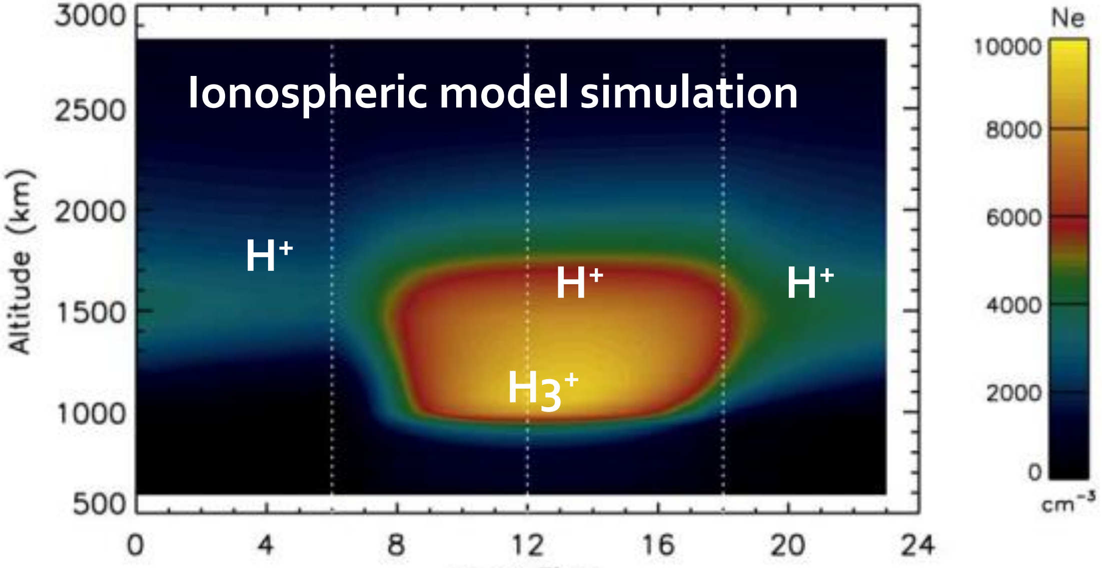
Ionospheric model simulation



At Saturn's equator:

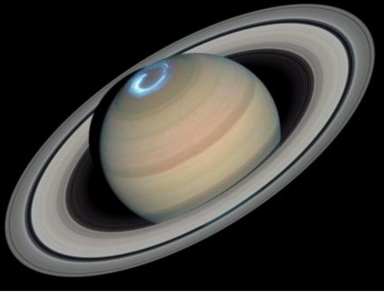
N_{MAX} ~ 10^3 cm^{-3}

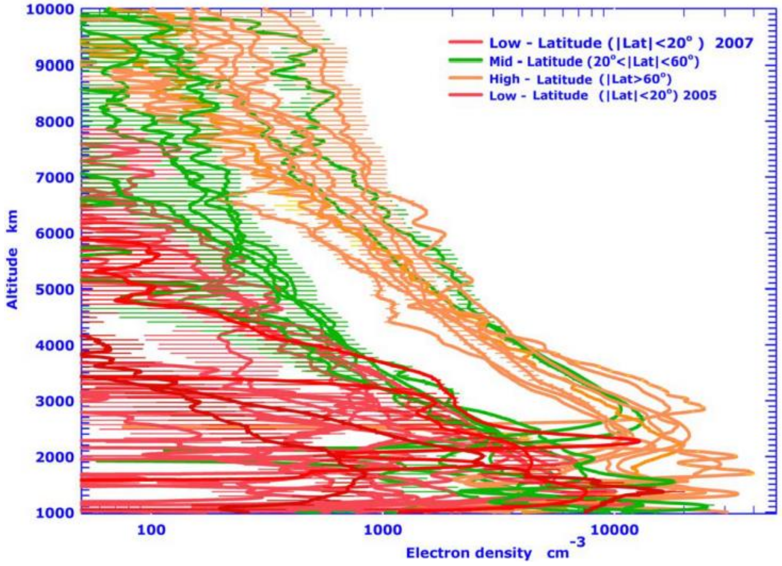
h_{MAX} ~ 1200-2800 km



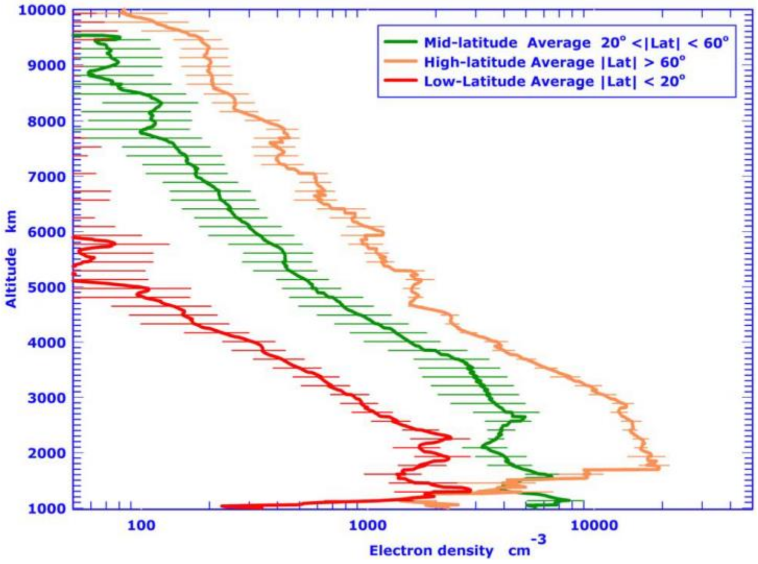
Galand et al (2009)

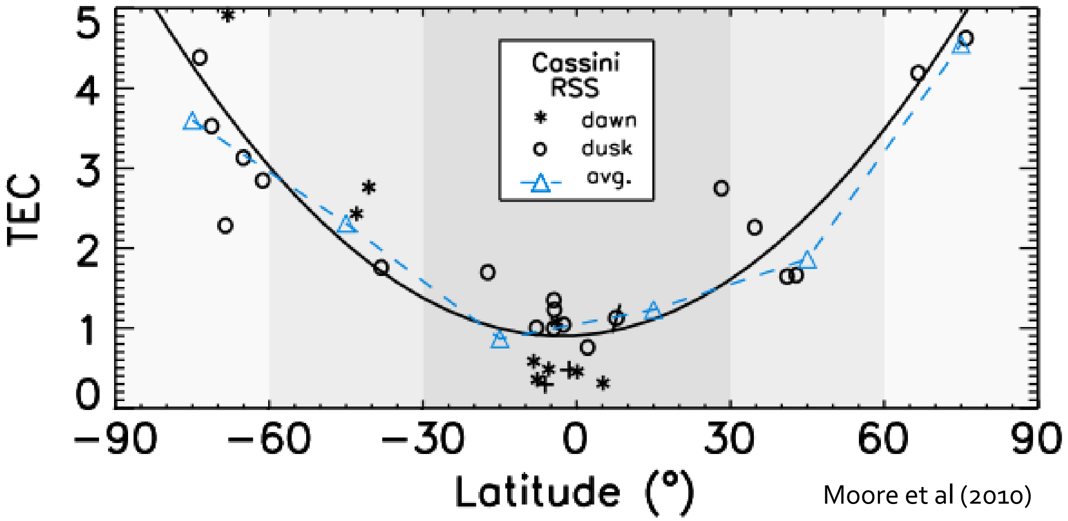
Latitudinal trend in N_e





Kliore et al (2009)





Moore et al (2010)

TEC = total electron content
(1 TEC unit = 10^{16} cm^{-2})

Question #3

- Photoionization rates at Saturn peak near the equator and fall off with latitude. The observed electron density trend is exactly the opposite. What else might be happening?

Upper atmospheric photochemistry of the giant planets revisited

- Modeled **N_{MAX}** larger than observed
  - Solution: convert long lived H^+ into short lived molecular ions:
    - Unconstrained charge exchange reaction

$H^+ + H_2(v \geq 4) \rightarrow H_2^+ + H_2$ R4

$k_4 \approx 1 \times 10^{-9}$ cm³ s⁻¹ (Huestis, 2008)

    - Water (or other external) influx

$H^+ + H_2O \rightarrow H_2O^+ + H$ R5

$k_5 = 8.2 \times 10^{-9}$ cm³ s⁻¹

$H_2O^+ + H_2 \rightarrow H_3O^+ + H$ R6

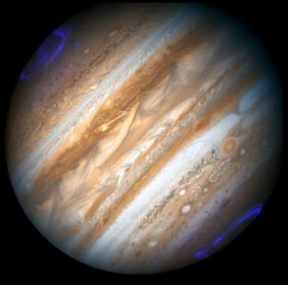
$k_6 = 7.6 \times 10^{-10}$ cm³ s⁻¹

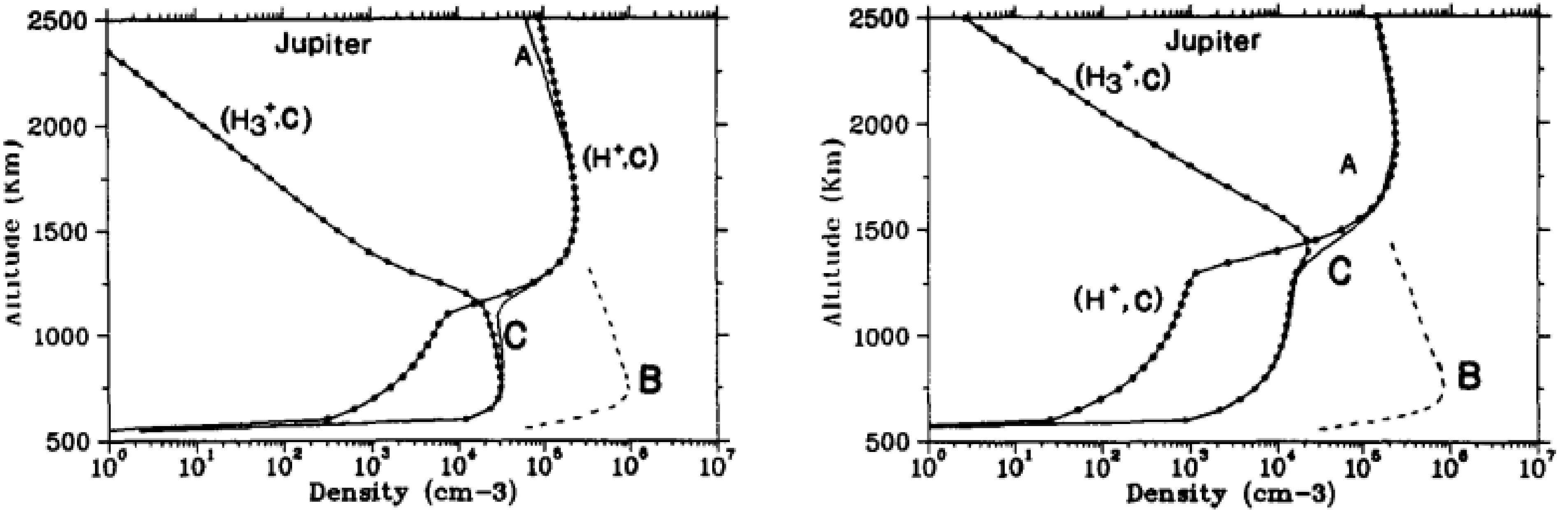
$H_3O^+ + e^- \rightarrow$ neutrals R7

$\alpha_4 = 1.74 \times 10^{-5}\, T^{-0.5}$ cm³ s⁻¹

- Modeled **h_{MAX}** lower than observed
  - Above reactions act to slightly raise **h_{MAX}**; in addition,
  - Forced vertical plasma drift?

Ionospheric models

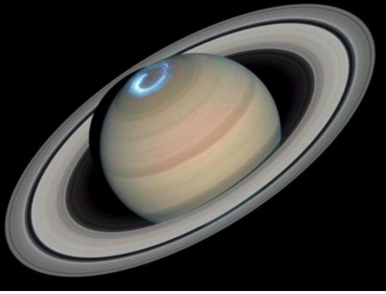


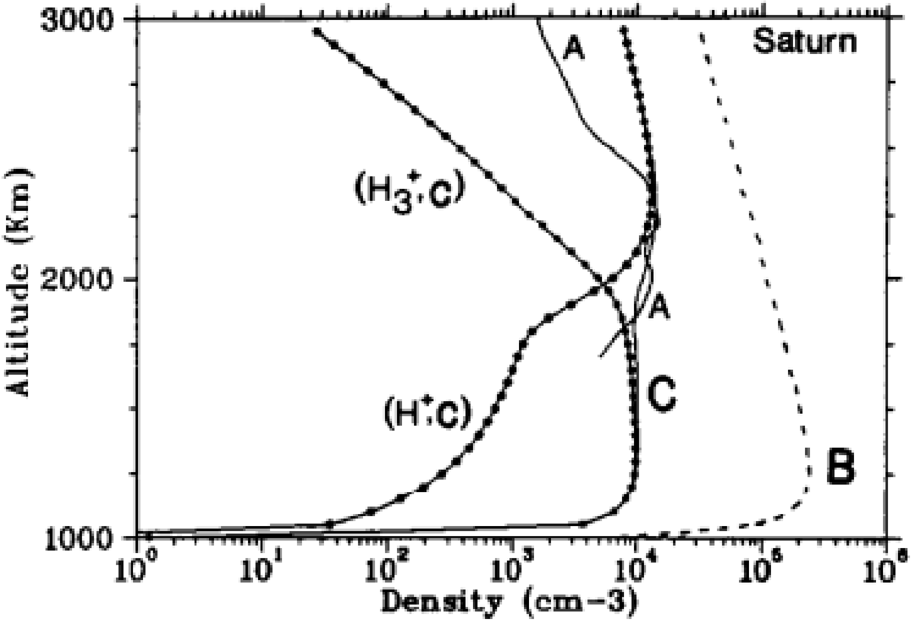


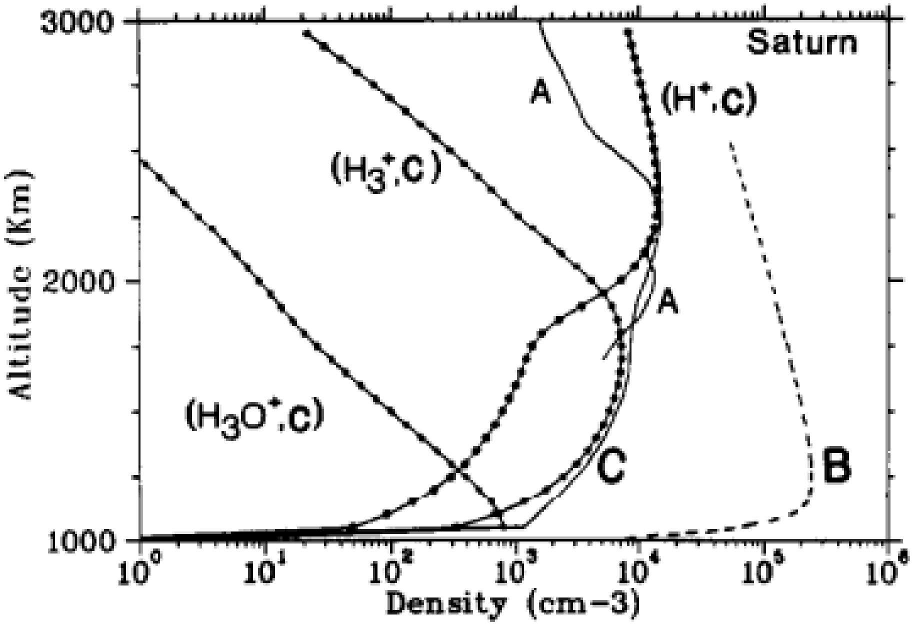
A = Voyager radio occultations
B = nominal model
C = model fit with forced vertical drift + enhanced $H_2(v \geq 4)$

Majeed and McConnell (1991)

Ionospheric models



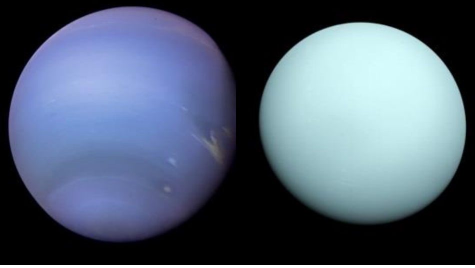


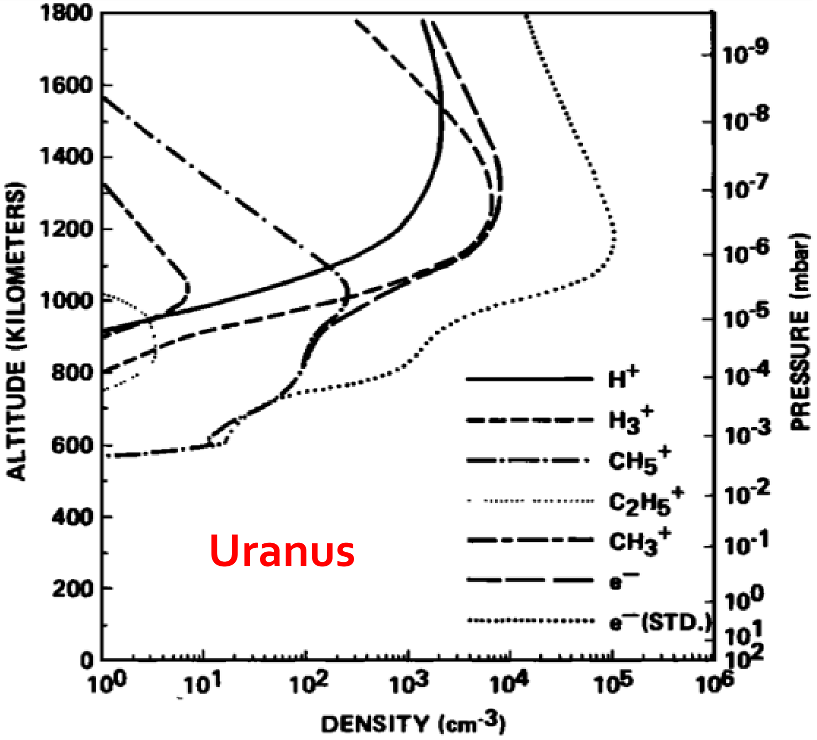


A = Voyager radio occultations
B = nominal model
C = model fit with forced vertical drift + enhanced $H_2(\nu \geq 4)$ (left) or water influx (right)

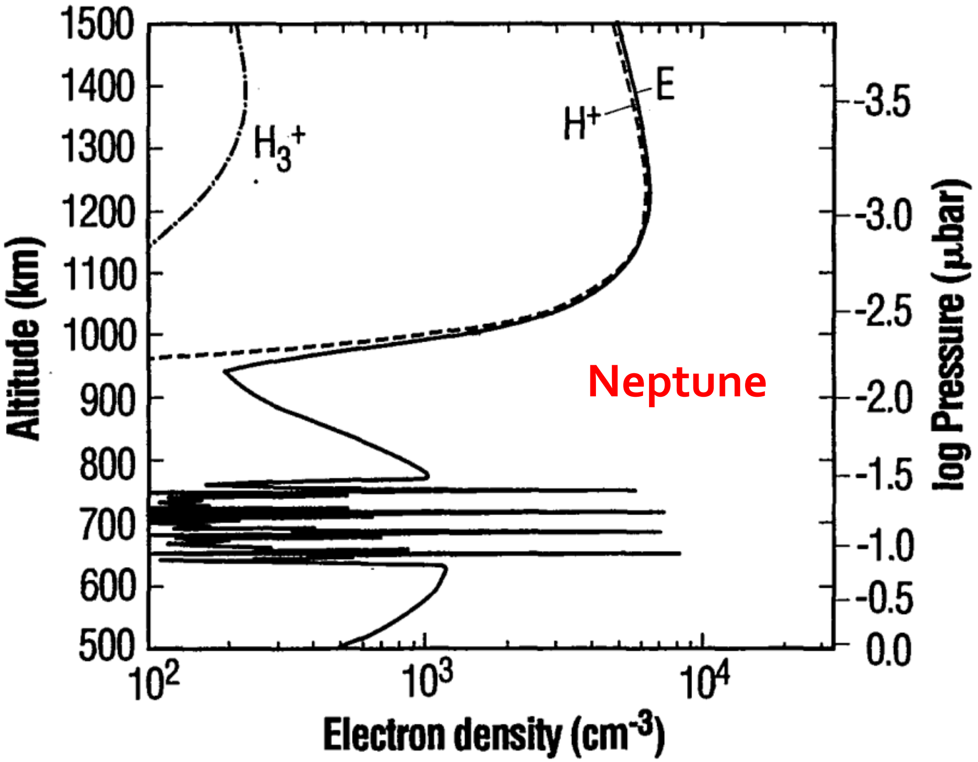
Majeed and McConnell (1991)

Ionospheric models





- Exploration of effects of varying upper atmospheric temperatures, water and methane influxes, ionospheric outflows, and electron precipitations



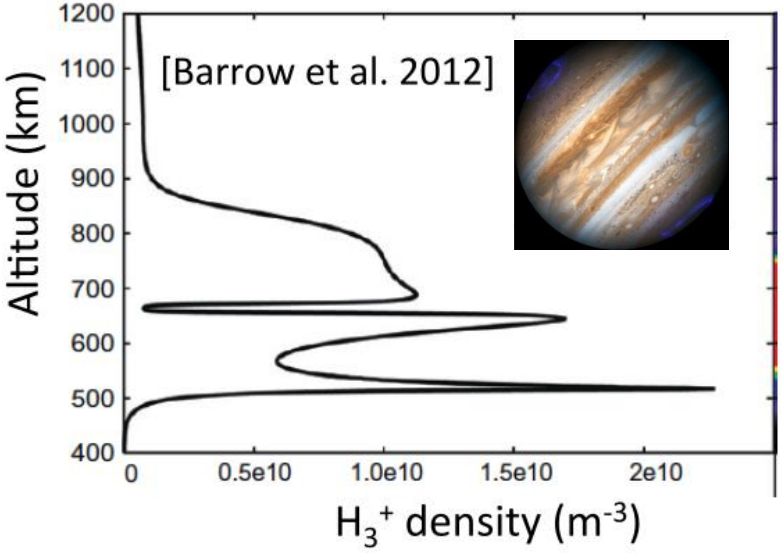
- No match to upper ionosphere
- Produces low altitude layers using meteoroid influx and vertical wind shears

Chandler and Waite (1986)

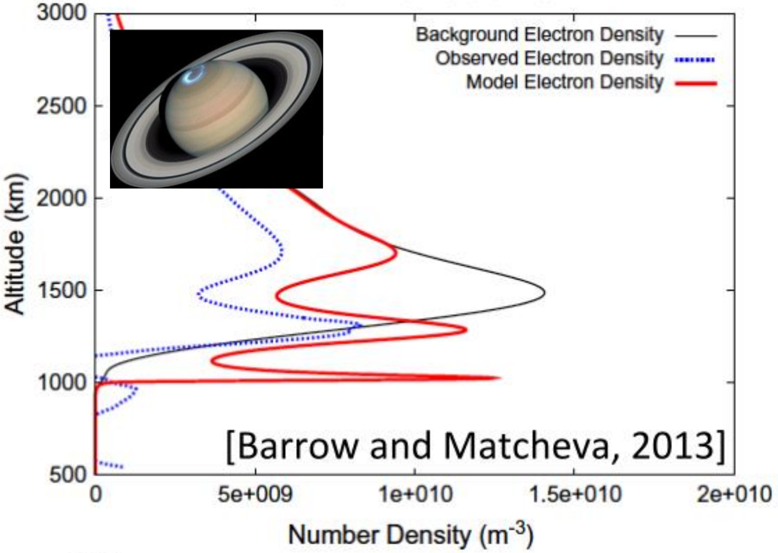
Lyons (1995)

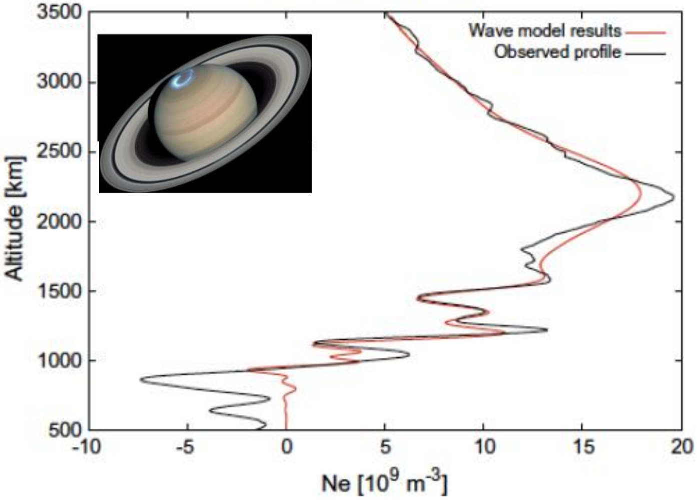
Coupling from below: Gravity waves

Simulations

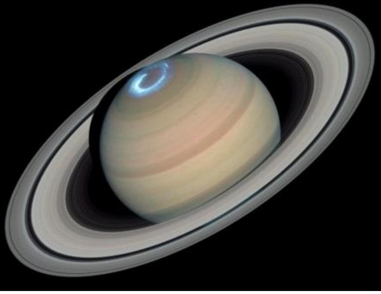

[Barrow et al. 2012]

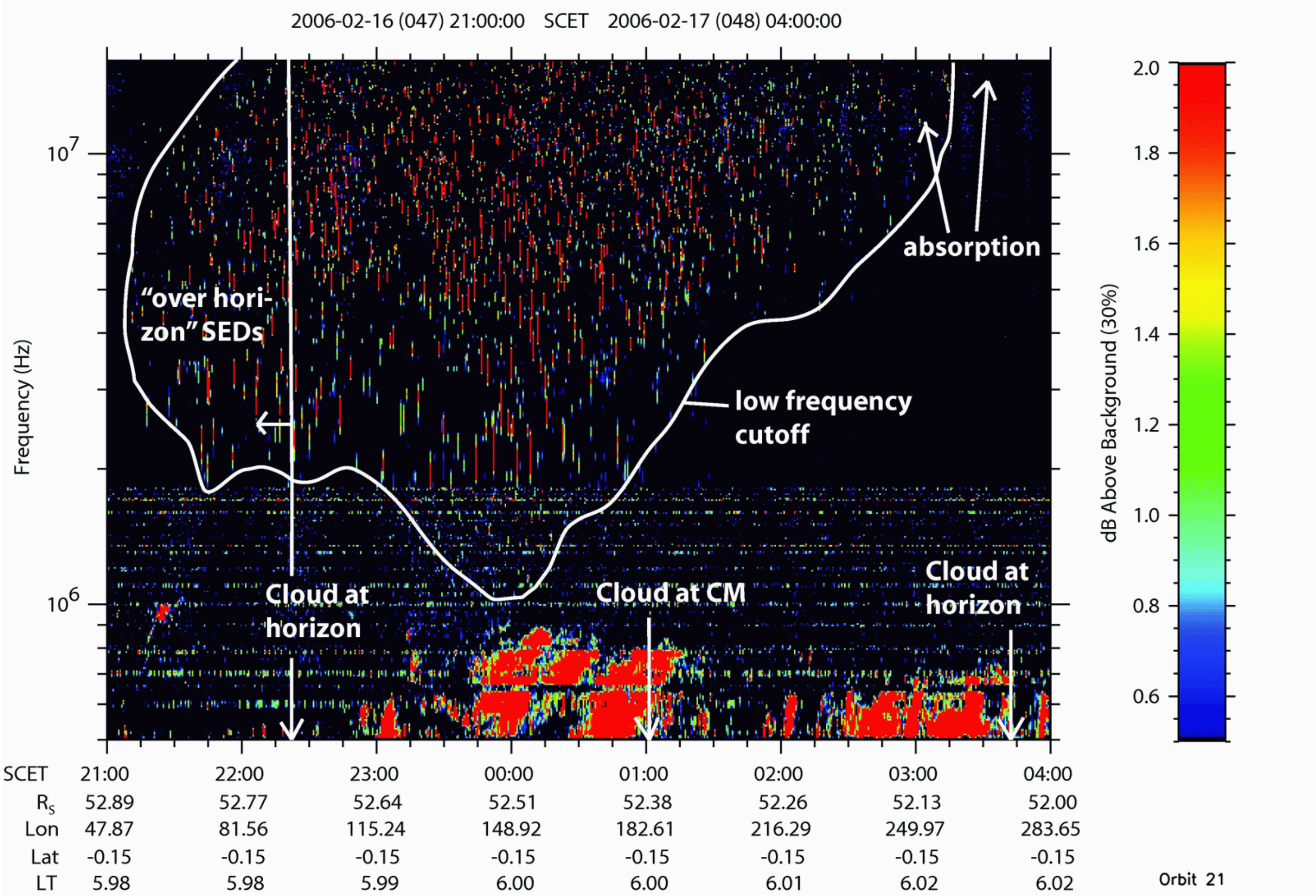
Simulations


[Barrow and Matcheva, 2013]



N_{MAX}(t) from SEDs





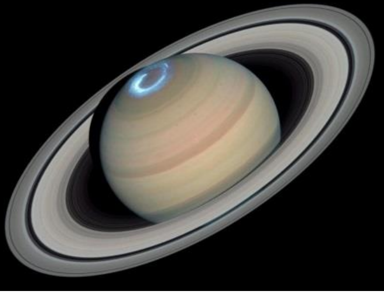
LT of storm from images, angle of incidence α calculated from storm and Cassini position

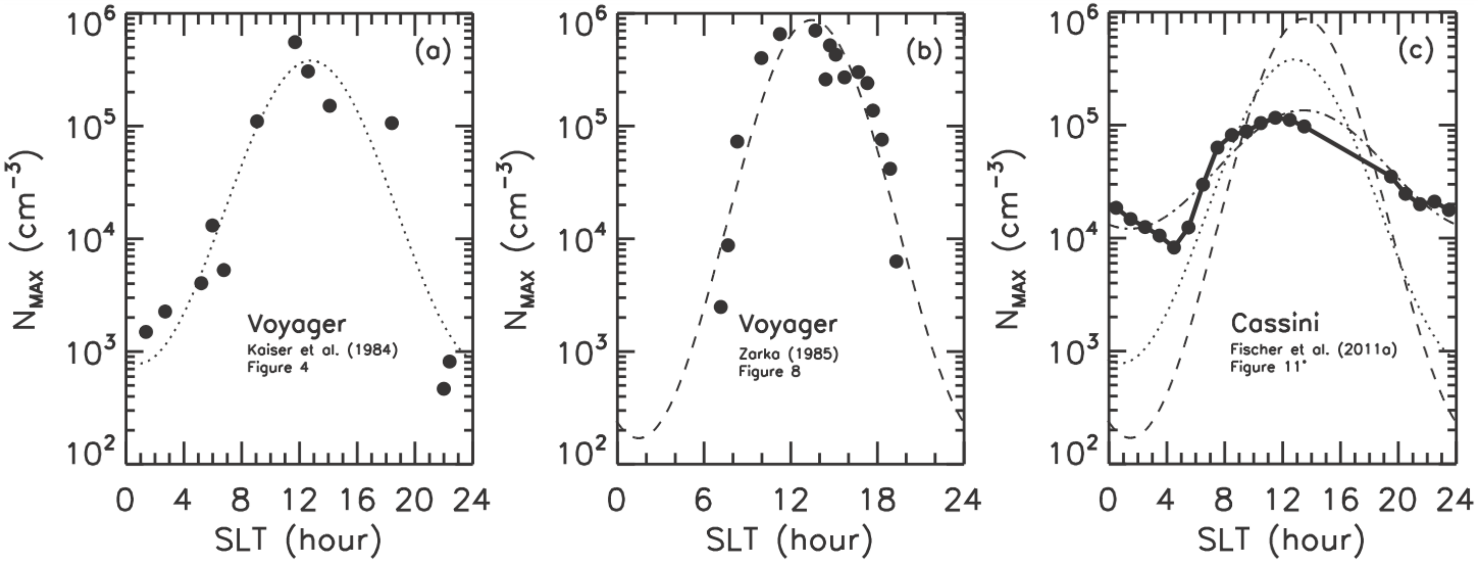
$$f_{cutoff} = \frac{f_{pe,\max}}{\cos(\alpha)}$$

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

Fischer et al (2011)

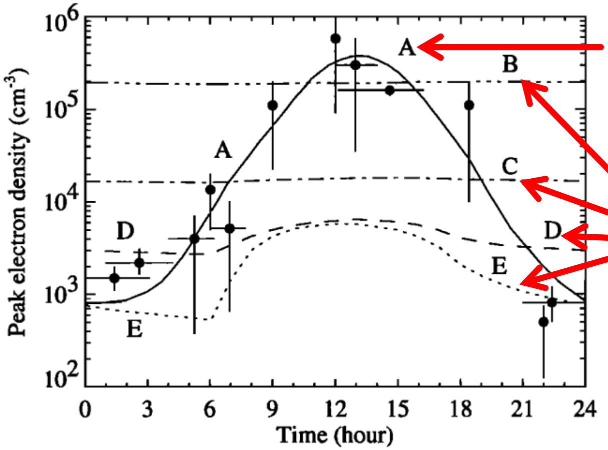
$N_{MAX}(t)$ from SEDs





Moore et al (2012)

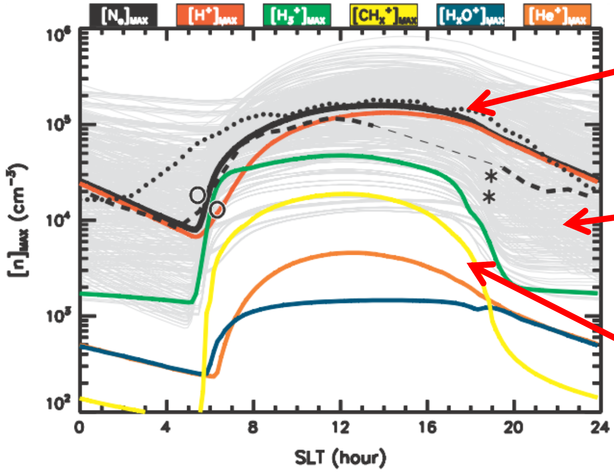
- Significant ionization enhancements required to match dawn-noon rise
- Drastic losses required to match nighttime decline
- Non-photochemical solution? Low altitude ion layers?



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)

Summary, Part I

- Ionization sources:
  - EUV and X-ray solar photons, and
  - magnetospheric, energetic particles (dominant in auroral regions)
- Giant planet ionospheres:
  - Dominant ionization species (H_2^+) minor constituent after chemistry
  - Major ions:
    - H^+: long-lived, minimal diurnal variation, subject to transport
    - H_3^+: short-lived, strong diurnal variation, predominantly in photochemical equilibrium
    - Hydrocarbon and metallic ions: extremely short-lived, bottomside “shoulder” of ionization
  - Unconstrained chemistry:
    - Populations of vibrational levels for H_2 (in particular $v \geq 4$)
    - Water (or other oxygen/metallic) influxes: variation with latitude, time, etc.
- Remaining unknowns:
  - Low altitude electron density layers: gravity waves or other vertical wind shear?
  - Origins of observed ionospheric structure and variability
  - Local time variations in ion and electron densities
  - SED explanation; lack of “JEDs”

Part II

Ionosphere-thermosphere-magnetosphere coupling at the giant planets

Outline, Part II

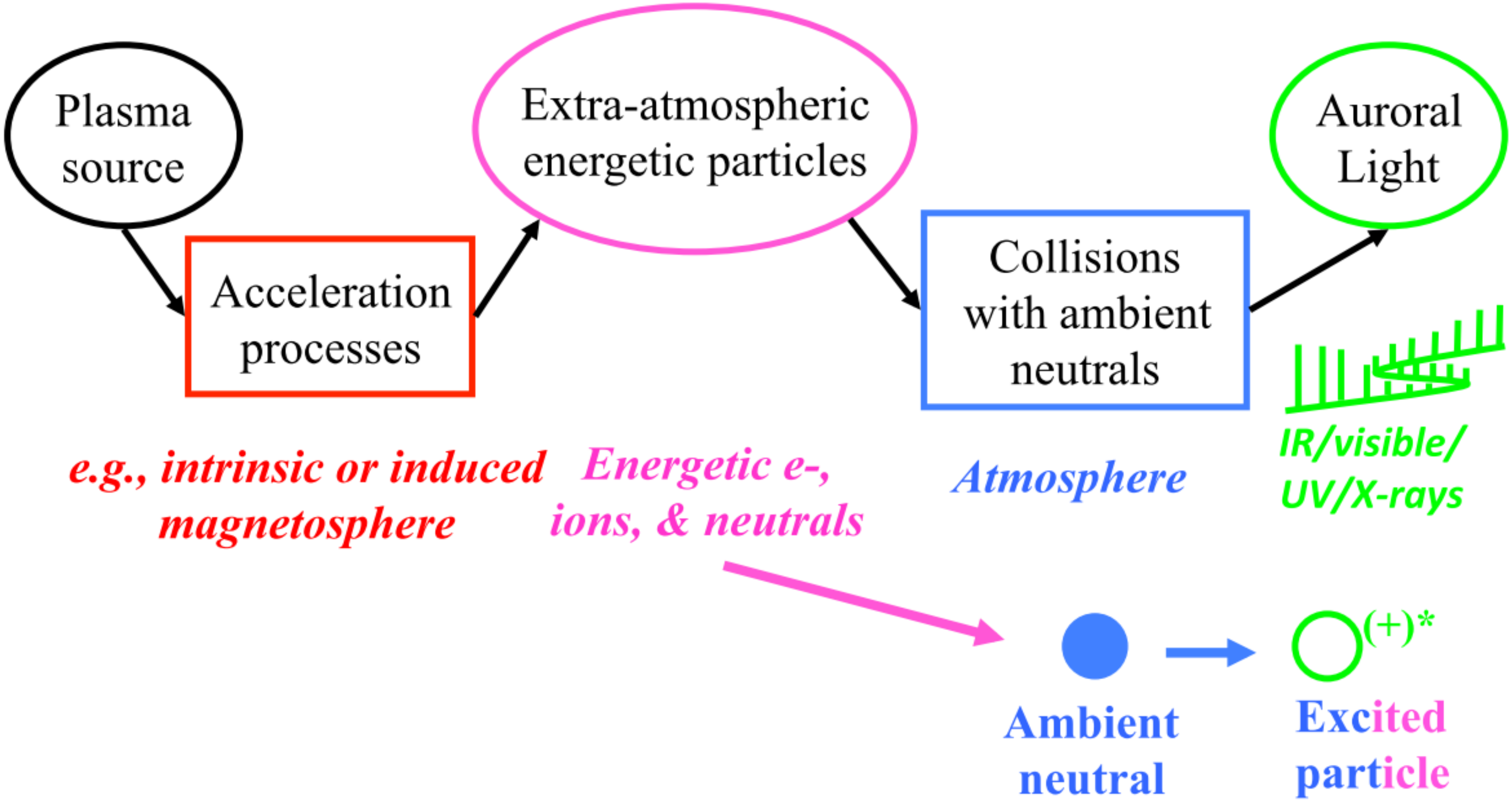
- Auroral emissions
  - Categories of aurora
  - UV vs. IR (i.e., H_3^+) aurora

- Ionosphere-thermosphere-magnetosphere and solar wind coupling
  - Saturn ring rain
  - The giant planet "energy crisis"
    - Upper atmospheric temperatures; heating sources
  - Ionospheric electrical conductivities

- Future prospects
  - Juno, JUICE, JWST, EChO, …

Auroral emissions

- Aurora: photo-manifestation of the interaction between energetic extra-atmospheric electrons, ions, and neutrals with an atmosphere



Plasma source

Acceleration processes

Extra-atmospheric energetic particles

Collisions with ambient neutrals

Auroral Light

e.g., intrinsic or induced magnetosphere

Energetic e-, ions, & neutrals

Atmosphere

IR/visible/ UV/X-rays

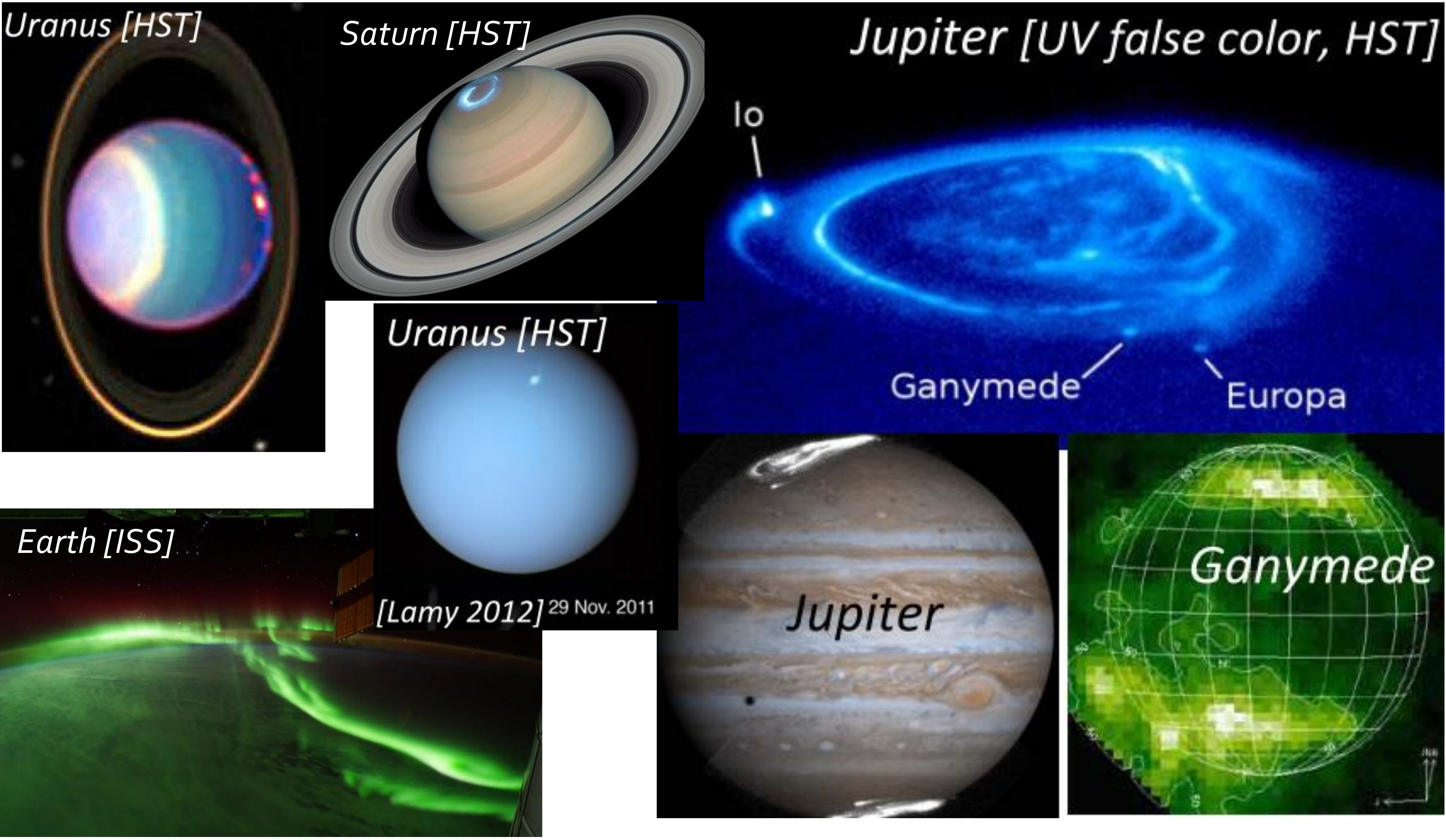
Ambient neutral

$^{(+)*}$

Excited particle

M. Galand

Auroral emissions in the solar system



Uranus [HST]

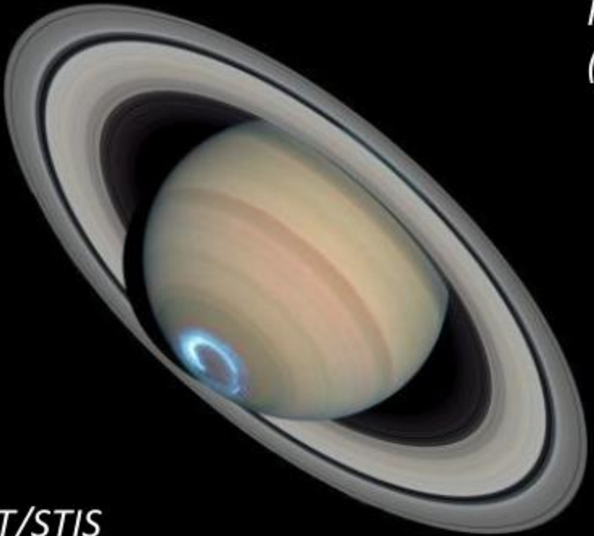
Saturn [HST]

Jupiter [UV false color, HST]

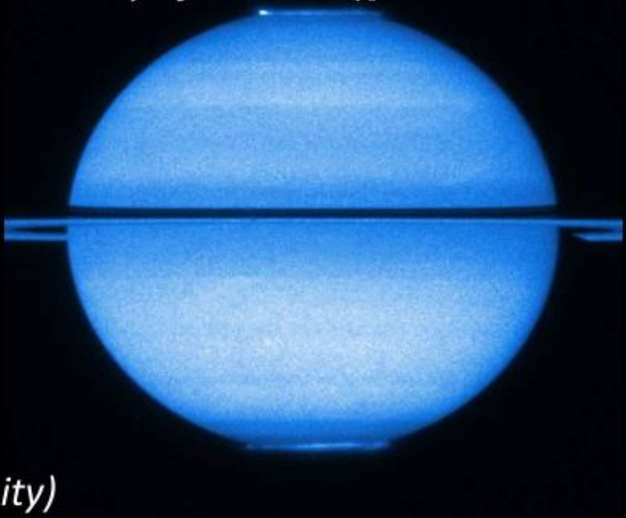
Uranus [HST]

[Lamy 2012] 29 Nov. 2011

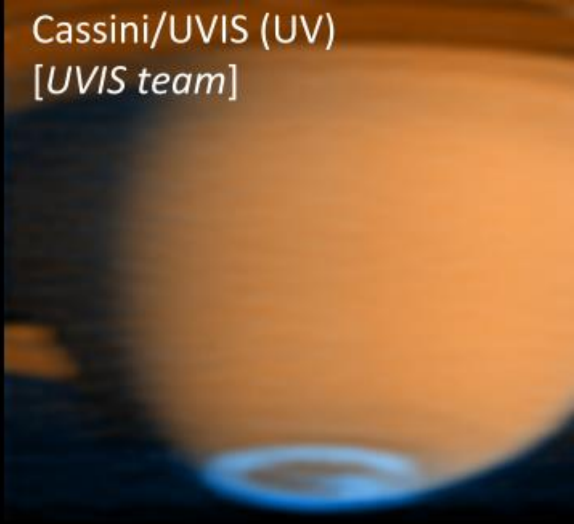
Earth [ISS]



HST/STIS
NASA/ESA/John Clarke (Boston University)



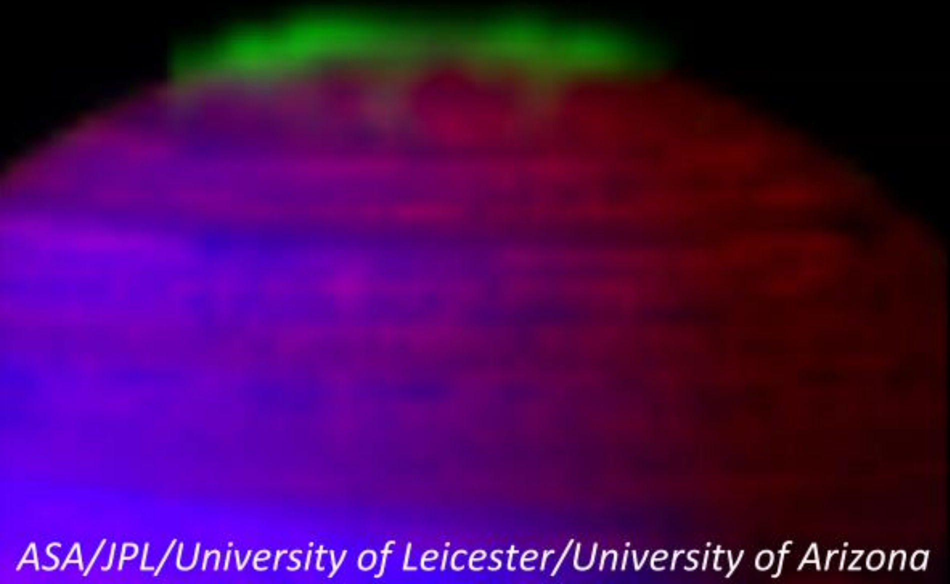
HST/STIS [NASA/ESA/Jonathan Nichols (University of Leicester)]



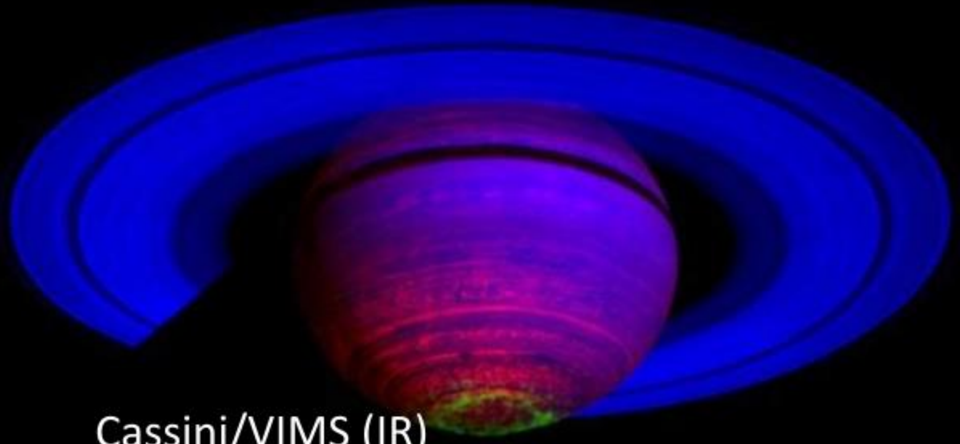
Cassini/UVIS (UV)
[*UVIS team*]

UV spectroscopic analysis → Particle characteristics

IR spectroscopic analysis→ H_3^+ density & temperature



ASA/JPL/University of Leicester/University of Arizona



Cassini/VIMS (IR)
NASA/JPL/Tom Stallard (Univ. Leicester)/

Auroral UV spectroscopic analysis

- Identification of energetic particle type
- Assessment of $\mathbf{E_m}$ and $\mathbf{Q_{prec}}$ of energetic particles
  - $\mathbf{E_m}$ = mean energy of precipitating particles (e.g., Maxwellian)
  - $\mathbf{Q_{prec}}$ = energy flux of precipitating particles

Color Ratio	Earth	Jupiter, Saturn
Two spectral bands chosen in:	N_2 LBH	H_2 Lyman and Werner
One band strongly absorbed by:	O_2 (< 160 nm)	CH_4 (< 140 nm)
Electron energy range covered:	0.2 – 20 keV	~10 – 200 keV
Type of aurora identified:	Electron aurora (discrete only)	Electron aurora (diffuse + discrete)

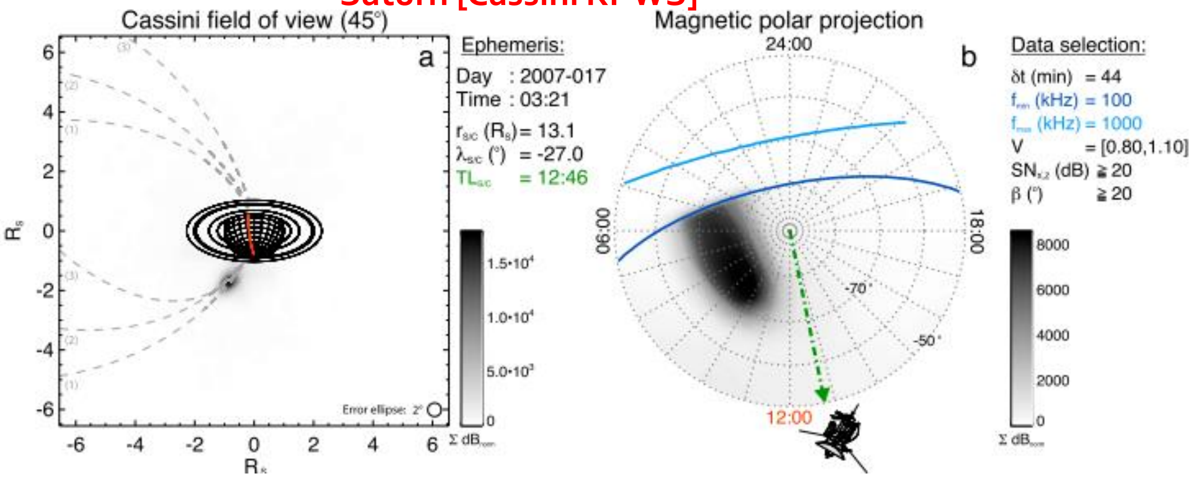
- Similar techniques can be applied at various other planets with different limitations on the product (e.g., Fox et al, 2008).

→ Above tasks require comprehensive modeling support

Giant planet auroral emissions: 4 main categories

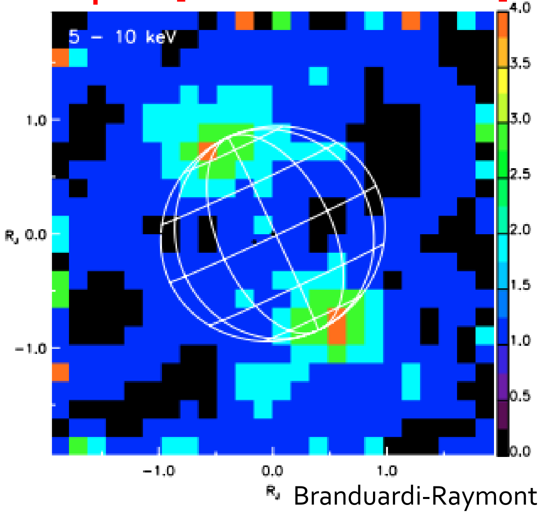
- (1) Emission from precipitating particles: radio and x-ray
  - Radio emission generated by precipitating electrons as they are accelerated into atmosphere along magnetic field lines
    - Originate in low density region above planet, near field-aligned potentials
    - Cause of auroral radio emission observed at all the giant planets (Zarka, 1998; Lamy et al., 2009)
  - X-ray emission bremsstrahlung emission from high-energy precipitating particles scattered by the atmosphere (e.g., Jupiter)
    - Some electron driven bremsstrahlung present (e.g., Branduardi-Raymont et al., 2007), but primarily due to highly charged heavy ions

Saturn [Cassini RPWS]



Lamy et al (2009)

Jupiter [XMM-Newton EPIC]



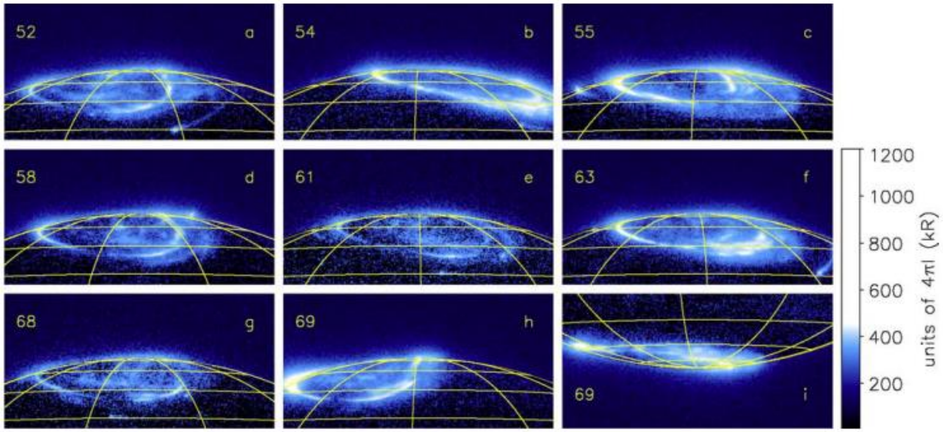
Branduardi-Raymont et al (2007)

Giant planet auroral emissions: 4 main categories

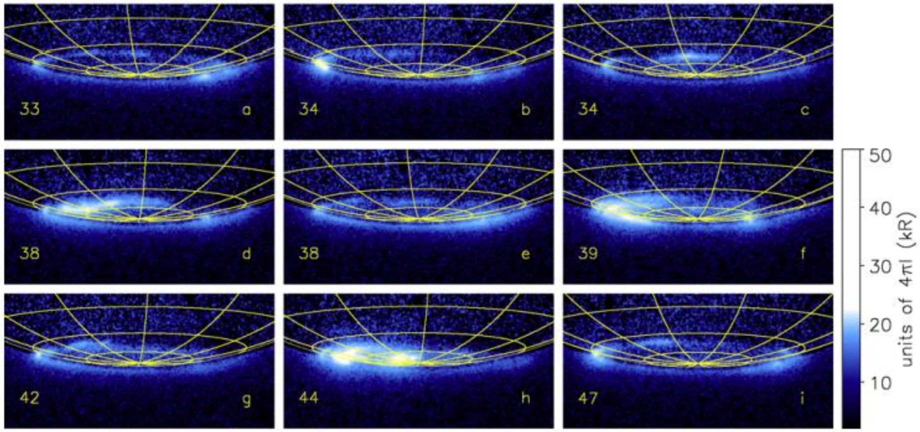
- (2) Atmospheric excitation
  - Prompt emission resulting from atmospheric atoms and molecules excited by precipitating particles
  - The "classic" aurora (e.g., Earth)
    - Similar on different planets, owing to composition differences
  - Brightest giant planet emissions:
    - UV Lyman-α (121.6 nm); visible light Balmer series (e.g., 410.2 nm); UV H_2 Lyman and Werner bands (dominating over ~90-170 nm)

→ Provides instantaneous view of the particle precipitation process

Jupiter



Saturn



Clarke et al (2009)

Giant planet auroral emissions: 4 main categories

- (3) Thermal auroral emission
  - Produced from heating generated by atmosphere-magnetosphere interaction
  - Molecular hydrogen, hydrocarbons, and hydrogen ions emit IR when thermalized to neutral atmosphere
    - Major heat sink in the upper atmosphere
    - H_3^+ most easily observed
    - Hydrocarbons provide majority of cooling
- (4) Ionization aurora
  - Ionization dominated by particle precipitation in auroral regions
  - Due to long thermal timescales and short ionization timescales, auroral structure is dominated by ionization, while overall brightness is dominated by temperature
  - Closely follows prompt UV auroral morphology; time and spatial lag due to H_3^+ recombination rates and temperature variations

Protonated molecular hydrogen: H_3^+

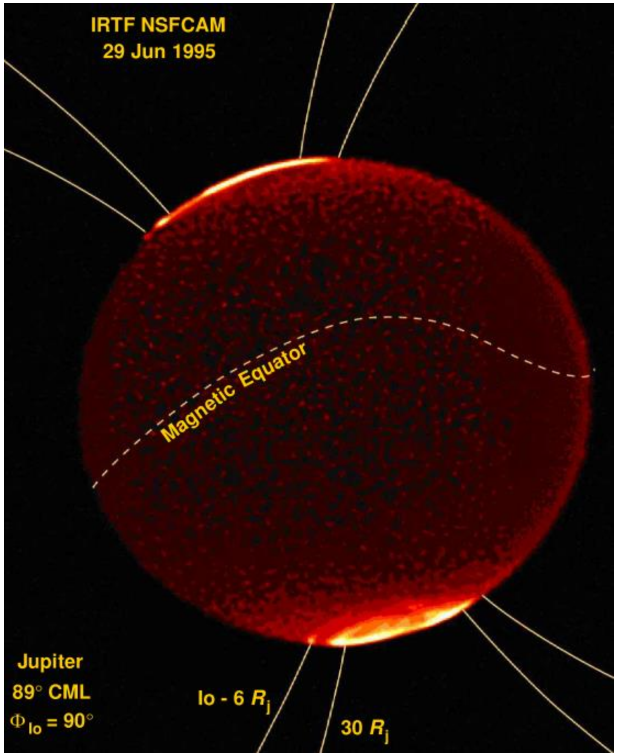
- First astronomical spectroscopic detection in the universe at Jupiter
  - Auroral IR measurements with CFHT (Drossart et al., 1989)

- Bright emission lines in K-band (2-2.5 μm) and L-band (3-4 μm) 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, T^4

- Can be used to derive ion temperatures, densities velocities

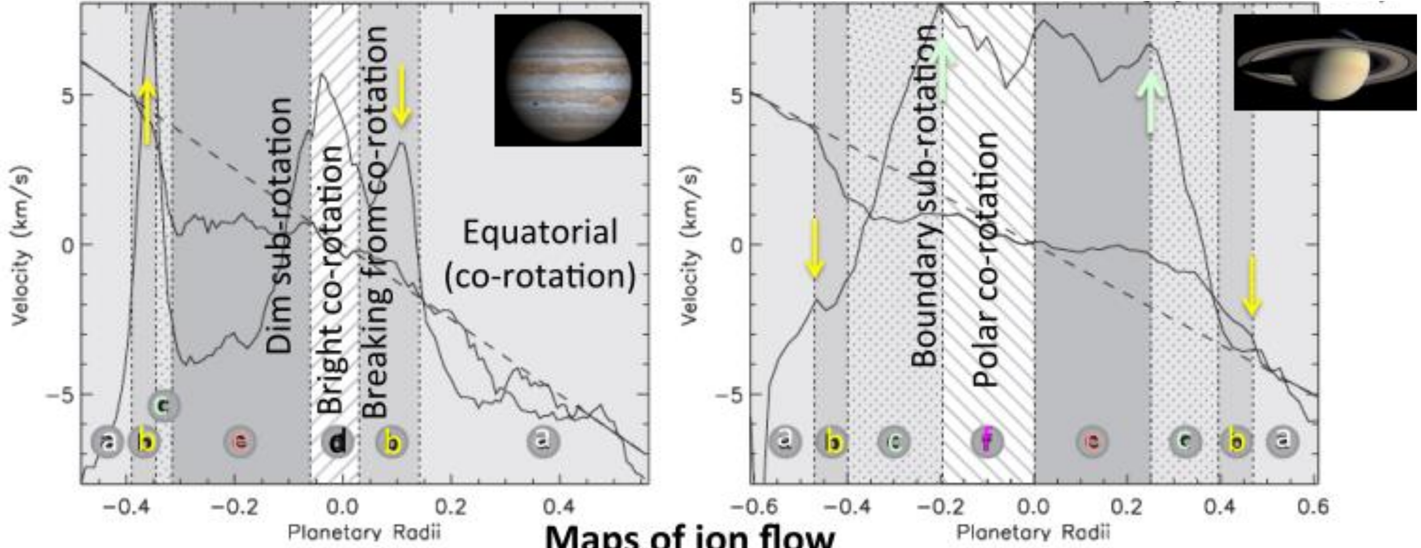
- Important as a coolant, e.g.:
  - Efficient thermostat at Jupiter
  - Hot exoplanets with dissociated H_2 lose a key cooling mechanism



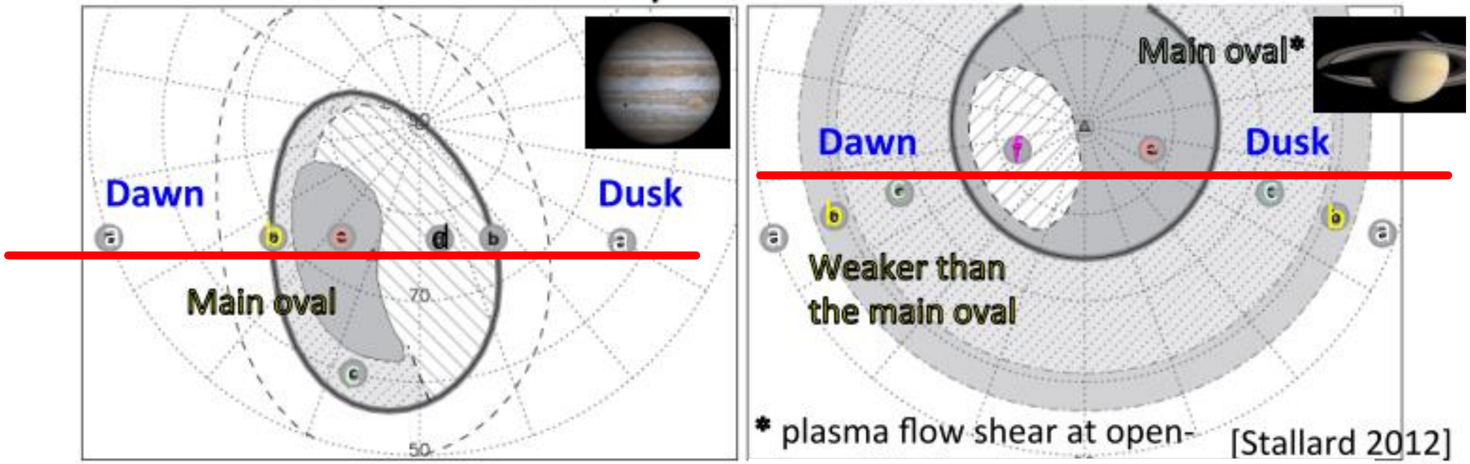
Connerney and Satoh (2000)

IR auroral spectroscopic analysis

H_3^+ line-of-sight velocity and normalized intensity (NASA-IRTF)



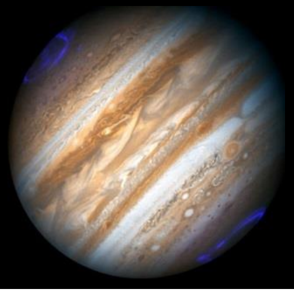
Maps of ion flow



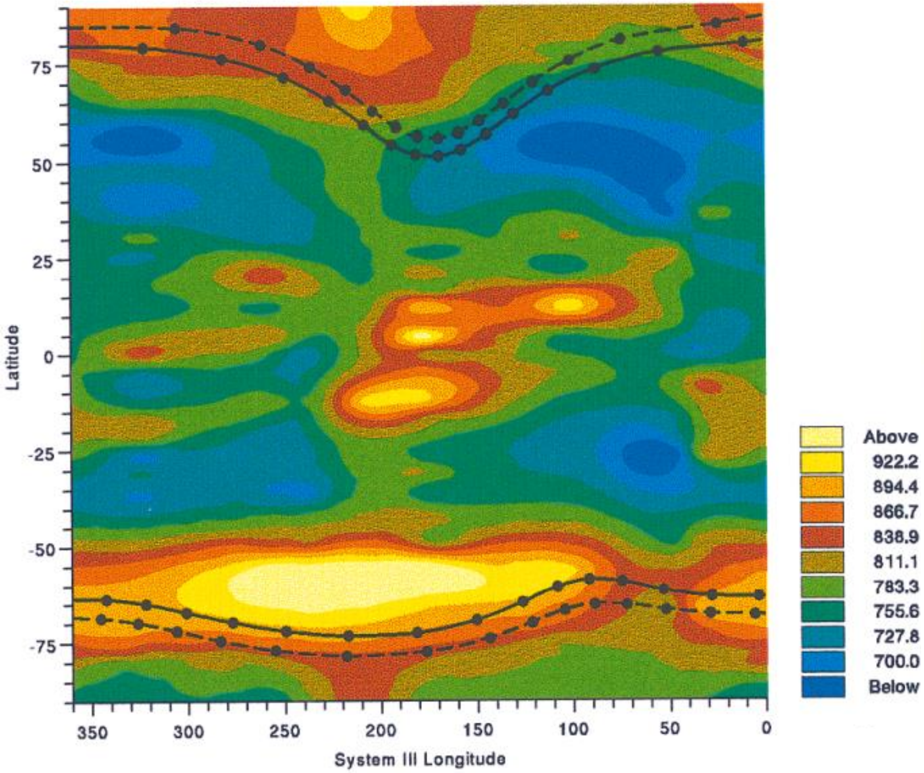
* plasma flow shear at open-

[Stallard 2012]

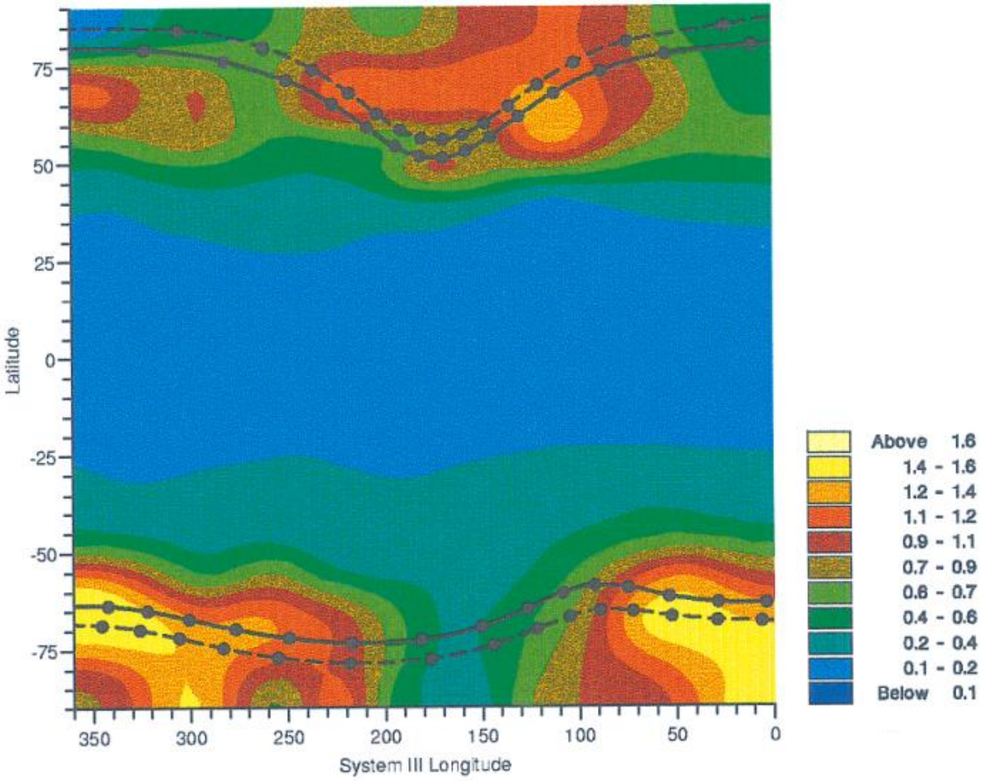
Global H_3^+ properties



Temperature

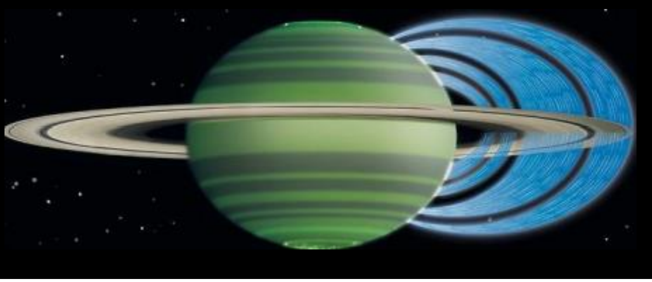


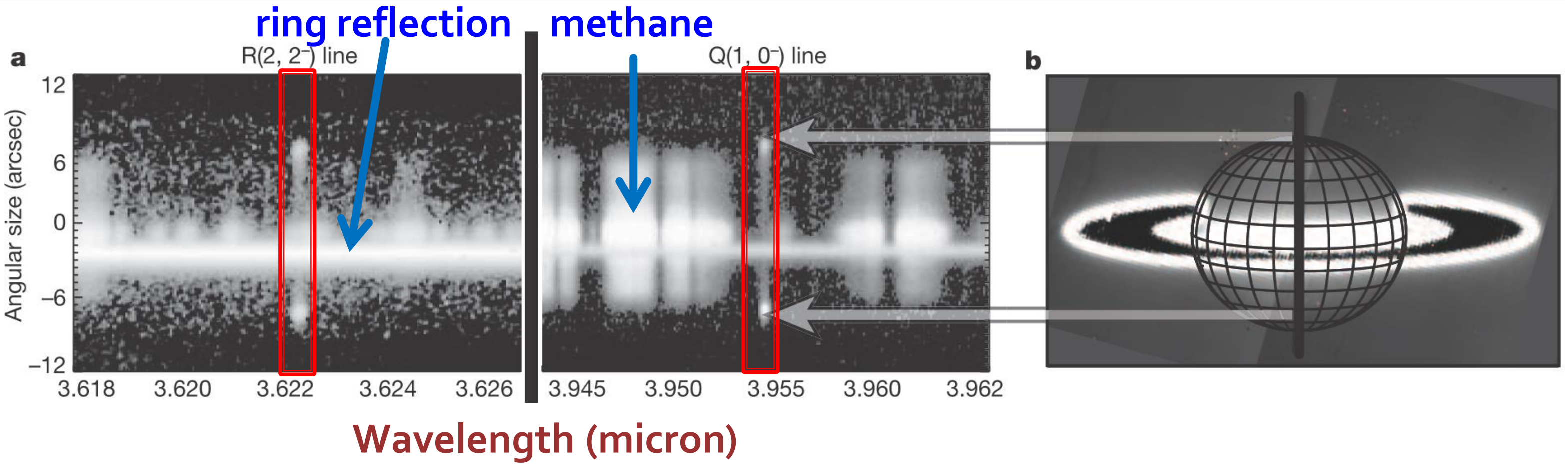
Column Density



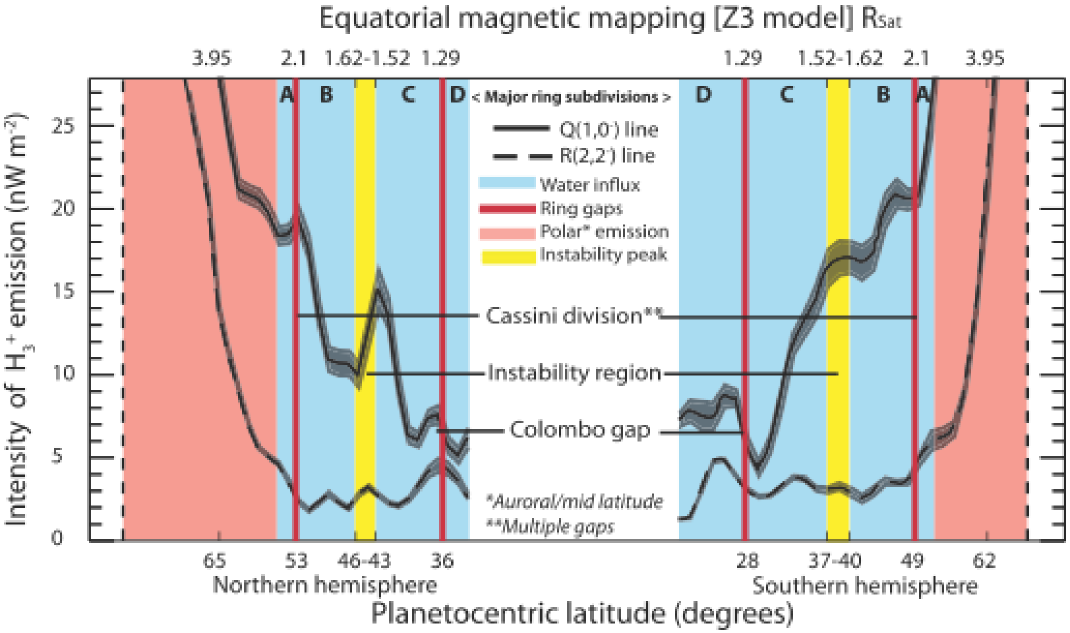
Lam et al (1997)

Saturn Ring Rain



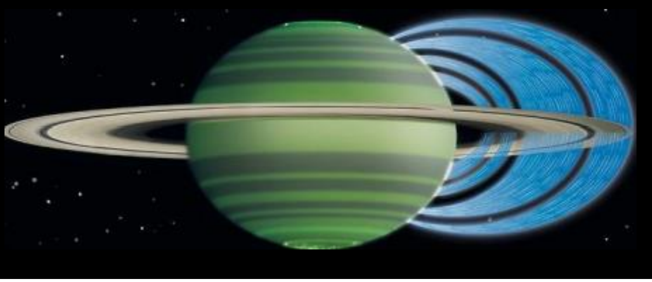


- local extrema mirrored at magnetically conjugate latitudes, and also map to structures in the rings
- First non-auroral detection of H3^{+} at Saturn
- Keck observations: 2011

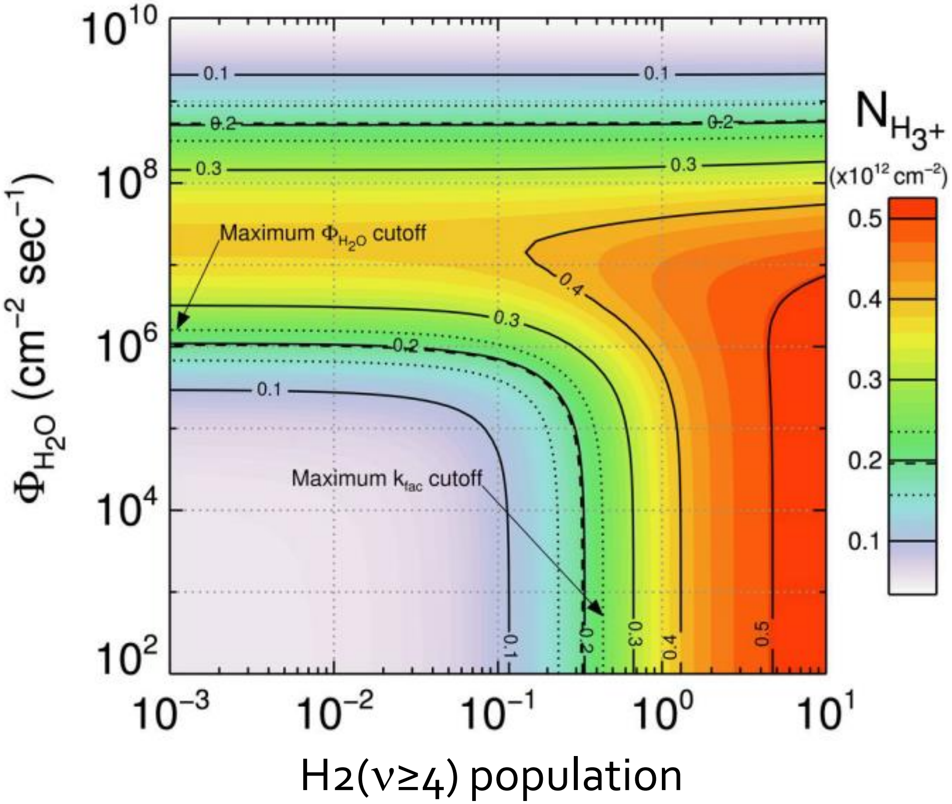


O'Donoghue et al (2013)

Impact of water influx

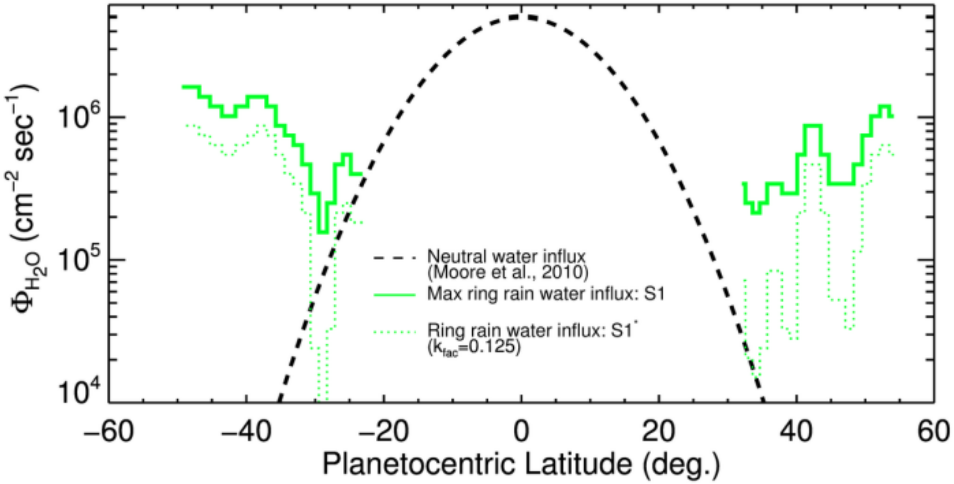


Family of solutions matching ring rain H_3^+ column density at -35°

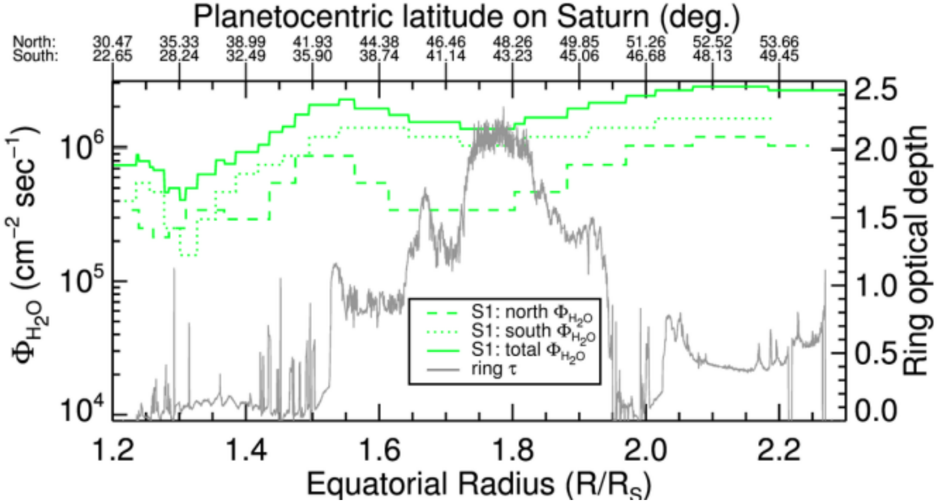


Moore et al (2014)

Global water influx at Saturn

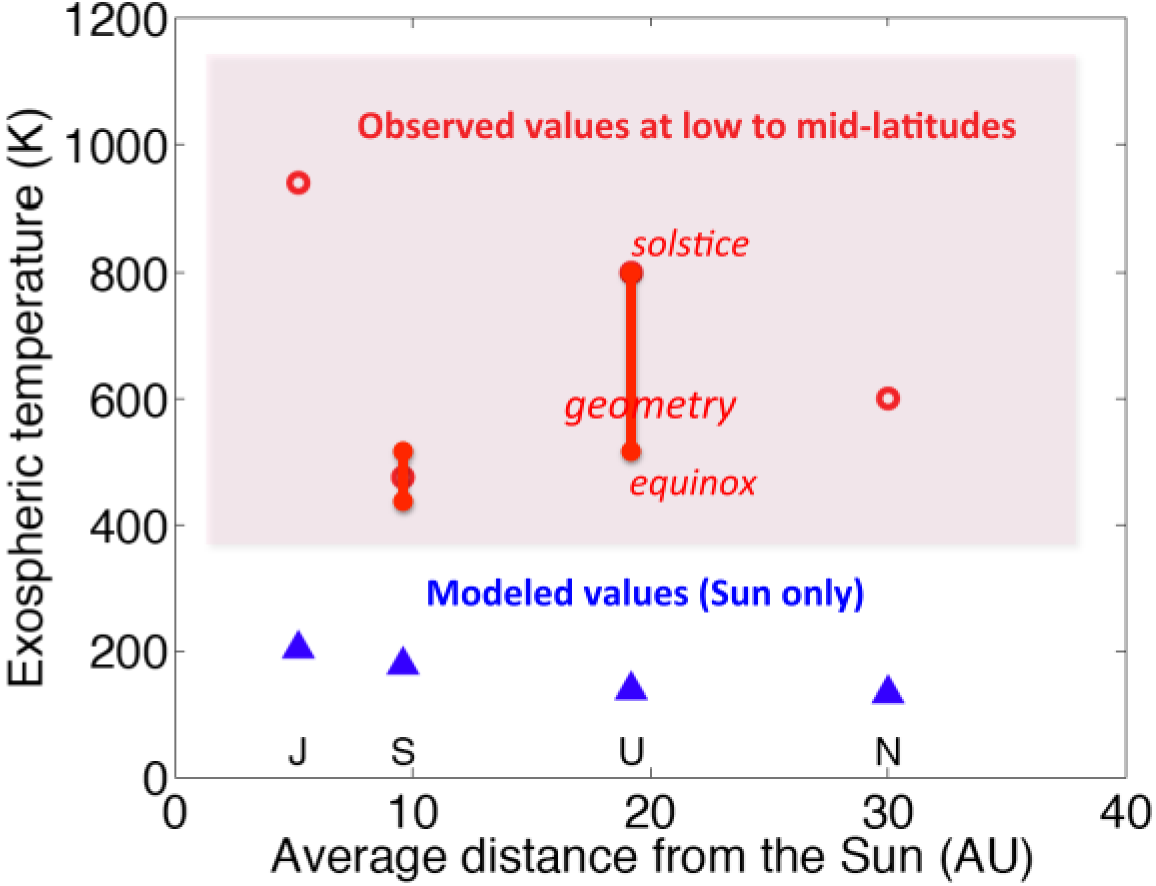


Water influx mapped to ring plane



The Giant Planet Energy Crisis

$$T_{exosphere}^{computed\ with\ sun\ only} << T_{exosphere}^{observed}$$



[After *Yelle and Miller*, 2004; *Melin et al., 2011, 2013*]

M. Galand

The Giant Planet Energy Crisis

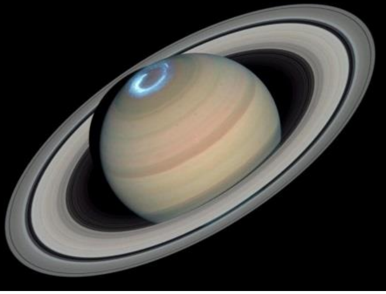
- **Heating sources:** forcing from above and below
  - Solar heating:
    - excitation/dissociation/ionization and exothermic chemical reactions
  - Particle heating:
    - via collisions and chemistry
  - “Ionospheric joule heating”
    - via auroral electrical currents and ion-drag heating at high latitudes (e.g., Vasyliũnas and Song, 2005)
  - Dissipation of upward propagating waves
    - e.g., gravity waves, acoustic waves, etc. (Matcheva and Strobel, 1999; Hickey et al., 2000; Barrow et al., 2012)

	Earth (TW)	Jupiter (TW)	Saturn (TW)
Solar EUV/FUV heating*	0.5	0.8	0.2
Auroral particle/Joule heating*	0.08	100	5-10

* Strobel (2002)

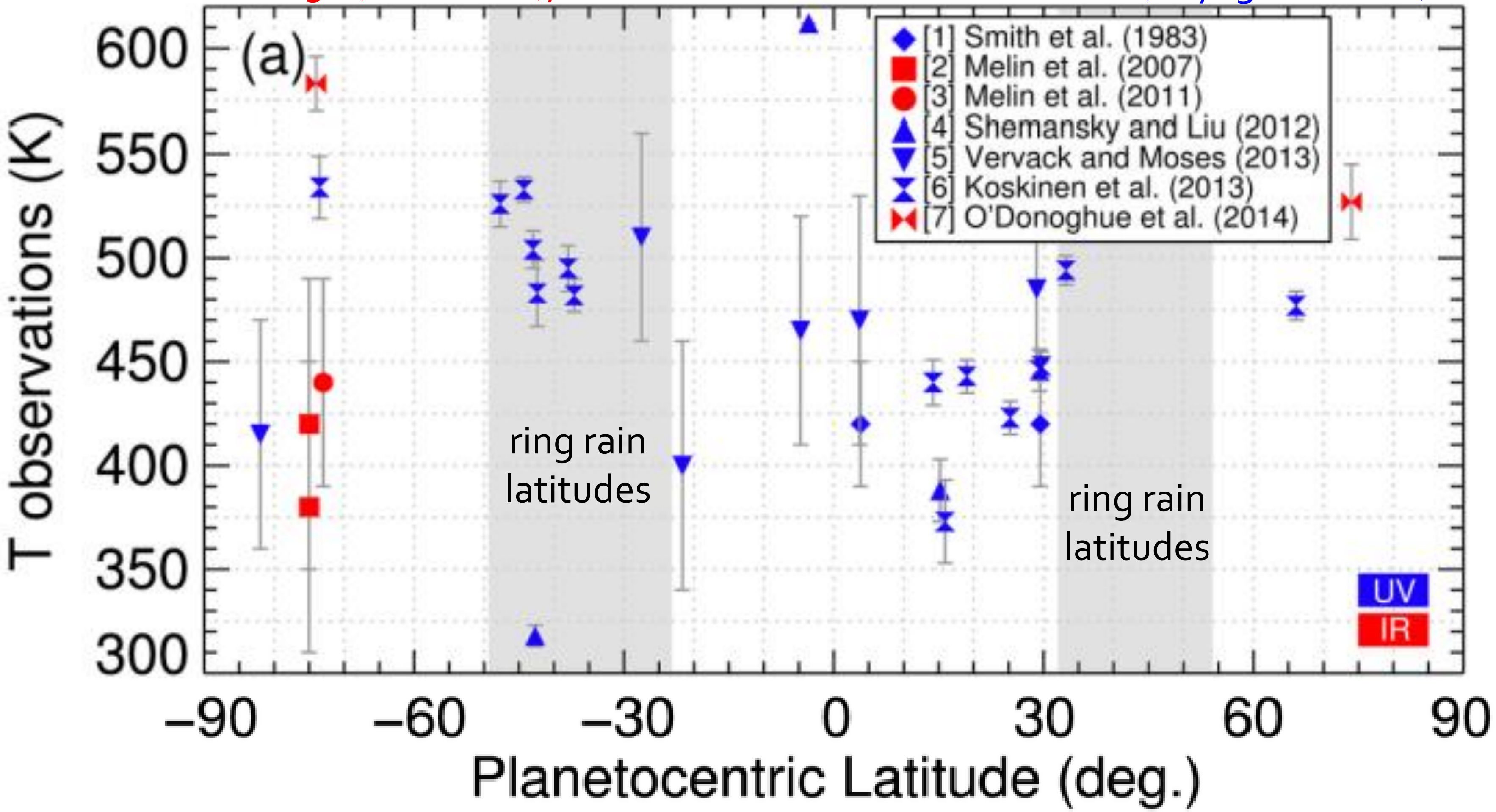
M. Galand

Saturn energy crisis: upper atmospheric temperatures



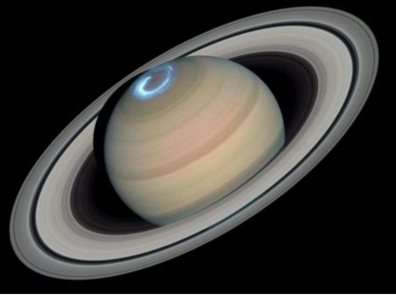
All published temperatures at Saturn:

IR = H_3+ (IRTF/Keck); UV = solar and stellar occultations (Voyager/Cassini)

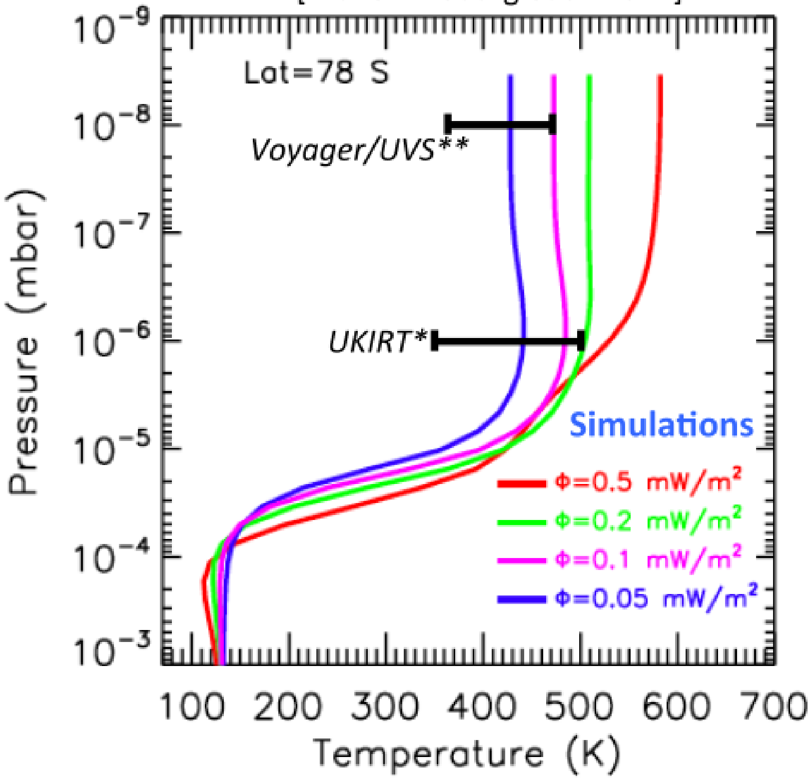


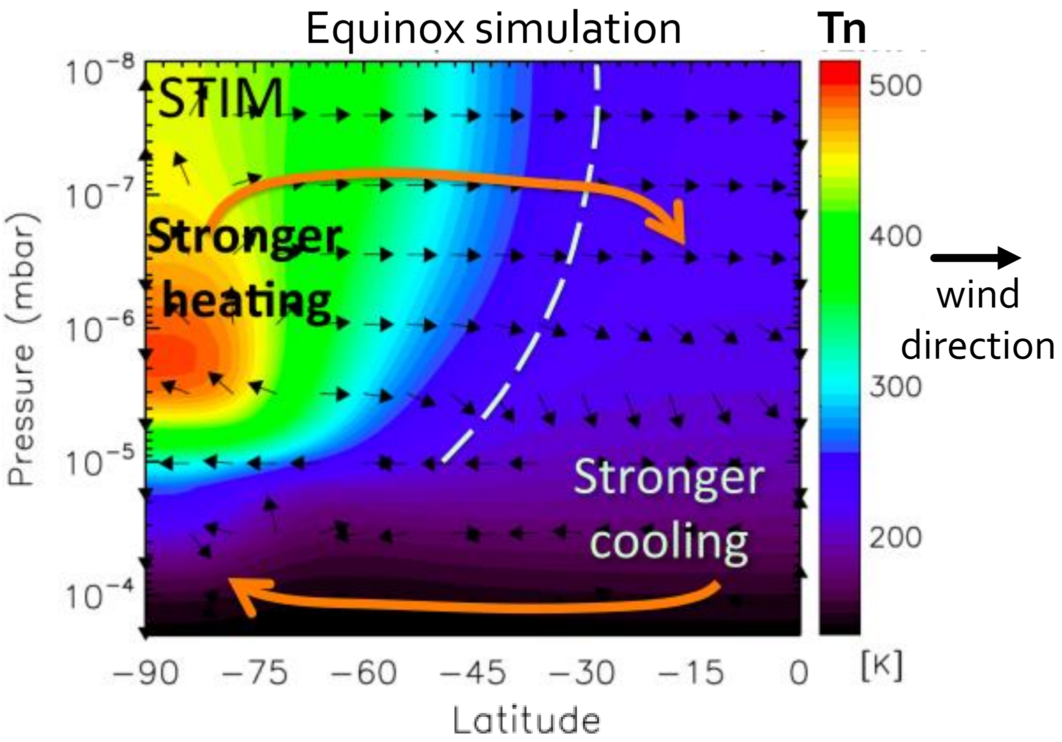
Moore et al (2014)

Saturn energy crisis:
ion drag fridge effect



[Müller-Wodarg et al. 2012]





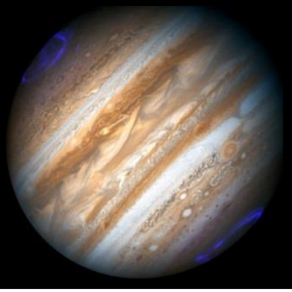
- **Auroral Joule heating sufficient to heat high latitude thermosphere**

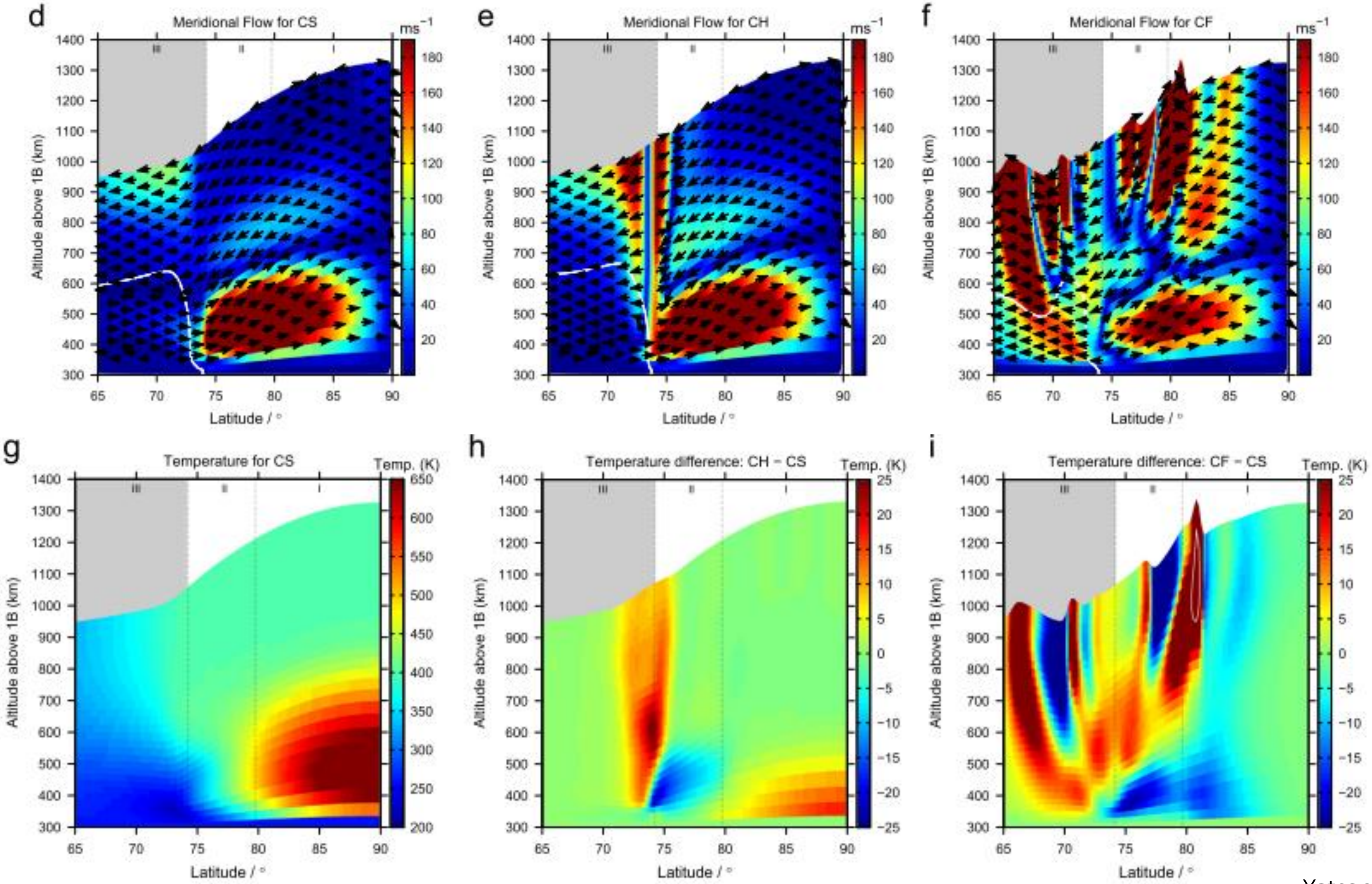
- **BUT polar sub-corotation due to auroral forcing (westward ion velocities) drives downward collapse and equator-to-pole circulation**
- **Input of more magnetospheric energy only exacerbates the ion drag fridge effect (Smith et al, 2007; Smith and Aylward, 2009)**

* Melin et al (2007)
** Vervack and Moses (2013)

Mueller-Wodarg et al (2012)

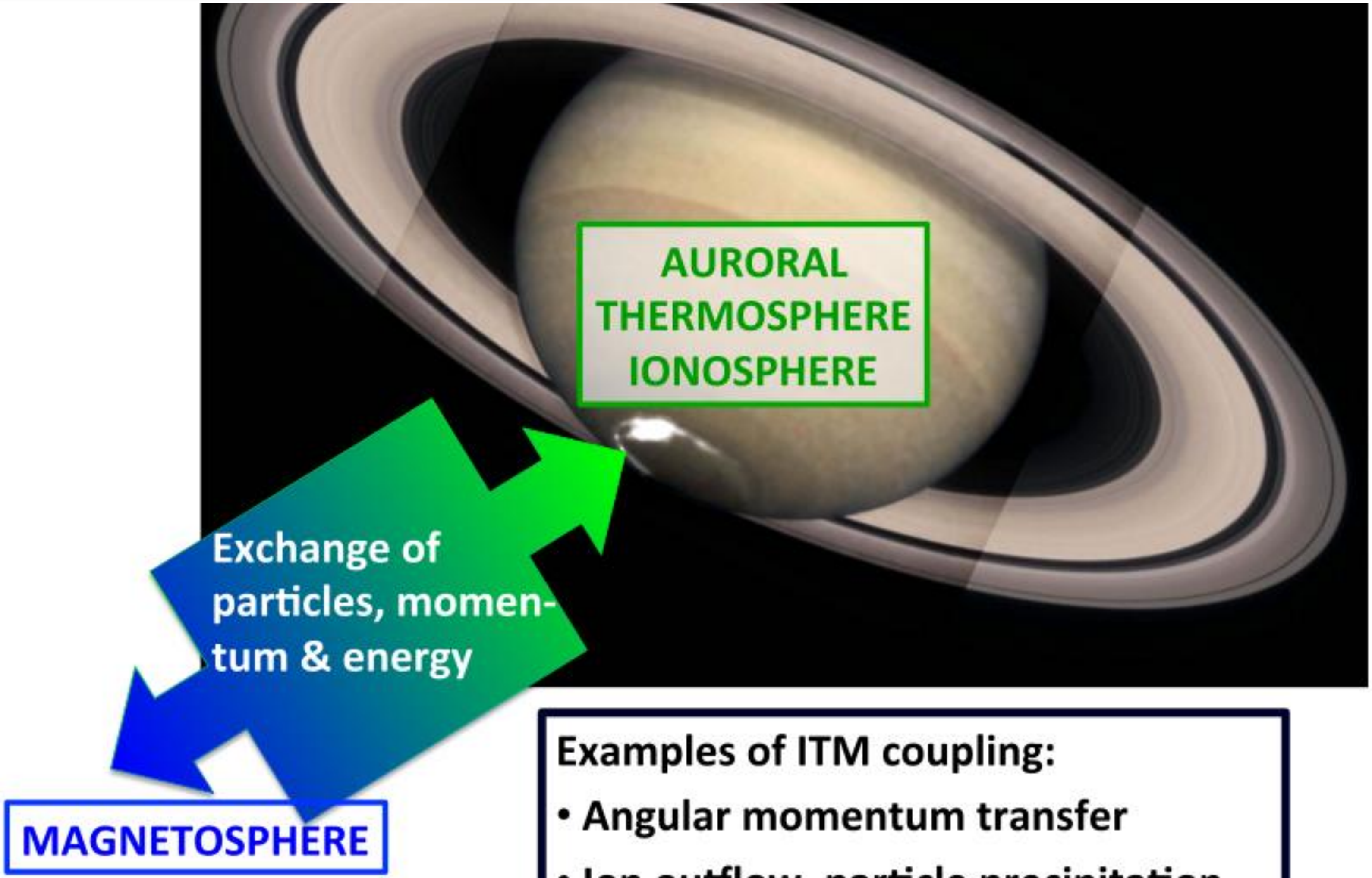
Jupiter energy crisis: time dependent coupling effects





Yates et al (2014)

Ionosphere-thermosphere-magnetosphere coupling



AURORAL
THERMOSPHERE
IONOSPHERE

Exchange of particles, momentum & energy

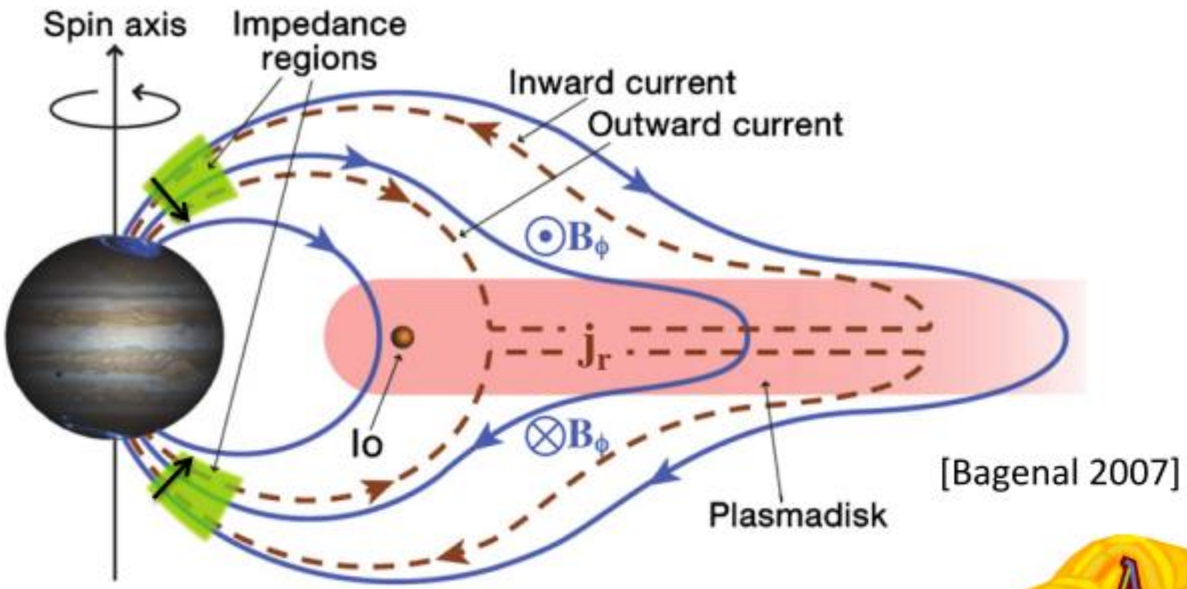
MAGNETOSPHERE

Examples of ITM coupling:

- Angular momentum transfer
- Ion outflow, particle precipitation

M. Galand

Ionosphere-thermosphere-magnetosphere coupling



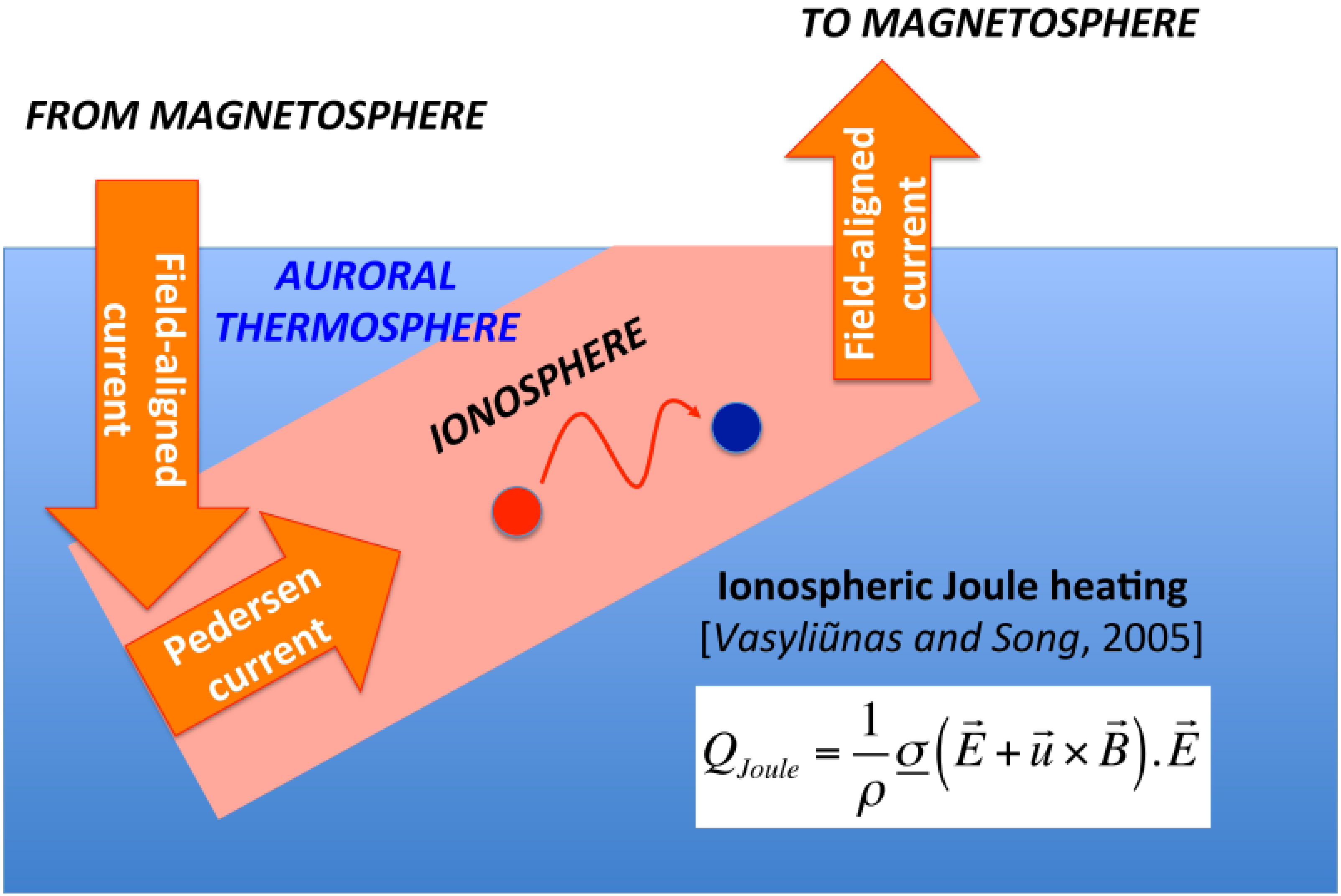
[Bagenal 2007]

- Overall, at high latitudes:

  the magnetosphere extracts angular momentum from the upper atmosphere through the magnetic field-aligned currents

M. Galand

Ionosphere-thermosphere-magnetosphere coupling



Ionospheric Joule heating
[*Vasyliũnas and Song*, 2005]

$$Q_{Joule} = \frac{1}{\rho} \underline{\sigma} \left(\vec{E} + \vec{u} \times \vec{B} \right) . \vec{E}$$

M. Galand

Ionospheric electrical conductances

Pedersen (σ_P) & Hall (σ_H) conductivities:

$$\sigma_P(z) = \sum_n \sum_i \frac{n_i e}{B} \left(\frac{\nu_{en\perp}\,\omega_e}{\nu_{en\perp}^2 + \omega_e^2} + \frac{\nu_{in}\,\omega_i}{\nu_{in}^2 + \omega_i^2} \right)$$

with $\boxed{\omega = \frac{eB}{m}}$

$$\sigma_H(z) = \sum_n \sum_i \frac{n_i e}{B} \left(\frac{\omega_e^2}{\nu_{en\perp}^2 + \omega_e^2} - \frac{\omega_i^2}{\nu_{in}^2 + \omega_i^2} \right)$$

Pedersen (Σ_P) & Hall (Σ_H) conductances:

$$\Sigma_P = \int_{ionosphere} \sigma_P(z)\,dz$$

$$\Sigma_H = \int_{ionosphere} \sigma_H(z)\,dz$$

Indices: e (electrons), i (ions), n (neutrals)

Variables:

- n, number density
- ω, gyro-frequency (= e B / m)
- ν_{in}, ion-neutral collision frequency
- $\nu_{en\perp}$, effective electron-neutral collision frequency perpendicular to B
- B, magnetic field

Conductance: mho ℧ (inverse of resistance, ohm backwards)

Conductivity: mho/m 1 mho = 1 Siemens (the SI unit)

[e.g., Richmond 1995]

M. Galand

Ionospheric electrical conductances in auroral regions

Pedersen ————————

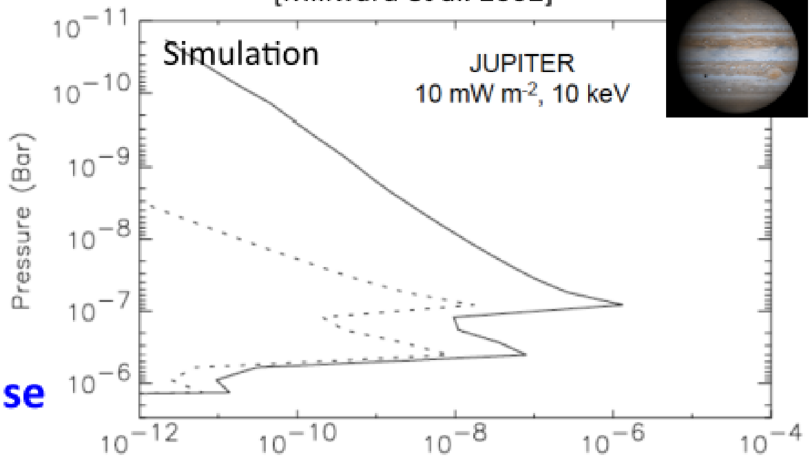
Hall - - - - - - - - - - - - - -

At a given planet, when intense e- precipitation (within the reaction time of the ionosphere): $\Sigma \propto Q_{prec}$

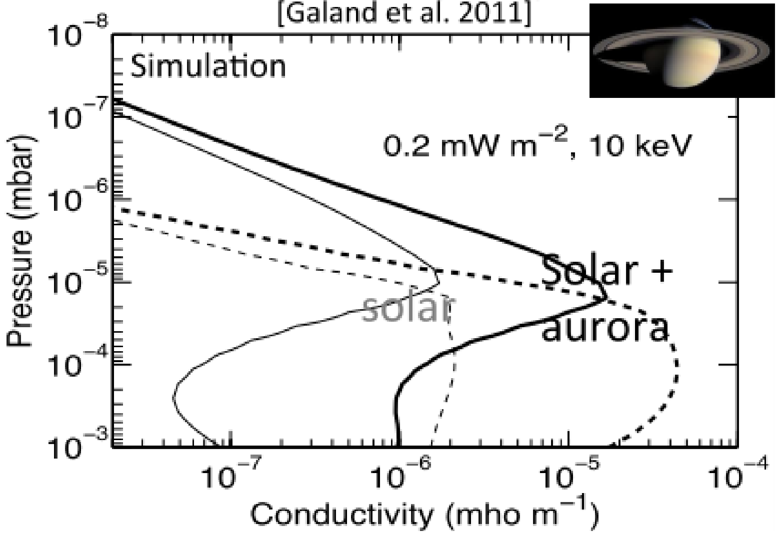
Pedersen conductance

Jupiter	Saturn
60 keV, 10 mW m^{-2}	10 keV, 1 mW m^{-2}
2 mho	12 mho

[Millward et al. 2002]



[Galand et al. 2011]



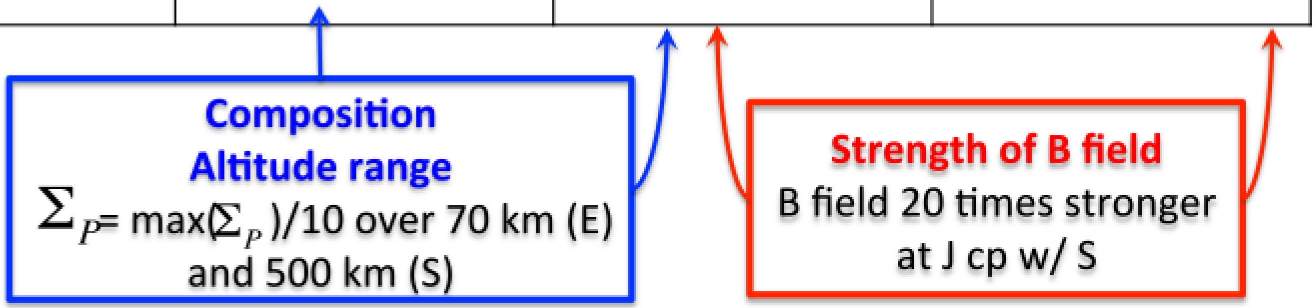
M. Galand

Question

- What might be causing the difference in conductance at Jupiter and Saturn?

Ionospheric electrical conductances in auroral regions

Auroral electron mean energy & energy flux	**Earth** *[Fuller-Rowell and Evans, 1987]*	**Saturn** *[Galand et al., 2011]*	**Jupiter** *[Millward et al., 2002]*
10 keV 1 mW m^{-2}	Σ_P= **4-6 mho**	Σ_P= **11-12 mho**	Σ_P= **0.03 mho**



Composition
Altitude range
Σ_P= max(Σ_P)/10 over 70 km (E) and 500 km (S)

Strength of B field
B field 20 times stronger at J cp w/ S

Planetary angular velocity

Angular velocity of the neutrals

Slippage parameter(1) for Jupiter(2) & Saturn(3): $k = \dfrac{\Omega - \omega_n}{\Omega - \omega_i} = \sim 0.5$

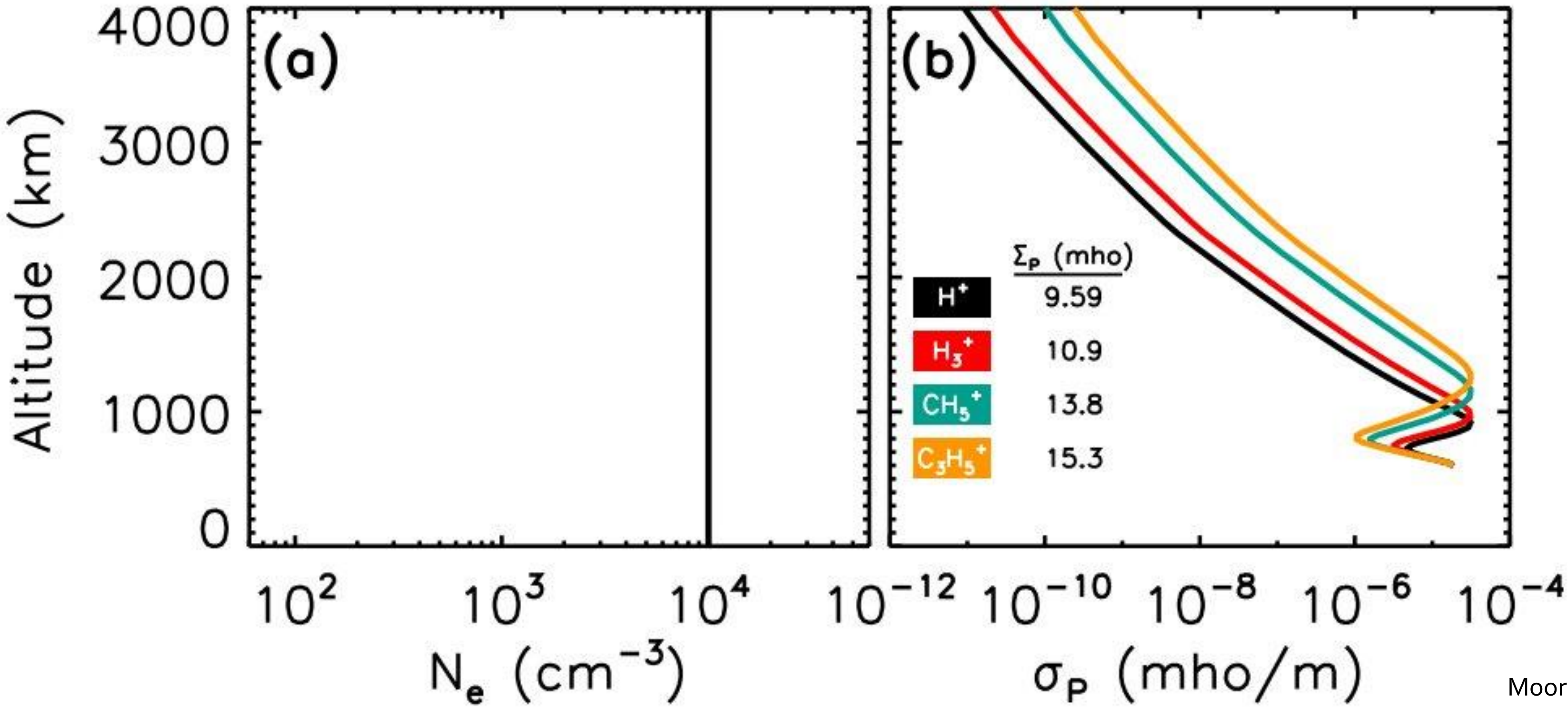
Angular velocity of the ions

(1) *Huang and Hill* [1989]; (2) *Cowley et al.* [2004]; (3) *Galand et al.* [2011]

M. Galand

Ionospheric conductances: importance of altitude and m_i

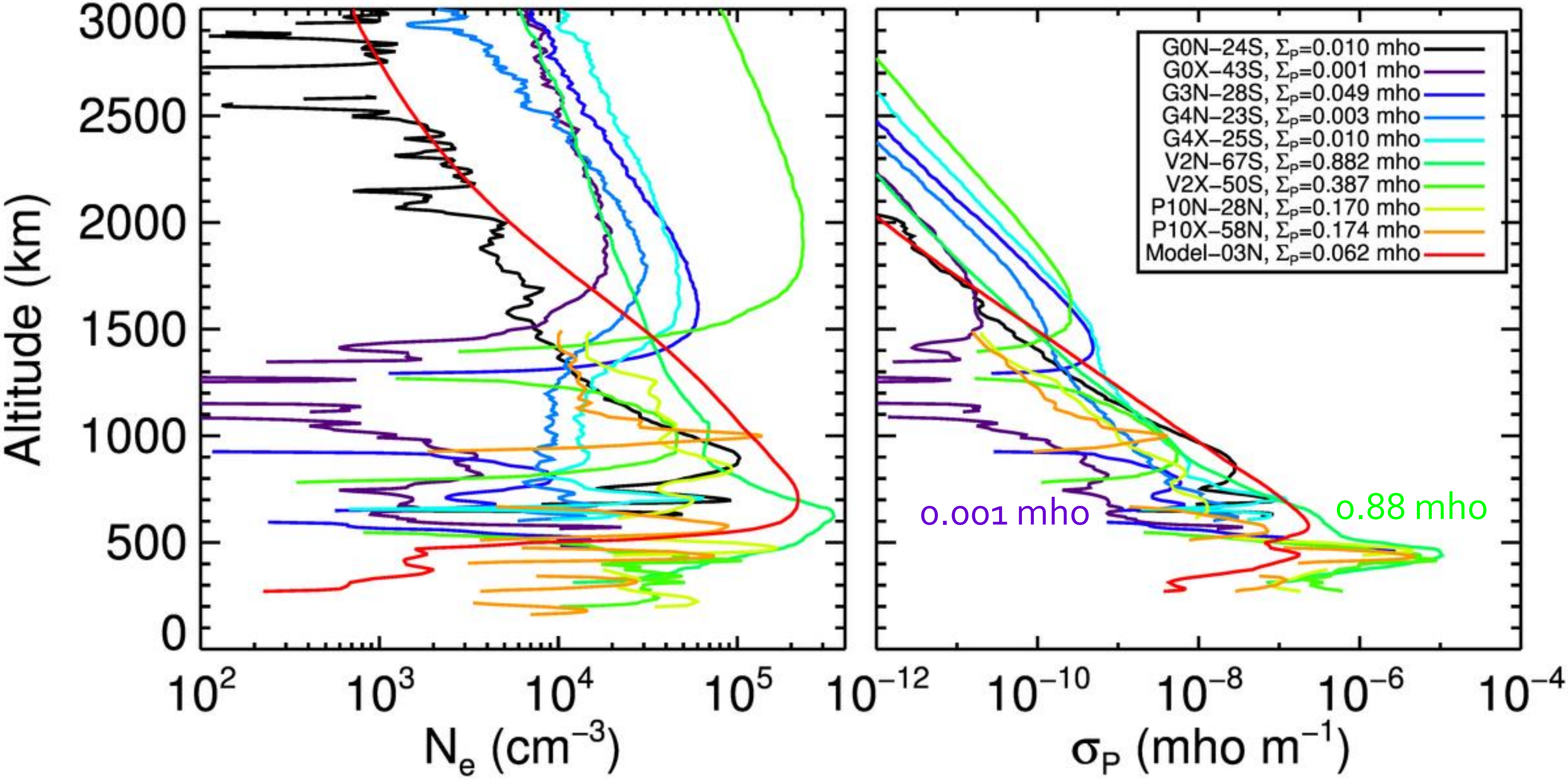
- Assume electron density is constant with altitude
- Assume ionosphere is composed of entirely one ion
- ~50% difference in derived Pedersen conductance, mostly due to mass
- Pedersen layer near 1000 km at Saturn (~600 km at Jupiter)



Moore et al (2010)

Ionospheric conductances from radio occultation observations

- Electron density profiles from Galileo, Voyager and Pioneer
- Background atm. and ion fractions based on model, scaled to observed N_e

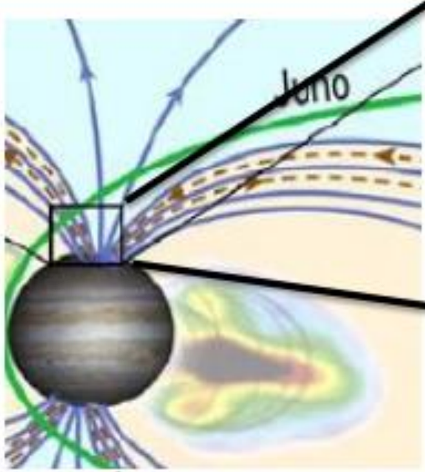


0.001 mho

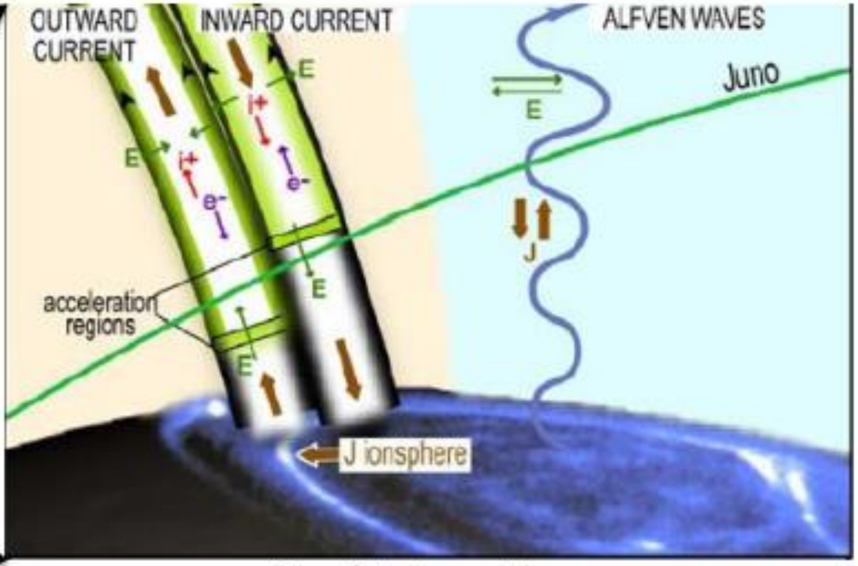
0.88 mho

Future Prospects

JUNO
over the polar regions



Credit: *Juno Team*



Credit: *Juno Team*

July 2016!

JUNO observations through the magnetic field lines connected to the auroral ionosphere, close/within the acceleration region (expected to be 2-3 RJ from center [e.g., *Ray et al., 2009*]):

- Electric currents along magnetic field lines
- Plasma/radio waves revealing processing responsible for particle acceleration
- Energetic particles precipitating into atmosphere creating aurora
- Ultraviolet/IR auroral emissions regarding the morphology of the aurora

Summary, Part II

- Analysis of auroral emissions:
  - **Valuable probe** of ionosphere (IR), auroral particle source, ITM coupling, and magnetic field line configuration
  - **Jupiter:** main oval driven by breakdown in co-rotation (Io)
  - **Saturn:** main oval mapped in the outer magnetosphere varying with solar wind conditions (Enceladus)
  - **Uranus:** solar wind dominated
- Ionosphere-Thermosphere-Magnetosphere (ITM) coupling
  - **Ionospheric electrical conductances:**
    - Uncertainties in conductivities driven by limitation in electron (and ion) density estimates
    - Differences in B field strength between Jupiter and Saturn yield significant conductance differences. Larger energy fluxes at Jupiter don't compensate for the stronger B field. Implications for ITM coupling
  - **Simulations:**
    - Critical to estimate the upper atmosphere response self-consistently
    - Play a key role in efforts to understand underlying physics
  - **Energy crisis** remains unsolved:
    - Investigate shorter timescales, E field variability unconstrained, role of waves, mid-latitude e^-?
  - Lessons learned from Saturn useful for **upcoming exploration of Jupiter** (Juno/JUICE) and **exoplanets** (EChO, JWST)

Comparative cross body approach

✓**Diversity** among solar system bodies in terms of:

- *physical, magnetic field, atmospheric, energy forcing settings*

→makes *comparative aeronomy* an exciting and enriching field of research

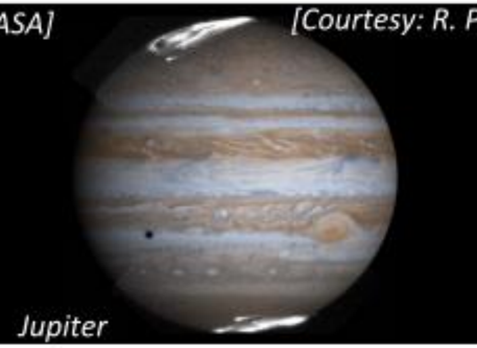
✓Comparative aeronomy challenges our understanding of atmospheric processes, coupling with neighboring regions, and planet evolution, as well as open new doors for extrapolating beyond our Solar System.

[Credit: D. Hardy, astroart.org/ STFC]

Exoplanet

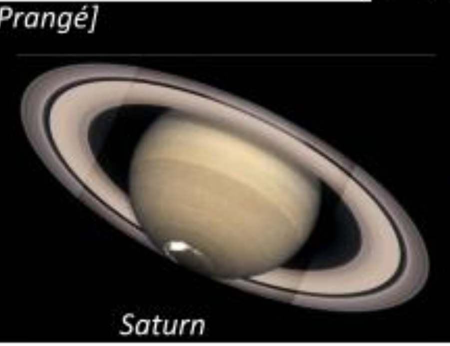
[Credit: NASA]

Earth

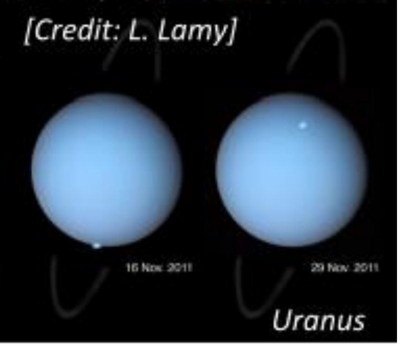


[Courtesy: R. Prangé]

Jupiter



Saturn



[Credit: L. Lamy]

Uranus

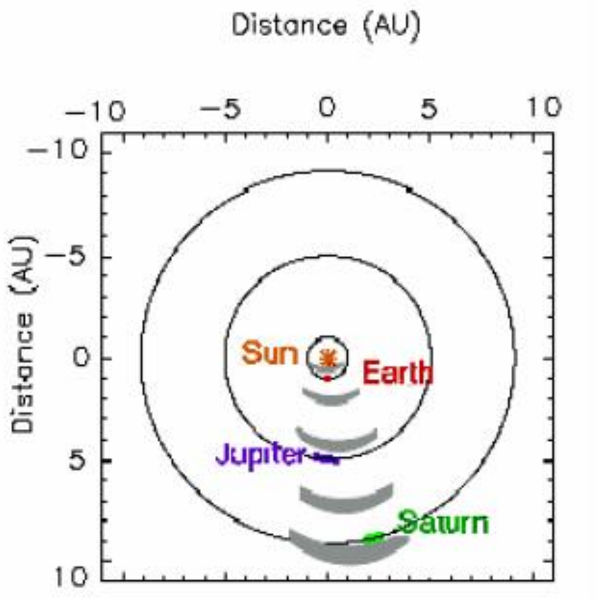
M. Galand

Coupling with the solar wind:

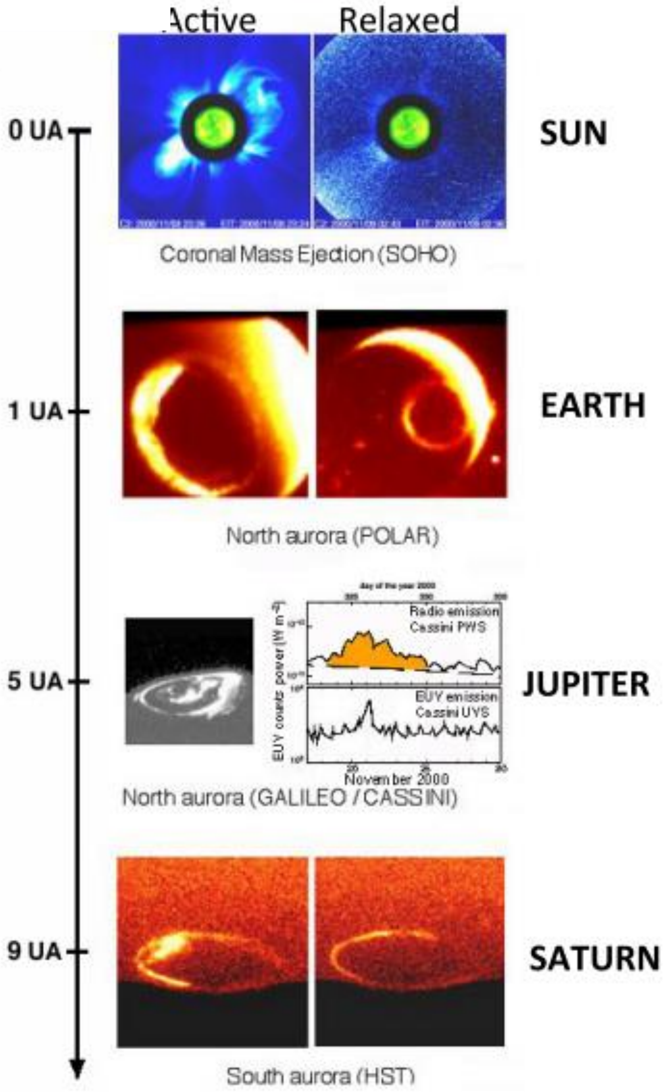
interplanetary shock to Earth, Jupiter, Saturn

First synoptic view of a CME-driven interplanetary shock hitting the Earth, Jupiter and Saturn, triggering major – but different – auroral responses at all three planets

→ *Highlights the difference in setting and allows us to learn more about sw-MI coupling by comparing different responses*



[Prangé et al., Nature, 2004]



Coronal Mass Ejection (SOHO)

North aurora (POLAR)

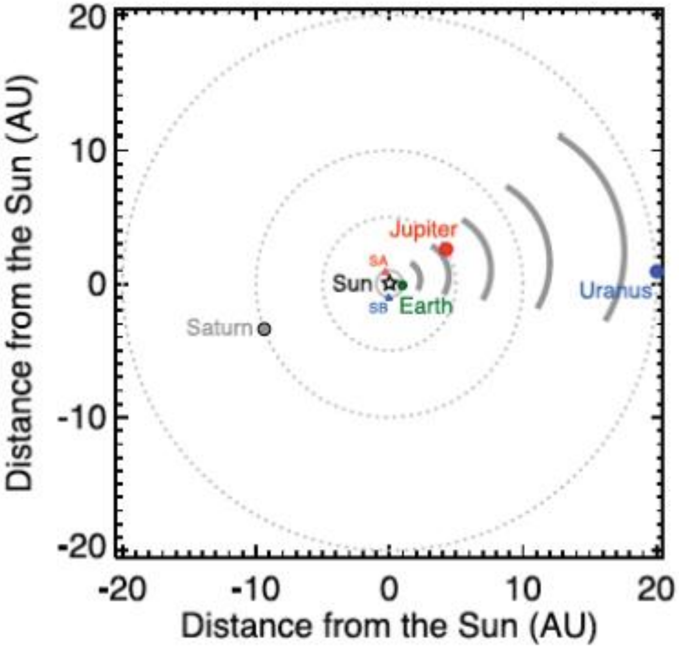
North aurora (GALILEO / CASSINI)

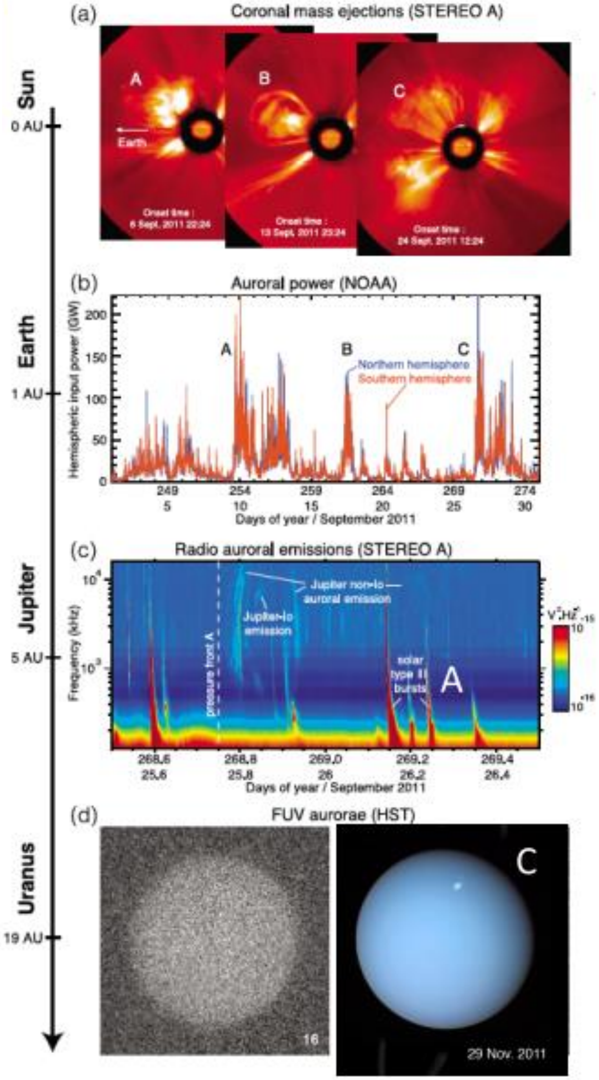
South aurora (HST)

M. Galand

Coupling with the solar wind:

interplanetary shock to Earth, Jupiter, Uranus





[Lamy et al., GRL, 2012]

M. Galand