Saturn's other ring current

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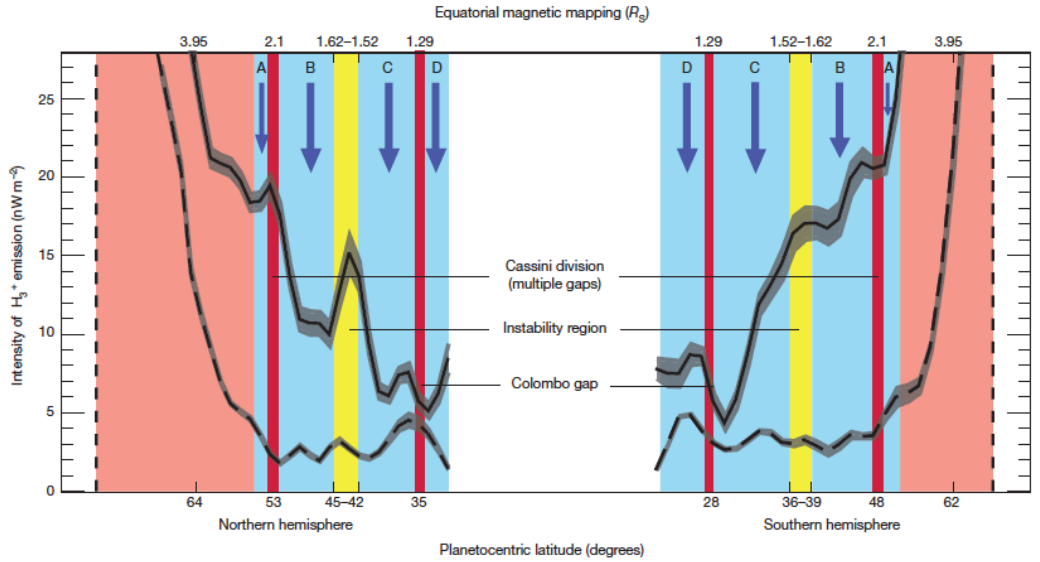
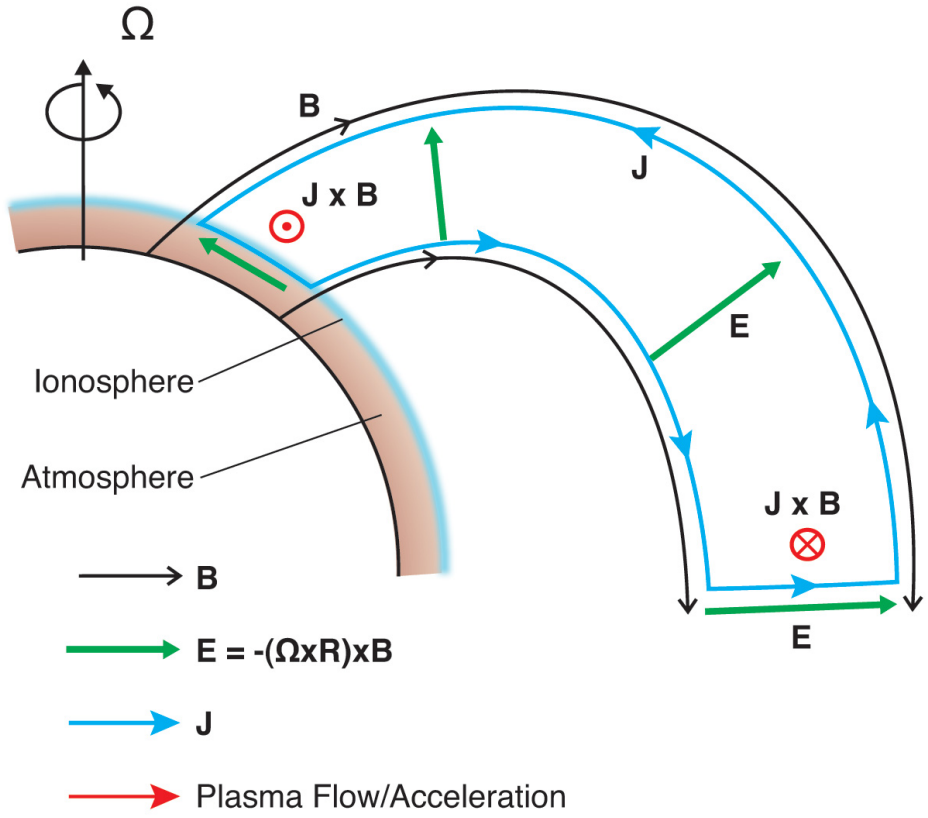
Ring rain or joule heating?

- O'Donoghue et al., 2013 reported structure in H_3^+ emission on magnetic field lines connected to Saturn's main rings
- Interpreted as "ring rain"
  - Precipitation of H_2O or O-bearing species
  - Alters ionospheric chemistry and H_3^+ abundance
- Could also be a result of heating
  - H_3^+ line is thermal emission
  - Could joule heating
- Required input power is unclear
  - Output reported at one H_3^+ line versus total input power



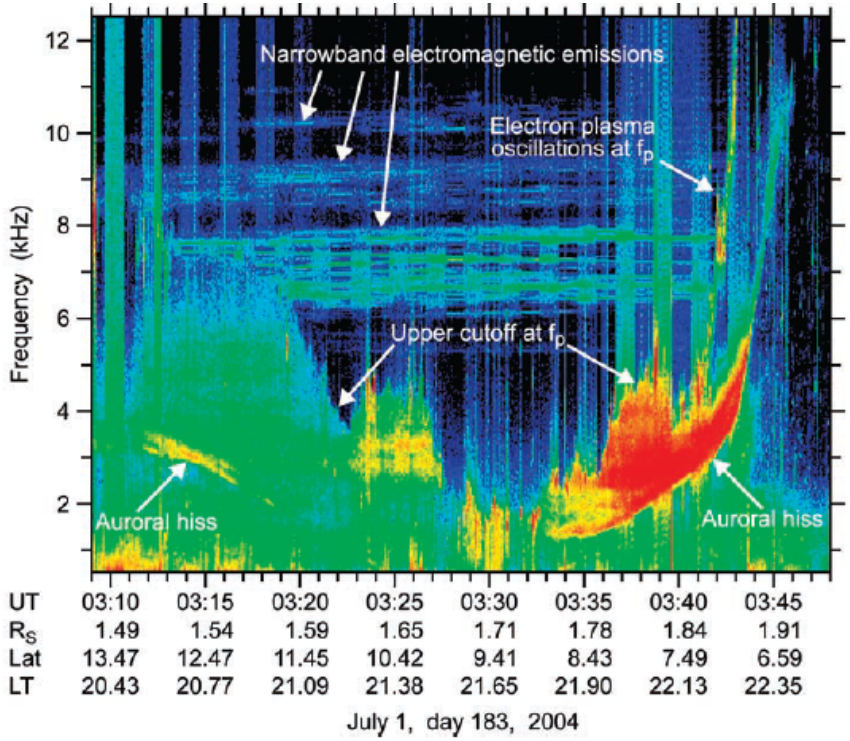
Ring-ionosphere coupling

- Ring ionosphere is collisionally coupled to the rings
- Saturn's ionosphere is collisionally coupled to the neutral atmospehre
  - Saturn's rotation rate
- Differential motion causes an induced E = - v x B electric field
- Field drives currents across the rings, along magnetic field lines and closing in the Saturn's ionosphere



Evidence of field-aligned currents

- Plasma wave observations during Cassini orbital insertion [Gurnett et al., 2005; Xin et al., 2006]
  - Auroral hiss generated by field-aligned electron beams
  - Minimum frequency seen on the same field line as the source electrons
  - Near synchronous orbit
  - Interpreted as evidence of a ring-ionosphere current system

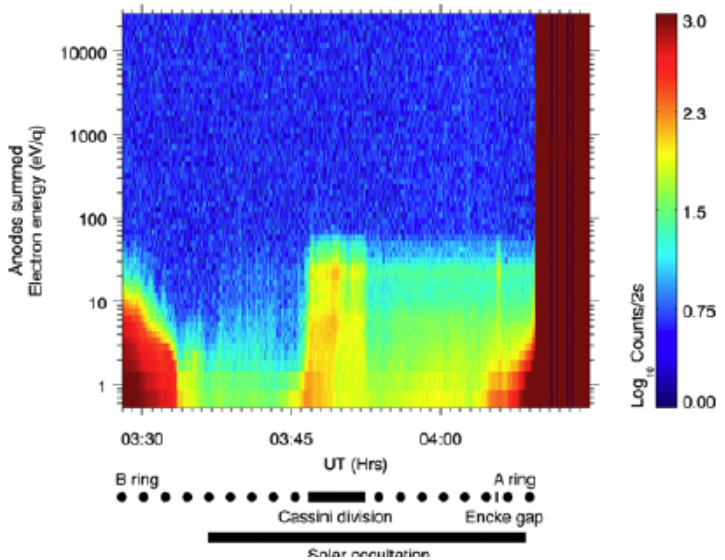


- Electron energy and field-aligned potential must be relatively small (<<1 keV)
  - Otherwise electrons would produce mid-latitude aurora

What determines the resulting currents?

- Collisional coupling between ring ionosphere and rings (guess)
  - ion column density * ion mass / ½ orbital period (?)
  - 10^{14} m^{-2} * 32 AMU / $1.8x10^{4}$ s = $3x10^{-16}$ kg-m^{-2}-s^{-1}
- Collisional coupling between Saturn's ionosphere and neutrals
  - Total Electron Content * ion mass * ion-neutral collision at the peak
  - $2x10^{16}$ m^{-2} * 3 AMU * 10 s^{-1} = 10^{-9} kg-m^{-2}-s^{-1} [Moore et al., 2010]
- Height-integrated conductance of Saturn's ionosphere
  - 1-10 S (assume 3 S) [Moore et al., 2010]
- Field-aligned potential drops
  - Observed to be small
  - Field-aligned drops would accelerate electrons and produce aurora, which is not observed

Data and models of the ring ionosphere

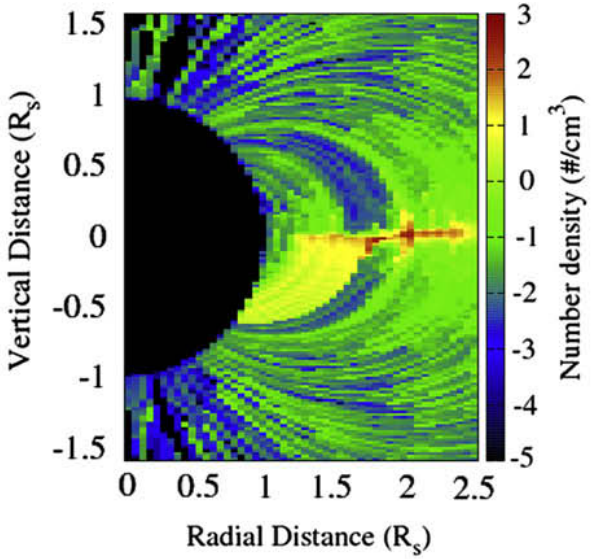


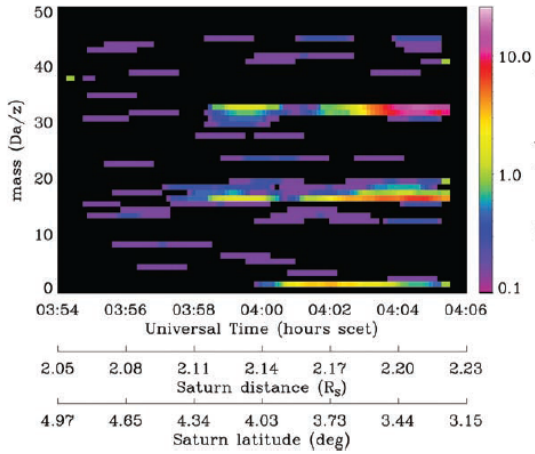
Tseng et al. 2009

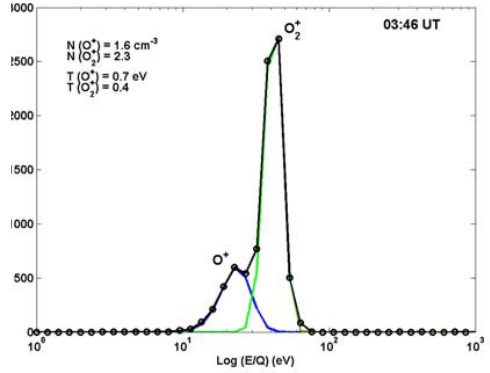
Waite et al.2005

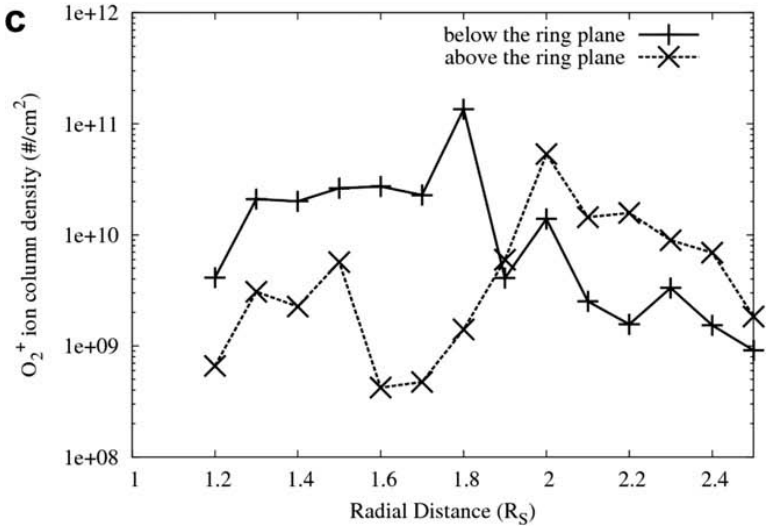
Coates et al., 2005

Tokar et al. 2005





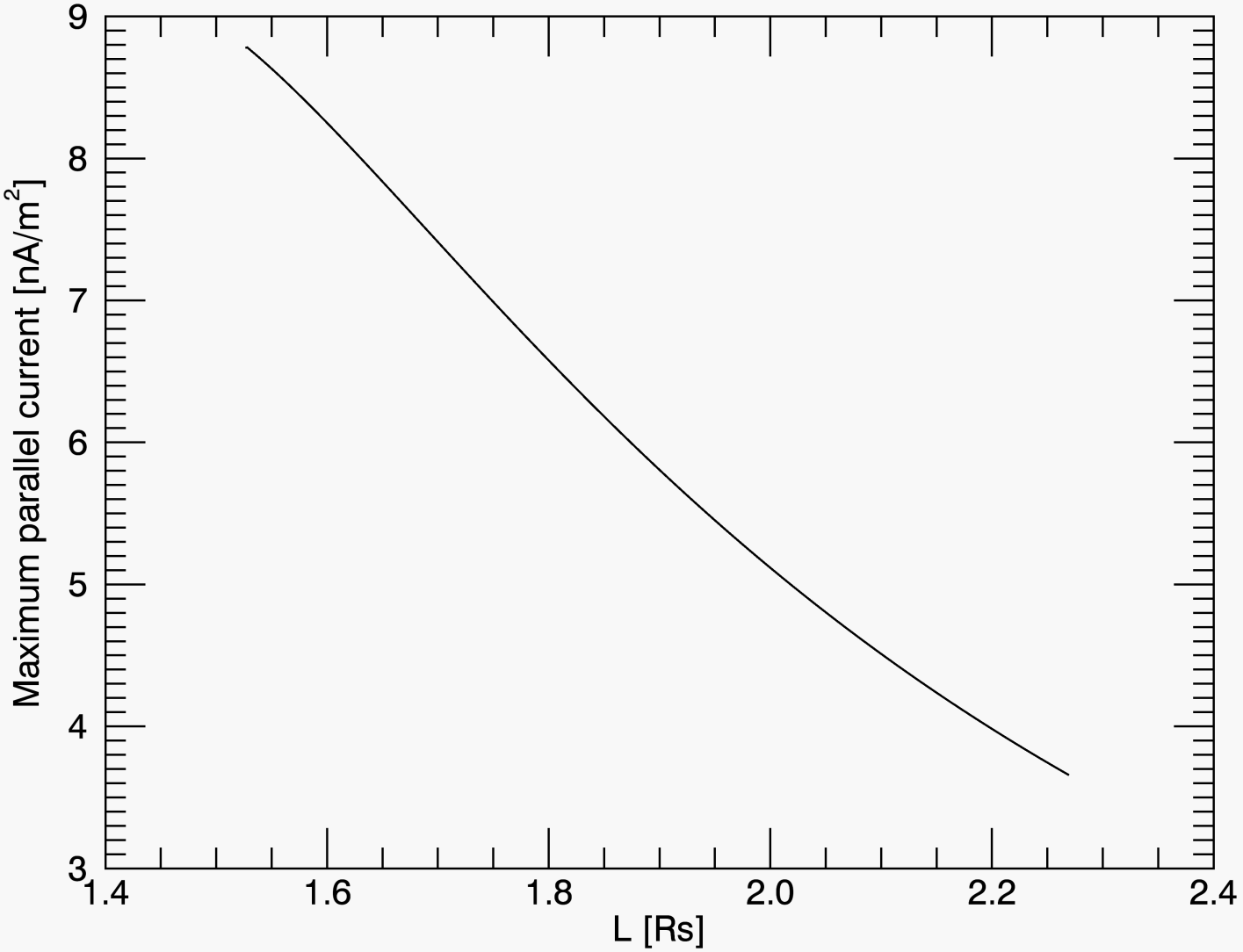




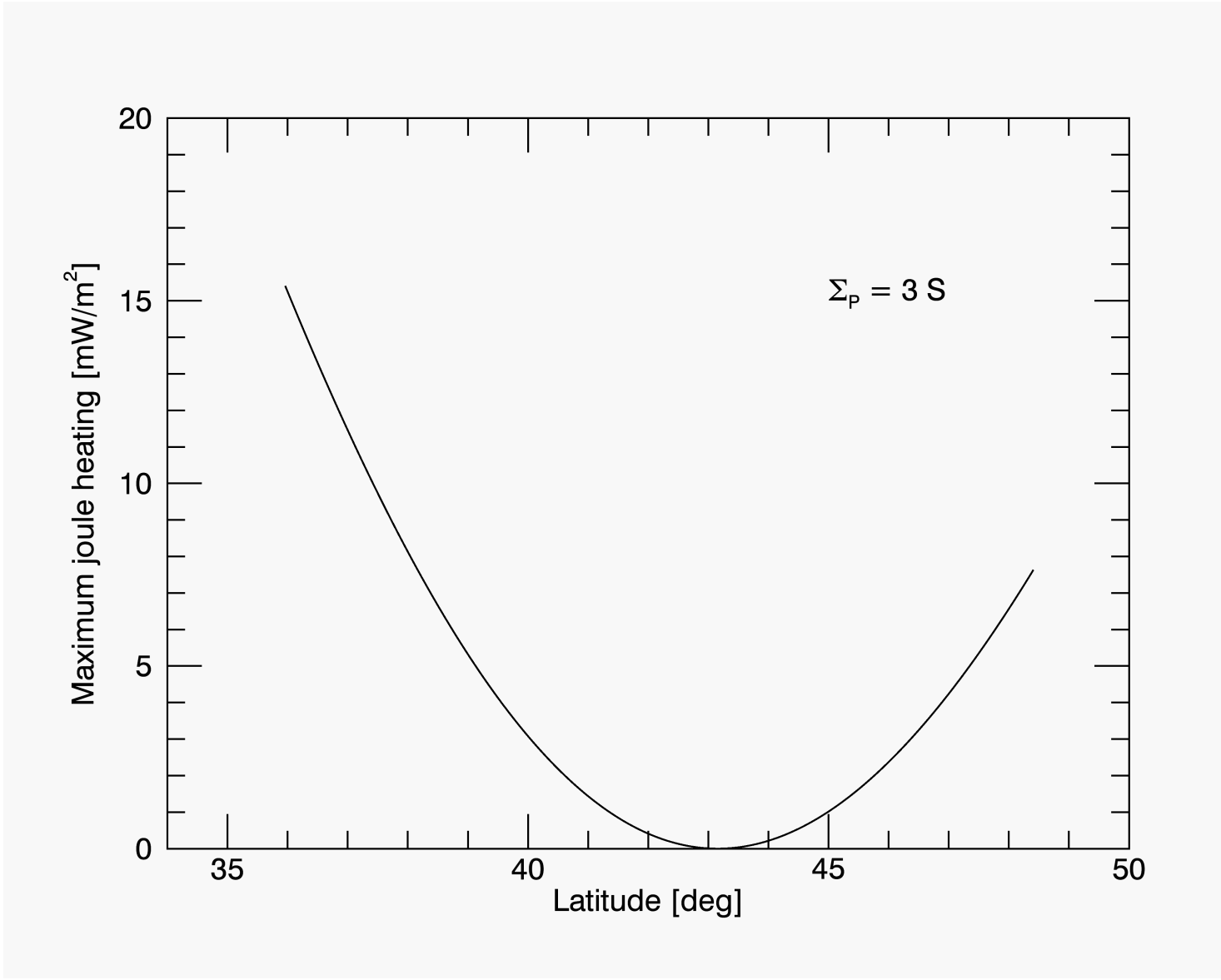
Upper limit on ring current

- Assume ionosphere-thermosphere coupling is strong
  - Ionosphere does not slip relative to neutrals
  - $v_{ionosphere} = \Omega\ r \cos \lambda$
- Assume ring ionosphere-ring coupling is strong
  - Ring ionosphere does not slip relative to rings
  - $v_{ring\ ionosphere} = (GM/r)^{1/2}$
- Assume ring conductivity is much greater than Saturn's ionospheric conductiviy
- These assumptions give the maximum possible current

Upper limit on field-aligned current



Upper limit on Joule heating



Problem with the upper limit

Current closes through the ring plane $j_r = -\frac{1}{L^{1/2}} j_\lambda$

In the ring plane, there is a torque $T = j_r \frac{B_0}{L^3} r = -\frac{1}{L^{5/2}} j_\lambda B_0 R$

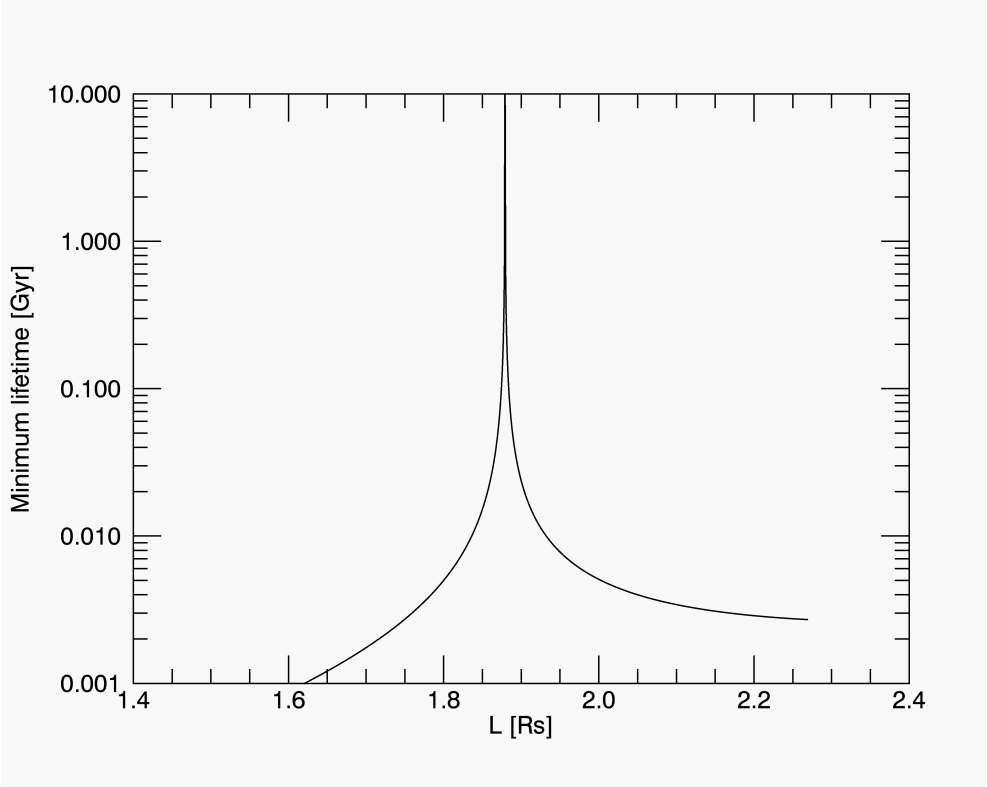
For a uniform mass density in the rings, the moment of inertia per area:

$$I = r^2 \frac{M_{rings}}{\pi\left(R_{outer}^2 - R_{inner}^2\right)} \sim r^2 \frac{3x10^{19}\ \text{kg}}{\pi\left(2.82R^2\right)}$$

Timescale for altetring the rings

$$\frac{\omega}{\alpha} = \frac{\sqrt{GM/r}}{T/I}$$

Since the rings are still there, the real current is much less than the upper limit



More general calculation of currents

$$\frac{d\Phi}{dL} = \frac{R v_{ring\ ionosphere} B_0}{L^3}$$

$$j_{\lambda,ionosphere} = \Sigma_{ionosphere,P}\left(-\frac{2\sin\lambda}{\cos^3\lambda}\frac{v_{ring\ ionosphere}B_0}{L^3} + v_{ionosphere}B_0\cos\lambda\right)$$

$$j_{r,rings} = -\frac{1}{L^{1/2}} j_{\lambda,ionosphere}$$

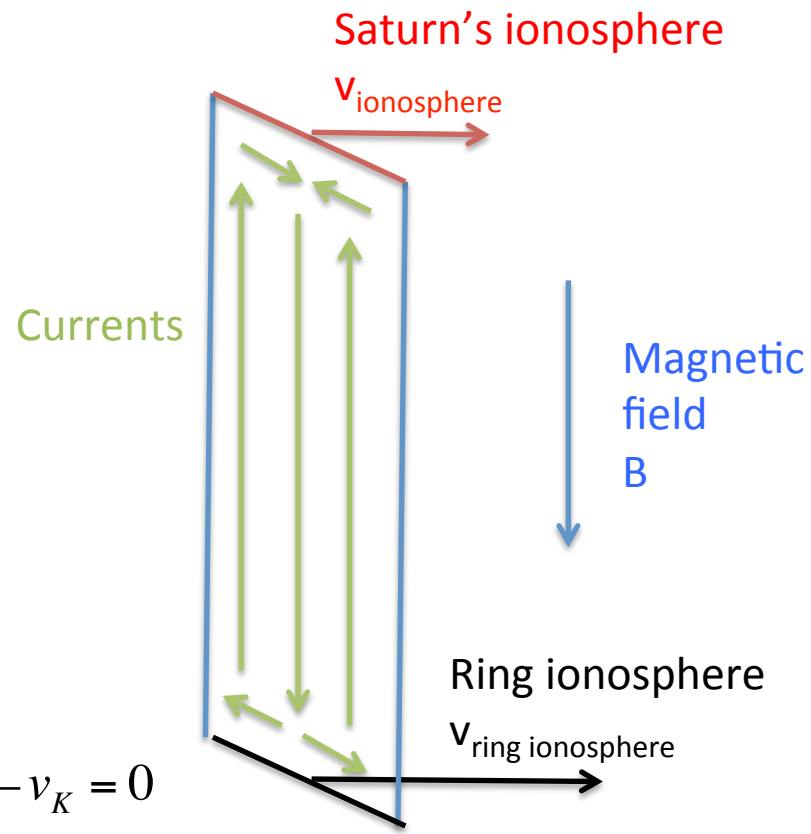
$$0 = \frac{j_{r,rings}B_0}{L^3} + C_{ring-ring\ ionosphere}\left(\sqrt{\frac{GM}{LR}} - v_{ring\ ionosphere}\right)$$

$$0 = j_{\lambda,ionosphere}B_0\cos\lambda + C_{ionosphere-thermosphere}\left(\Omega R\cos\lambda - v_{ionosphere}\right)$$

Plus boundary conditions on j_r at the edges of the rings

Approximate 1D version

- Pretend magnetic field lines are straight
- More rigorous field mapping gives same answer to within a factor of a few



$$v_{ionosphere} = \frac{C_{rings}}{C_{ionosphere} + C_{rings} + \dfrac{C_{ionosphere} C_{rings}}{B^2 \Sigma_P}} v_K = 0$$

$$v_{ring\ ionosphere} = \frac{\left(1 + C_{ionosphere}\right) C_{rings}}{C_{ionosphere} + C_{rings} + \dfrac{C_{ionosphere} C_{rings}}{B^2 \Sigma_P}} v_K = 10^{-4}$$

Conclusions

- The difference between the ring's velocity and neutral atmosphere's drives a current system
- The ring ionosphere is only weakly coupled to the rings
  - Ions should be very close to corotating with the planet
- Maximum current of 100 MA (For $\Sigma_{P,ionosphere} = 3$ S)
  - Likely current is under 1 MA
- Joule heating of the ionosphere is small
  - Under 10 μ W/m^2
  - May contribute to the H_3^+ observations
- The field-aligned currents density is small and unlikely to produce aurora (which are not observed)