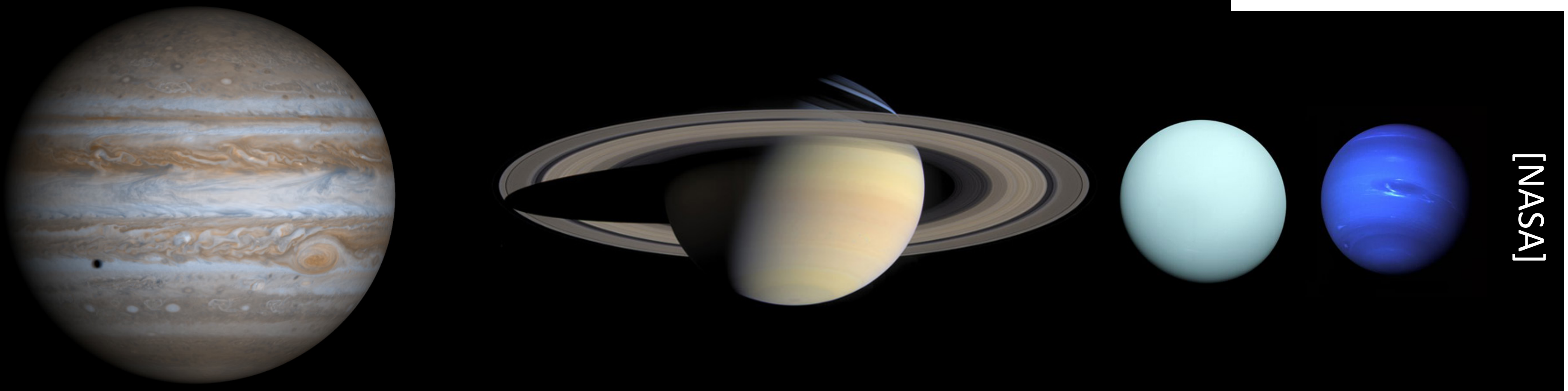
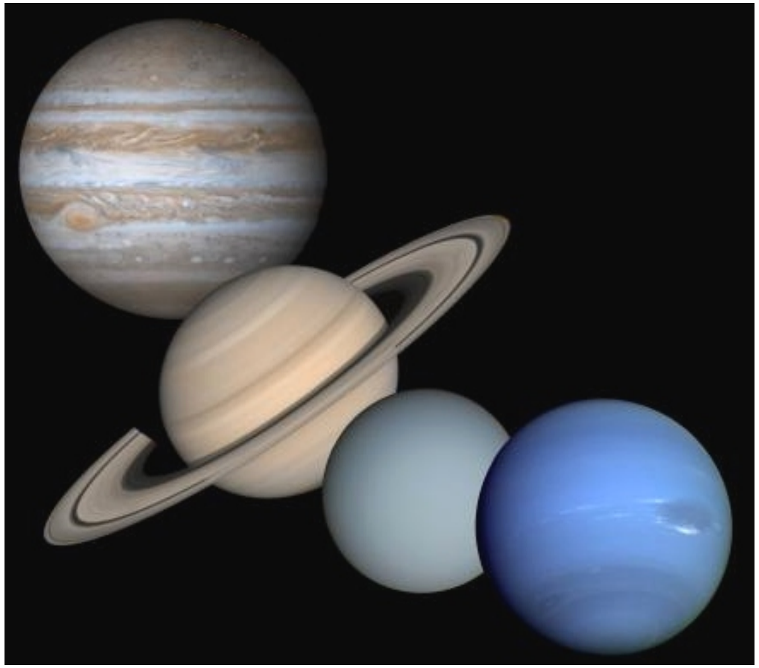
Imperial College London



Planetary outer atmospheres: interfaces from atmospheres to magnetospheres

Marina Galand
Imperial College London, UK

Why should we care about giant planets?




[Artist's impression: C Carreau/Esa]

Our Solar System is the only piece of the Universe that we can examine *in situ*.

To understand the many extrasolar giant planets being discovered, we need to study giant planets in our own neighbourhood.

Outline

1. **Setting the scene**
    - Thermosphere/Ionosphere
    - Energy sources
2. **Ionosphere at the giant planets**
    - What? How? Where? How much?
3. **Auroral emissions**
4. **Magnetosphere-ionosphere-thermosphere coupling**
    - Energy crisis at the giant planets
5. **Future prospect**

Setting the scene

Atmospheres in the solar system

Atmosphere composition

N_2 atmospheres
- Earth
- Titan
- Triton
- Pluto

CO_2 atmospheres
- Venus
- Mars
- Callisto (exosphere)

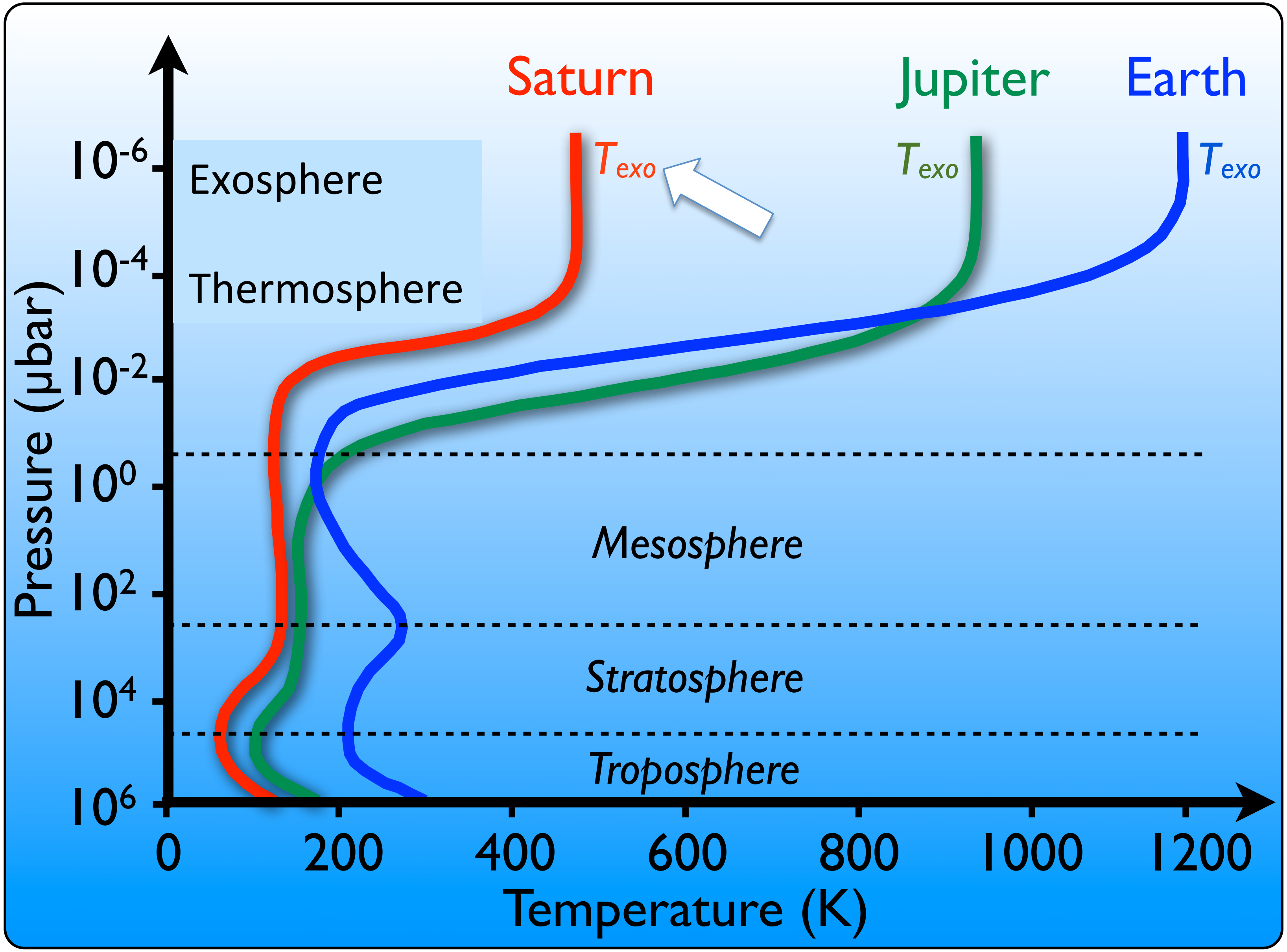
He/H/H_2 atmospheres
- Jupiter: P10/P11/V1/V2/Ulysses/Cassini, Galileo
- Saturn: P11/V1/V2, Cassini-Huygens
- Uranus: V2
- Neptune: V2

H_2O atmosphere (exosphere)
- Comets
- Enceladus

O/O_2/H_2O atmosphere (exosphere)
- Ganymede
- Europa

SO_2 atmosphere (exosphere)
- Io

Thermal Profiles



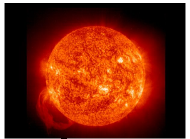
[Credit: I. Müller-Wodarg]

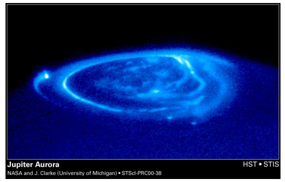
Outer (Upper) Atmosphere

– ***Gravitationally bound***

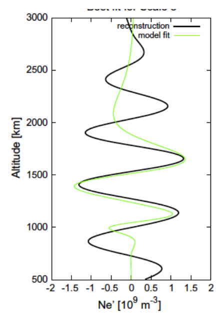
– ***Key transition region*** between the lower atmosphere and the magnetosphere/space environment

– ***Energy and momentum sources***:





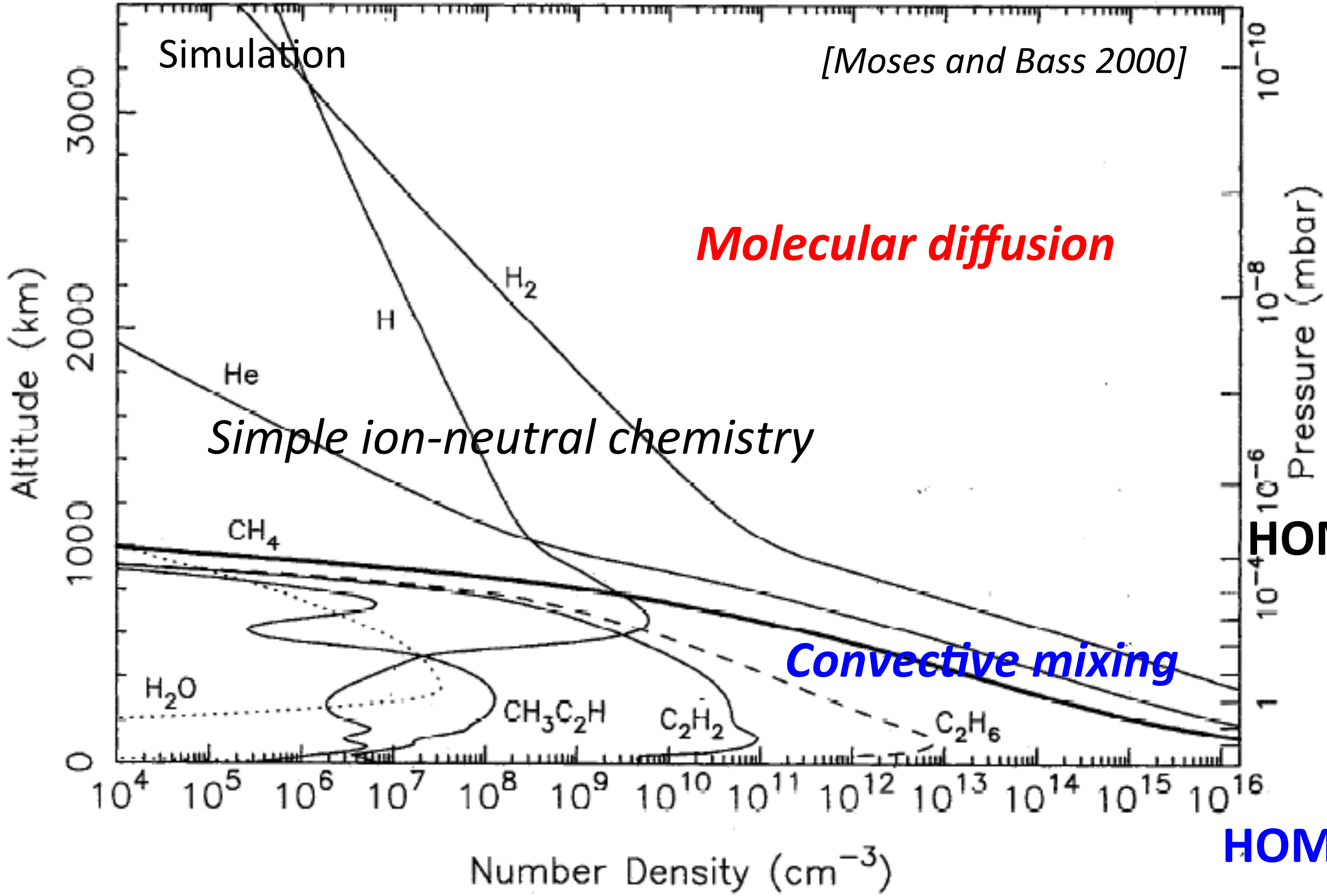
- EUV/FUV solar radiation
- Energetic particles from the planetary magnetosphere
- Forcing from below (e.g., gravity waves)



– ***Exist at all bodies*** with “dense-enough” atmosphere

Thermosphere of Saturn

Reference altitude (0 km) = 1 bar level



HETEROSPHERE

HOMOPAUSE

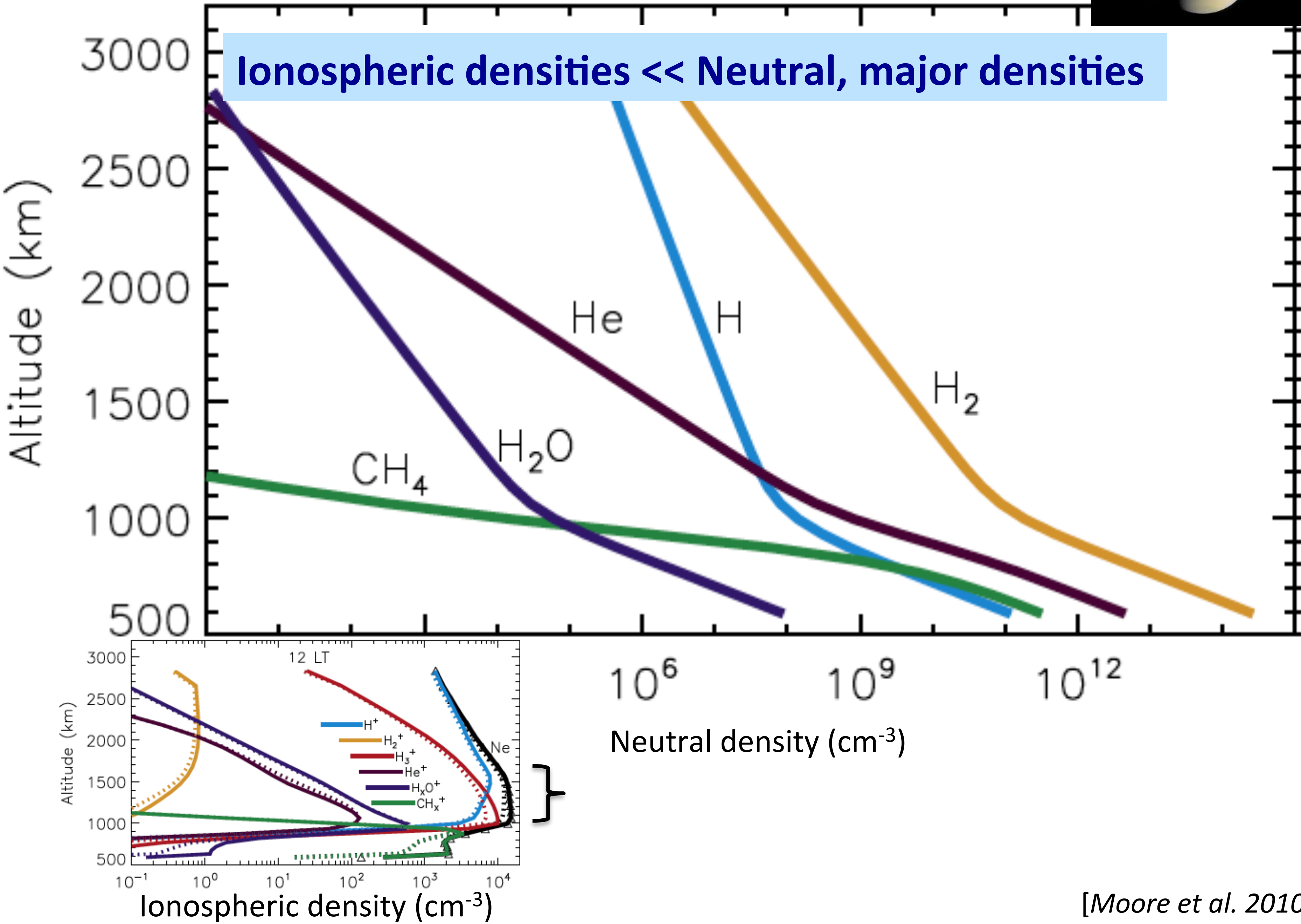
HOMOSPHERE

Ionosphere

- ***Ionized part*** *of the upper atmosphere*
- ***Present at any planet*** *(or moon)* which has an atmosphere
- ***Conducting layer****:*
  - Key source of *heating* of the high latitude upper atmosphere
- ***Key layer for coupling*** between the upper atmosphere and the magnetosphere:
  - *Closure of magnetospheric current system*

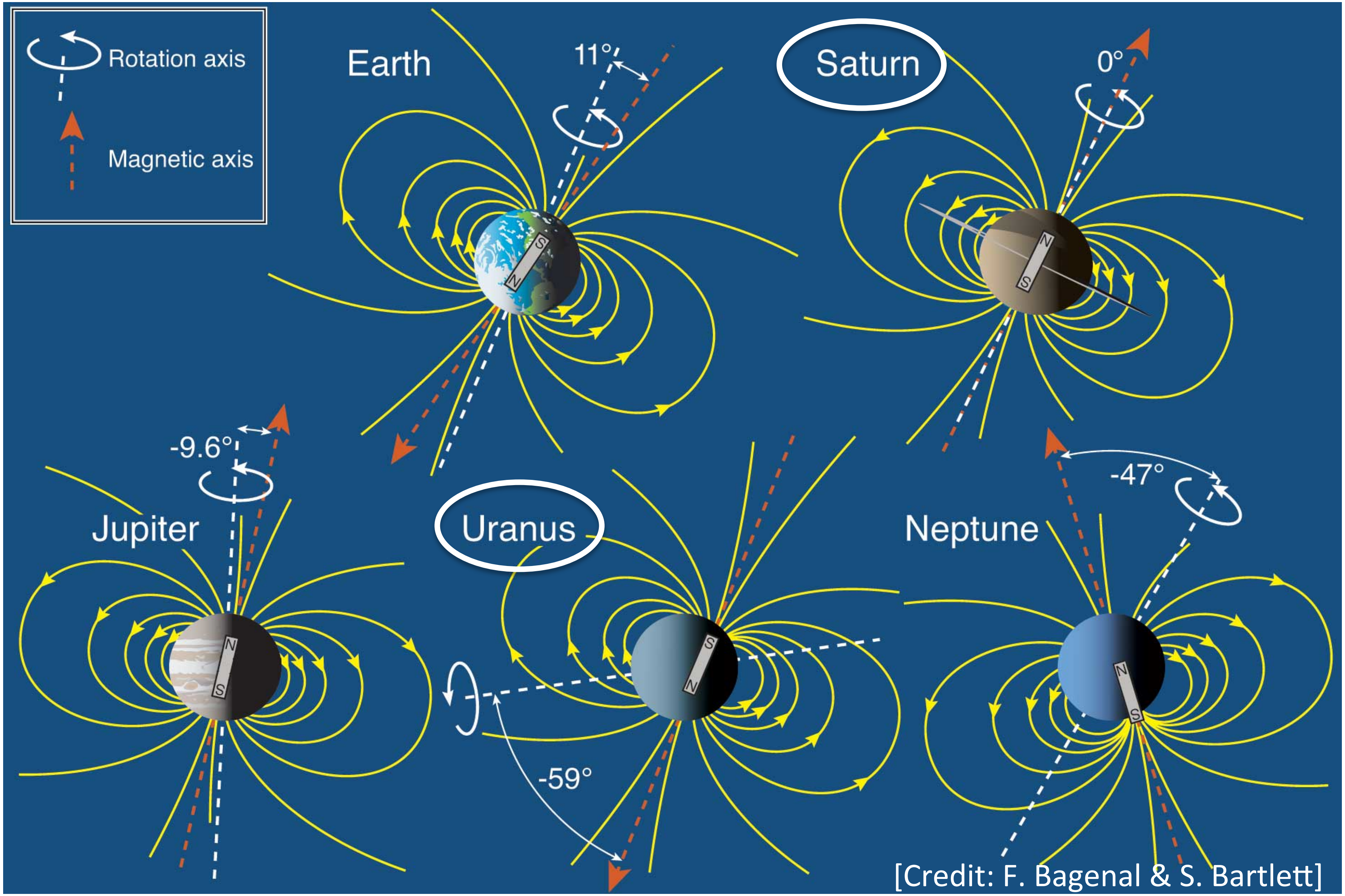
Saturn's ionosphere

Ionospheric densities << Neutral, major densities



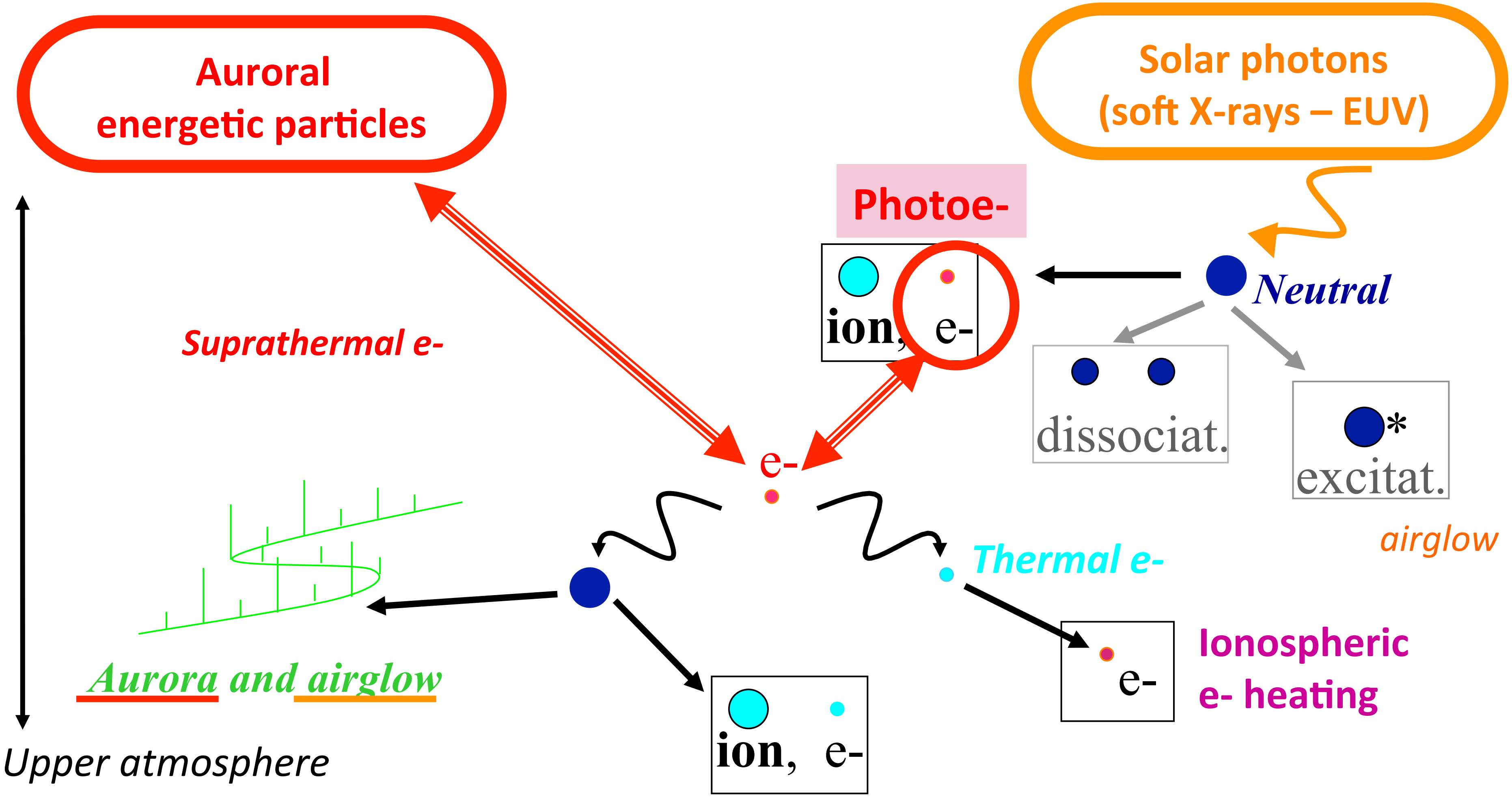
[*Moore et al. 2010*]

Tilts of planetary magnetic fields with respect to their rotation axis



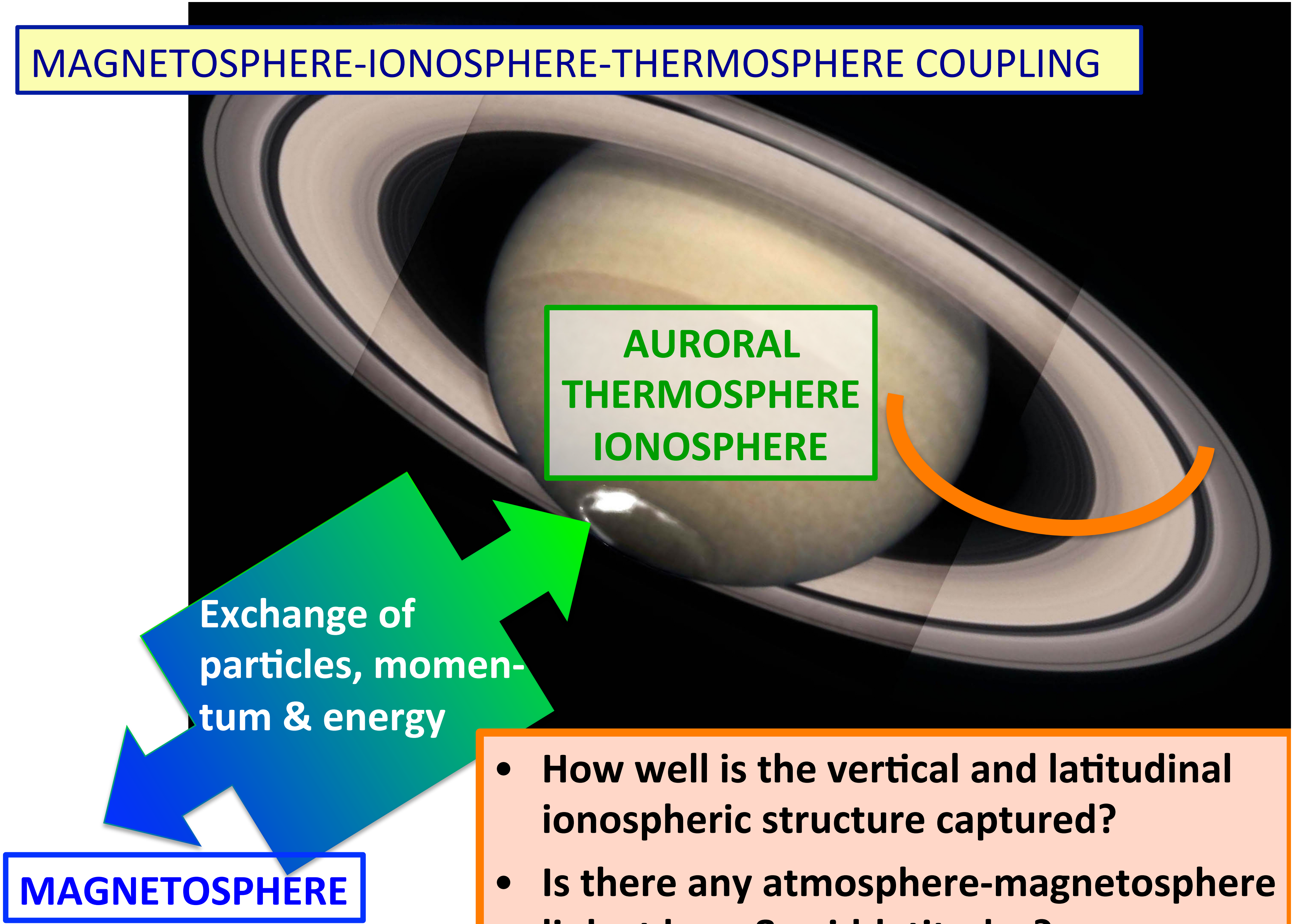
[Credit: F. Bagenal & S. Bartlett]

Introduction: Solar and magnetospheric particle deposition



- ***Creation of an ionosphere***
- ***Major contribution on chemistry, dynamics, & energetics***

MAGNETOSPHERE-IONOSPHERE-THERMOSPHERE COUPLING



- How well is the vertical and latitudinal ionospheric structure captured?
- Is there any atmosphere-magnetosphere link at low- & mid-latitudes?

Ionosphere at the Giant Planets

Ionization sources

- **Ionisation potential**:
  - H_2: 15.43 eV ←→ 80 nm
  - H: 13.60 eV ←→ 91 nm
  - CH_4:12.55eV ←→ 99 nm

13 eV ←→ ~100 nm

- **Solar EUV radiation (1-10, 10-100 nm)**:
  - Solar flux / (Sun-planet distance)^2
- **Energetic particles** from the space environment
  - A few keV to a few 100s keV

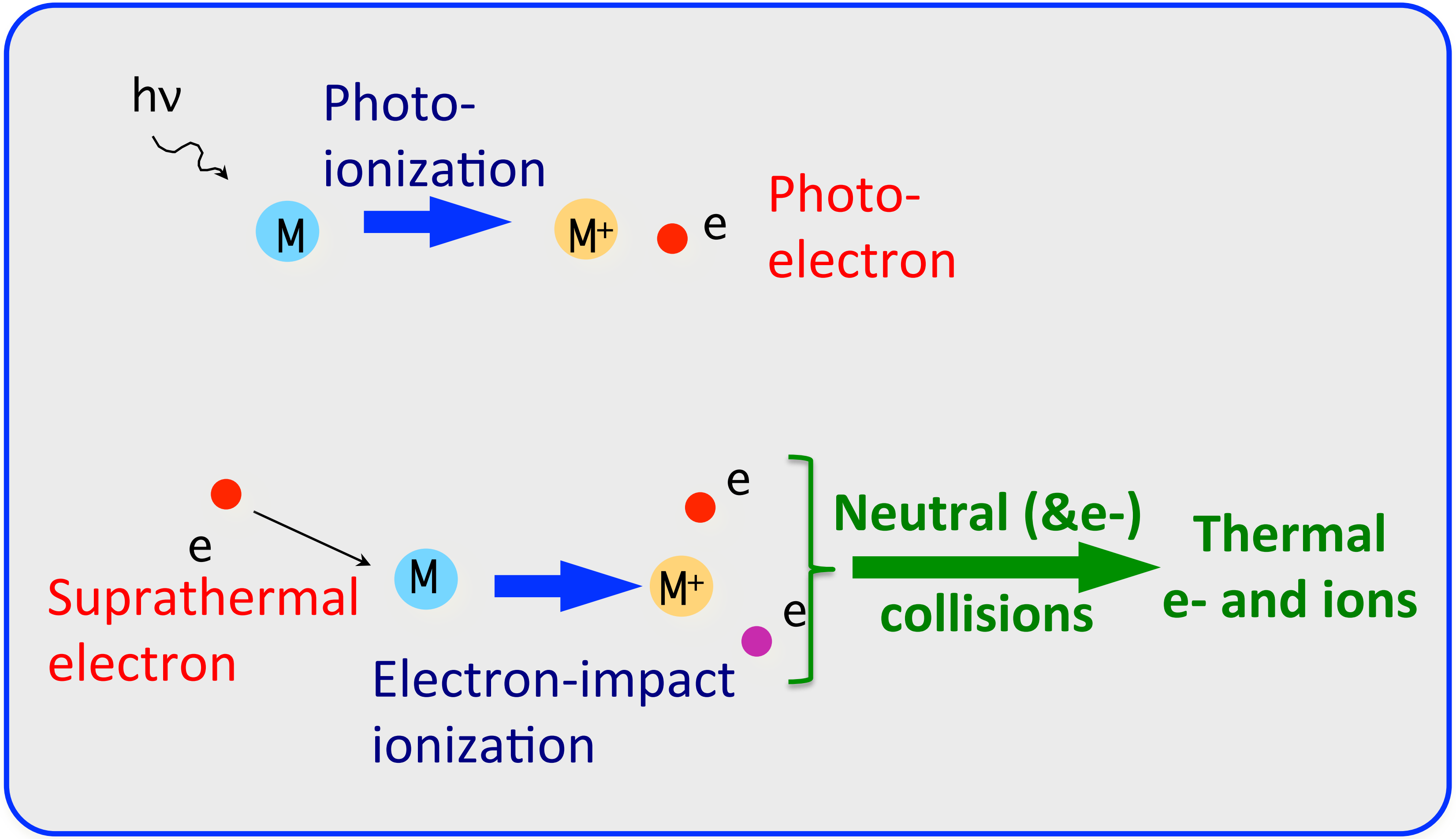
Energy sources

	Solar EUV input*	Auroral input*	Auroral particle input**
Earth (1 AU)	500 GW	80 GW	1-10 keV
Jupiter (5.2 AU)	800 GW	10^5 GW	30-200 keV 2-30 mW m^{-2}
Saturn (9.5 AU)	200 GW	(5-10)x10^3 GW	10-20 keV ~ 1 mW m^{-2}
Uranus (19 AU)	8 GW	100 GW	-
Neptune (30 AU)	3 GW	1 GW	-

* *Auroral input refers to "particle + Joule heating" (Strobel 2002)*

** *Values valid for the main auroral oval, inferred from the analysis of auroral emissions (e.g., Fox et al. 2008, Gustin et al. 2004, 2009)*

Two electron populations



Plasma population in the upper atmosphere

- **Ionospheric, thermal population** (e-, ions):
  - Bulk of the plasma population
  - Thermalized through collisions

  → **Fluid treatment: macroscopic quantities**

  - Number density n (continuity equation), bulk velocity $\underline{u}$ (momentum equation), temperature T (energy equation)

- **Suprathermal particles** (e-, ion, neutrals):
  - Of solar or magnetospheric origin (also: meteor, …)
  - Small in terms of density (high energy tail)
  - Source of energy to the upper atmosphere (e.g., ionisation, excitation/dissociation, thermal electron heating)

  → **Kinetic treatment: microscopic quantity**

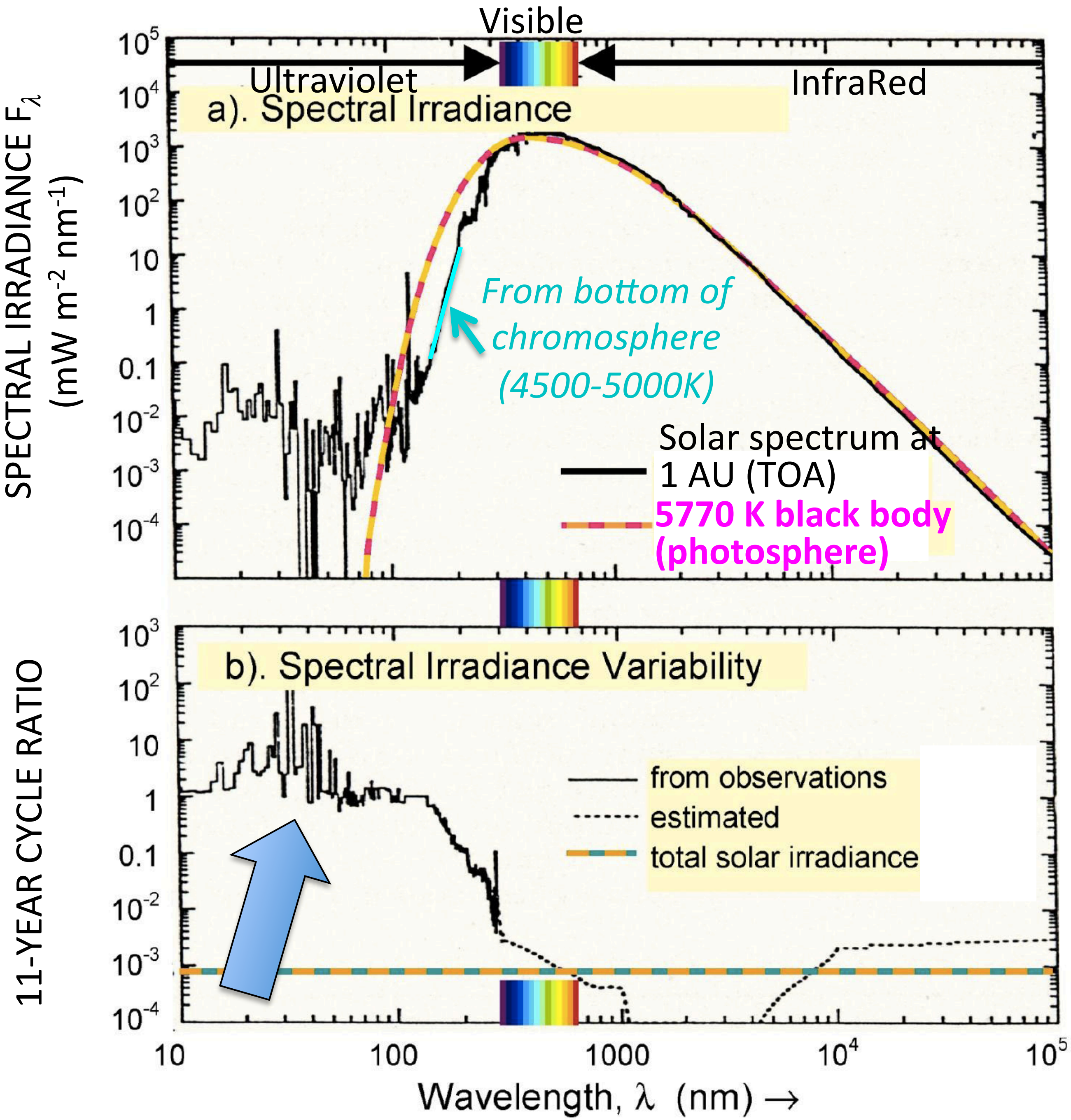
  - Particle intensity I_e (Boltzmann equation) → Pe, Qe, …

Solar spectrum and its variability

SOLAR SPECTRUM:
9% in UV,
38% in visible,
53% in near IR (0.7-4μm)

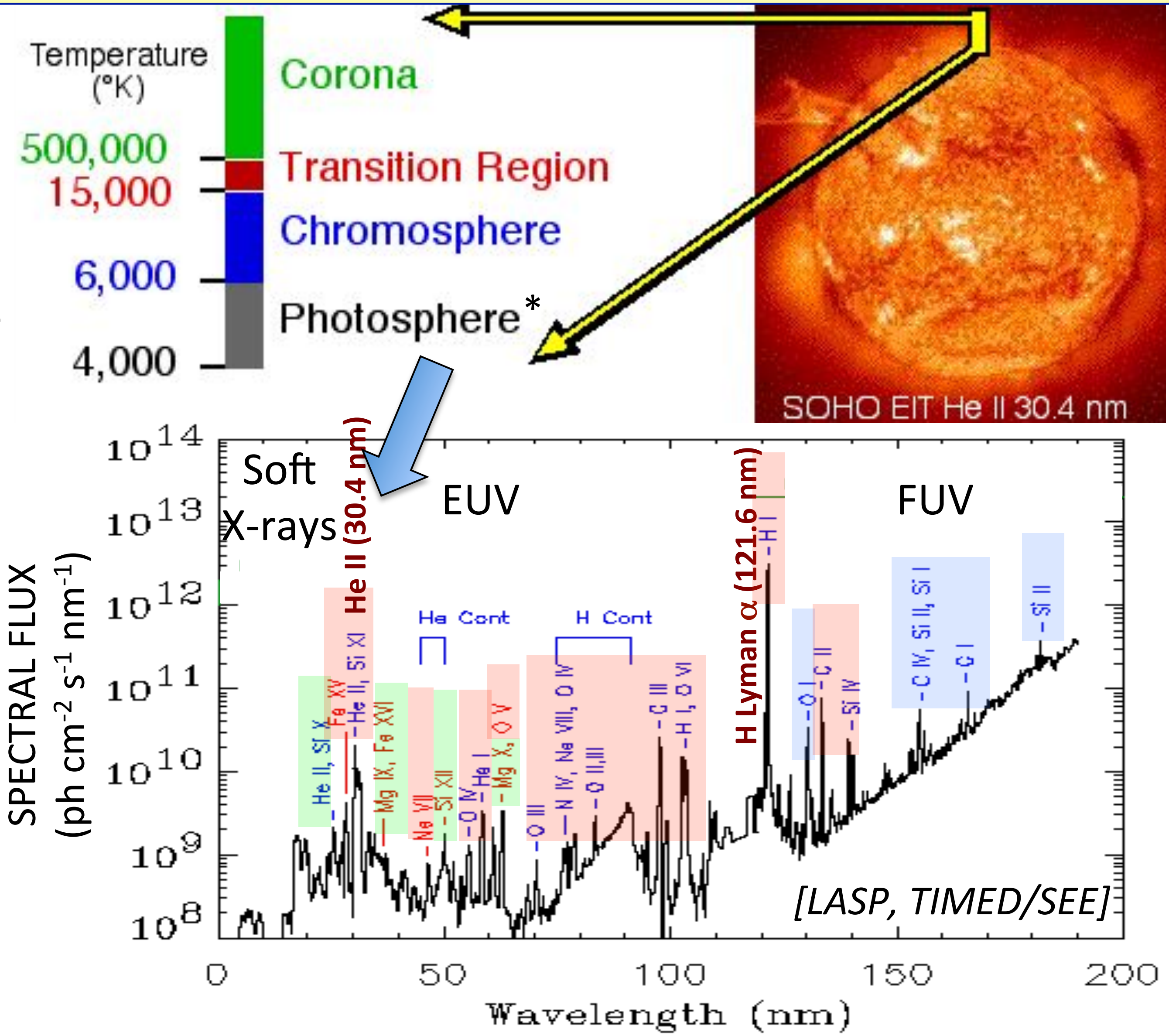
At 1 AU

$$\frac{F_\lambda^{max} - F_\lambda^{min}}{F_\lambda^{min}}$$



Lean (1991)
[adapted by Lockwood]

Solar spectrum – origin of the soft X-ray, EUV and FUV



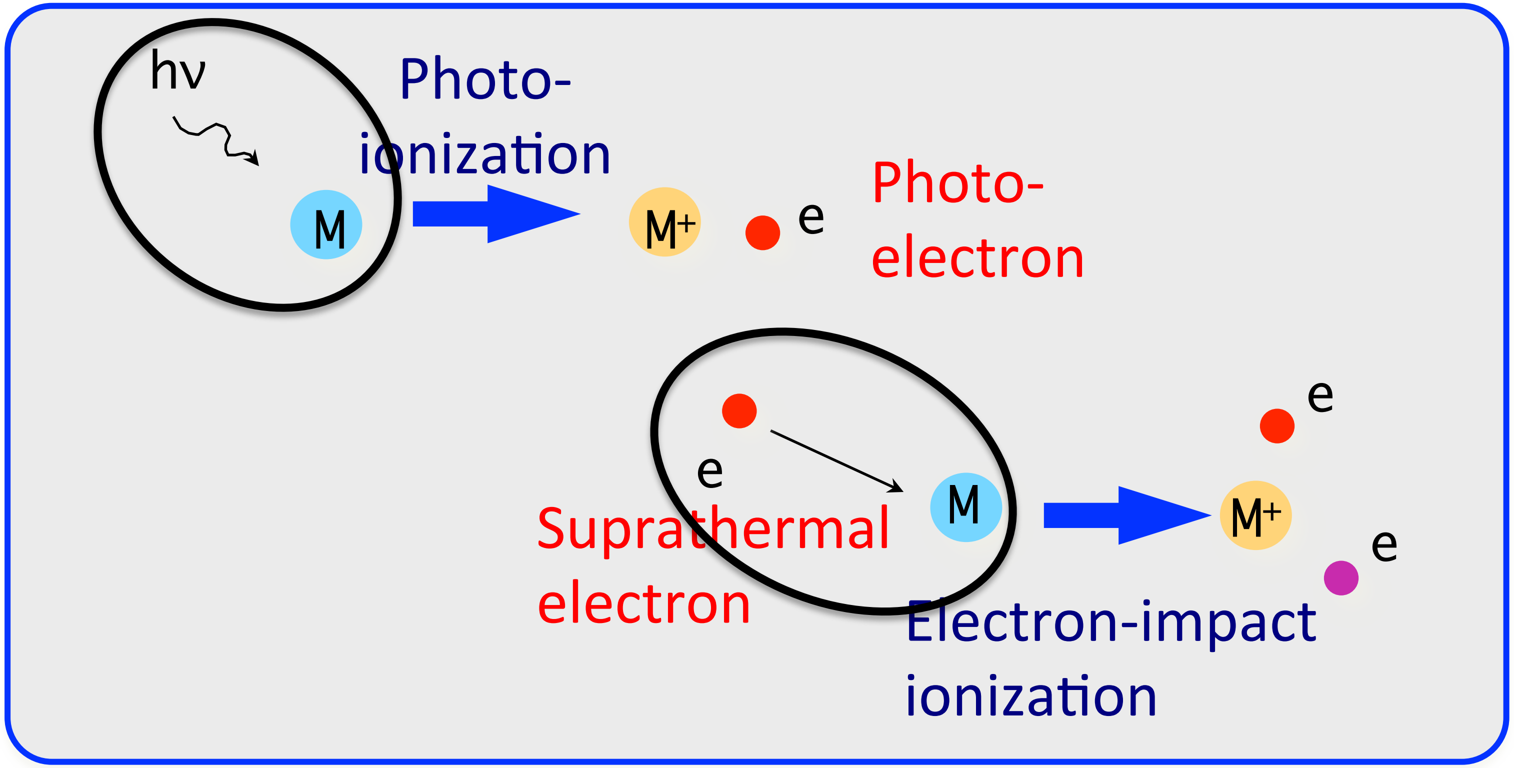
* visible surface of the Sun

The solar soft X-ray and EUV radiation from the hot transition region and corona are responsible for the creation of an ionosphere.

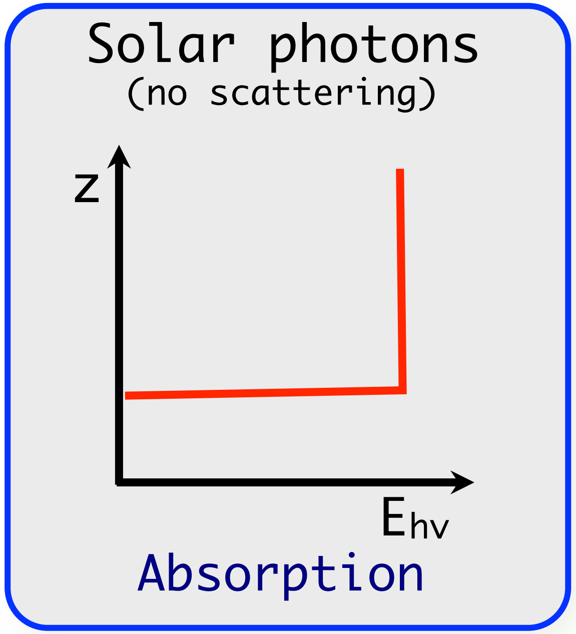
Ionization processes

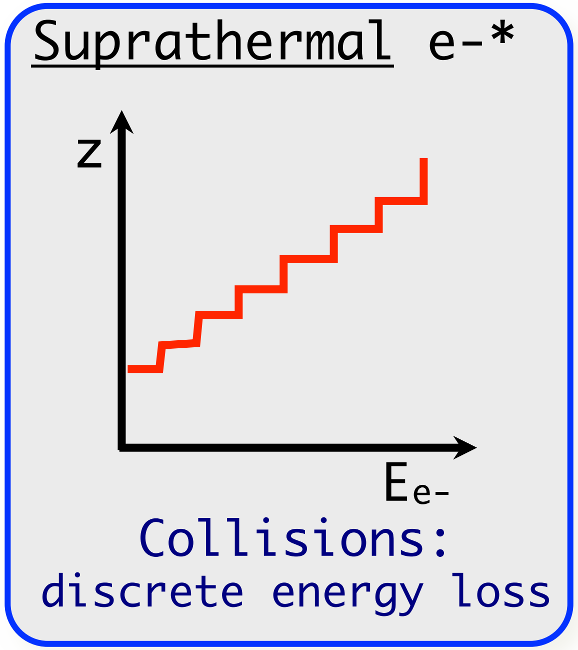
Range of ionization processes:

- Photoionization: $h\nu + M \rightarrow M^+ + e^-$
- e-impact ionization: $e^- + M \rightarrow e^- + M^+ + e^-$



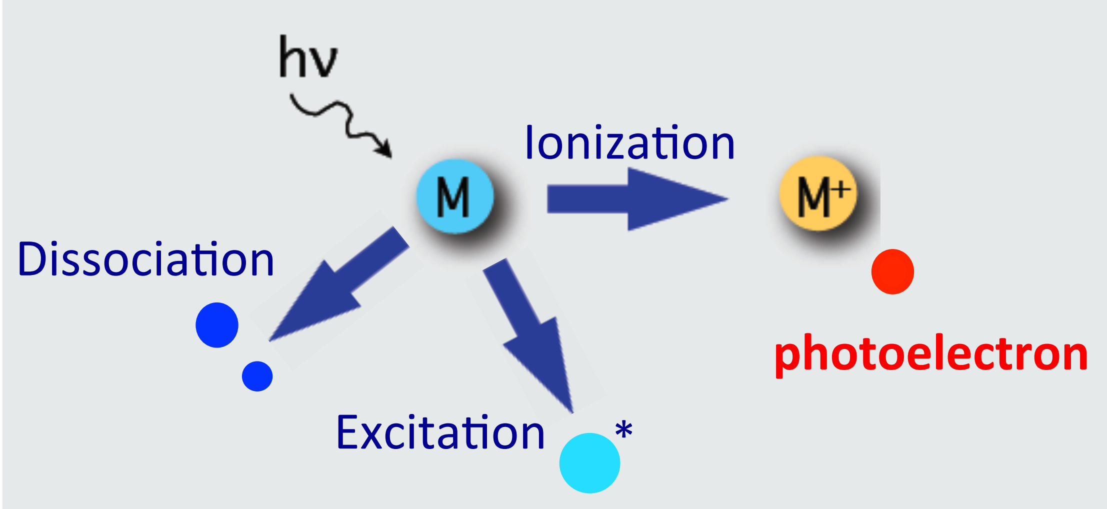
Energy deposition





** Photoelectrons, Auroral electrons, secondary electrons*

Absorption of solar radiation in an atmosphere



✓ In the EUV, primarily extinction in the beam
→ apply Beer-Lambert Law

✓ **Attenuated solar flux** at wavelength λ and at altitude z:

$$I_\lambda(z) = I_\lambda^{TOA} \exp\left(-\sum_n \sigma_n^{abs}(\lambda) \int_z^\infty n_n(z') \sec(\chi) dz' \right)$$

Solar flux at top of atmos

Photo-absorption cross section

Optical depth τ

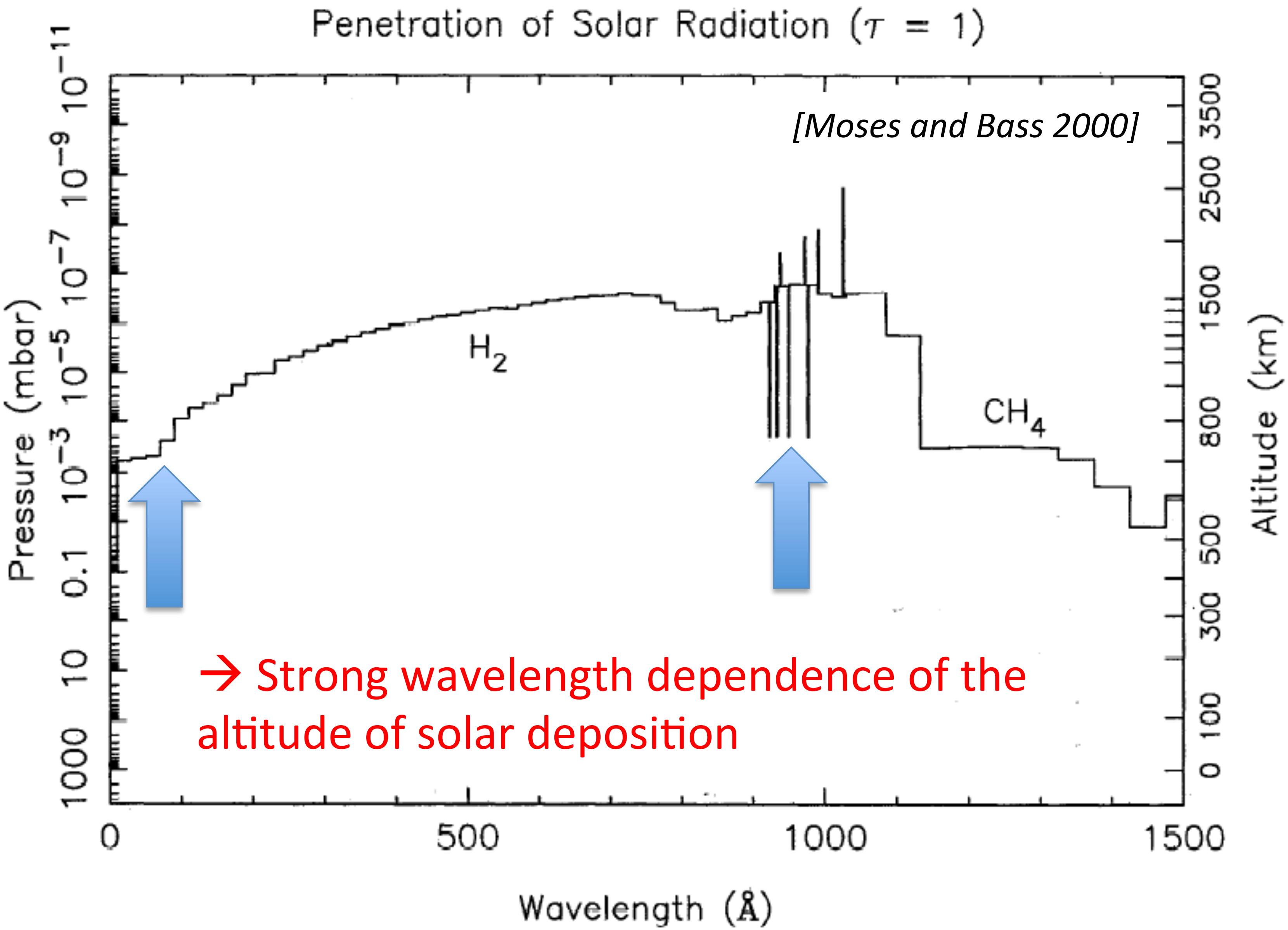
Number density of neutral n

Solar zenith angle

✓ **Photoelectron production rate** at λ:

$$P_{e,\lambda}(z) = \sum_n \sigma_n^{ioni}(\lambda) n_n(z) I_\lambda(z) \propto I_\lambda^{TOA} \propto \frac{1}{(d_{Sun-Planet})^2}$$

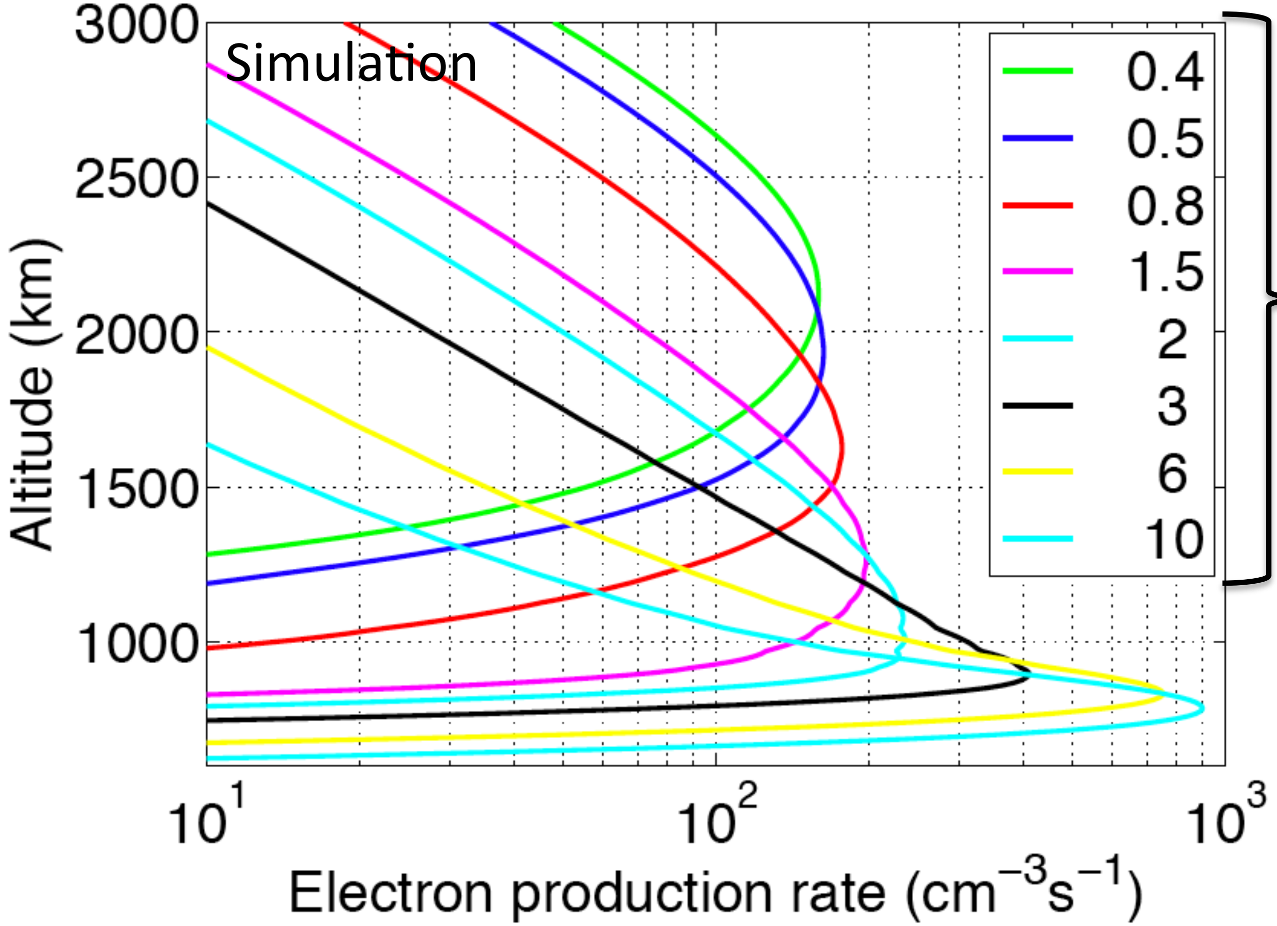
Altitude of deposition



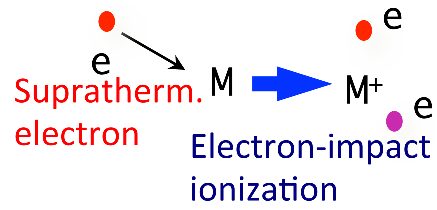
→ Strong wavelength dependence of the altitude of solar deposition

Energy deposition of auroral electrons

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

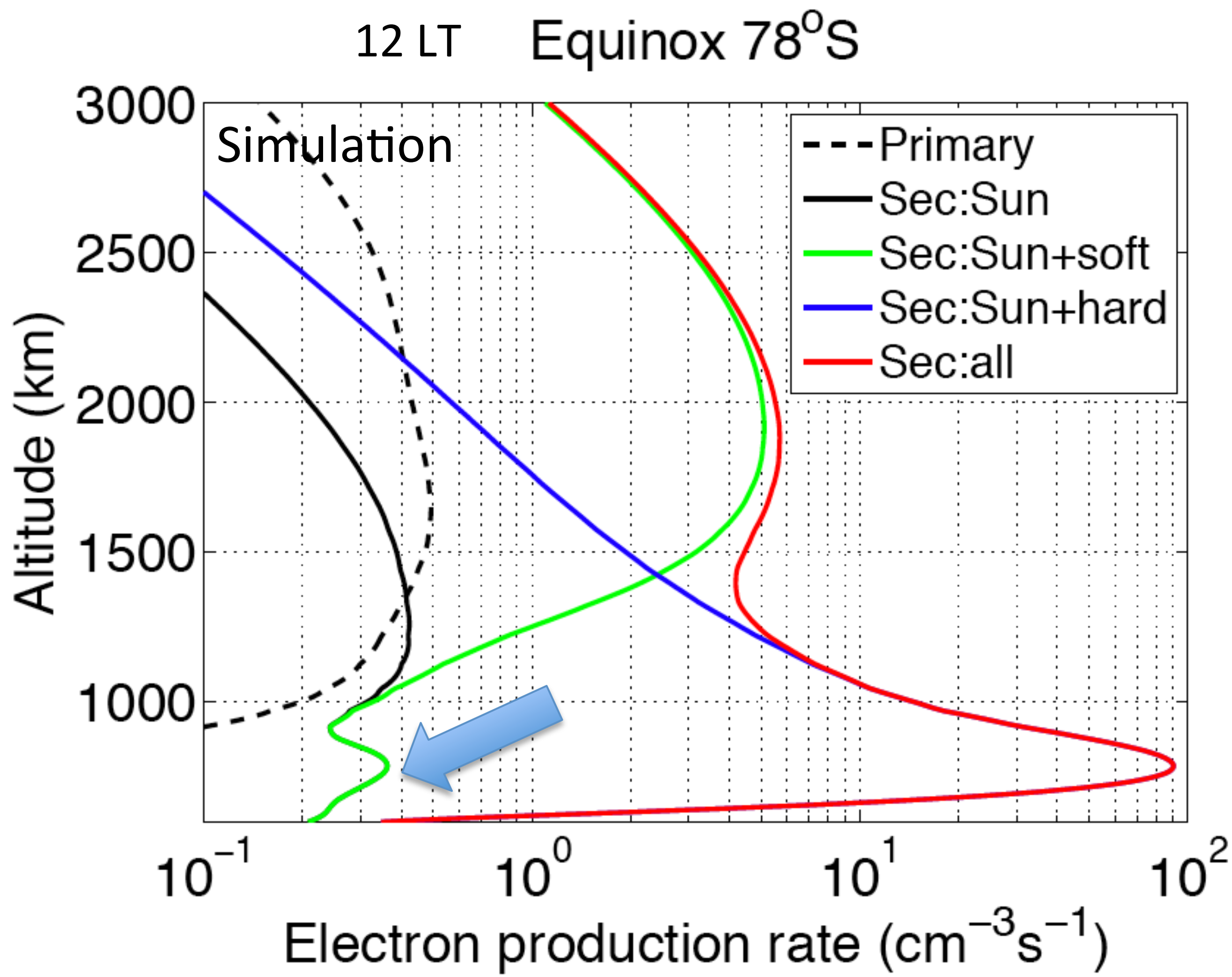


Incident e- energy (keV)



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

Solar versus auroral particle deposition



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

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

- **Soft + Hard component**

Continuity equation applied to the ionospheric plasma

Thermal Ion Continuity Equation

$$\frac{\partial n_i}{\partial t} = P_i - L_i - \nabla.(n_i \underline{u})$$

Loss

Transport

Production

$\underline{u}$, bulk velocity

Chemical loss of atomic ions

- **Radiative Recombination of Atomic Ions**

$$X^+ + e \xrightarrow{RR} X + photon$$ **Slow**

$$L_{X^+}^{RR} = \alpha_{X^+}^{RR} \; n_{X^+} \; n_e$$ Ion loss Rate

- **Ion-atom Interchange**

$$X^+ + YZ \xrightarrow{IAI} XY^+ + Z$$ **Dominant**

$$L_{X^+,YZ}^{IAI} = k_{X^+,YZ}^{IAI} \; n_{X^+} n_{YZ}$$

Chemical loss of terminal, molecular ions

- **Dissociative Recombination of e- and molecular ions**

$$XY^+ + e \xrightarrow{DR} X + Y$$

$$L^{DR}_{XY^+} = \alpha^{DR}_{XY^+} \, n_{XY^+} \, n_e$$

Dominant for terminal ions

- **If XY^+ is the dominant ion,**

$$L^{DR}_{XY^+} \approx \alpha^{DR}_{XY^+} \, n_e^2$$

Photochemical equilibrium

Thermal Ion Continuity Equation

$$\frac{\partial n_i}{\partial t} = P_i(z) - L_i(z) - \nabla.(n_i \underline{u})$$

Production Loss Transport

$\underline{u}$, *bulk velocity*

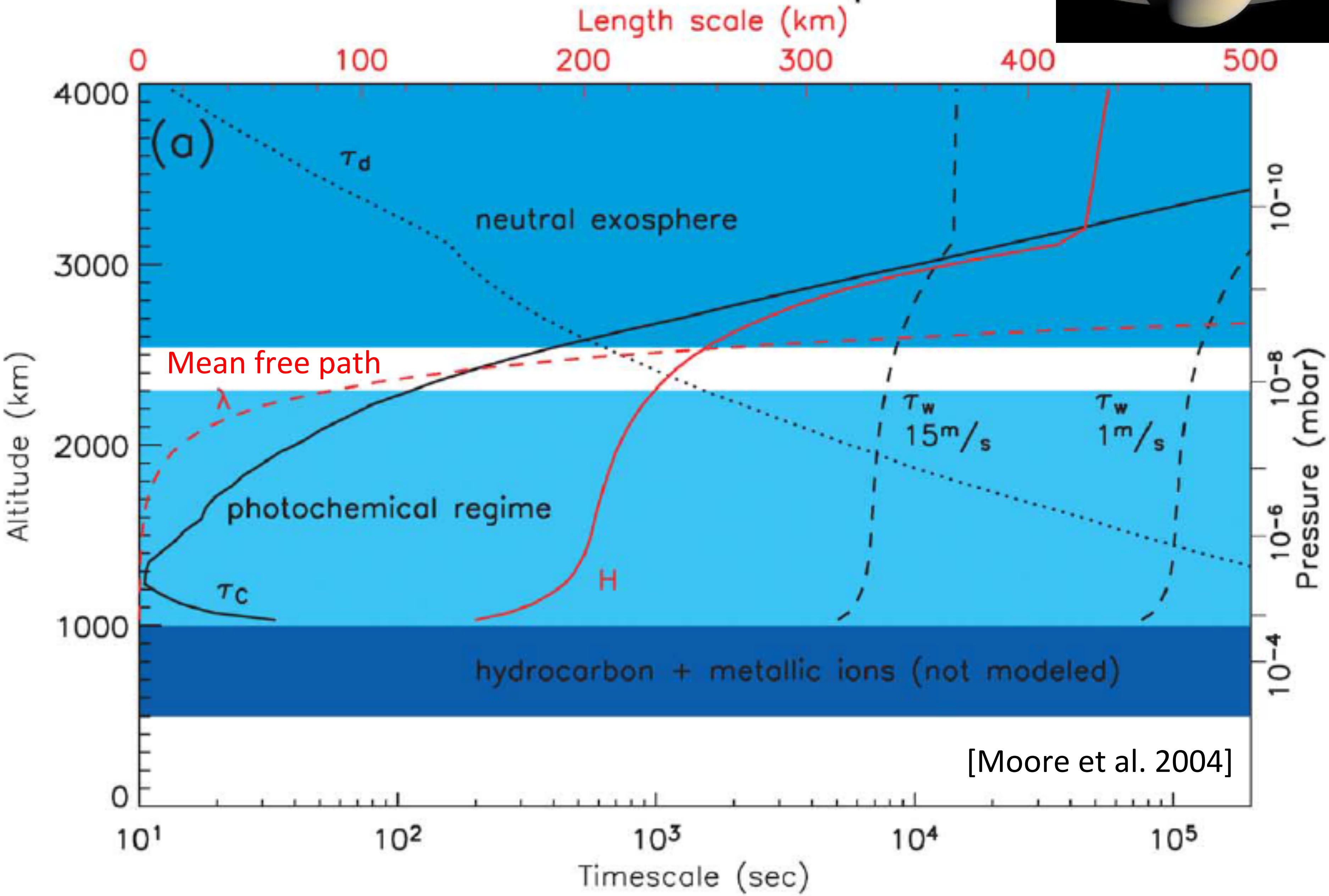
For molecular, terminal ion i:

$$P_i(z) = \alpha_i(Te)n_i(z)n_e(z)$$
$$\approx \alpha_i(Te)n_e^2(z)$$

- **Chemical loss timescales:**
  - Atomic ion or non-terminal ion: $t_c = \dfrac{1}{k\, n_{YZ}}$ $X^+ + YZ \xrightarrow{IAI} X + YZ^+$
  - Terminal molecular ion: $t_c = \dfrac{1}{\alpha\, n_e}$ $XY^+ + e^- \xrightarrow{DR} X + Y$
- **Transport loss timescales:**
  - Diffusion timescale: $t_d = \dfrac{H_a^2}{D_a \sin^2 I}$
  - Timescale associated with the neutral wind: $t_w = \dfrac{H_p}{U \sin I \cos I}$

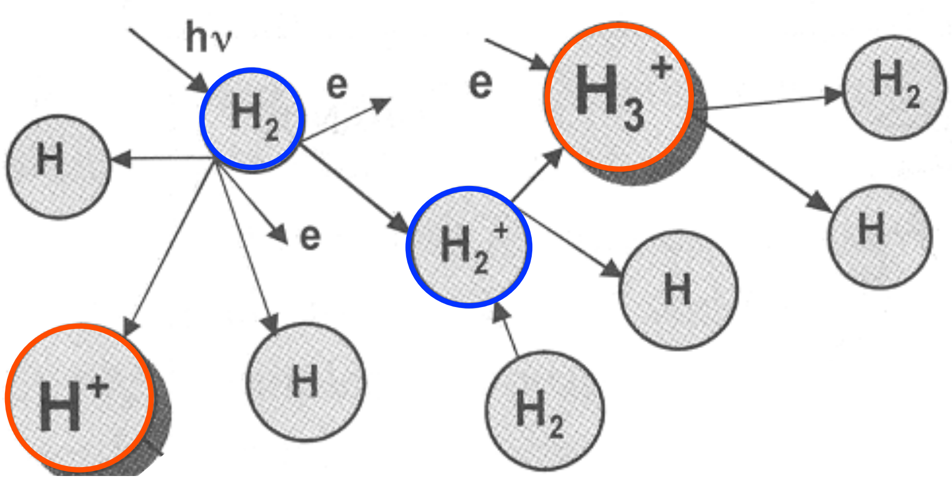
with H_a and H_P are the atmosphere and plasma scale heights (typical length scales), I is the magnetic field dip angle (cp w/ horizontal), U is the meridional (N/S) neutral wind speed and D_a is the ion-neutral diffusion coefficient.

Photochemical equilibrium at Saturn



[Moore et al. 2004]

Photo-chemistry in an H_2 atmosphere



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

$k_0 = 2.0 \times 10^{-9}\ cm^3\ s^{-1}$

$H_3^+ + e^- \rightarrow$ neutral products

$\alpha_0 = 1.73 \times 10^{-6} \times Te^{-0.5}\ cm^3\ s^{-1}$

with Te in K.

- Charge exchange reaction **$H^+ + H_2(v \geq 4) \rightarrow H_2^+ + H$** **(1)**

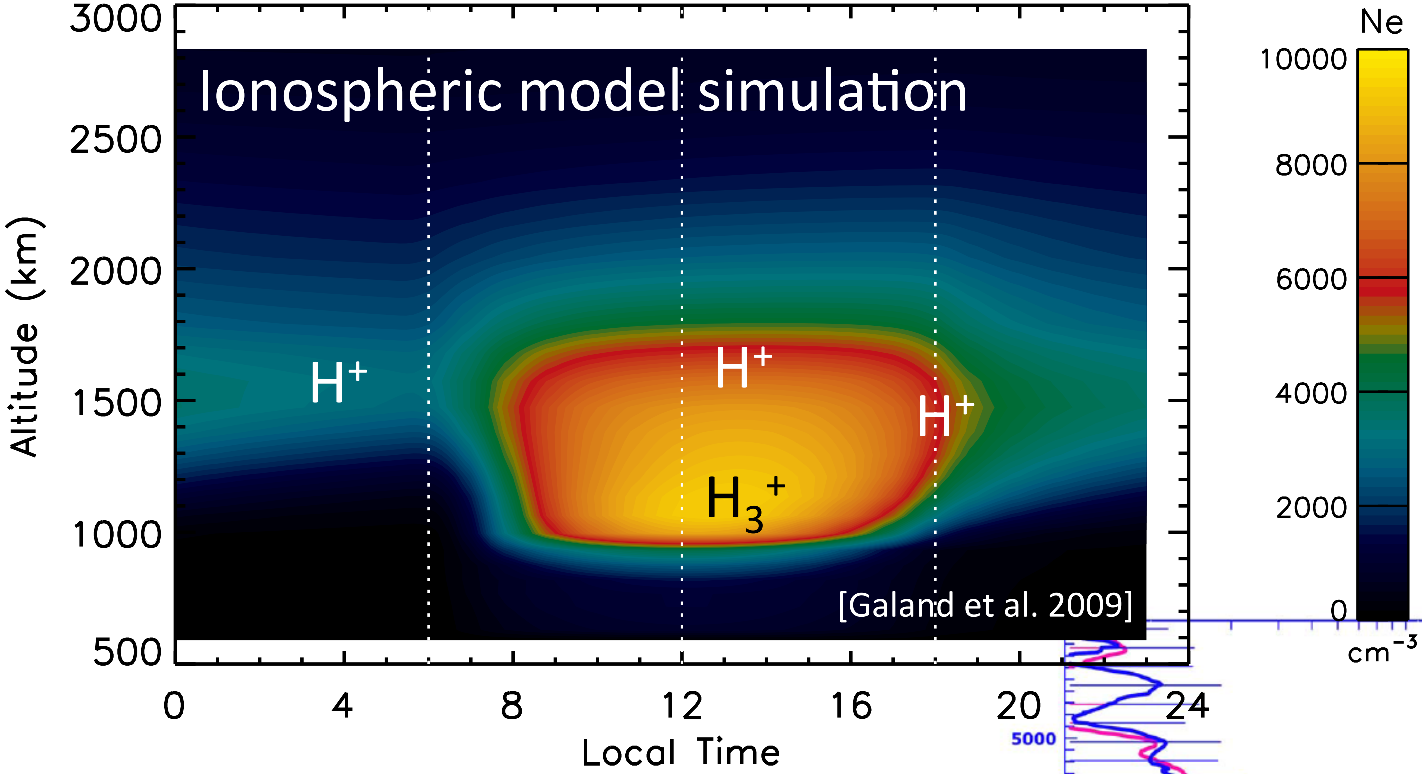
  controls the abundance of H_3^+ as it is quickly followed by:

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

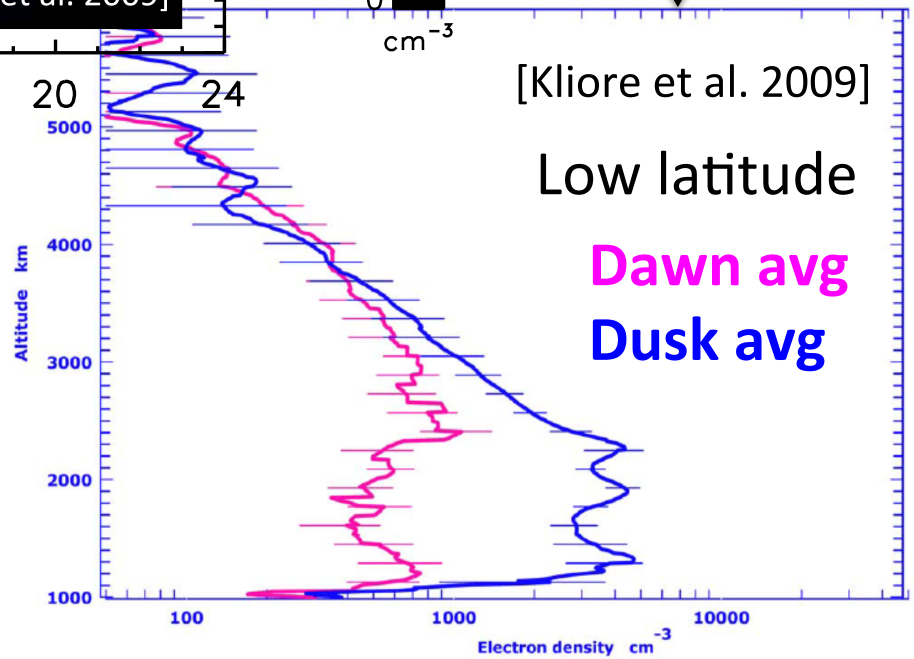
- Reaction rate **$k_1^* = k_1\ [H_2(v \geq 4)]/[H_2]$**
  - Large $[H_2(v \geq 4)] \rightarrow$ large $k_1^* \rightarrow$ more H^+ converted in $H_3^+ \rightarrow$ decrease in ionospheric densities

  ➢ $k_1 = 10^{-9}\ cm^3\ s^{-1}$ [*Huestis*, 2008]

Dawn-dusk asymmetry

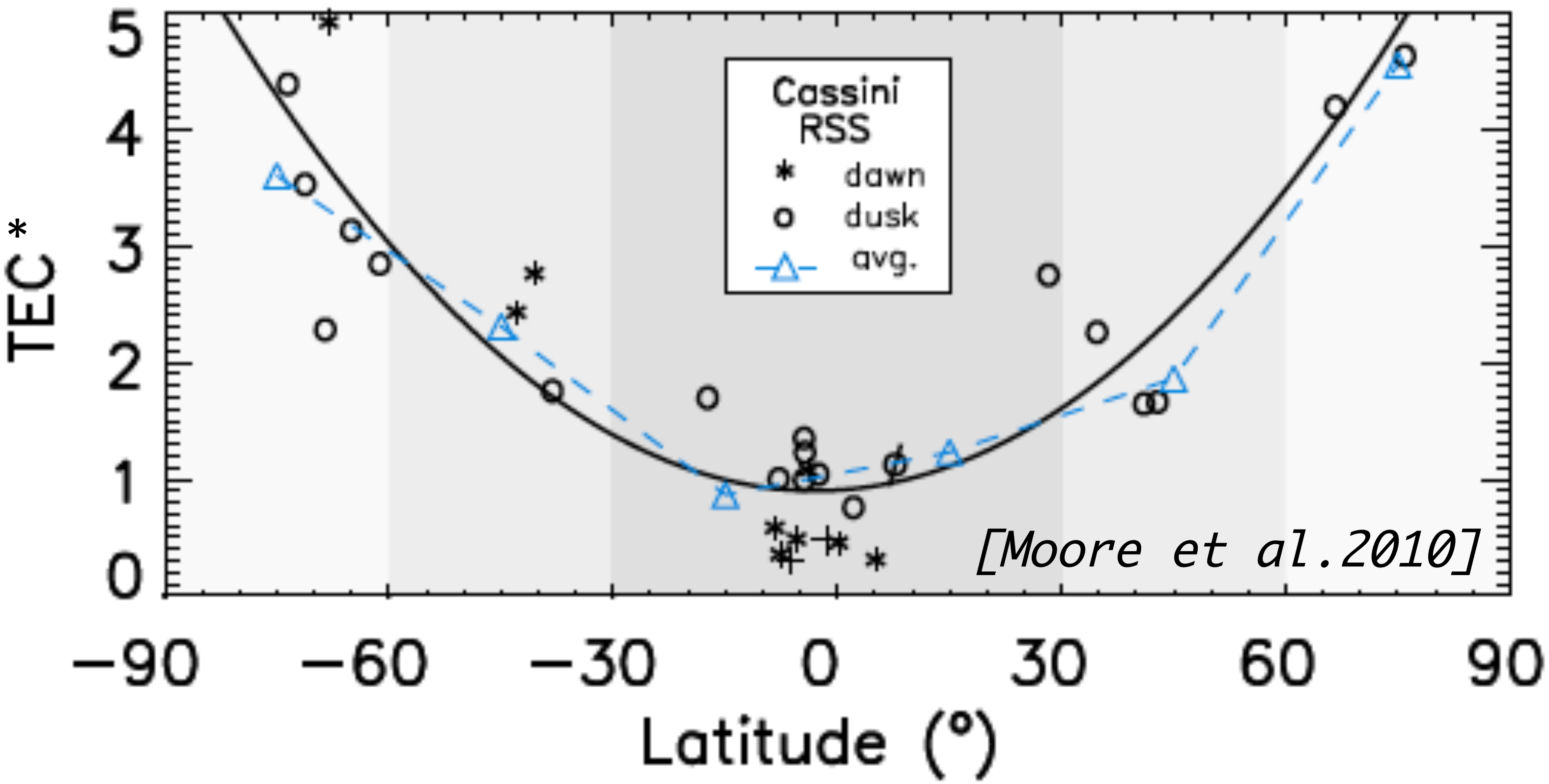


From Cassini/ Radio Science Subsystem (RSS) data



The ionosphere of Saturn

From Cassini/Radio Science Subsystem (RSS) data



*Total Electron Content [1 TEC unit = $10^{16} m^{-2}$]

Why is there a minimum in TEC at low latitudes?...

Photochemistry in Gas Giant atmospheres

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

$k_2 = 8.2 \times 10^{-9}\ cm^3\ s^{-1}$

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

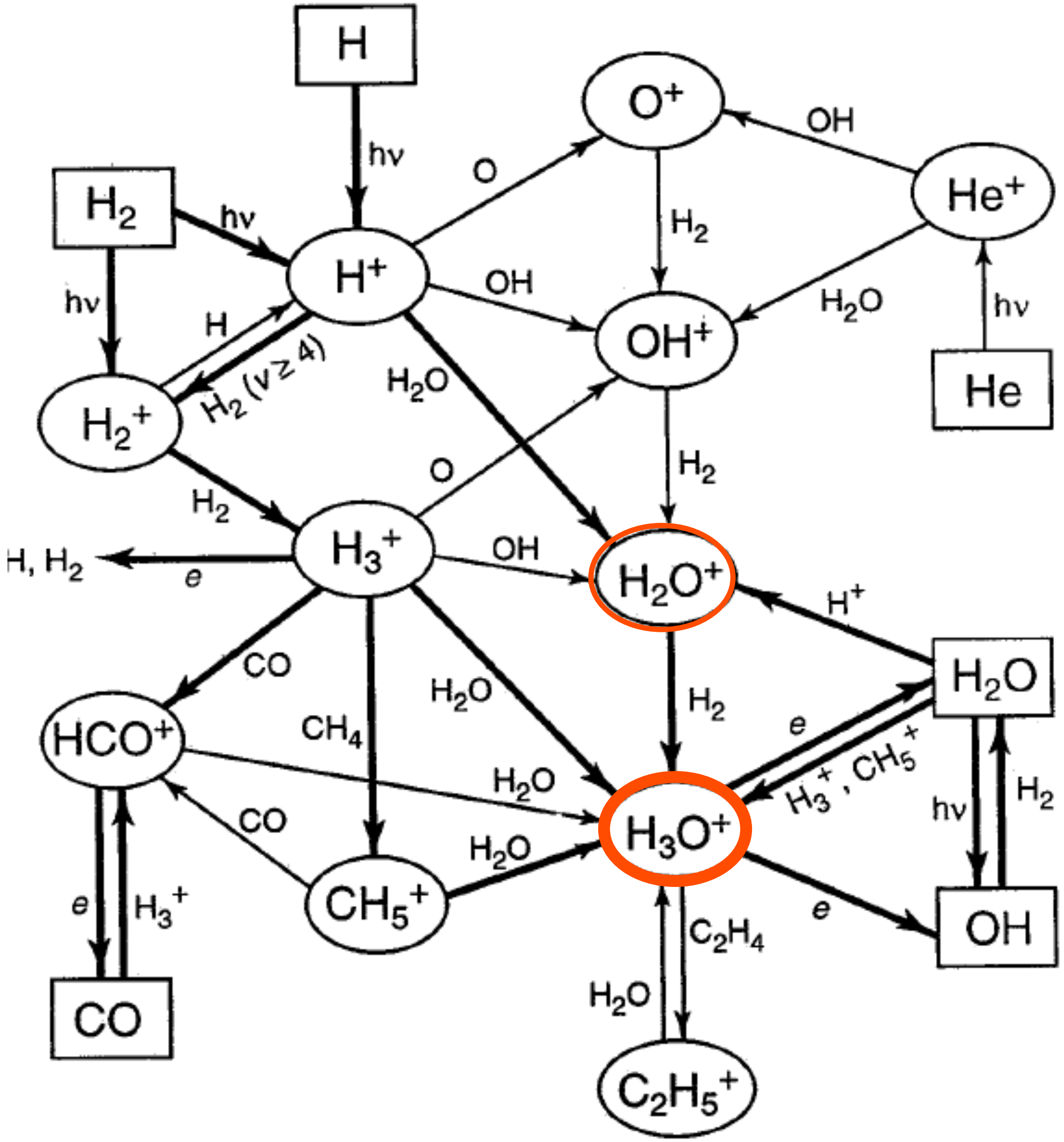
$k_3 = 7.6 \times 10^{-10}\ cm^3\ s^{-1}$

$H_3^+ + H_2O \rightarrow H_3O^+ + H_2$

$k_4 = 5.3 \times 10^{-9}\ cm^3\ s^{-1}$

$H_3O^+ + e^- \rightarrow$ **neutral products**

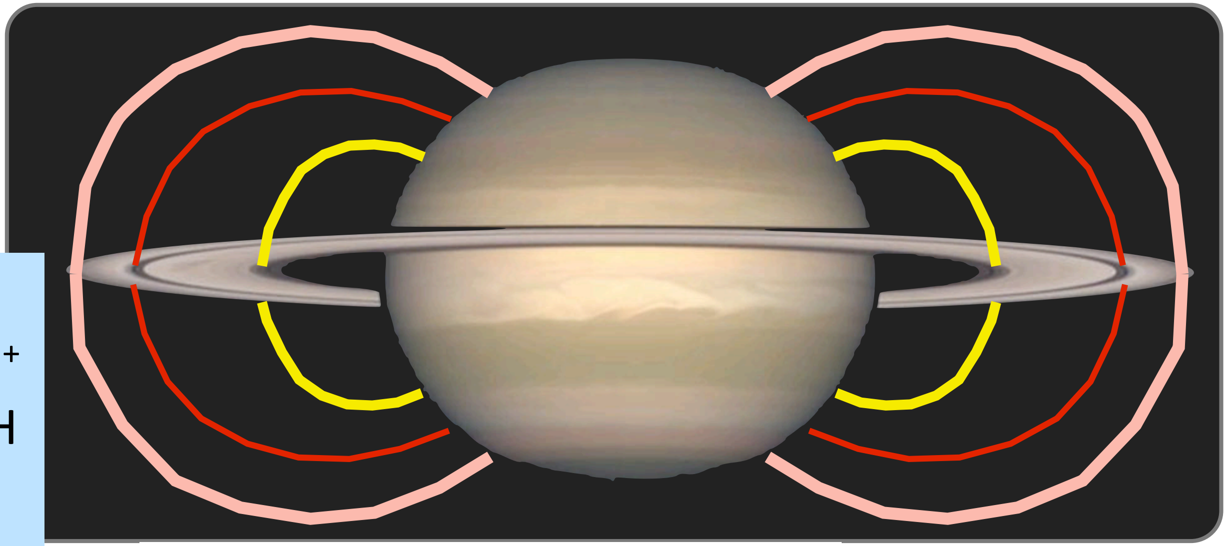
$\alpha_5 = 1.74 \times 10^{-5} \times Te^{-0.5}\ cm^3\ s^{-1}$ with Te in K.

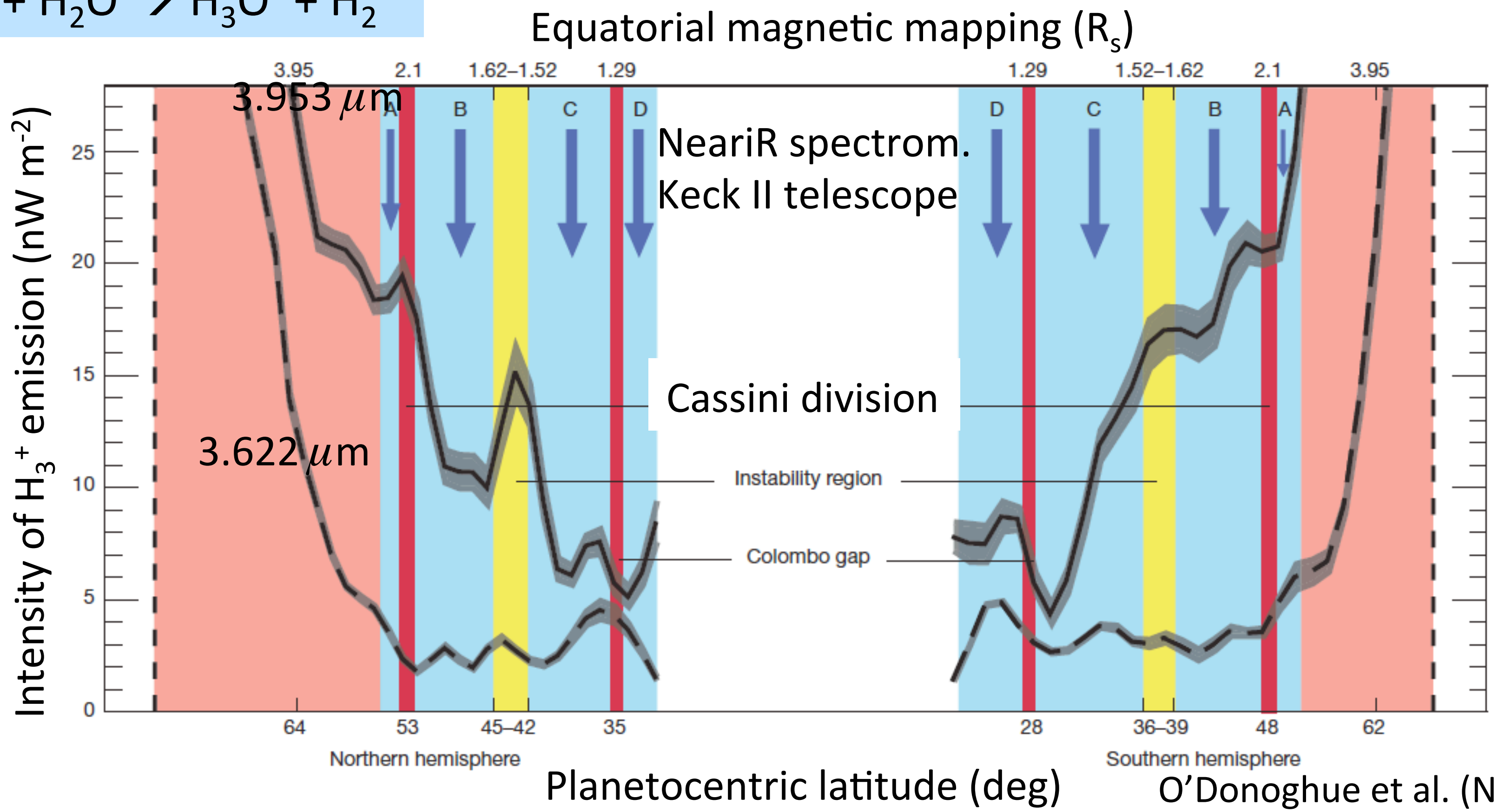


[Moses and Bass 2000]

Ring rain at Saturn

From the rings: H_2O^+
React with H_2 …→ H_3O^+
H_3O^+ + e- → H_2O or OH
OH + H_2 → H_2O + H
H_3^+ + H_2O → H_3O^+ + H_2

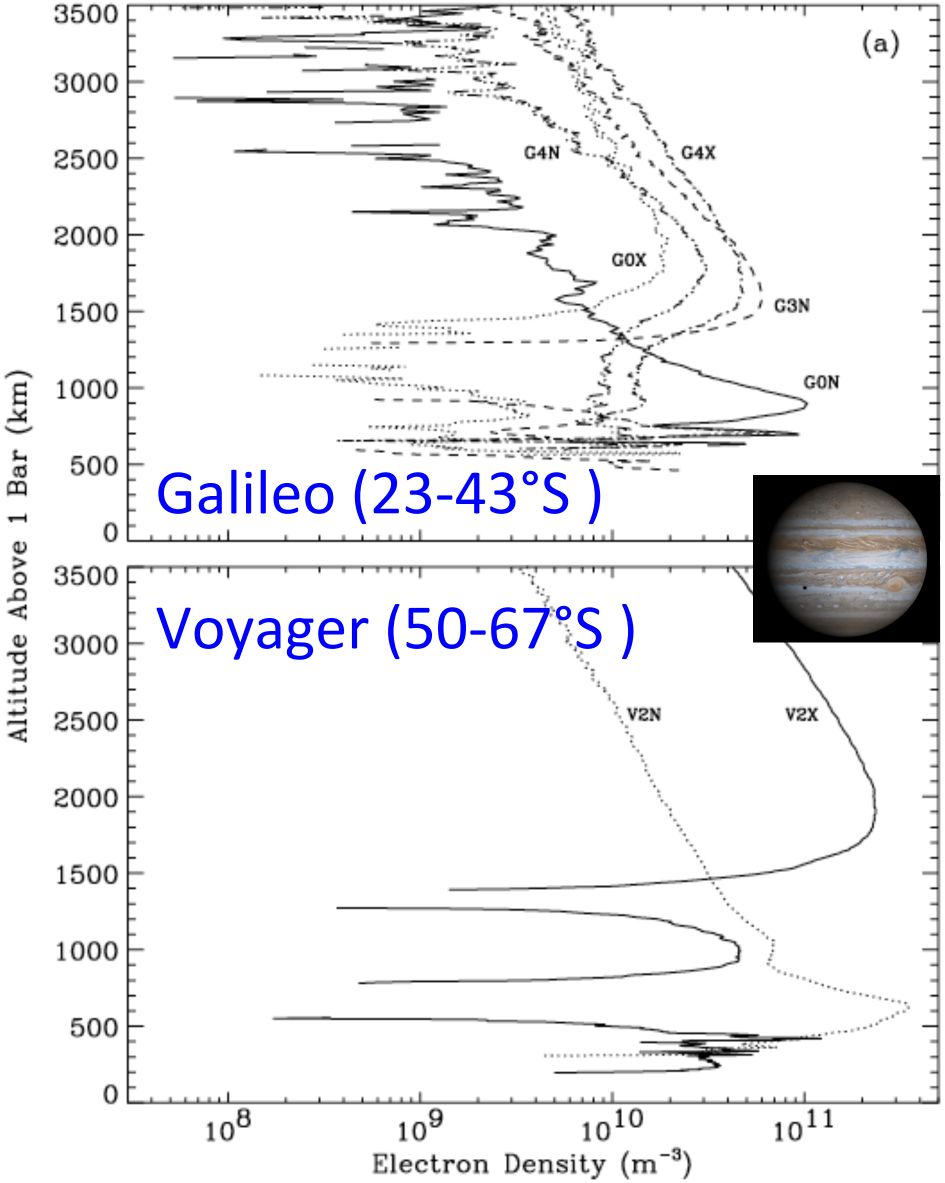


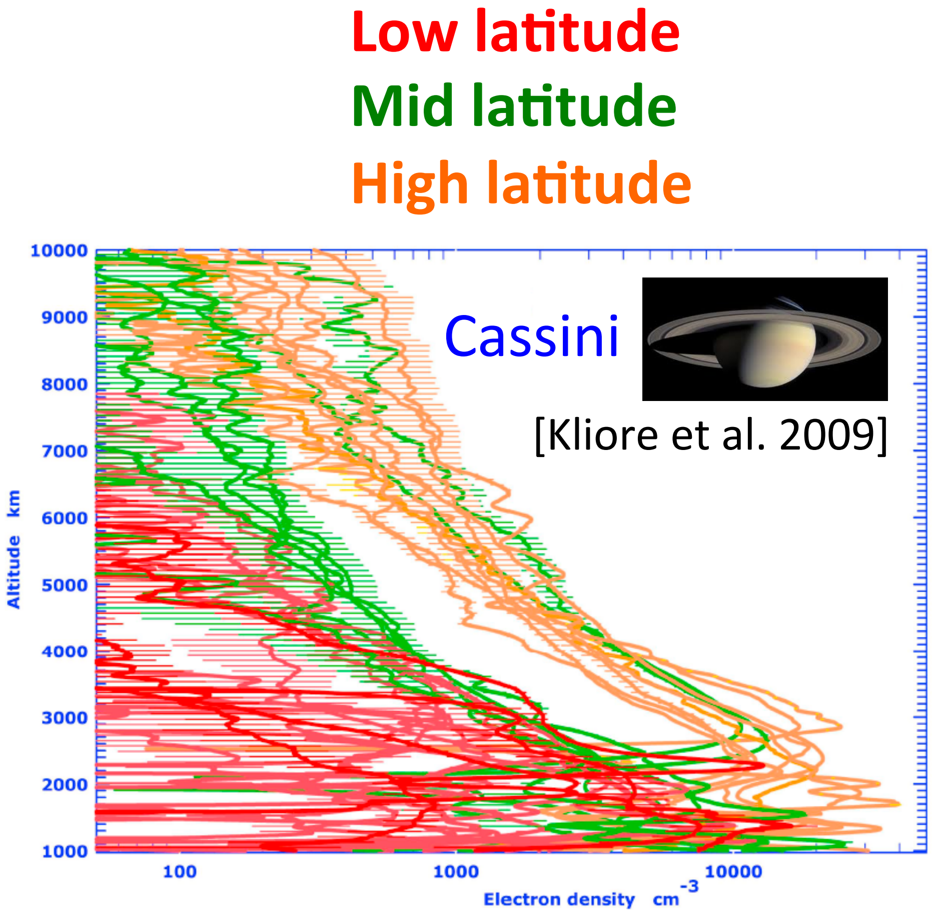


O'Donoghue et al. (Nature, 2013)

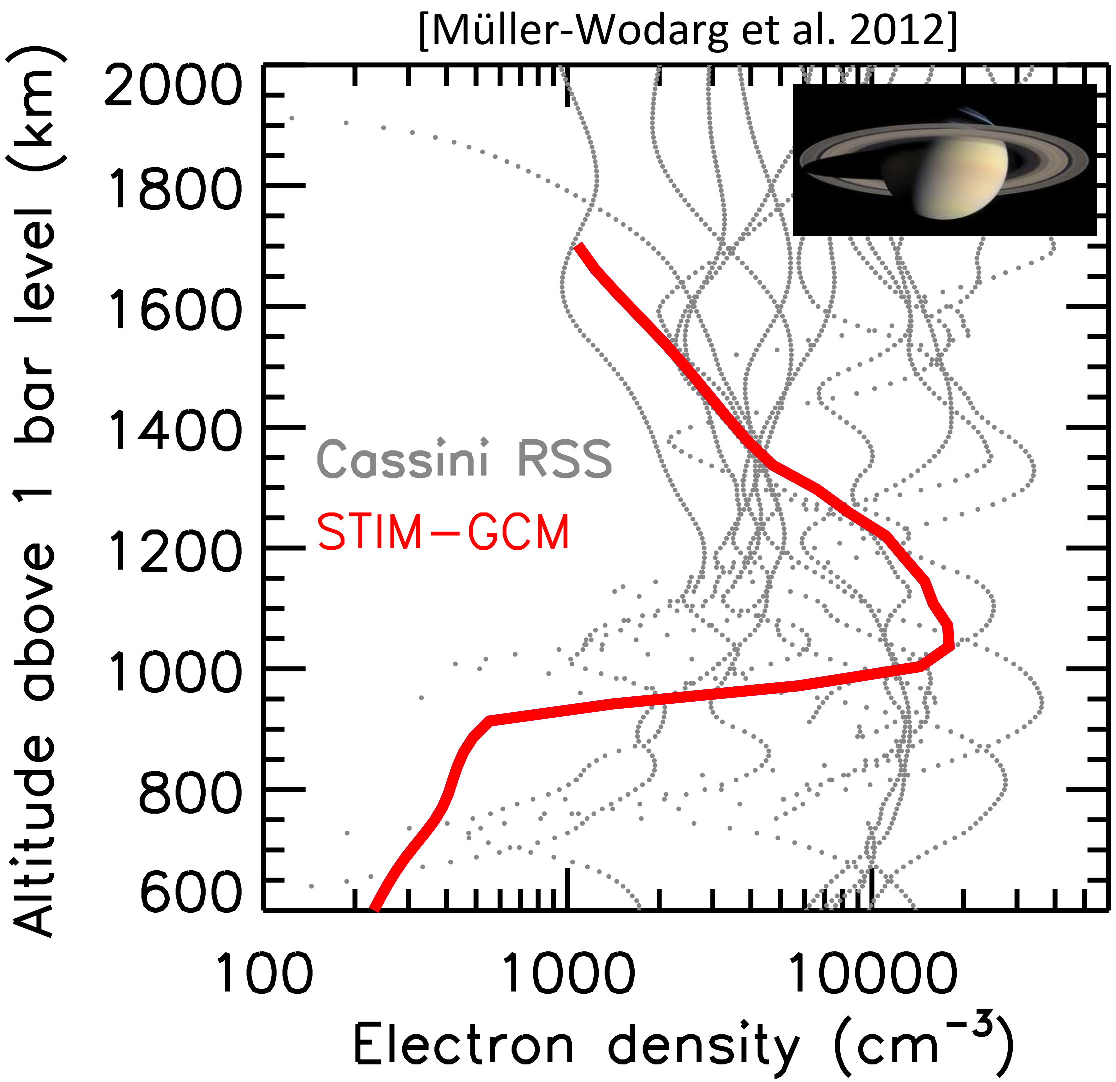
Measured ionospheric profiles at Jupiter and Saturn

[Yelle and Miller 2004]





Vertical structure of the ionosphere

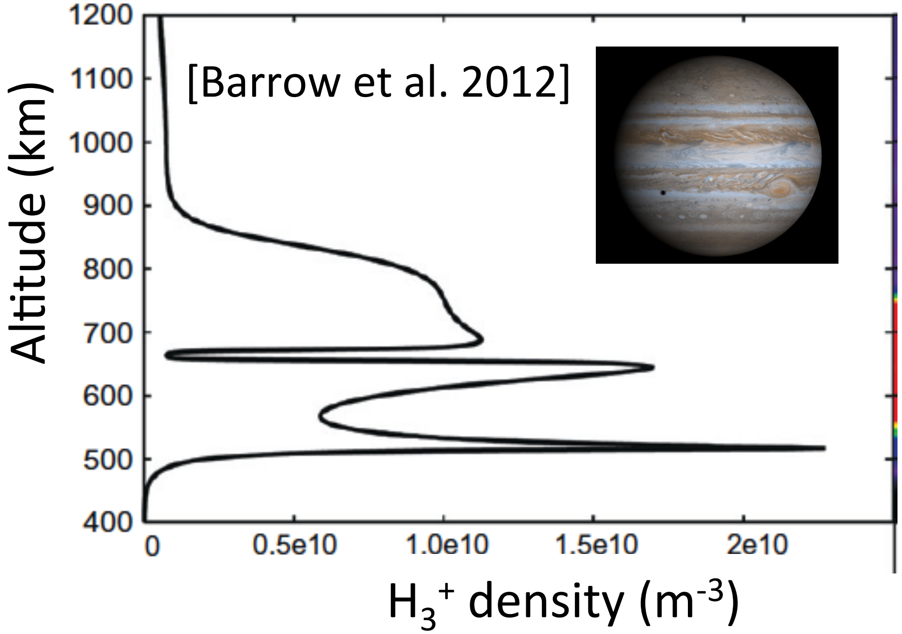


* Cassini/Radio Science Subsystem

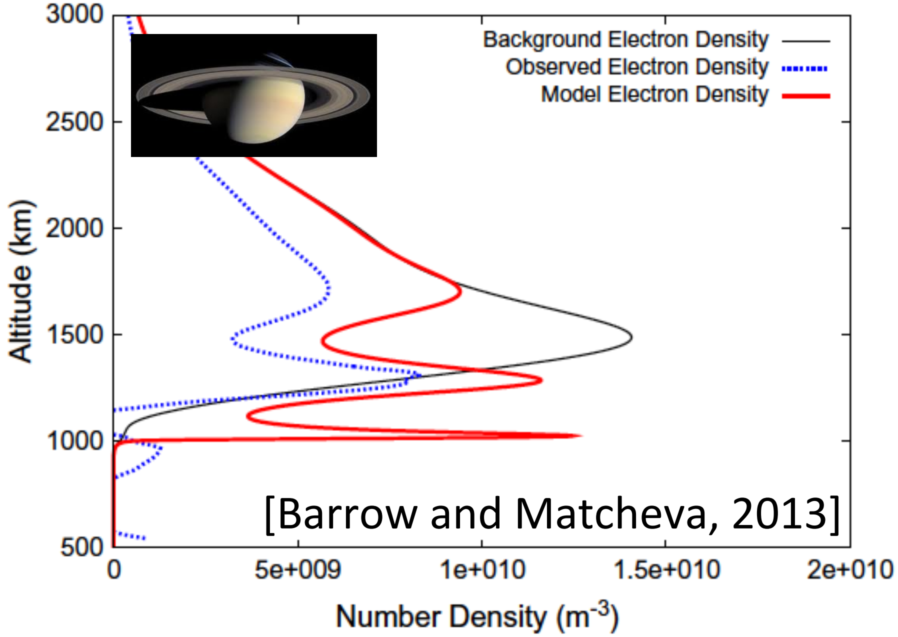
* Saturn Thermosphere-Ionosphere Model – General Circulation Model

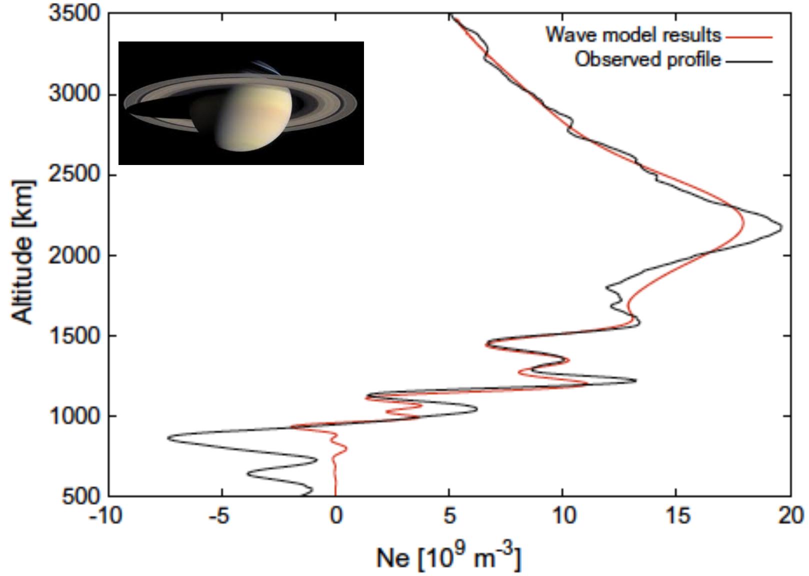
Effect of atmospheric gravity waves

Simulations



Simulations





TAKE HOME MESSAGE: Ionosphere

- ***Ionization sources:***
  - EUV solar radiation and magnetospheric, energetic particles
- ***Photo-absorption versus particle deposition***:
  - Altitude of absorption of solar radiation driven by:
    - Photo-absorption cross section
    - Column density of absorbers
  - Altitude of deposition of auroral electrons driven by:
    - Column density of atmosphere (primarily)
- ***Ionospheric composition:***
  - Dominant ion species photo-produced → usually not most abundant: need to take into account chemistry
- ***Ionospheric density:***
  - Limitation in electron density estimates: H_2 vibrat., ion drift, water inflow
- ***Vertical/latitudinal structure:***
  - Ring contribution to latitudinal and vertical structure
  - Atmospheric gravity wave contribution to vertical structure

SECOND LECTURE

Outline

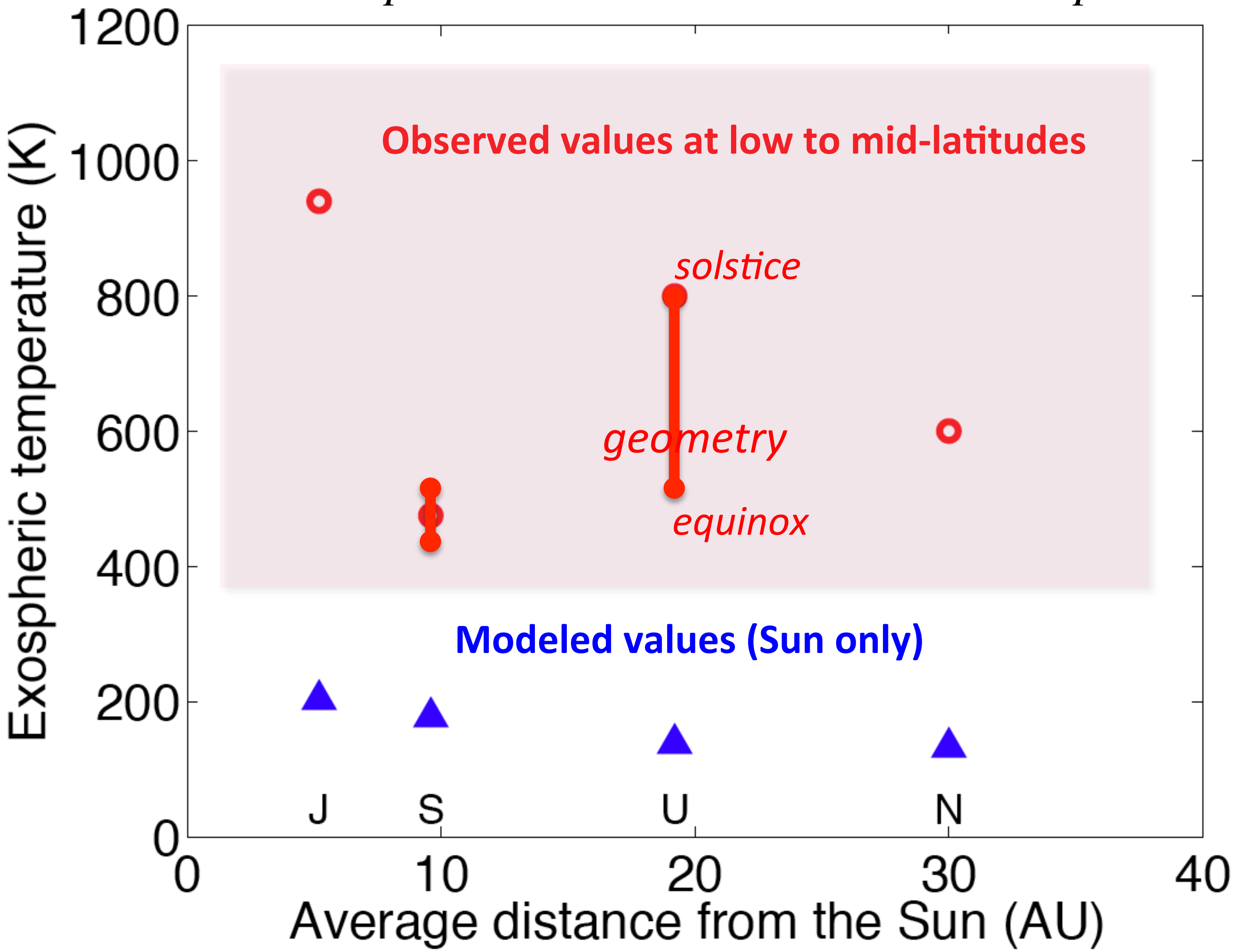
1. **Setting the scene**
   - Thermosphere/Ionosphere
   - Energy sources
2. **Ionosphere at the giant planets**
   - What? How? Where? How much?
3. **Auroral emissions**
4. **Magnetosphere-ionosphere-thermosphere coupling**
   - Energy crisis at the giant planets
5. **Future prospect**

Open questions

- ***What drive ionospheric structure and variability at the giant planets? (see 1st lecture)***
- ***What causes the energy crisis at the giant planets?***
- ***What drive the hemispheric differences observed at Saturn in the magnetosphere and auroral, ionospheric regions?***
- ***Is the variable rotation rate observed in the Saturnian magnetosphere linked to atmospheric dynamics?***

Energy Crisis at the Giant Planets

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



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

Energy crisis at the giant planets

◆ **HEATING SOURCES: forcing from above/below**

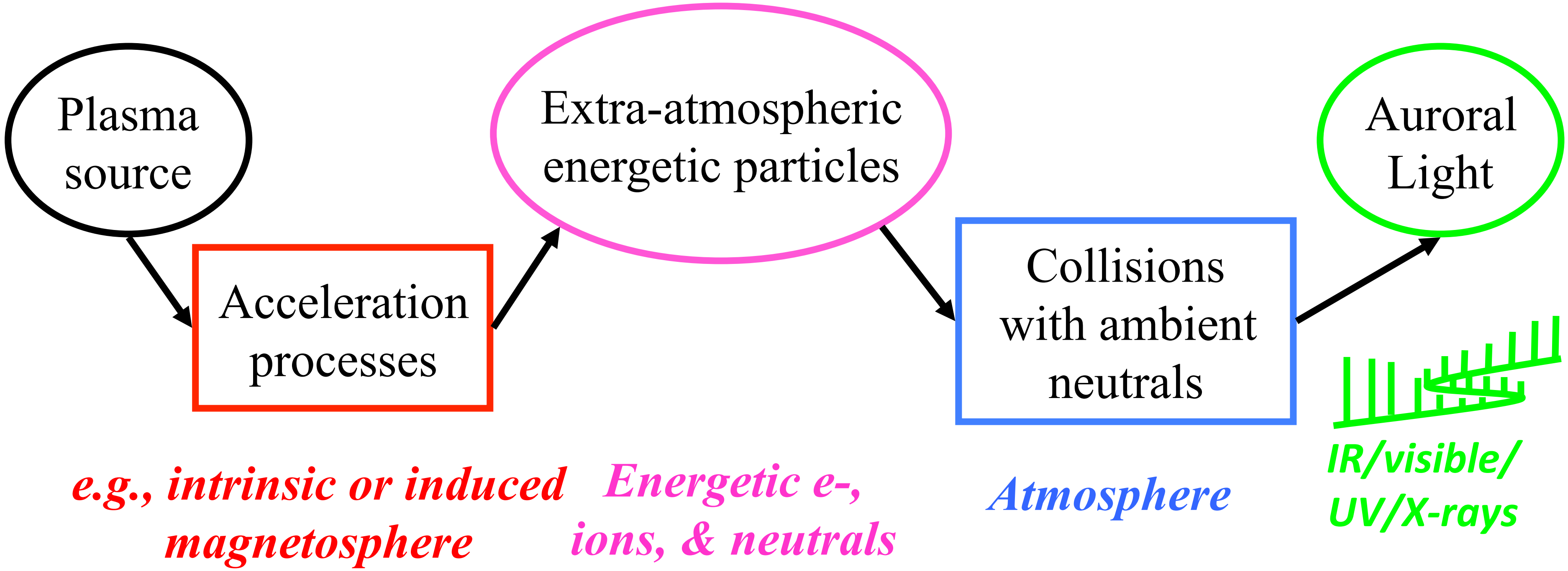
- ***Solar heating*** through excitation/dissociation/ionization + exothermic chemical reactions
- ***Particle heating*** via collisions + chemistry [e.g., Waite et al. 1983, 1987; *Grodent et al.*, 2001]
- ***"Ionospheric Joule heating"*** via auroral electrical currents and ion-drag heating [*Vasyliũnas and Song*, 2005] **at high latitudes**
- ***Dissipation of upward, propagating waves*** (such as gravity waves, …) [*Matcheva and Strobel 1999, Hickey et al. 2000; Barrow et al. 2012*]
- …

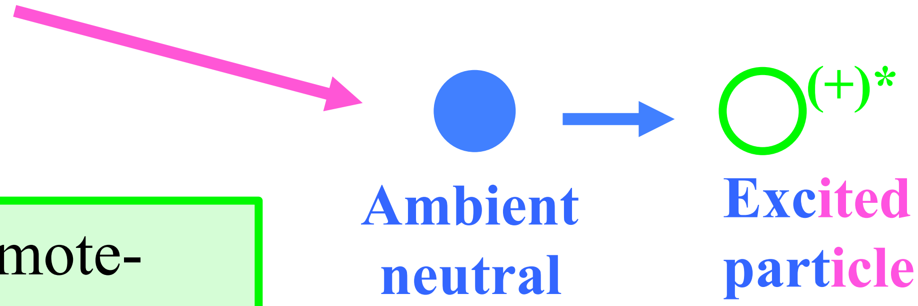
[*: *Strobel*, 2002]

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

Auroral emissions

Aurora is the *photo-manifestation of the interaction of energetic extra-atmospheric electrons, ions, and neutrals with an atmosphere.*

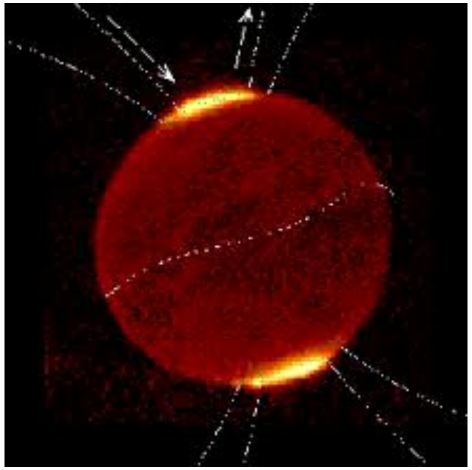




Aurora: unique and valuable remote-sensing probe of the Solar System.

[Galand and Chakrabarti, 2002]

Protonated molecular hydrogen: H_3^+



- First time detected in the universe through its IR, thermal emissions
  - **Jupiter aurora** with Voyager/UVS (Drossart et al. 1989)

- Thermal emissions: tracer of **ionosphere-thermosphere response** to magnetospheric processes
  - ~10 min lifetime
  - Destroyed by hydrocarbons: $H_3^+ + X \rightarrow H_2 + XH^+$

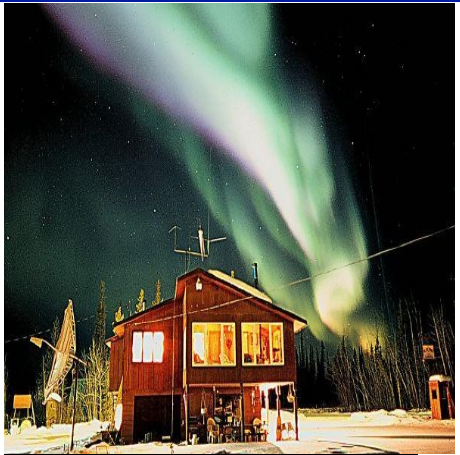
- Importance of H_3^+ as a **coolant** (as CO_2 at Earth)

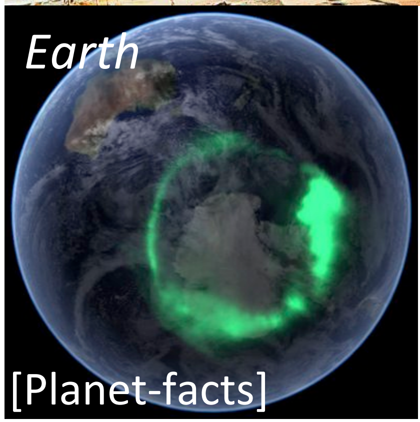
  → Efficient thermostat at Jupiter

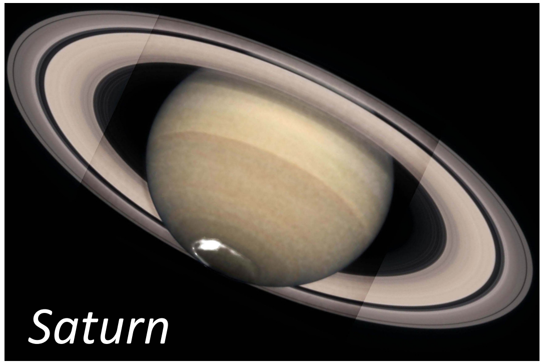
  → Exoplanet too close, fail to cool, as H_2 dissociated, no H_3^+ produced.

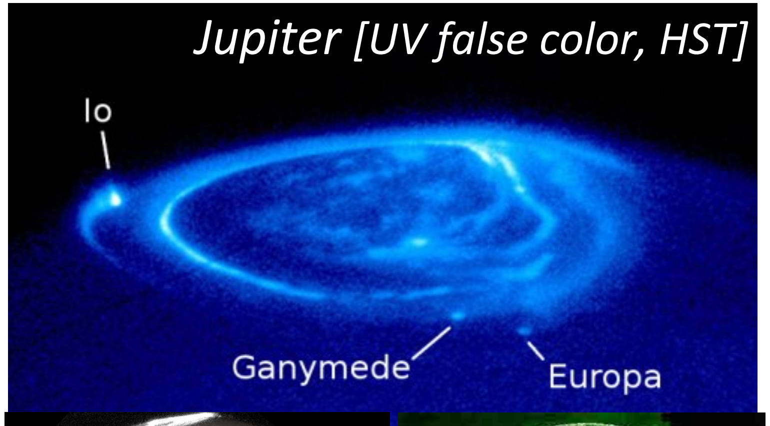
[Image: J. Connerney, T.Satoh, NASA Infrared Telescope Facility]

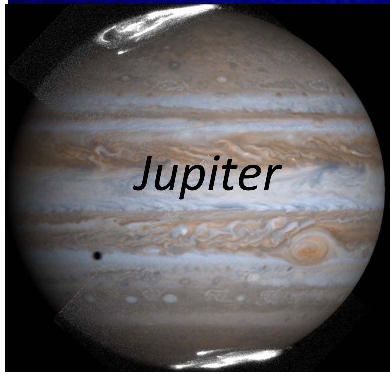
Auroral emissions in the Solar System

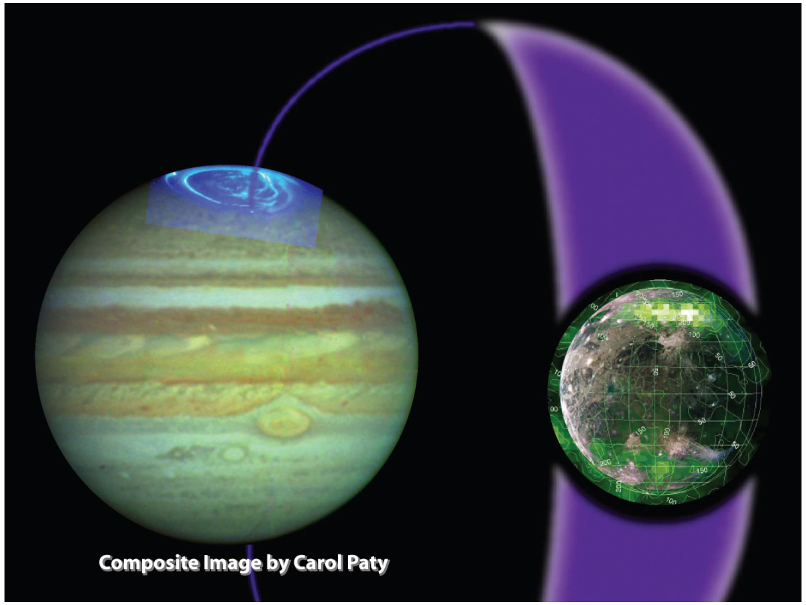




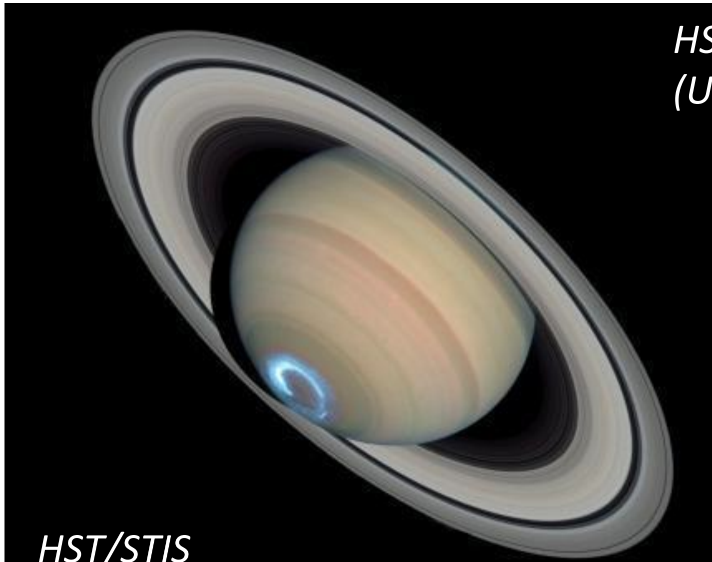








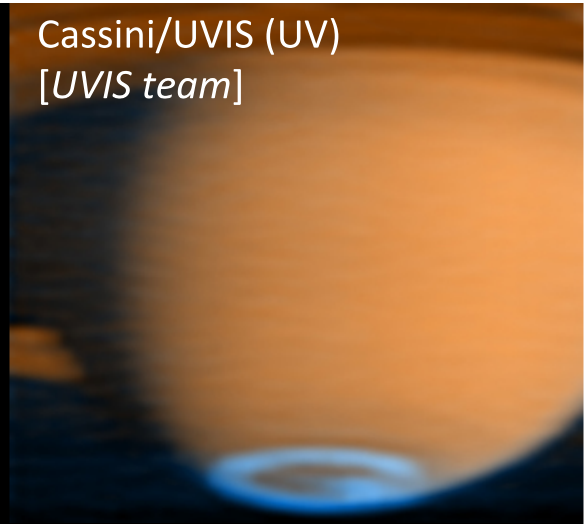
Aurora:
“The TV-screen of the I-T-M coupling”



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

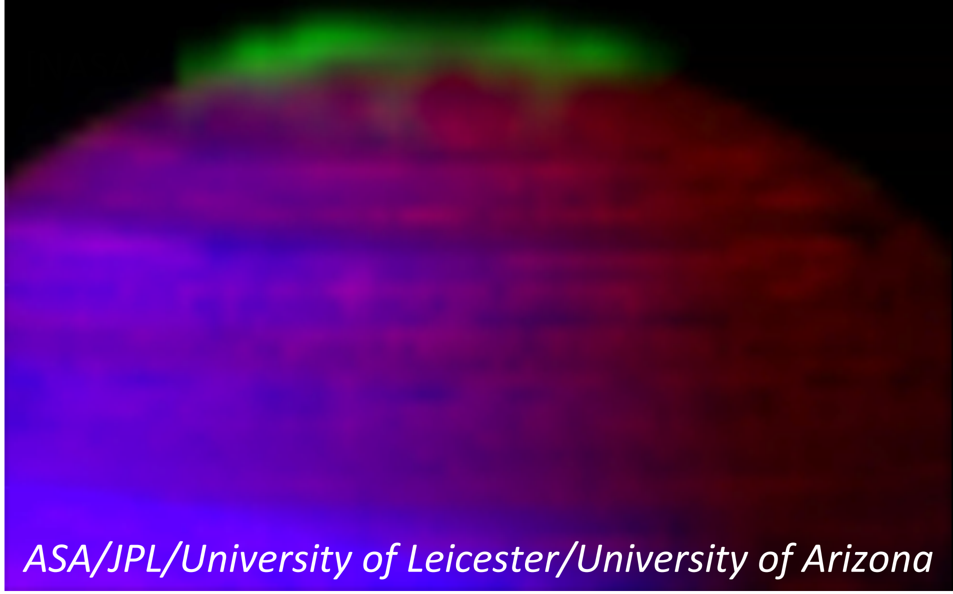
HST/STIS [NASA/ESA/Jonathan Nichols (University of Leicester)]

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

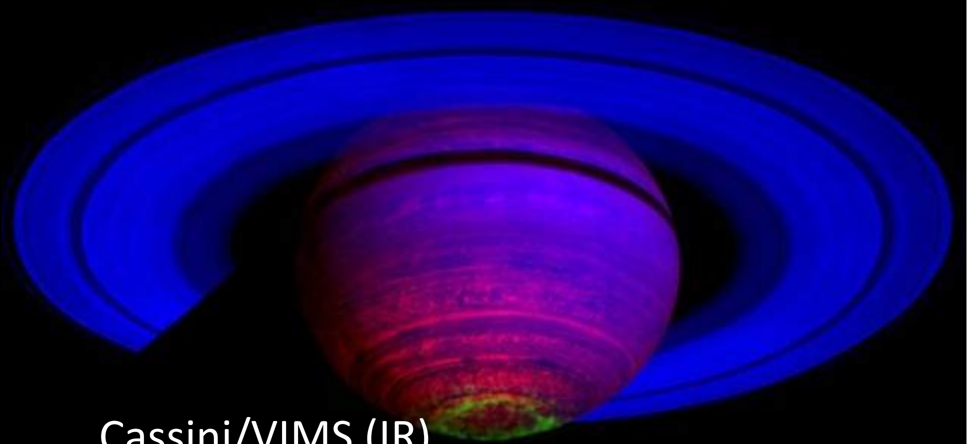


UV spectroscopic analysis → Particle characteristics

IR spectroscopic analysis→ H_3^+ density & temperature



ASA/JPL/University of Leicester/University of Arizona

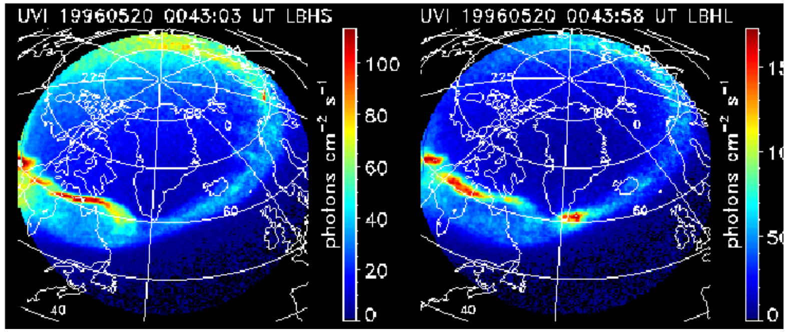


Cassini/VIMS (IR)
NASA/JPL/Tom Stallard (Univ. Leicester)/

AURORAL SPECTROSCOPIC ANALYSIS

- ➢ Identification of energetic particle type
- ➢ Assessment of (E_m, Q_{prec}) of energetic particles
- ✓ *Supported by comprehensive modeling*

POLAR UVI images

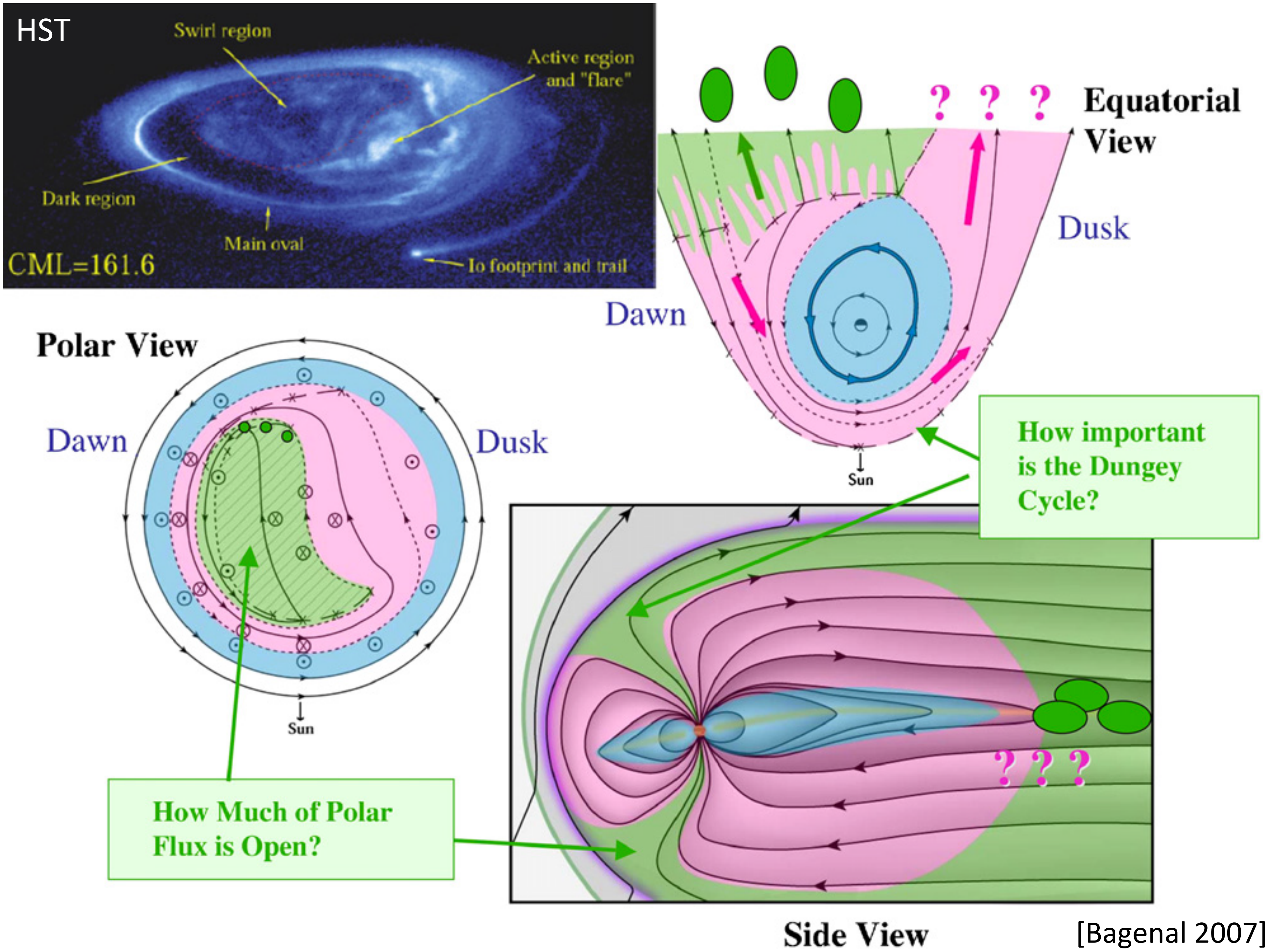


N_2 LBHS N_2 LBHL

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 to 200 keV
Type of aurora identified:	Electron aurora (discrete only)	Electron aurora (diffuse + discrete)

✓ *Similar techniques can be applied at various planets BUT different limitations on the product*

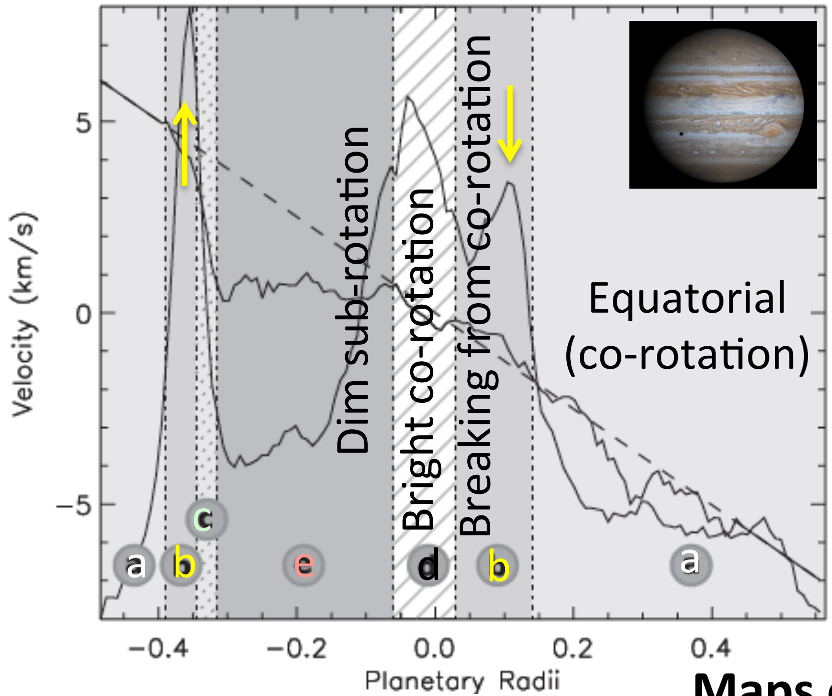
[Fox et al. 2008]

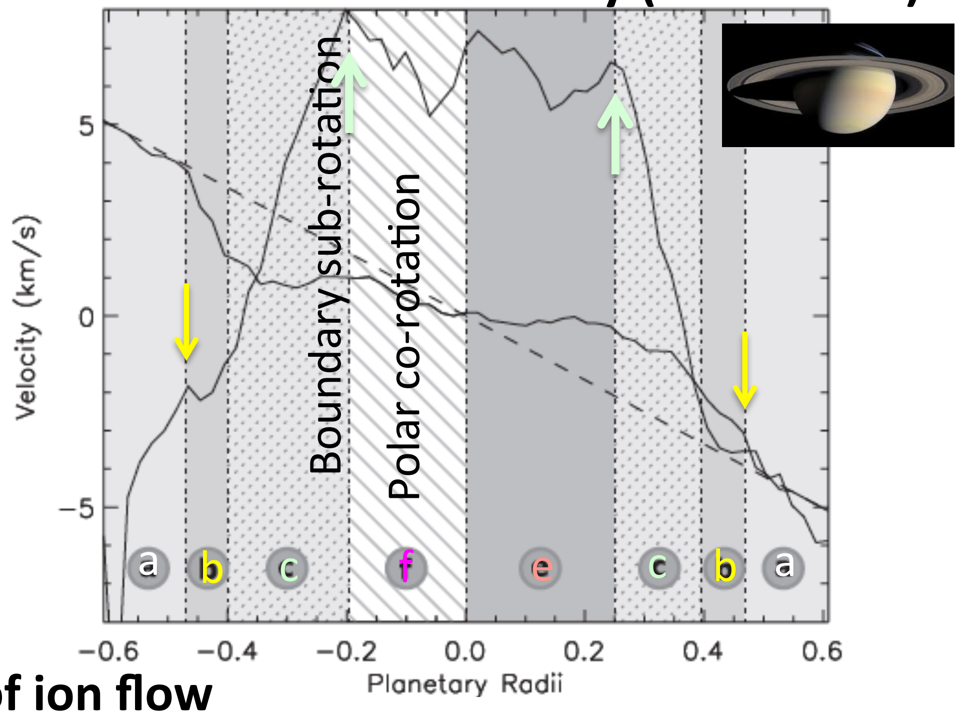


[Bagenal 2007]

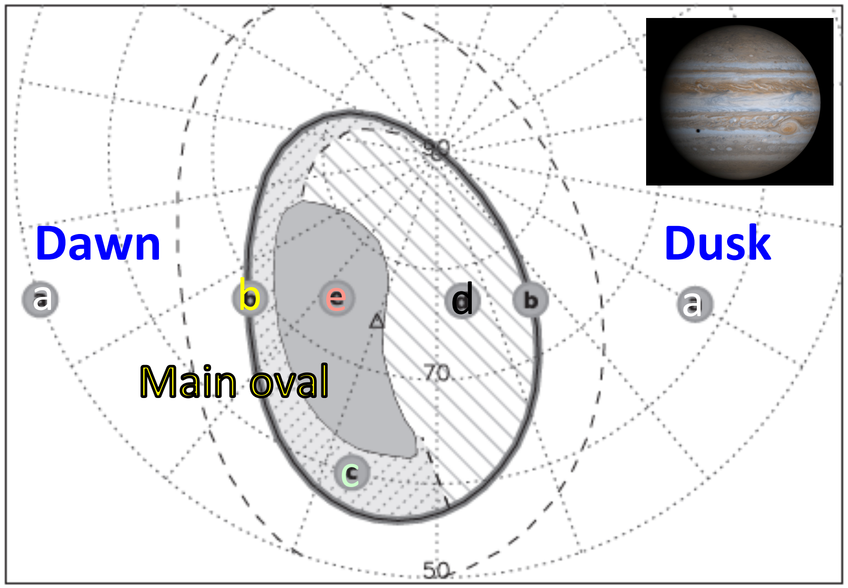
IR AURORAL SPECTROSCOPIC ANALYSIS

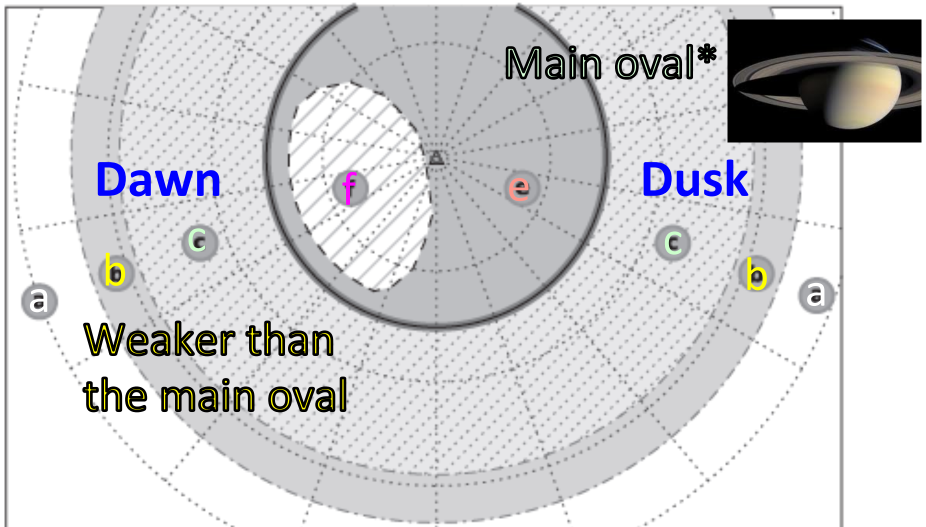
H_3^+ line-of signed velocity and normalize intensity (NASA-IRTF)





Maps of ion flow

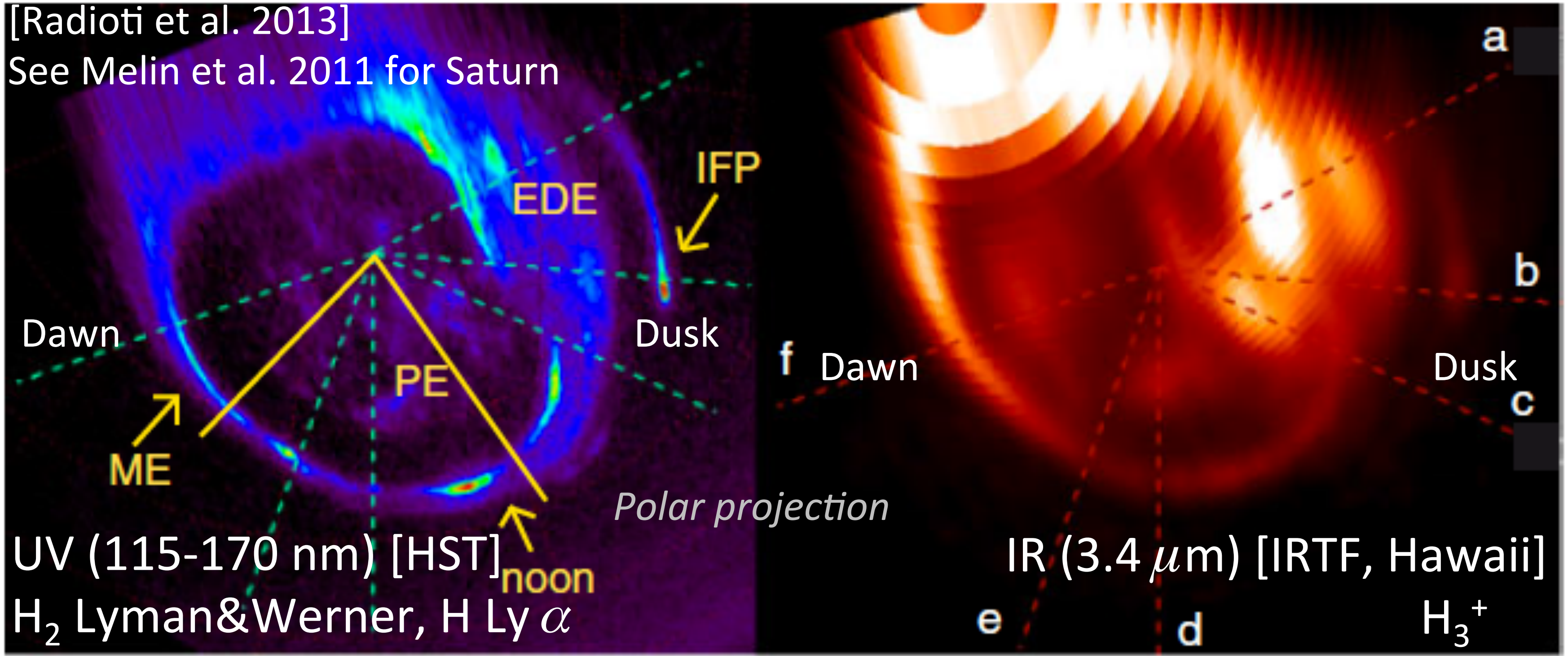




* plasma flow shear at open-closed field line boundary

[Stallard 2012]

Simultaneous UV/IR auroral emissions



- Direct impact of auroral e- on H_2
- Instantaneous
- Extend down to 250 km (visible)

- Thermal emissions ([H_3^+], T_H_3^+~ T_neutral (lifetime ~10 min)
- > 1000 km (destruction of H_3^+ by hydrocarbons below homopause)

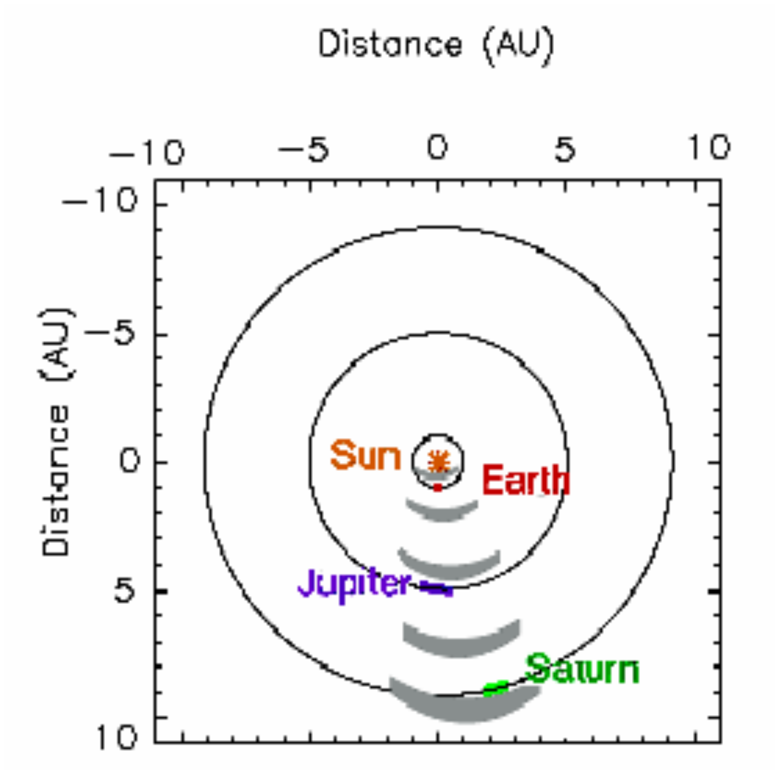
Main oval: Spatial distribution and temporal behavior of UV and IR emissions differ → IR emissions above homopause

All → IR emissions influenced by H_3^+ heating + time-delays.

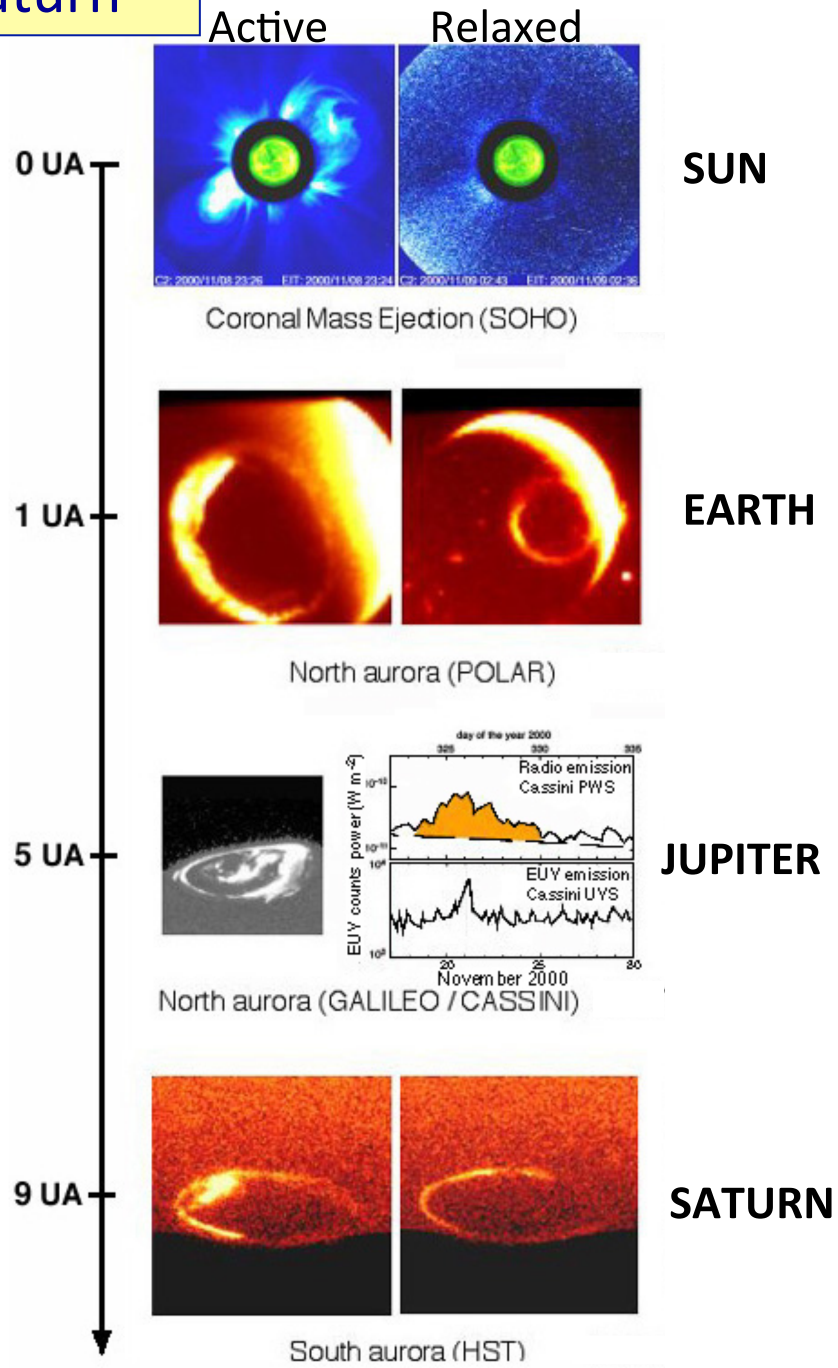
Interplanetary shock to Earth, Jupiter, Saturn

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

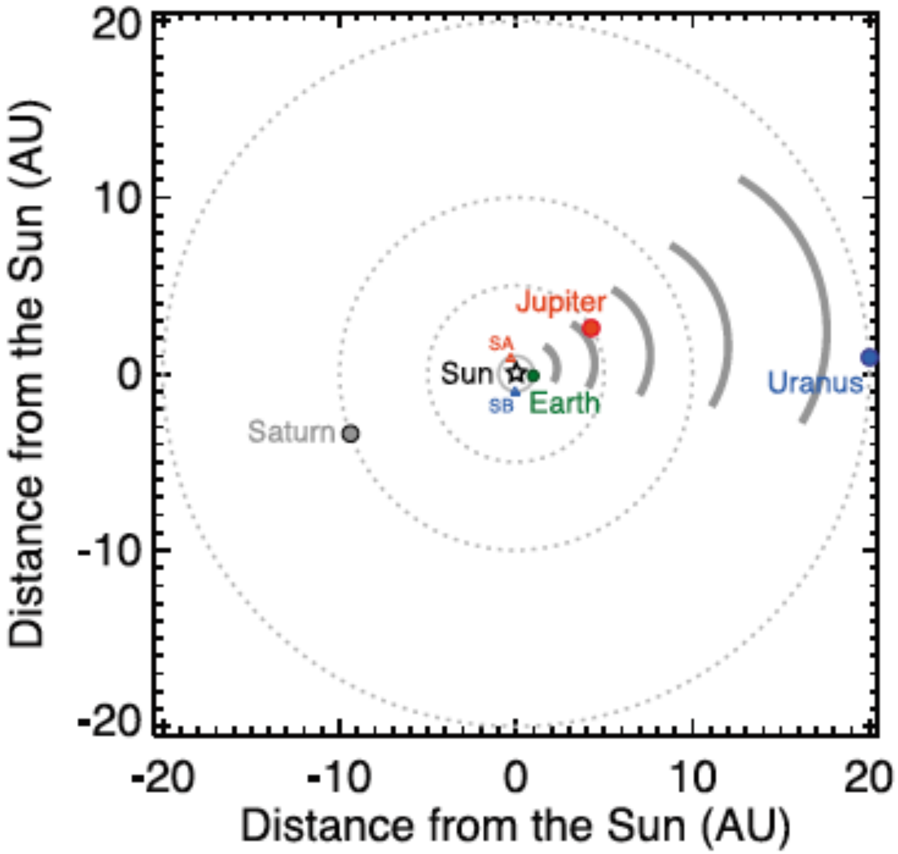
→ *Highlights the difference in setting and allows us to learn more about sw-MI coupling by comparing different responses*

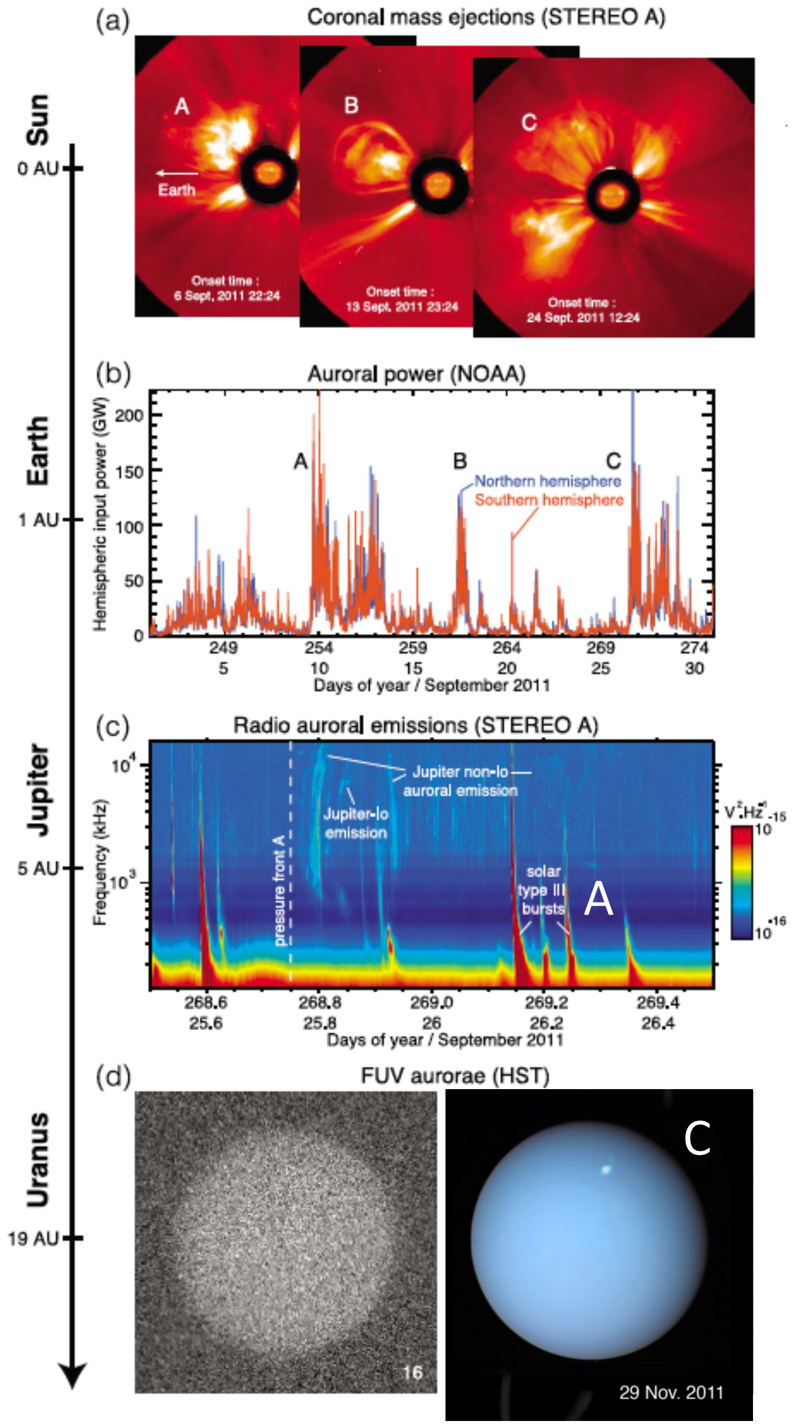


[Prangé et al., Nature, 2004]



Interplanetary shock to Earth, Jupiter and Uranus

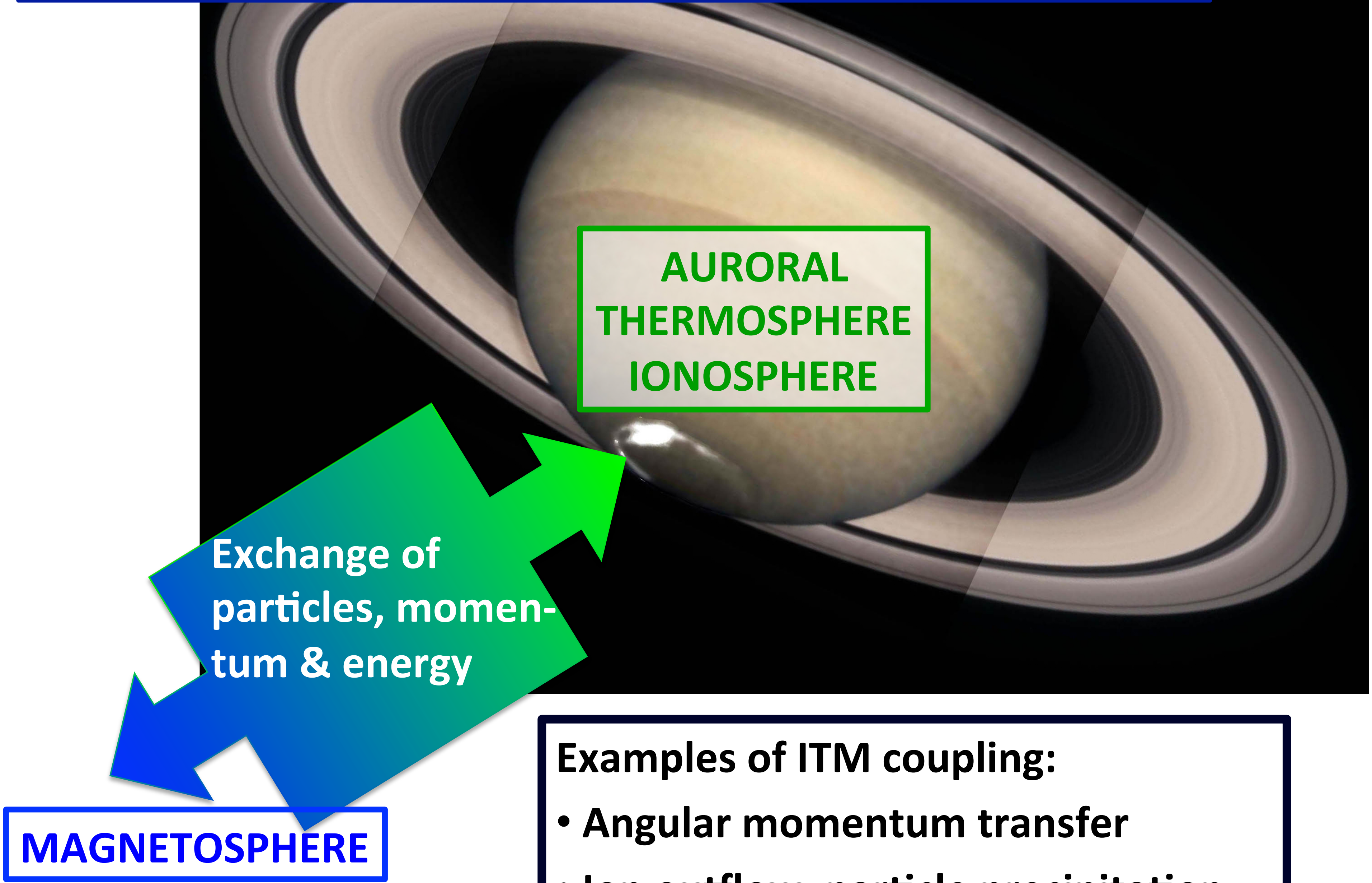




[Lamy et al., GRL, 2012]

Thermosphere-ionosphere-magnetosphere coupling

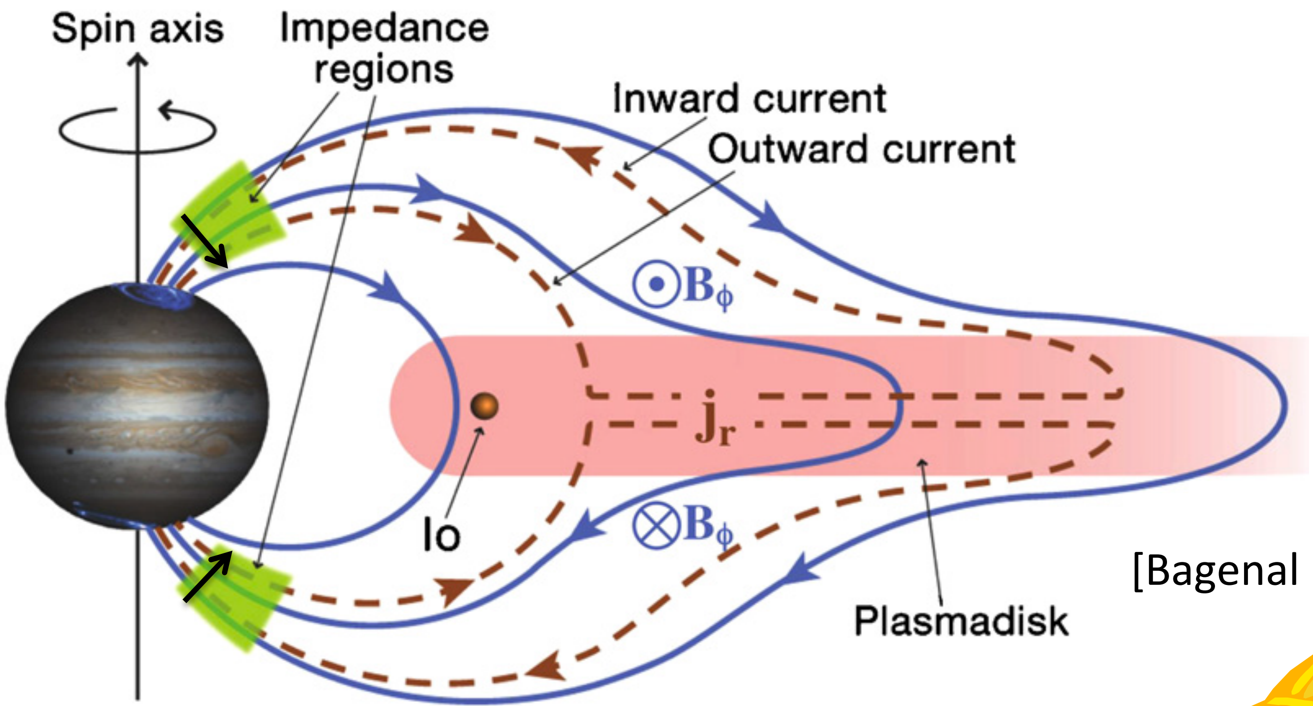
MAGNETOSPHERE-IONOSPHERE-THERMOSPHERE COUPLING



Examples of ITM coupling:

- Angular momentum transfer
- Ion outflow, particle precipitation

THERMOSPHERE-IONOSPHERE-MAGNETOSPHERE COUPLING

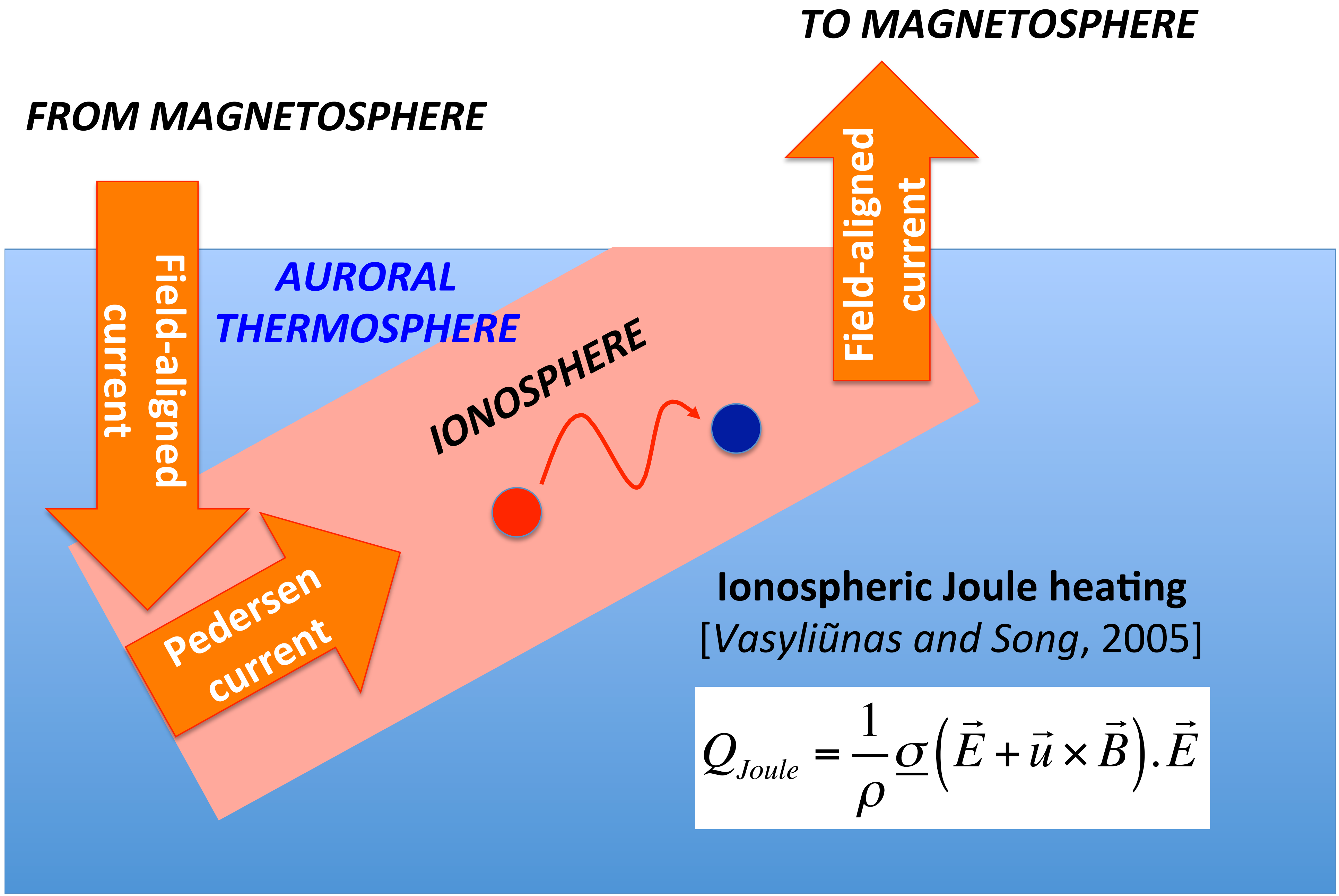


[Bagenal 2007]

- Overall, at high latitudes:

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

THERMOSPHERE-IONOSPHERE-MAGNETOSPHERE COUPLING



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

Electrical, ionospheric conductivities

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

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

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

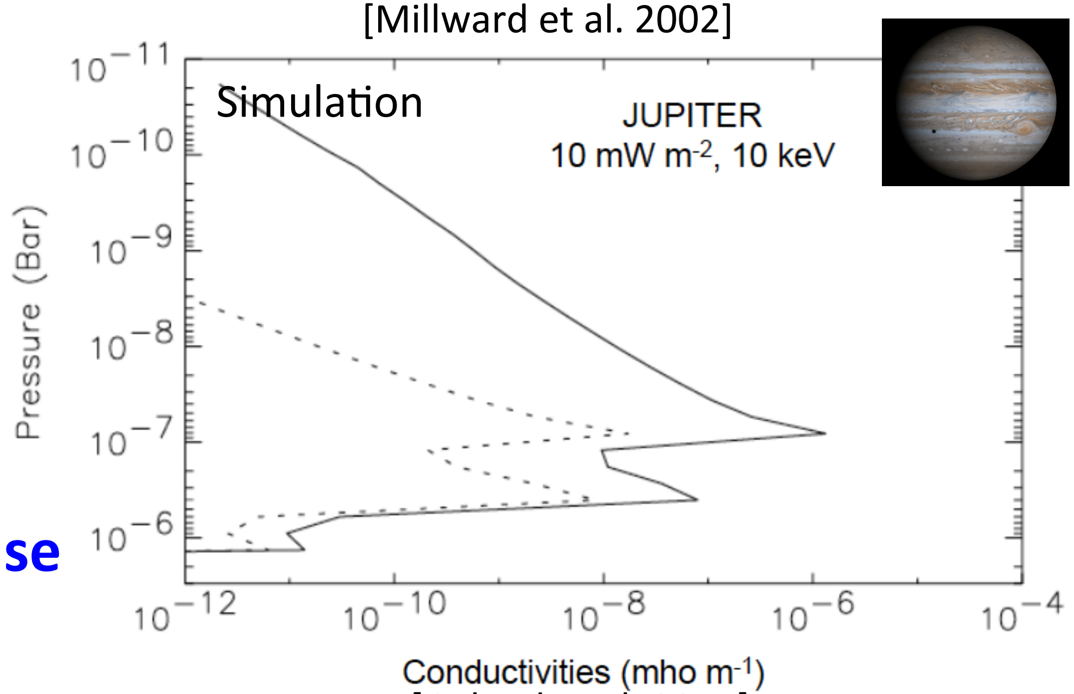
[e.g., Richmond 1995]

Ionospheric conductivites in auroral regions

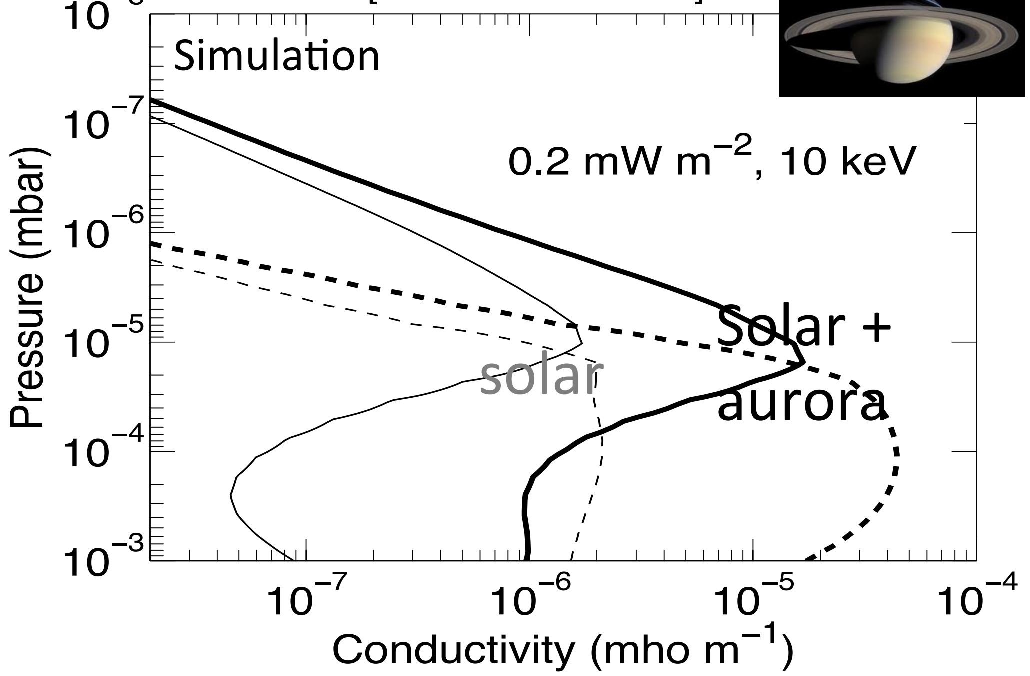
Pedersen ————
Hall - - - - - -

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

[Millward et al. 2002]



[Galand et al. 2011]



Pedersen conductance

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

Ionospheric 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

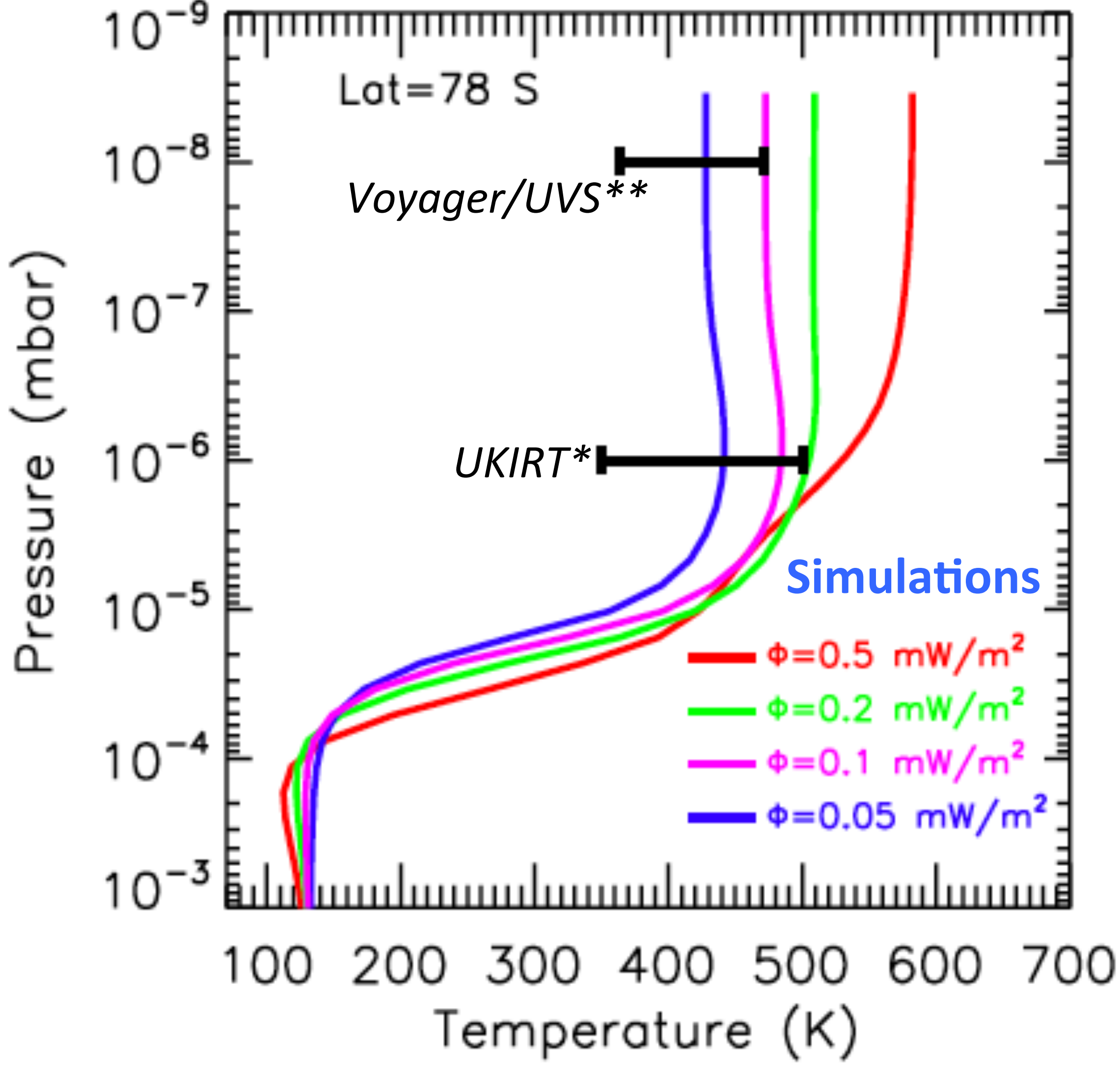
Slippage parameter(1) for Jupiter(2) & Saturn(3): $k = \frac{\Omega - \omega_n}{\Omega - \omega_i} = \sim 0.5$

Planetary angular velocity (Ω); Angular velocity of the neutrals (ω_n); Angular velocity of the ions (ω_i)

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

Ionospheric contribution to neutral temperature

[Müller-Wodarg et al. 2012]



** Melin et al. (2007)*

*** Vervack and Moses (2009)*

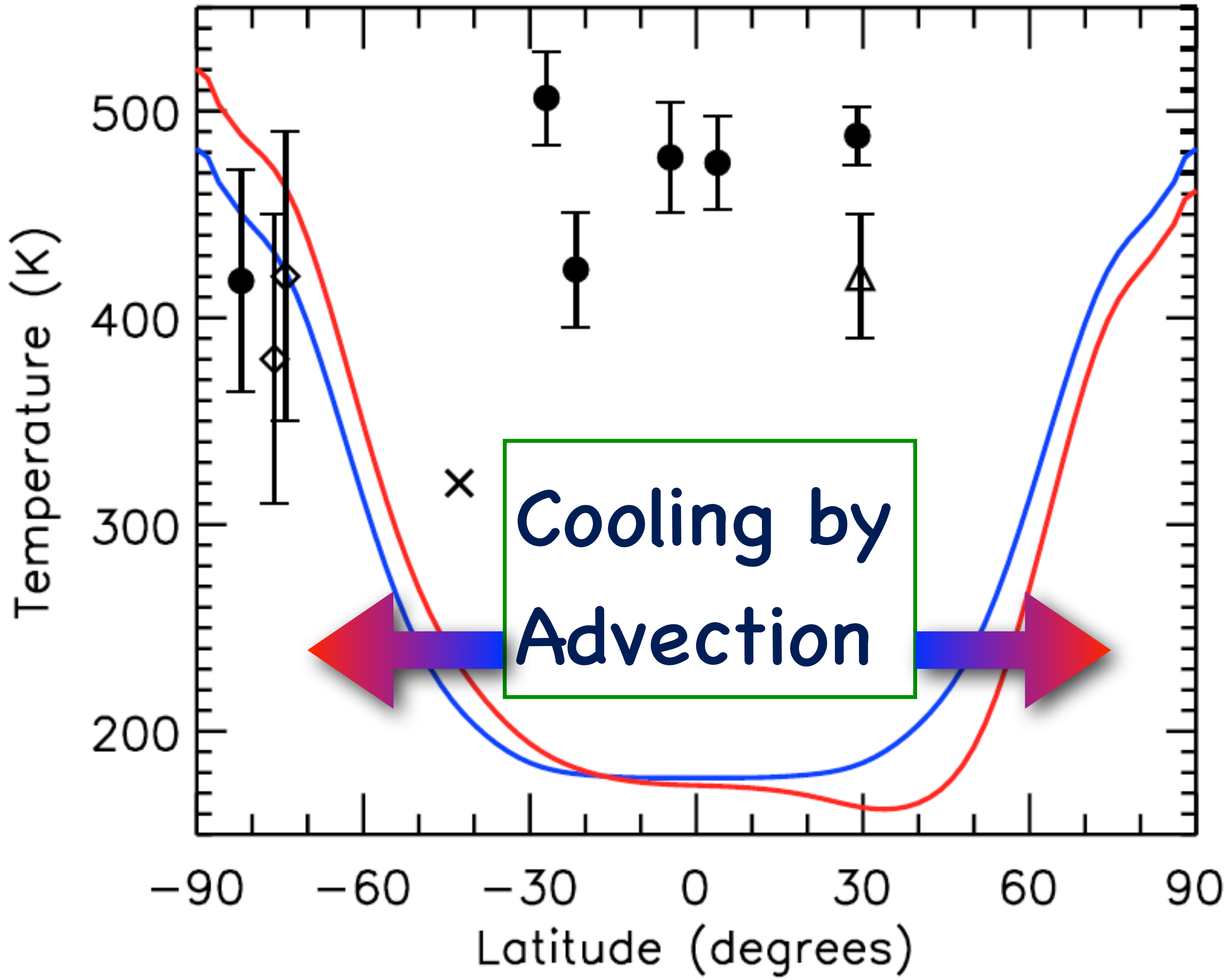
Auroral Joule heating sufficient to heat the high latitude ionosphere

Energy crisis at Saturn

Simulations:

STIM (Equinox)

STIM (Solstice)

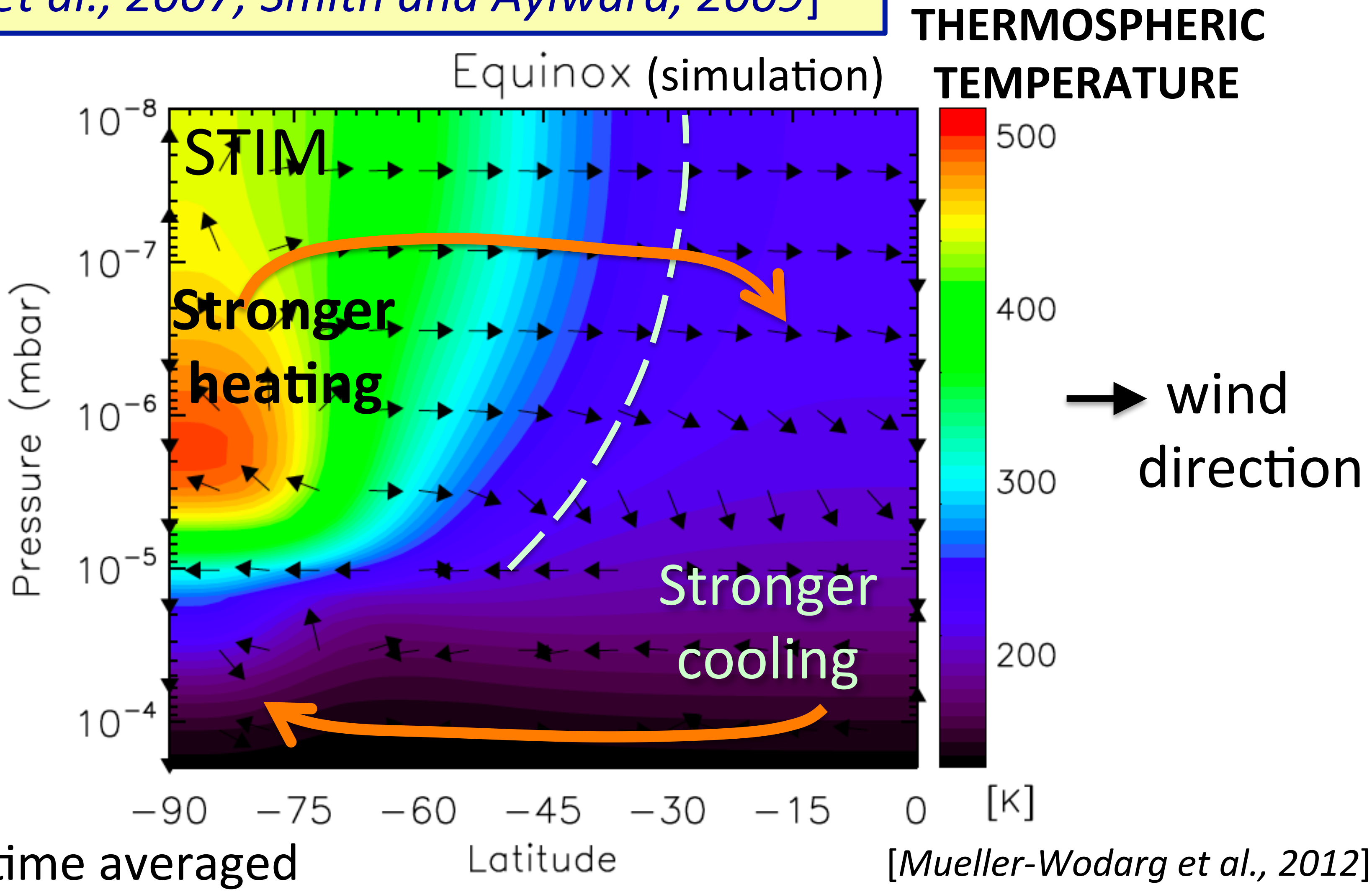


Points:

Measurements from Voyager UVS, Cassini UVIS and Ground Based IRTF

[Müller-Wodarg et al. 2012]

Ion drag fridge mechanism
[*Smith et al., 2007; Smith and Aylward, 2009*]

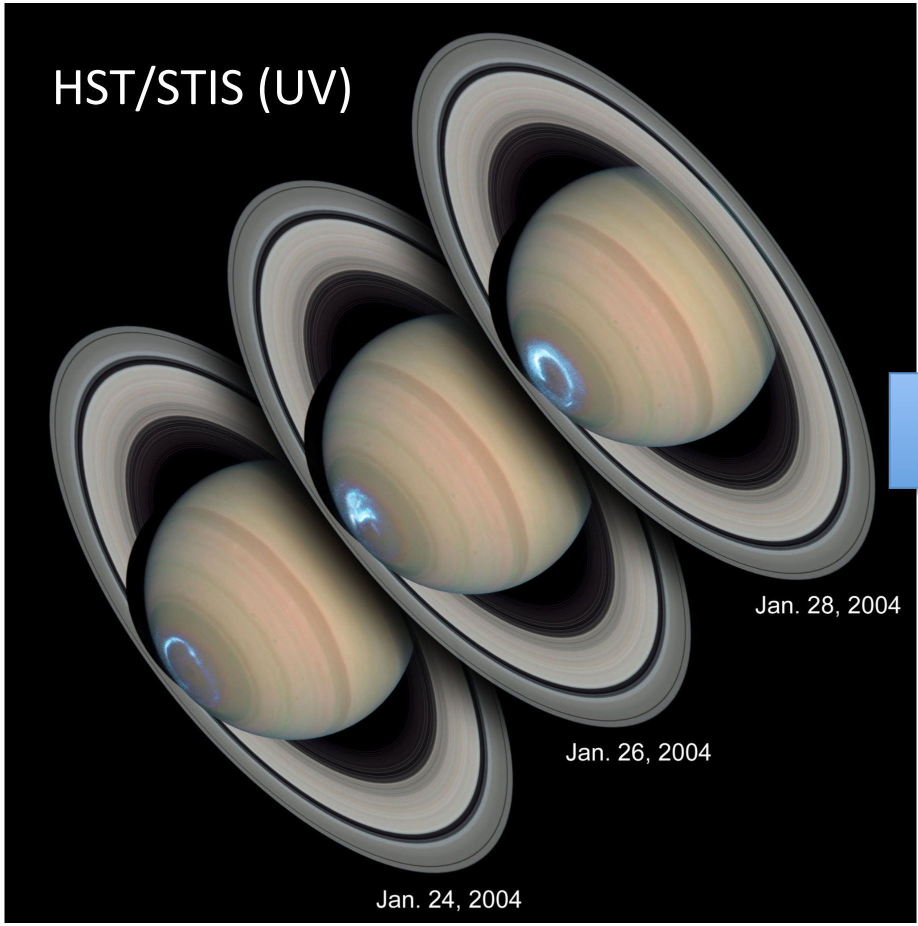


Local time averaged

[*Mueller-Wodarg et al., 2012*]

Polar sub-corotation due to auroral forcing (westward ion velocities due to ambient E fields) drives equator-to-pole circulation

Temporal change in auroral forcing



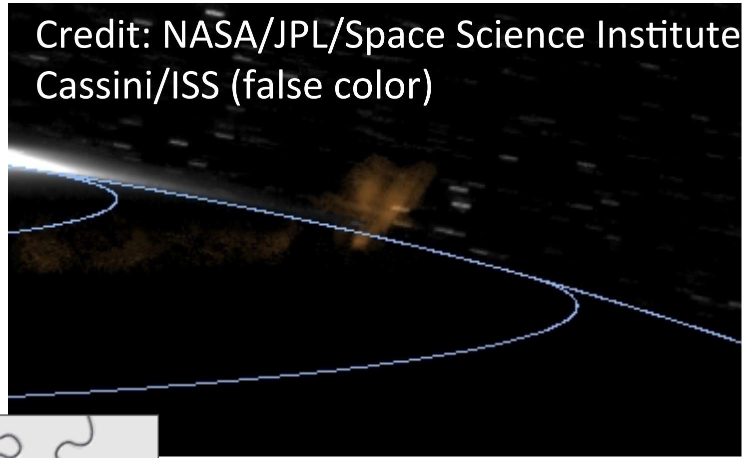
“Magnetic storm” response at Jupiter and Saturn remains largely **confined to auroral regions**
- no propagating gravity wave towards equator (as on Earth)

[Müller-Wodarg et al. 2013, Yates et al. 2013]

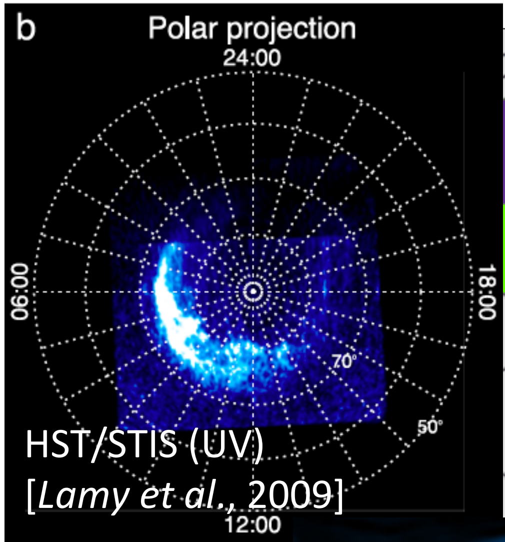
Energy trapped in high latitude regions
→ Would shorter timescales be more efficient?

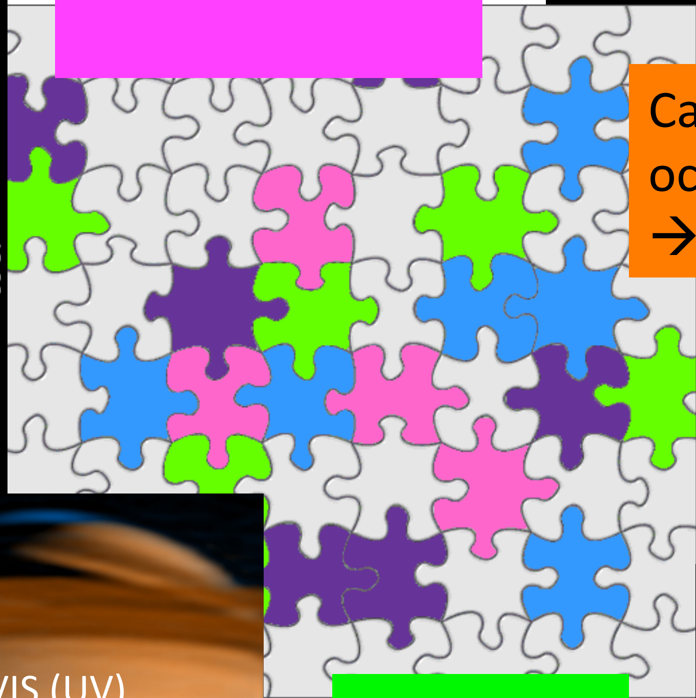
Future prospect

NASA/CASSINI (2004 → 2017) + Earth-based support

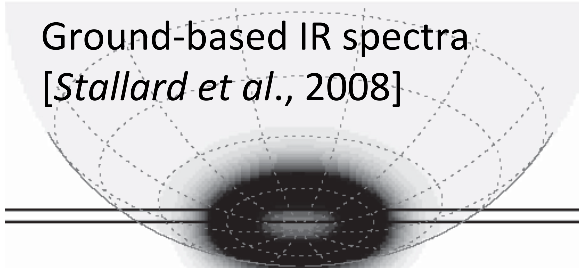


THERMOSPHERE/ IONOSPHERE COUPLED MODEL



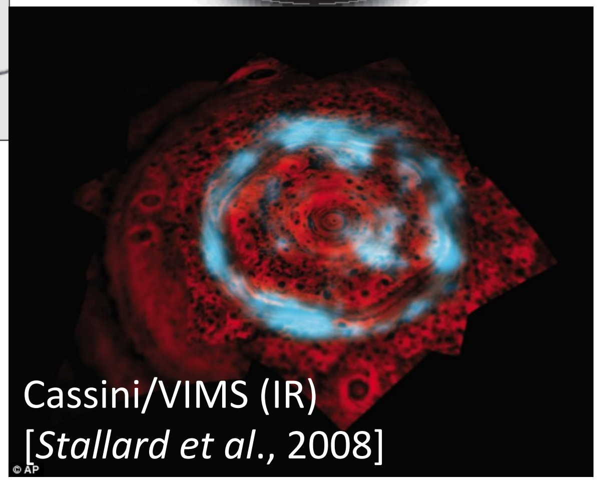


Cassini/RSS radio occultations → Ne

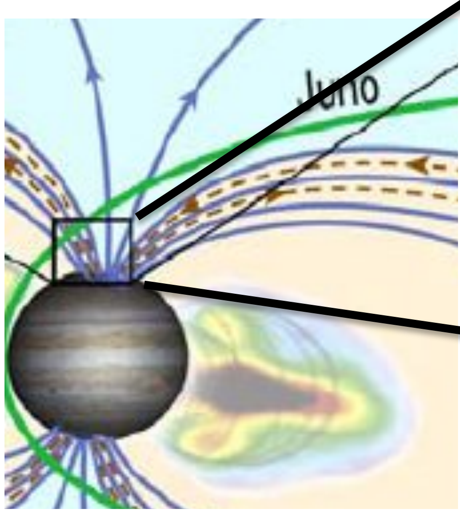


✓ **Combine as many as possible to better constrain the problem**

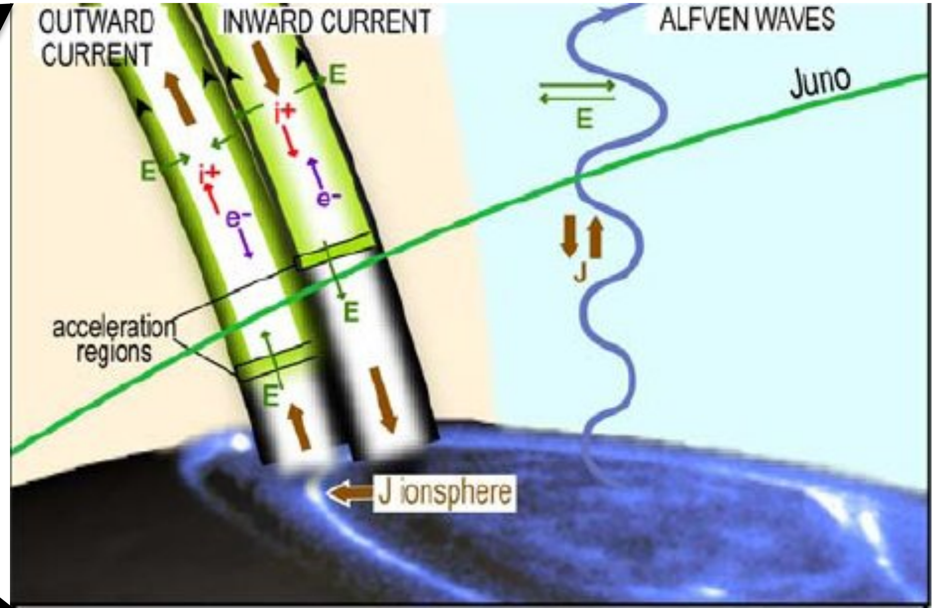
Voyager/ UVS Cassini/UVIS occultations →Tn



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

TAKE HOME MESSAGE

- ***ANALYSIS OF AURORAL EMISSIONS:***
  - **Valuable probe** of ionosphere (IR), auroral particle source, ITM coupling, and magnetic field line configuration
  - **Jupiter**: main oval driven by breaking down from co-rotation (Io)
  - **Saturn**: main oval mapped in the outer magnetosphere varying with solar wind conditions (Enceladus)
  - **Uranus**: solar wind dominated
- ***T-I-M COUPLING:***
  - **Electrical, ionospheric conductances**:
    - Uncertainties in conductivities driven by limitation in electron density estimate
    - Differences in B field strength between Jupiter and Saturn yield differences in conductances. Larger energy fluxes at Jupiter do not seem to compensate for the strong B field. Implication on T-I-M 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 timescale, E field variability unconstrained, role of waves, mid-lat e-?
  - Lessons learned from Saturn very useful for **upcoming exploration of Jupiter** (Juno / JUICE) and **exoplanets** (EChO)

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.