Satellites and interactions

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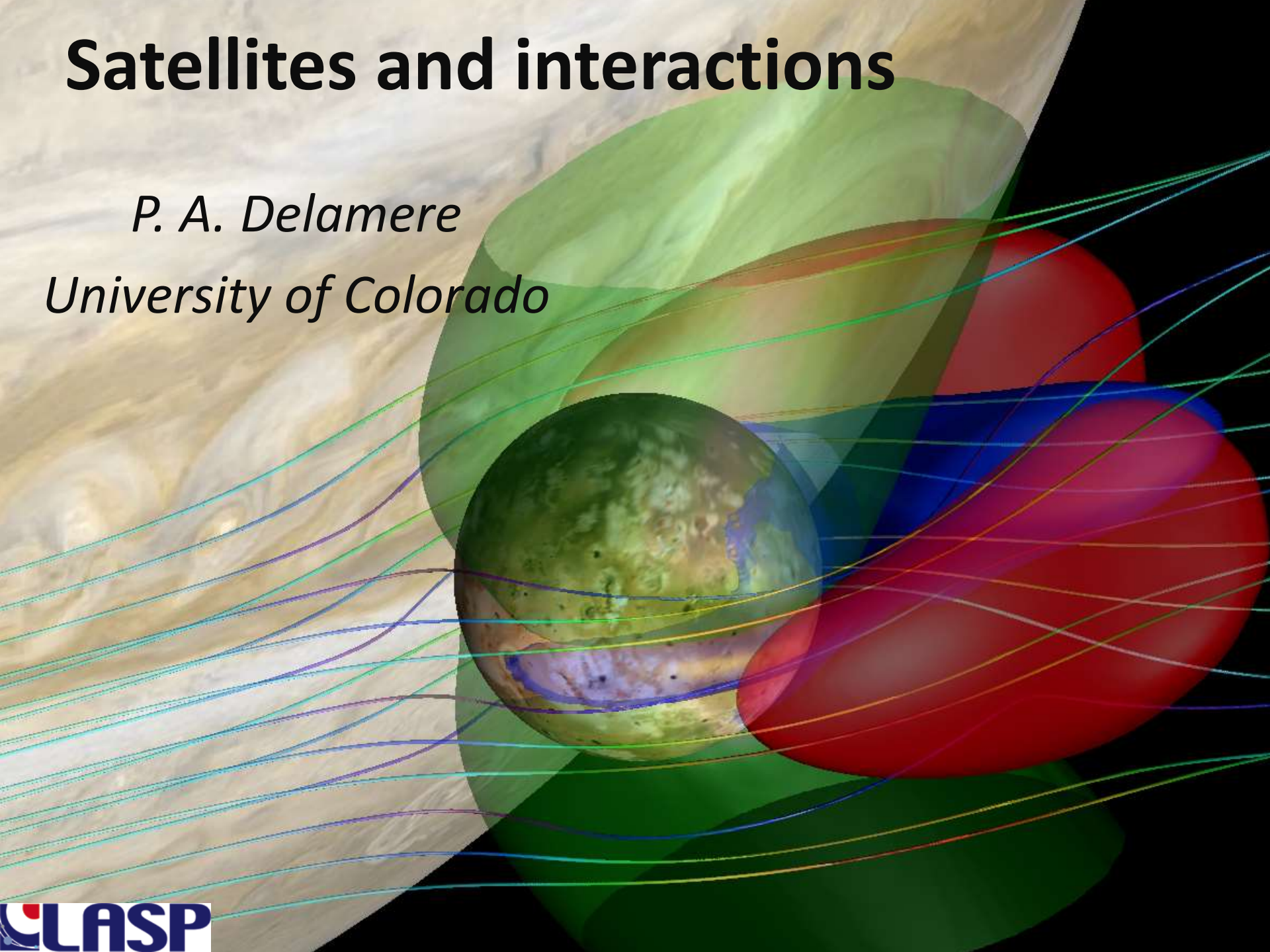
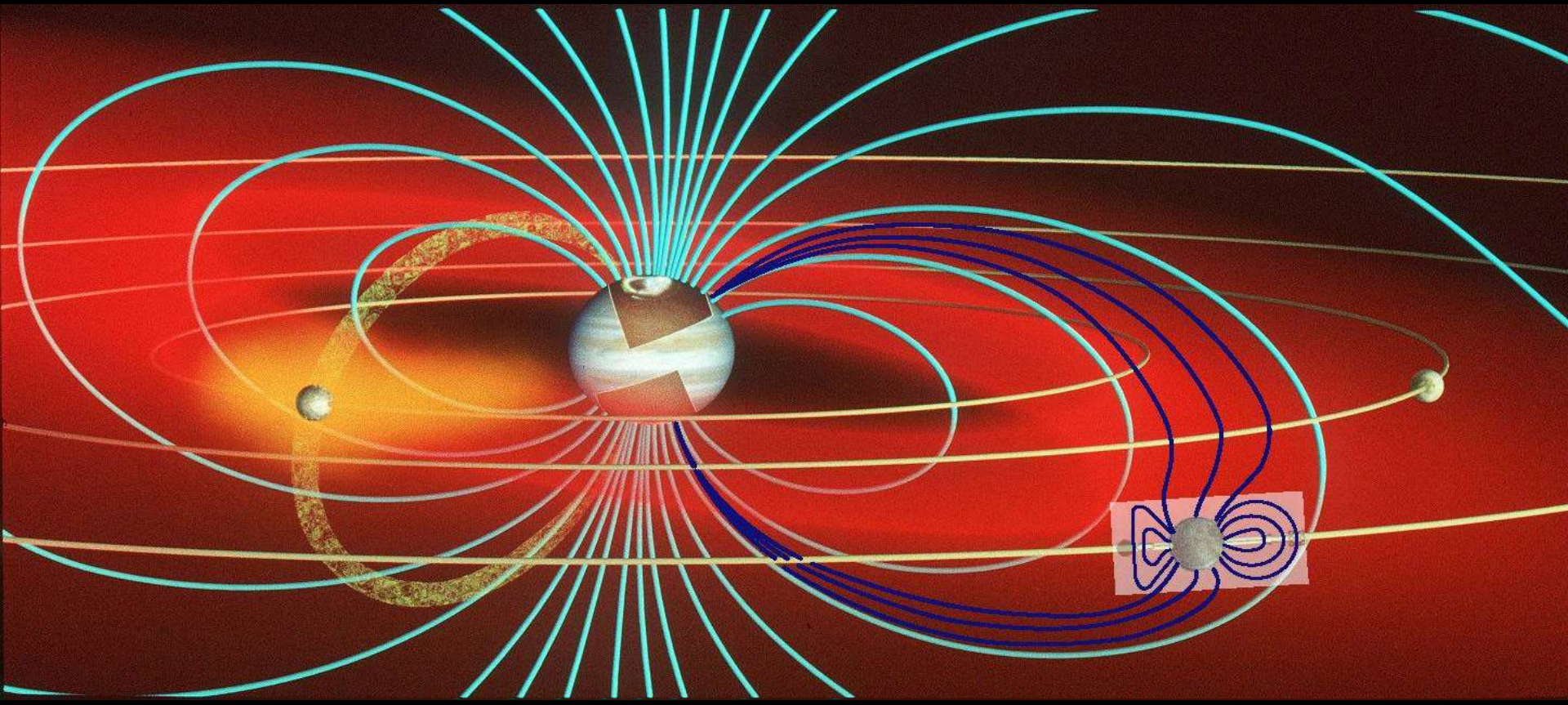
University of Colorado



Types of interactions

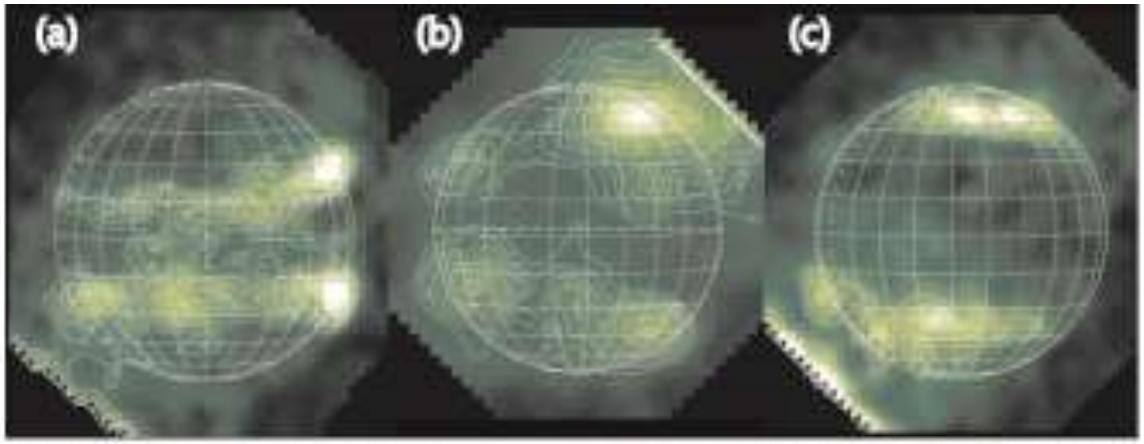
- Magnetized (internally generated magnetic field)
  - Mini-magnetosphere (Ganymede)
- Non-magnetized
  - Inert, no induced magnetic field and no neutral source (e.g. moon).
  - Induced magnetic field due to time-varying external magnetic field (e.g. Europa and Io)
  - Magnetic perturbation due to interaction with neutral source (.e.g. Io, Enceladus)
    - Conductivity due to ionization, charge exchange, collisions
    - Sub-Alfvenic flow (except Titan when outside of Saturn's magnetosphere)

Ganymede: A Magnetosphere within a Magnetosphere

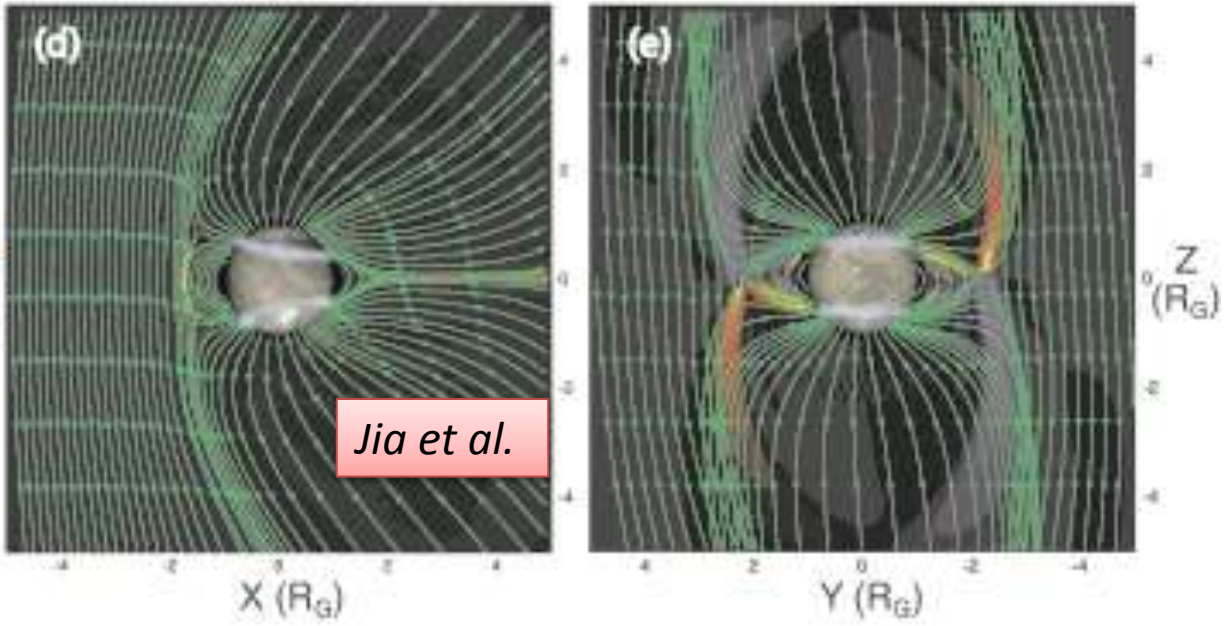


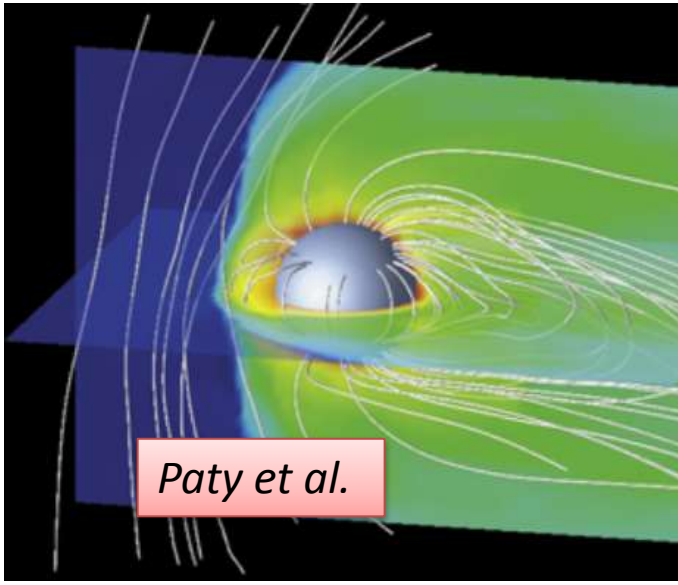
Torrence Johnson

Ganymede



HST observations of oxygen emissions
- *McGrath*





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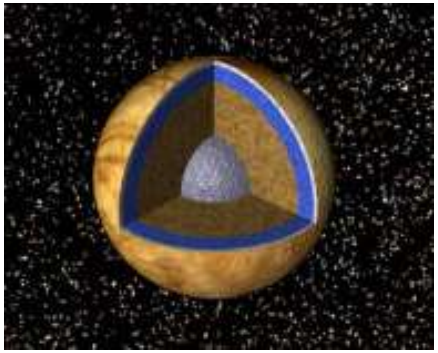
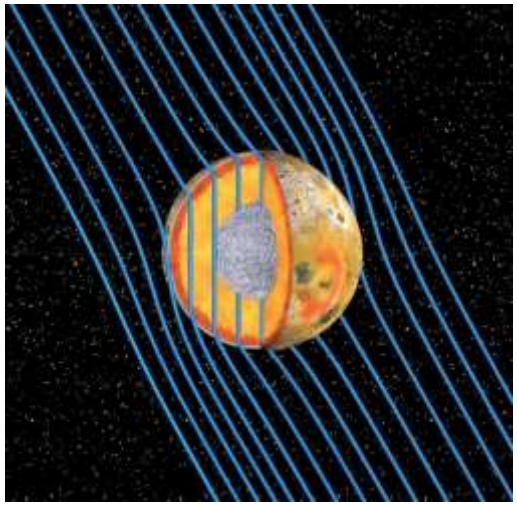
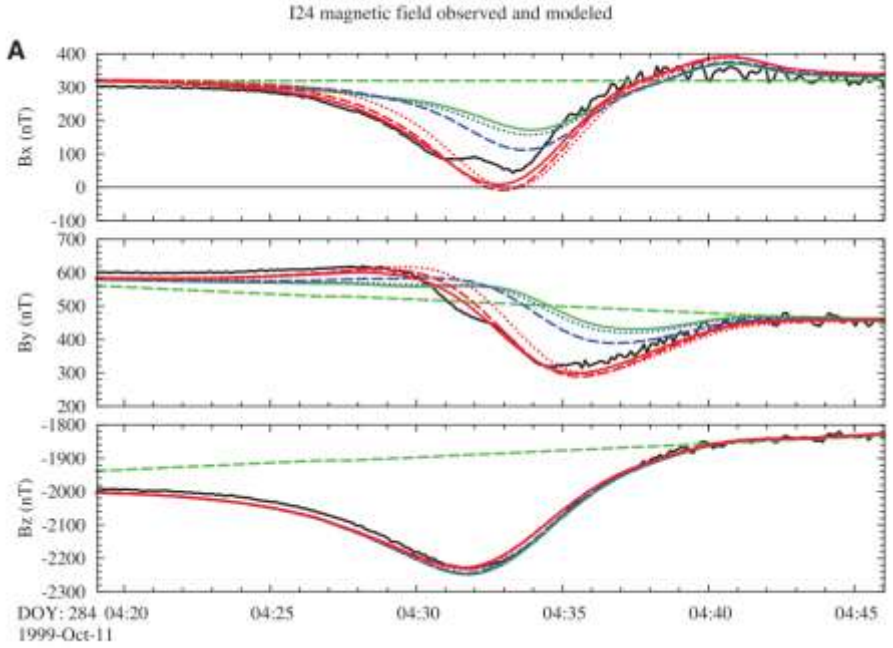
Induced magnetic fields (Europa and Io)

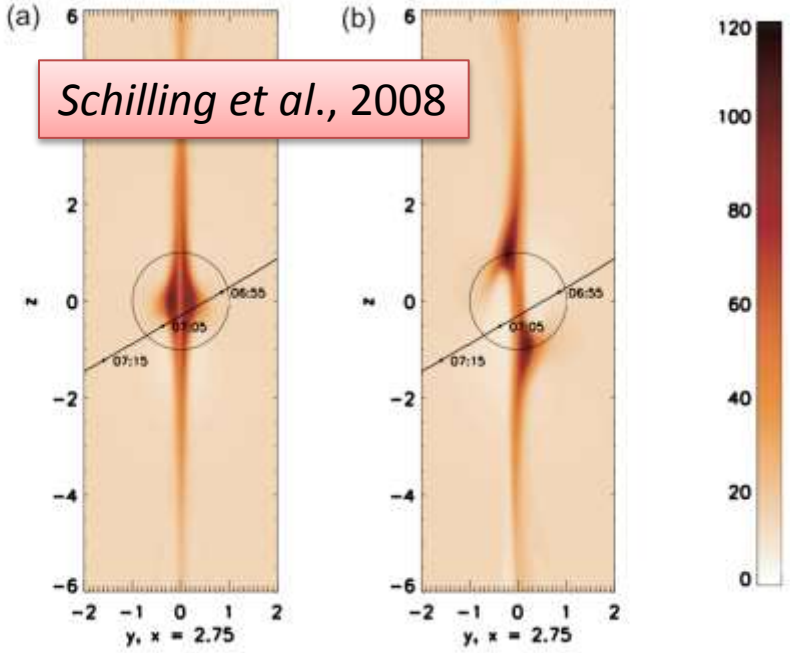




Khurana et al., 2011



Schilling et al., 2008



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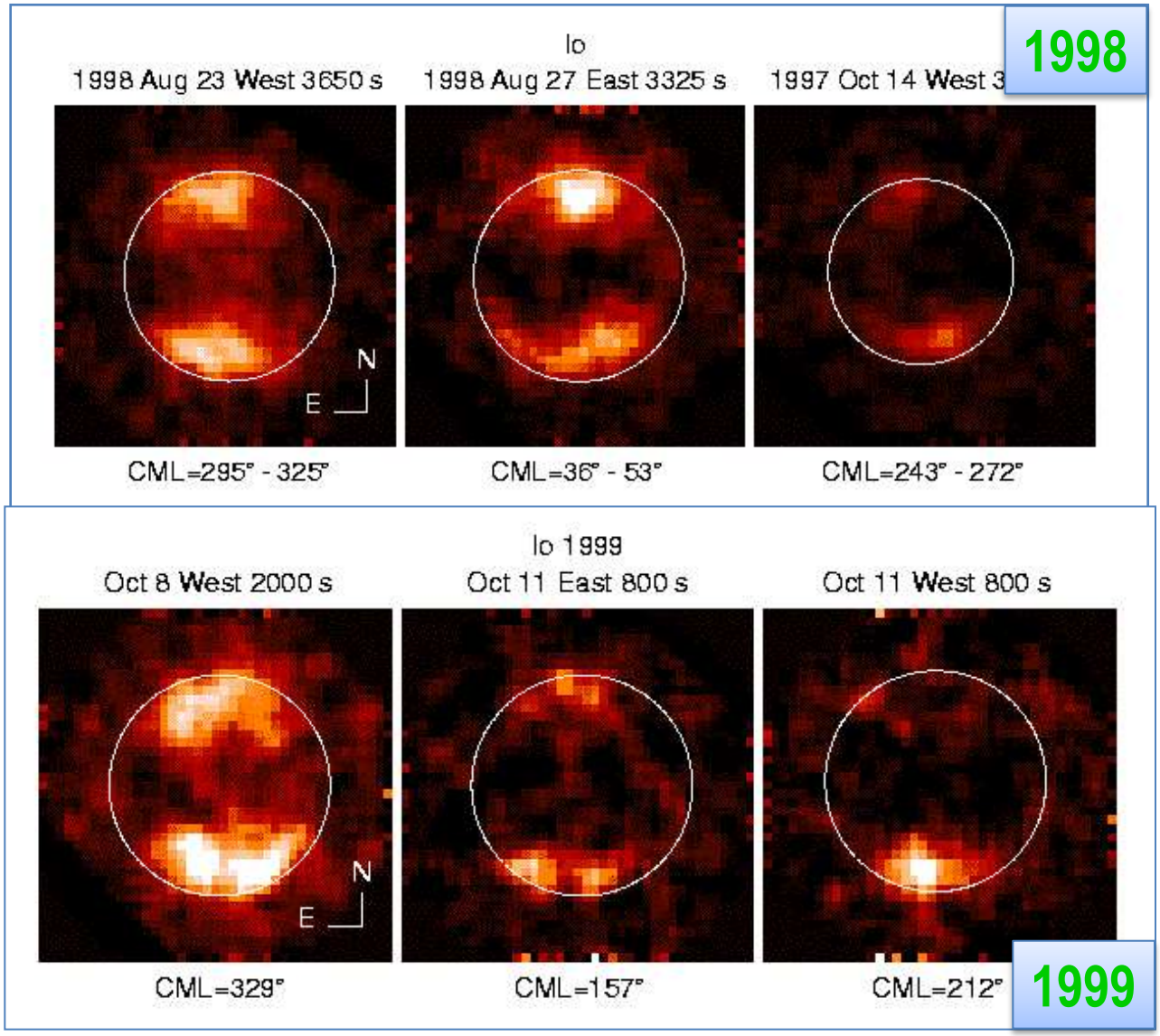
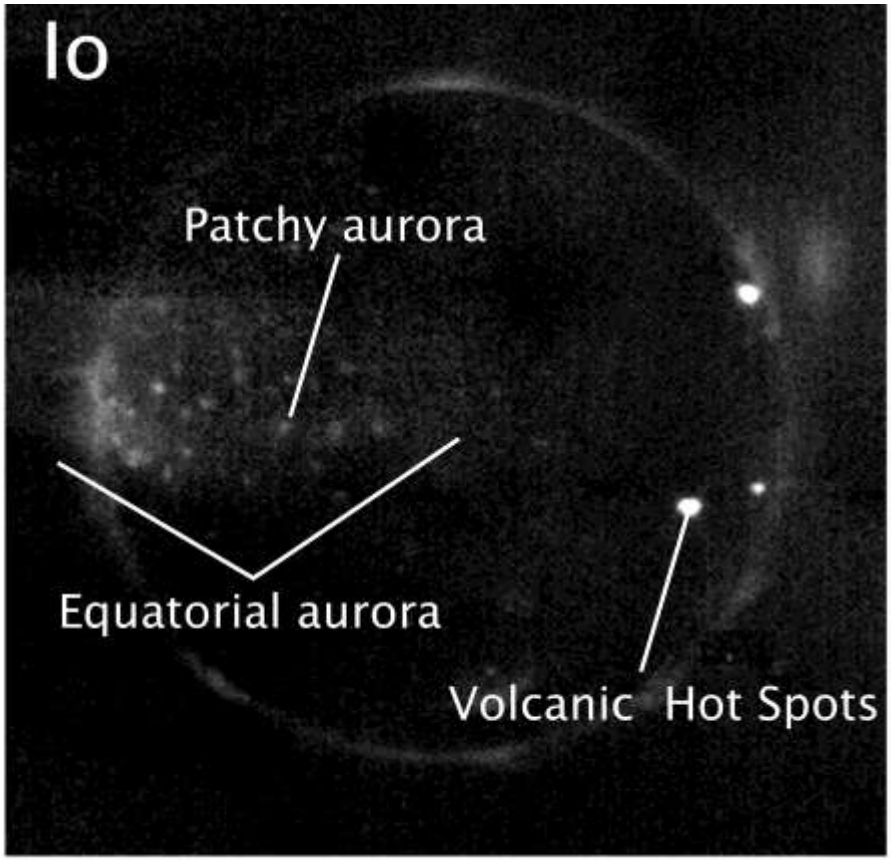
Io's SO_2 Atmosphere

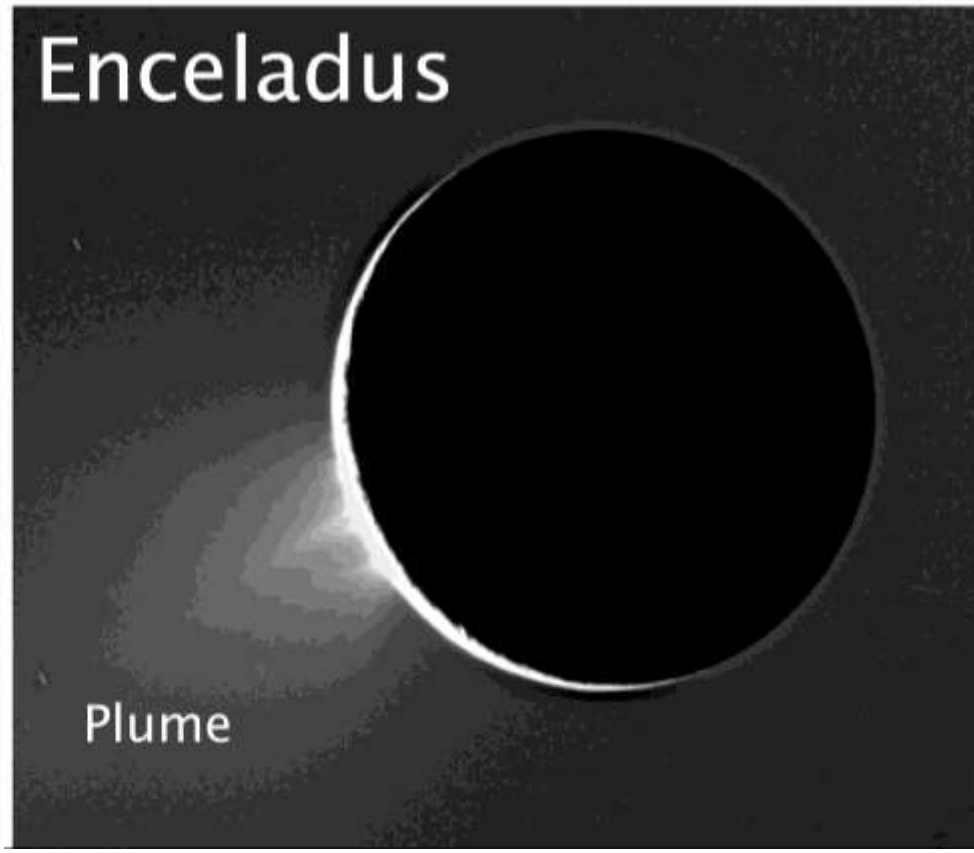
Lyman-α Images →

$\mathcal{N}_{SO_2} \sim 10^{16}\ cm^{-2}$



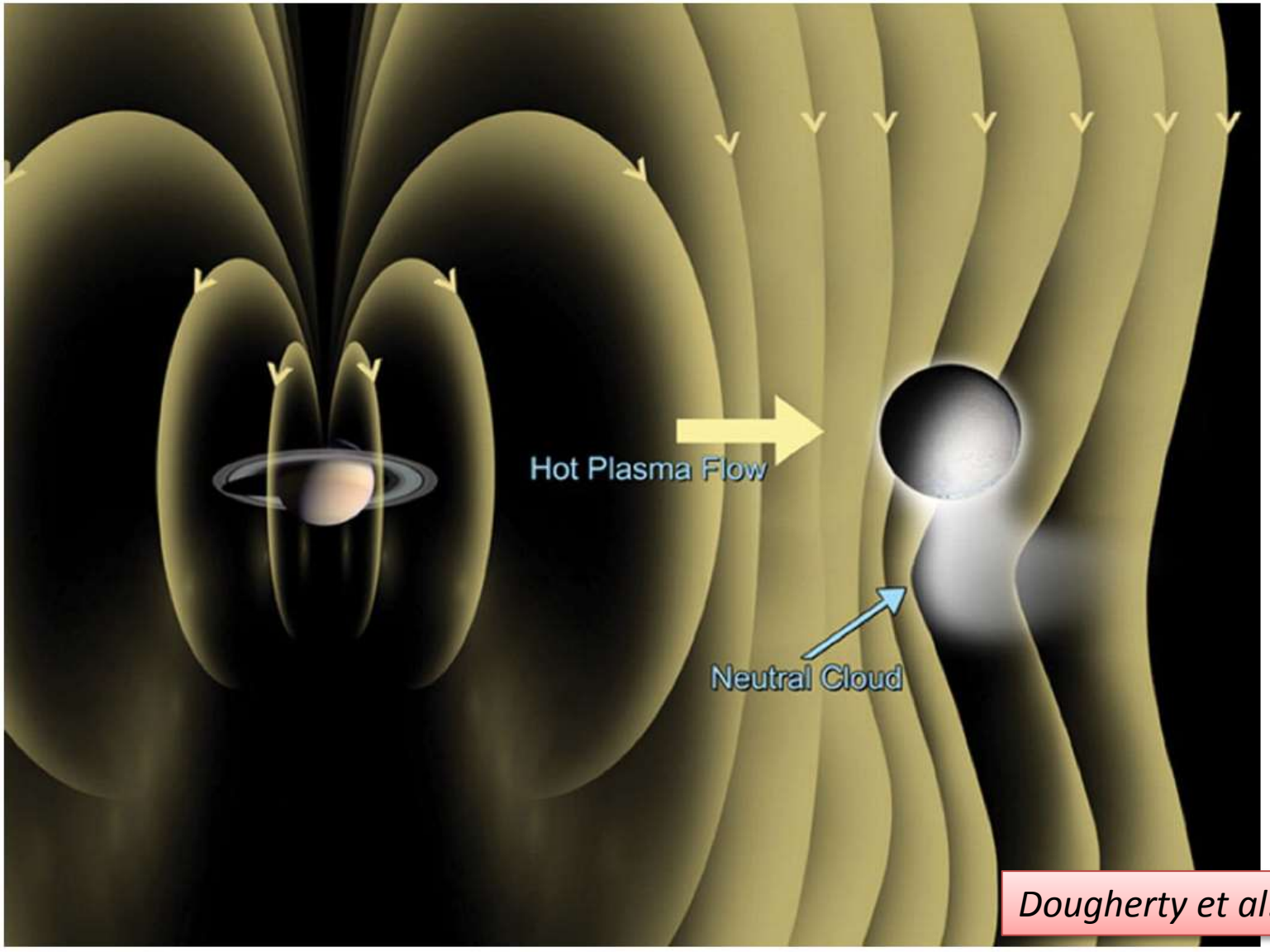
Neutral Sources





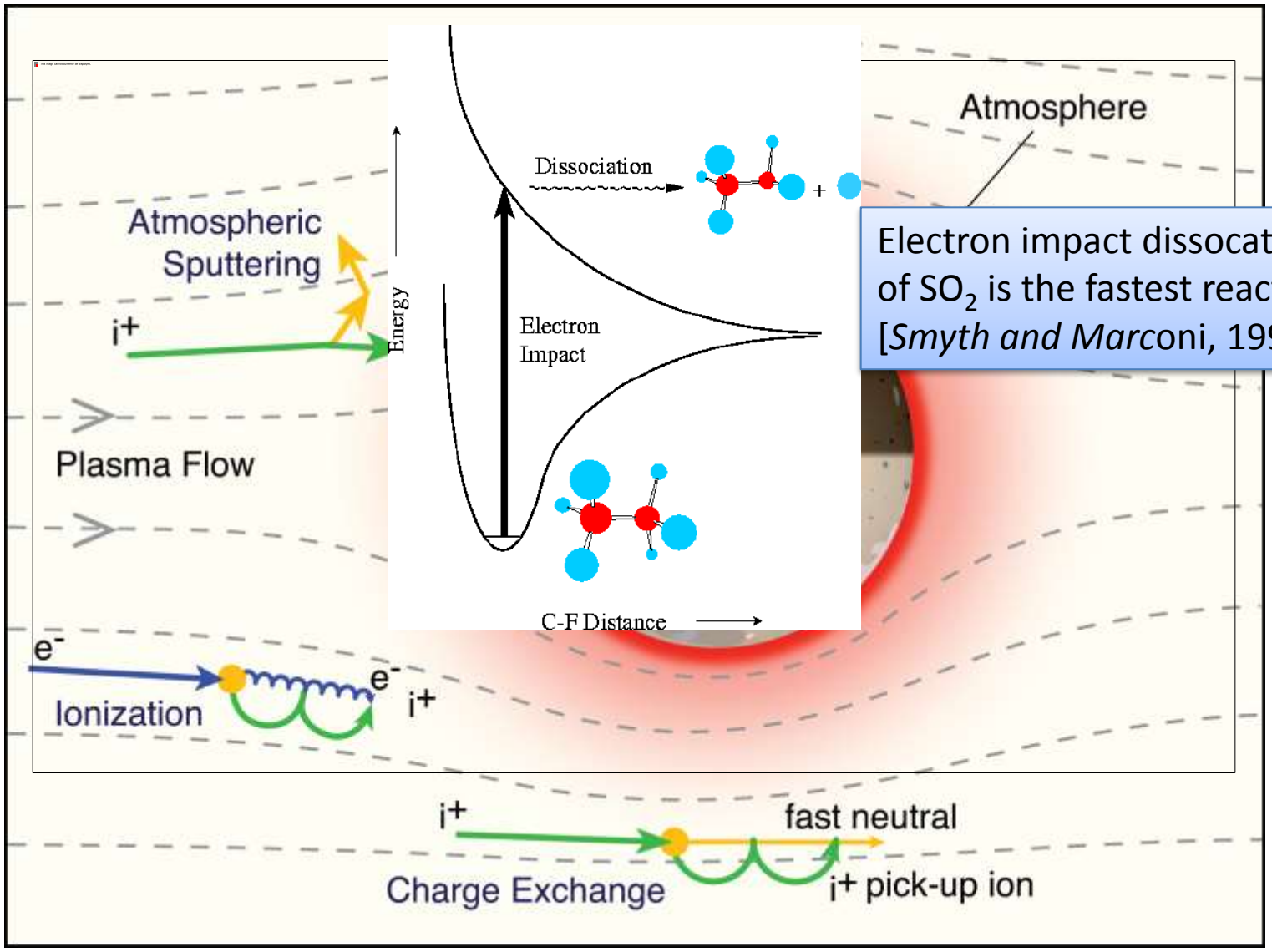
Spencer et al., 2007

Enceladus



Dougherty et al., 2006

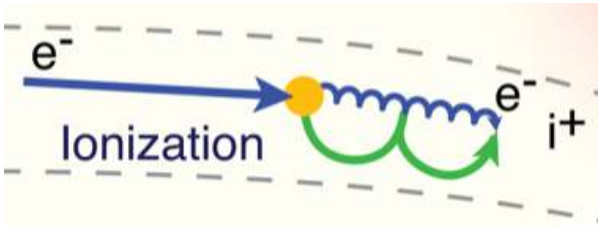
Interaction processes



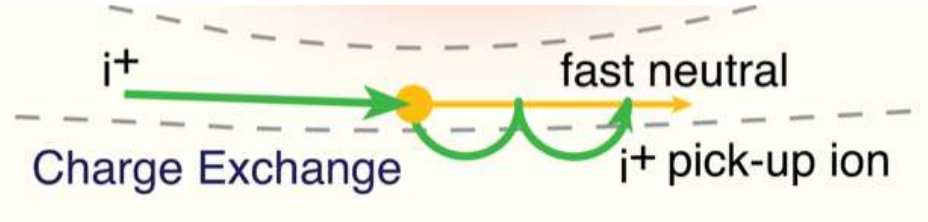
Electron impact dissocation of SO_2 is the fastest reaction [*Smyth and Marc*oni, 1998]

Momentum loading (pickup)

- Ionization

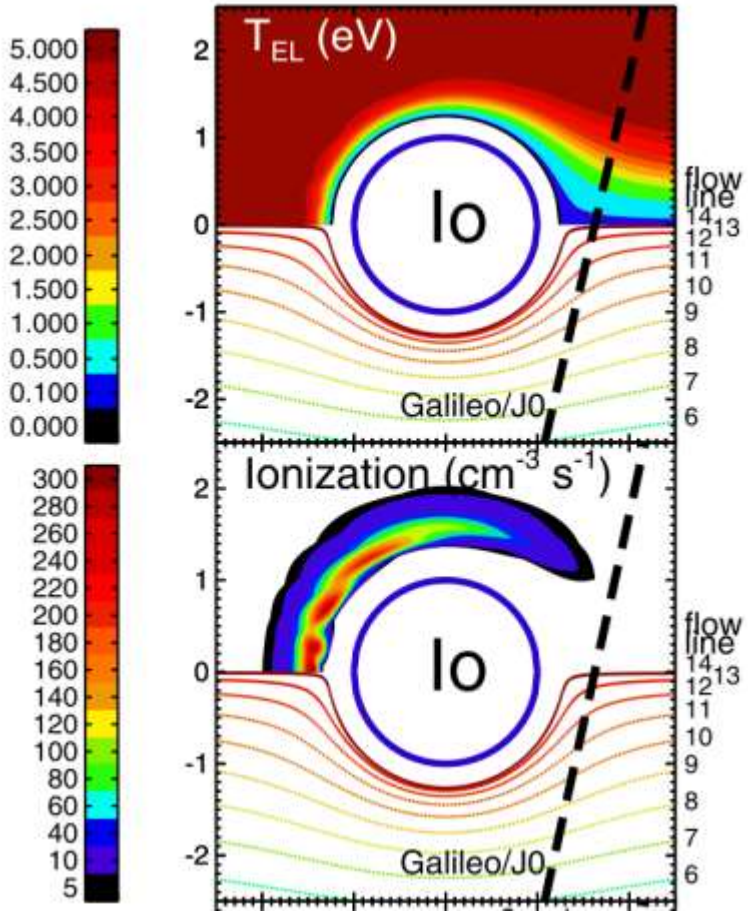


- Charge exchange

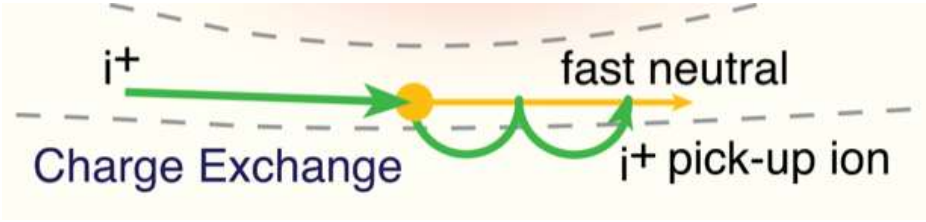


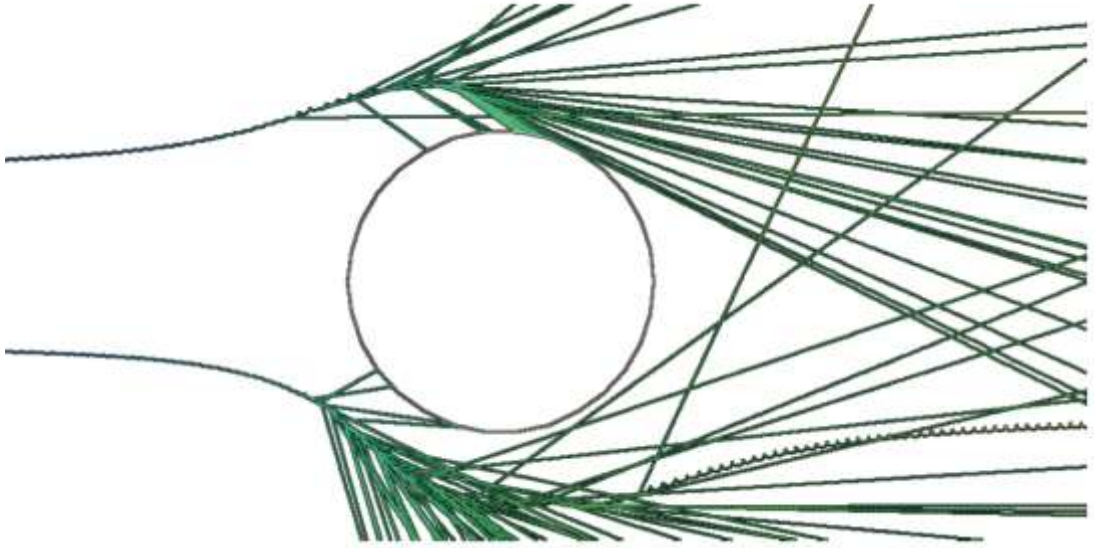
  - New ions stationary in satellite rest frame
  - “Picked-up" by local plasma flow
  - Ionization adds mass
  - Charge exchange does not add mass (usually)
  - Both transfer momentum from ambient plasma to new

Ionization and Charge Exchange



Ionization limited by electron temperature [*Saur et al.*, 1999; *Dols et al.*, 2008]





Charge exchange amplified by "seed" ionization. Results in an avalanche of reactions [*Fleshman et al.*, 2011]

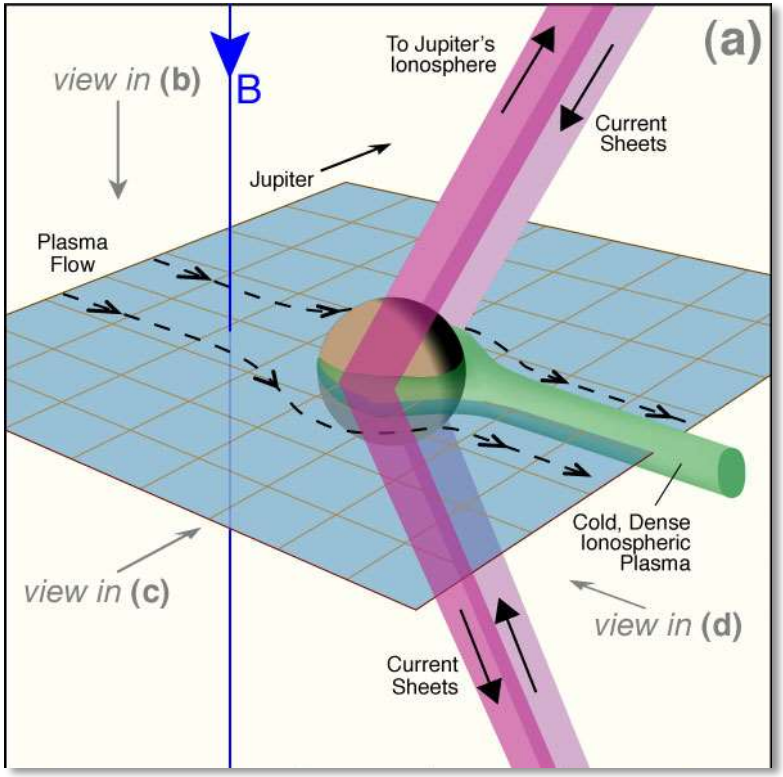
Electrodynamic consequences

- Momentum loading generates currents

$$\dot{M}\mathbf{v} = \int \mathbf{J} \times \mathbf{B} dV$$

$$\mathbf{J} = \frac{\nabla \times \mathbf{B}}{\mu_o}$$

Ionization + charge exchange

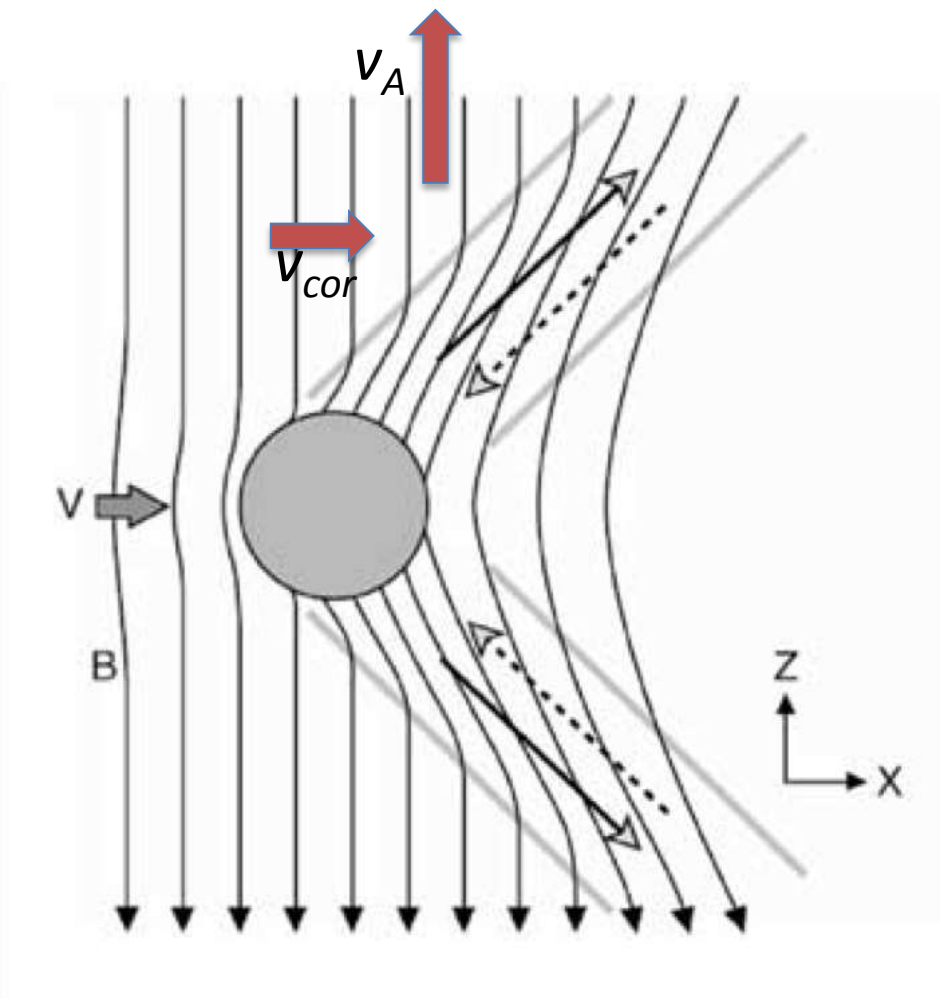


Momentum transfer

- Magnetic field perturbation due to “pick up” (e.g. ionization and charge exchange)

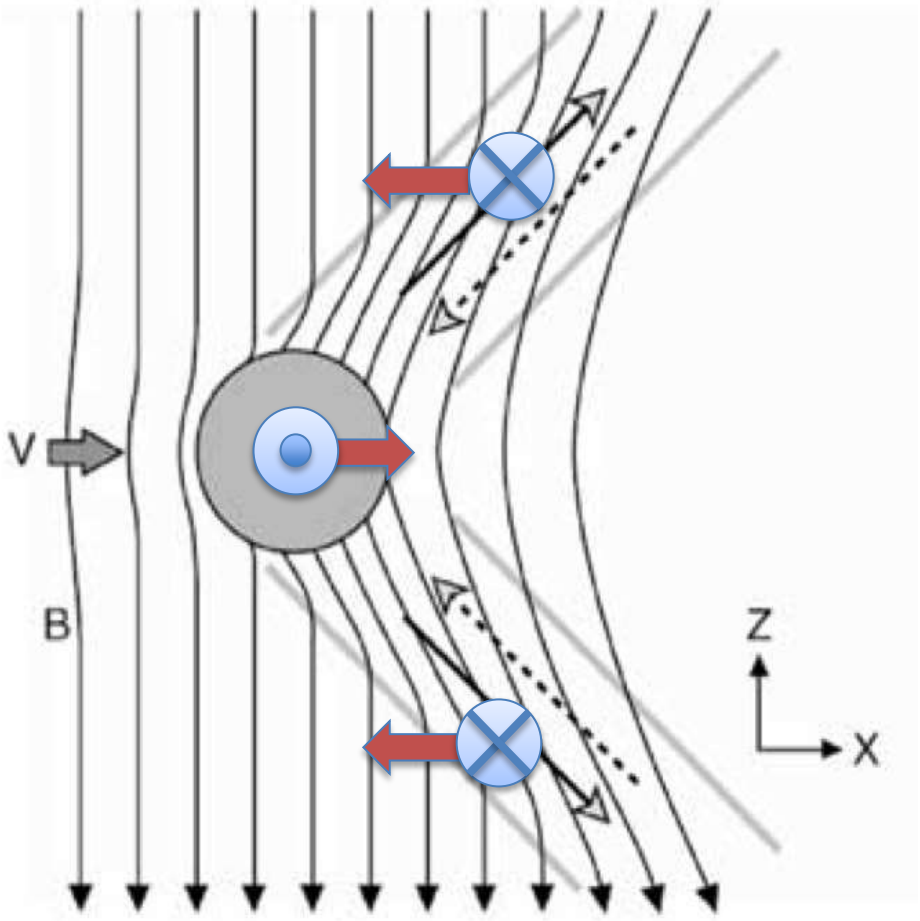
$$\frac{v_{cor}}{v_A} = \frac{\delta B_x}{B_z}$$

- Alfven characteristic determined plasma mass density and magnetic field.



Momentum transfer

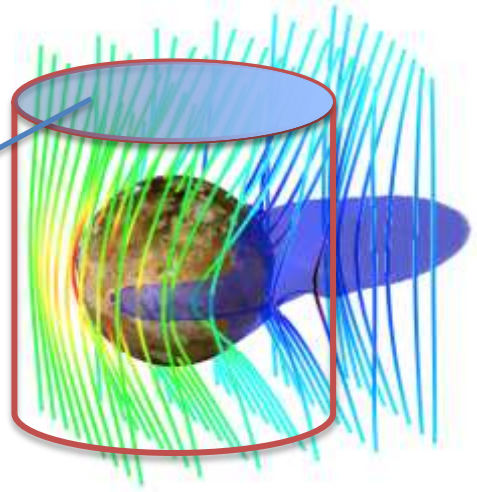
- Alfven wing magnetic field topology results in forces on charged particles via Maxwell stresses.
  - Acceleration of iogenic plasma at the expense of torus plasma.
  - Ultimately, Jupiter's atmospheric is the source of momentum and energy.



Estimate of momentum loading

- Maxwell stress

$$\frac{dp_x}{dt} = 2(\delta B_x)B_z A/\mu_o = (2\rho_{torus} v_A A)v_x$$



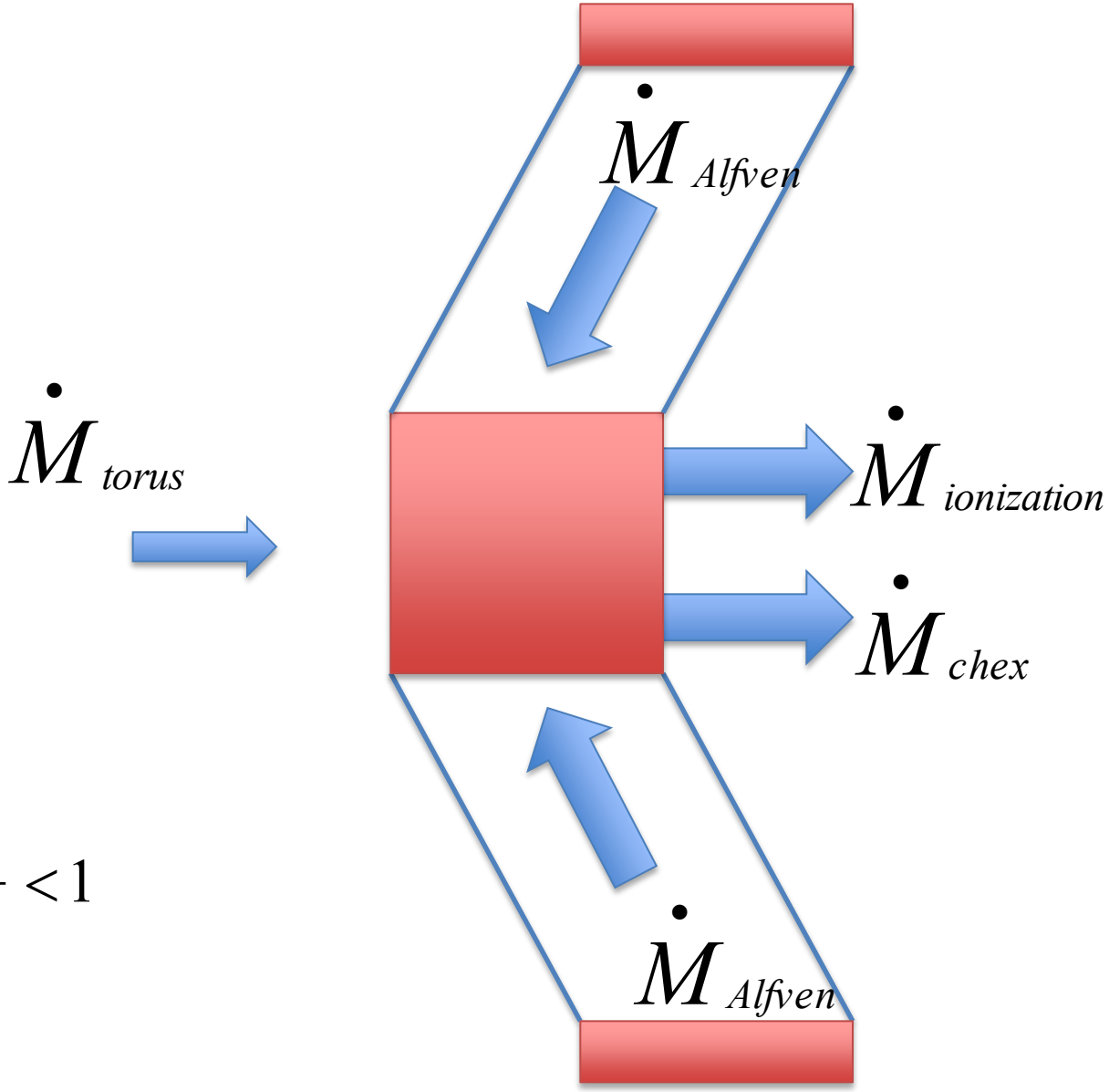
- Plasma mass coupling rate

$$\dot{M}_{Alfven} = 2\rho_{torus} v_A A$$

- Momentum balance requires (ignoring upstream input, chemical processes)

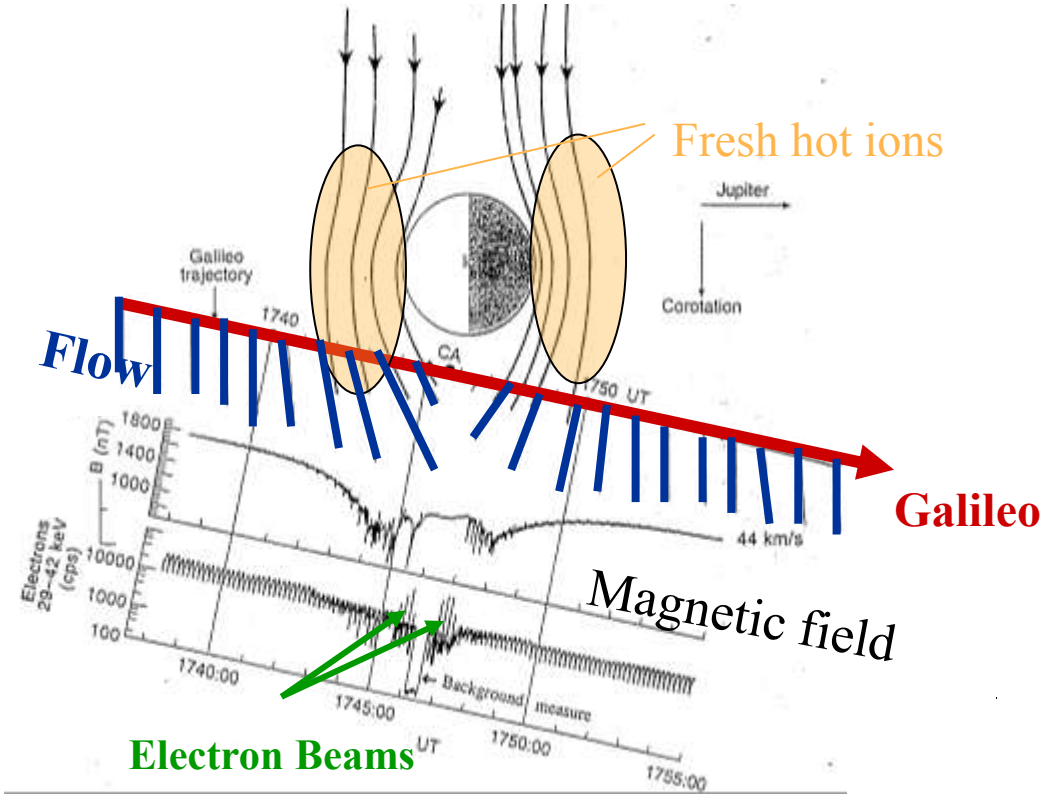
$$\dot{M}_{Alfven} = \dot{M}_{ionization} + \dot{M}_{chex} \approx 300 - 900 \quad \text{kg/s}$$

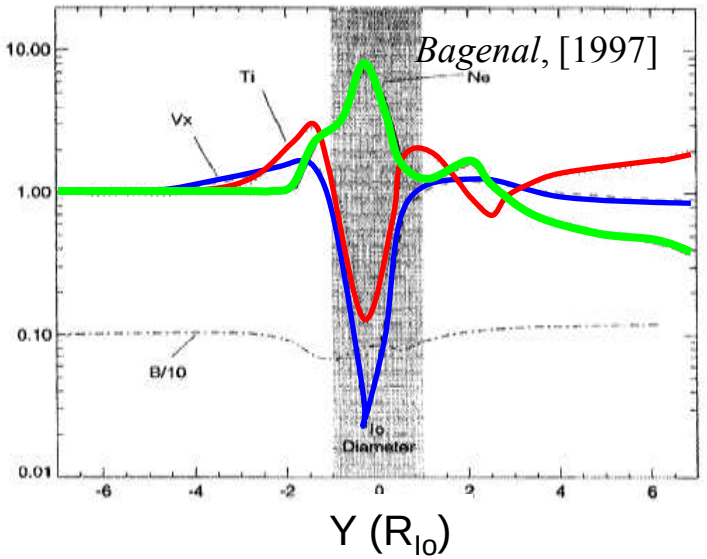
Momentum transfer

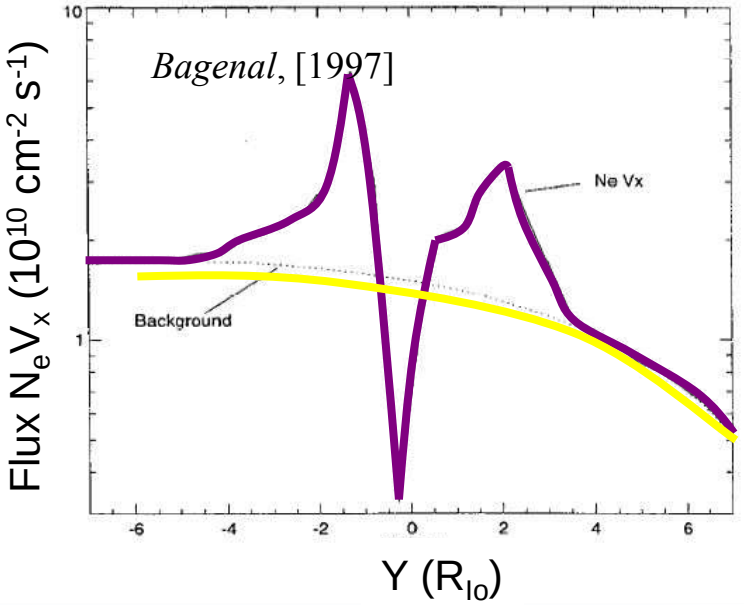


$$\frac{\dot{M}_{torus}}{\dot{M}_{Alfven}} < 1$$

Galileo Io Flyby - 1995

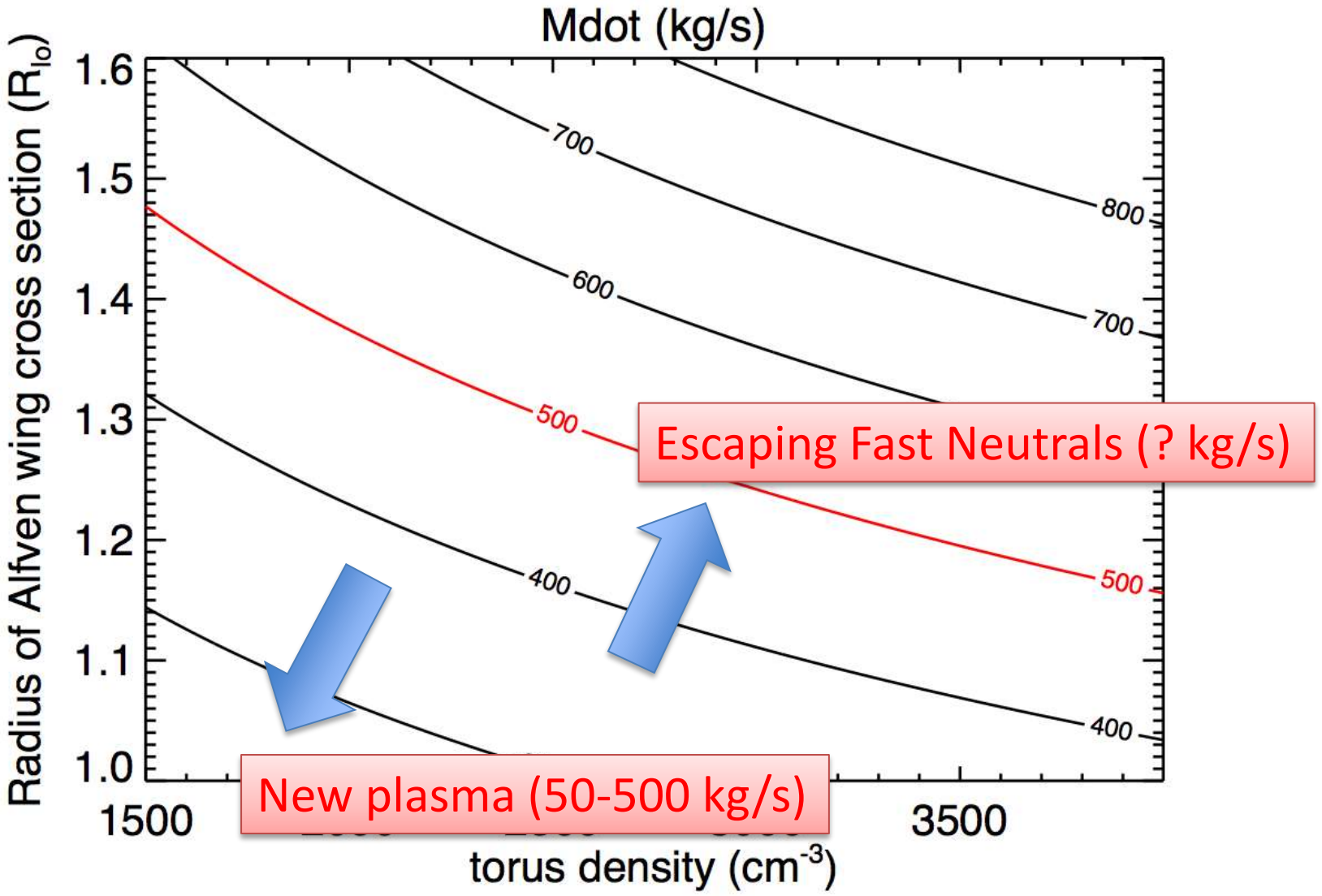




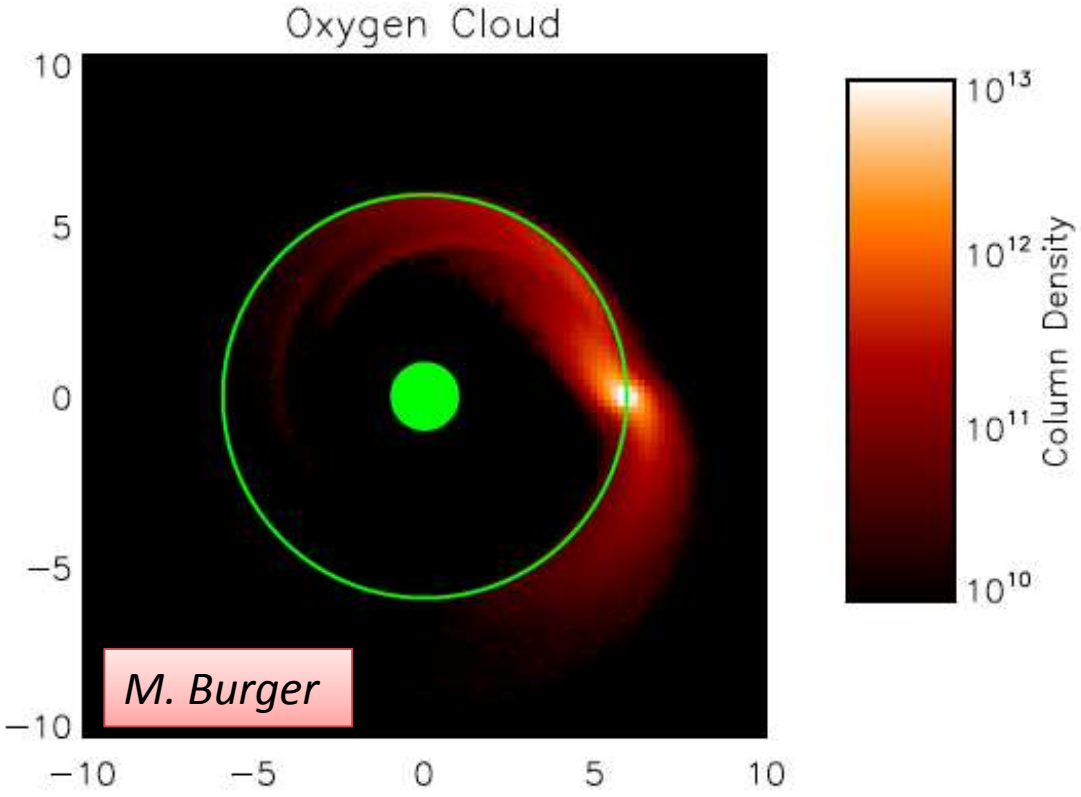


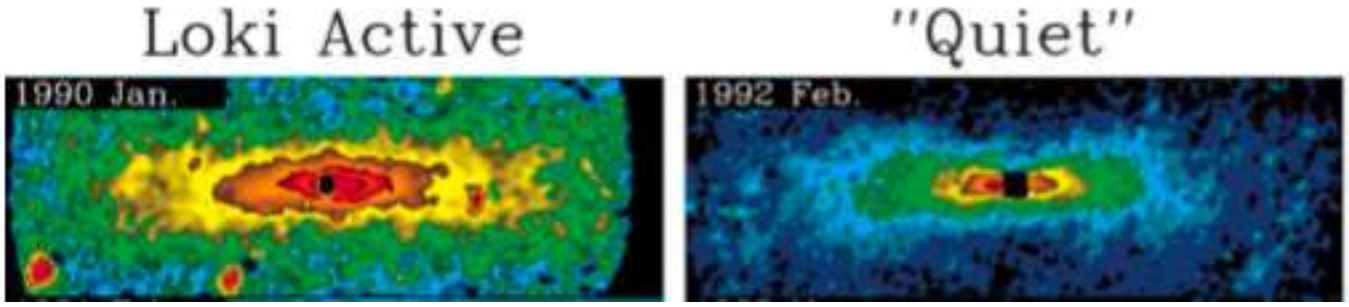
- Is the local interaction ionosphere-like (elastic collision dominated), or comet-like (mass loading dominated)?
- *Bagenal,* [1997]: 200-500 (kg/s)
- *Saur et al.*, [2003]: 50-200 (kg/s)

Mass transfer rate (Alfven wing)



Io's (partial) neutral torus





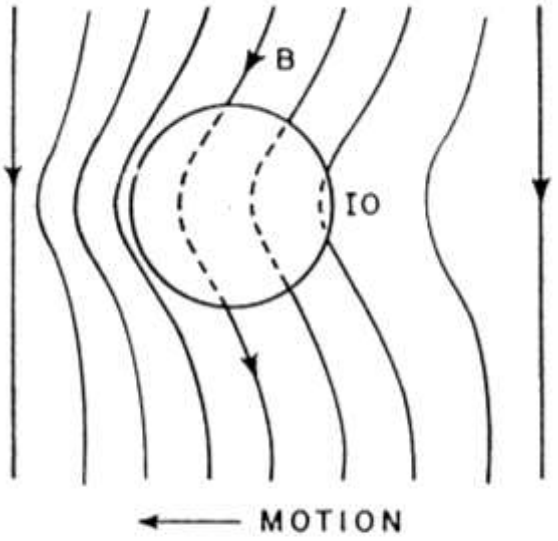
Energetics

$$I = JA = J\pi R_{Io}^2 = 3\times10^6(\mathrm{A})$$

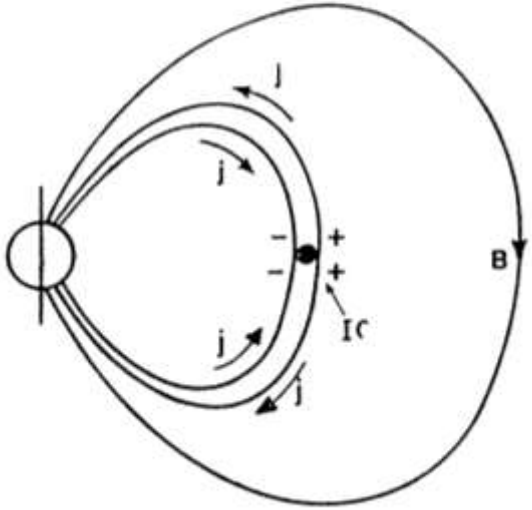
$$V \approx vB(2R_{Io}) = 400(\mathrm{kV})$$

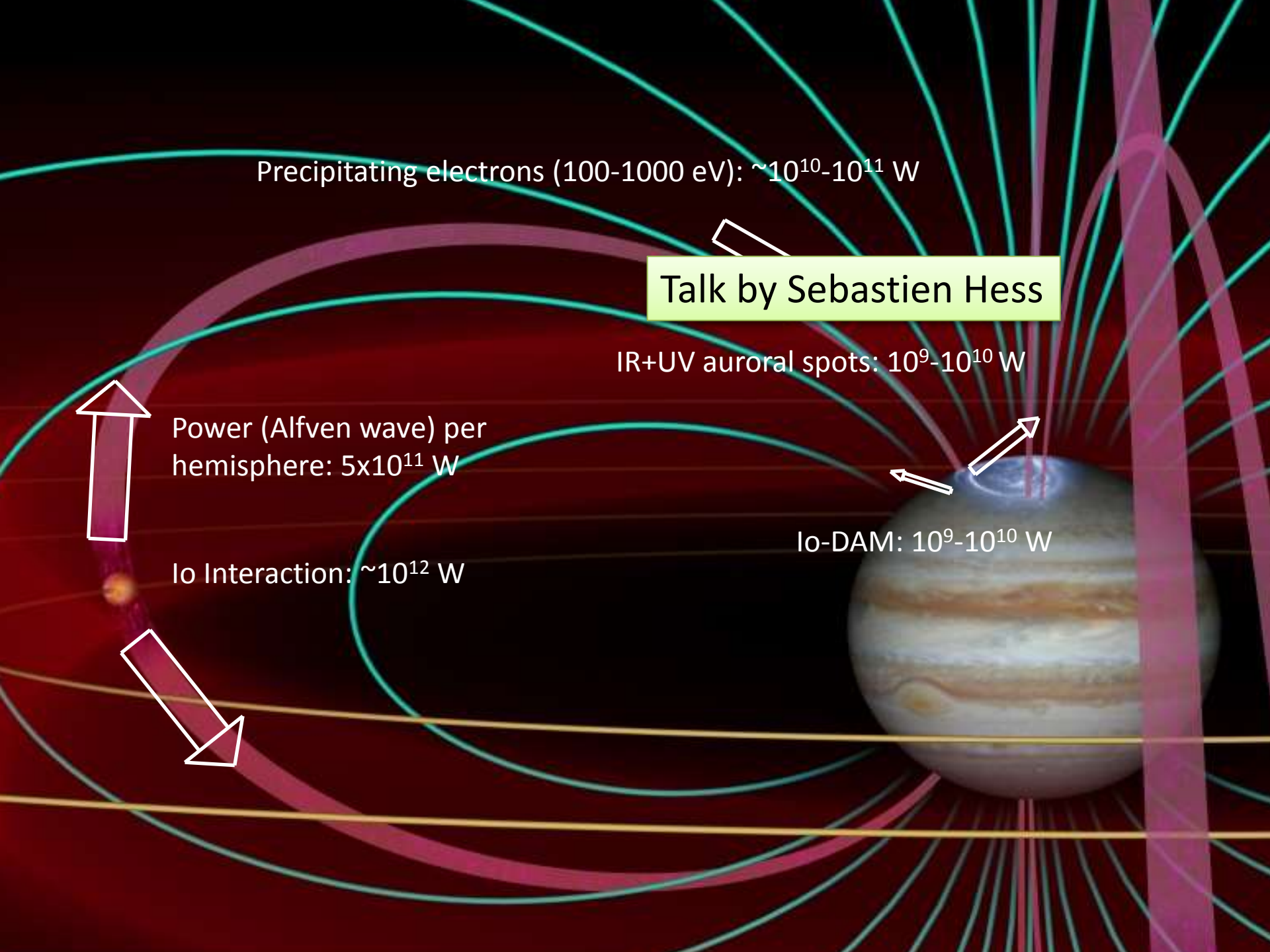
$$P = VI = 1.2\times10^{12}(\mathrm{W})$$

Marshall & Libby (1967)



Piddington & Drake (1968)



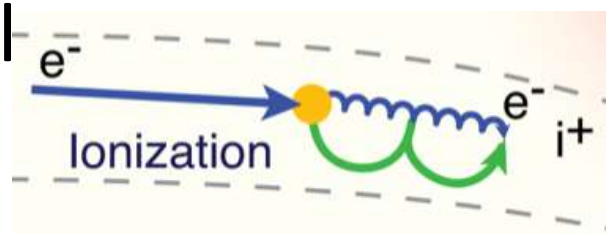

Precipitating electrons (100-1000 eV): ~10^{10}-10^{11} W
Talk by Sebastien Hess
IR+UV auroral spots: 10^{9}-10^{10} W
Power (Alfven wave) per hemisphere: 5x10^{11} W
Io-DAM: 10^{9}-10^{10} W
Io Interaction: ~10^{12} W

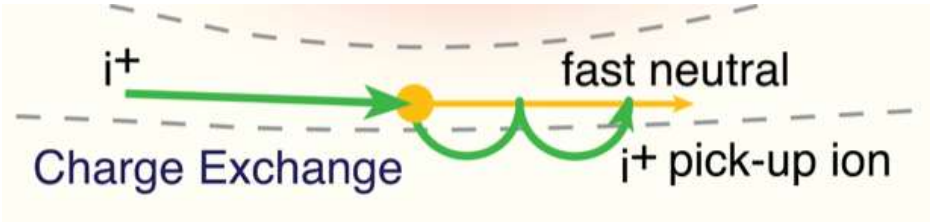
Pickup Energetics

- Pickup involves two parts:
  - Acceleration to corotation speed
  - Heating at local flow speed (on time scale of gyromotion)

$$P = \frac{\dot{M}}{\langle m \rangle}\left[\langle T \rangle + \langle m \rangle v^2/2\right] \approx \frac{(200\ \text{kg/s})}{22 m_p}(2(360)\ \text{eV}) = 7\times 10^{11}(\text{W})$$

- Much of the ≈1 TW of power is necessary for the pickup of roughly 200 kg/s into corotational fl





Outstanding issues

- How does the thermal electron temperature and hot electron beams affect the interaction?
  - Enceladus, T_e = 2 eV (little interaction)
  - Io, T_e = 5 eV (strong interaction)
- What are the important processes that shape the extended coronae/neutral clouds?
  - Electron impact dissociation vs. charge exchange
- What is the feedback between the neutral source and ambient plasma conditions (i.e. plasma torus)?
  - Enceladus' variable plume source
  - Io's volcanic activity
- Under what circumstances are energetic particles (keV-MeV) important (Europa, Ganymede, Callisto)?