AURORAL X-RAY EMISSION AT THE OUTER PLANETS

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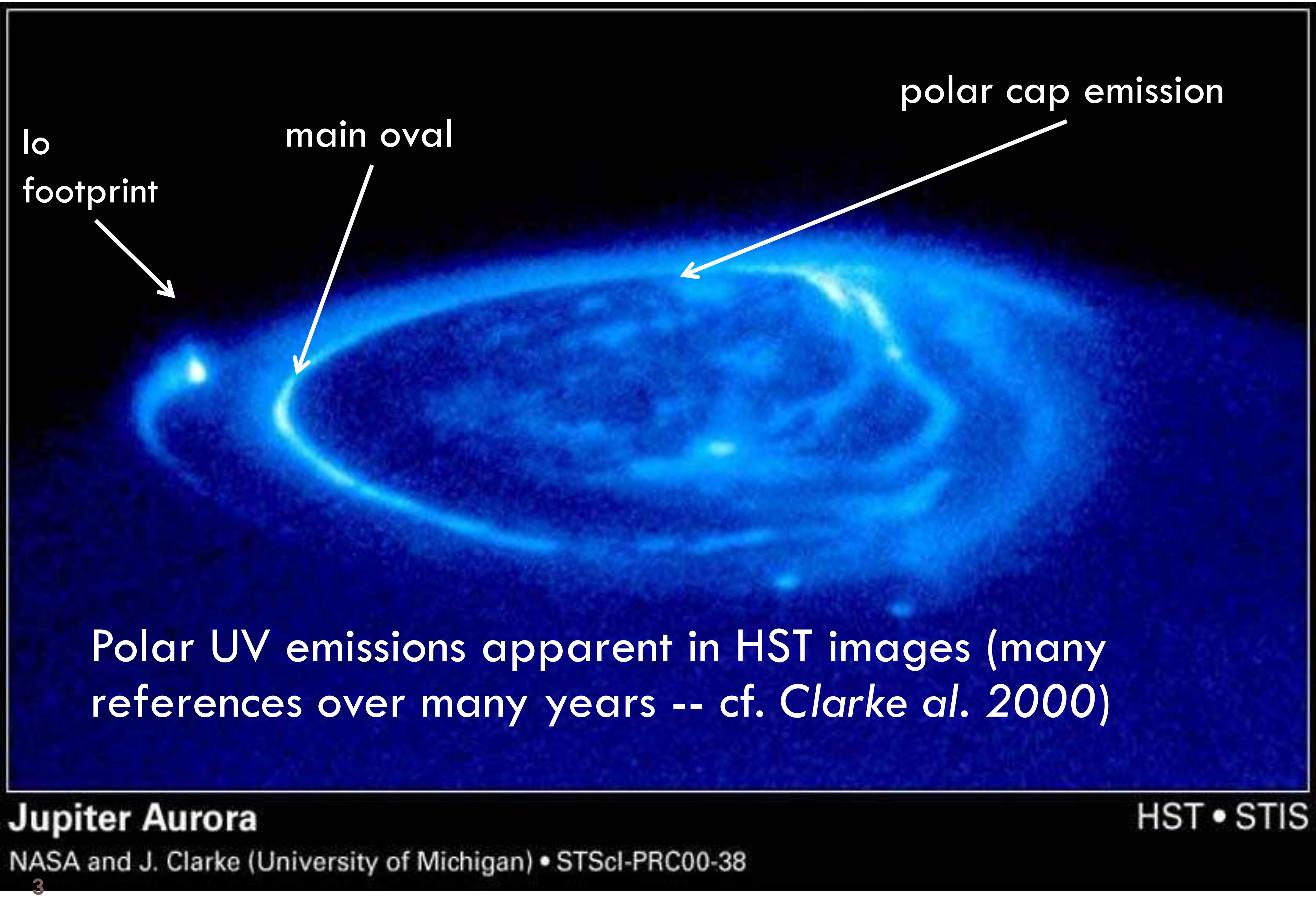
Overview

- Observations at the Jovian polar cap
- Ion precipitation vs. electron precipitation
  - Why is ion precipitation necessary?
- X-ray emission models
  - Atmospheric effects
  - The ions must be accelerated, why? And how?
- Why don't we see auroral X-rays from Saturn?

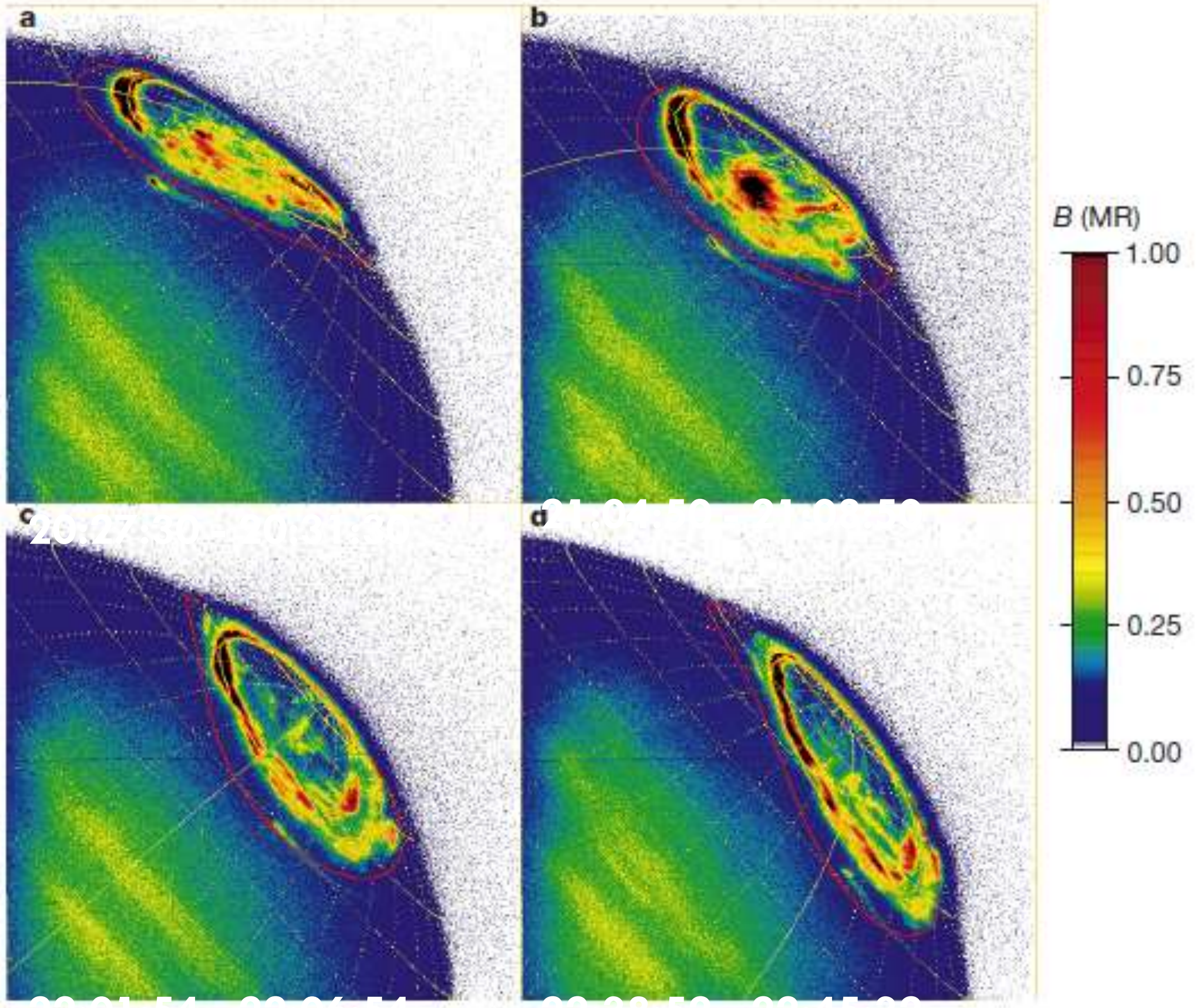


Polar UV emissions apparent in HST images (many references over many years -- cf. *Clarke al. 2000*)

Jupiter Aurora

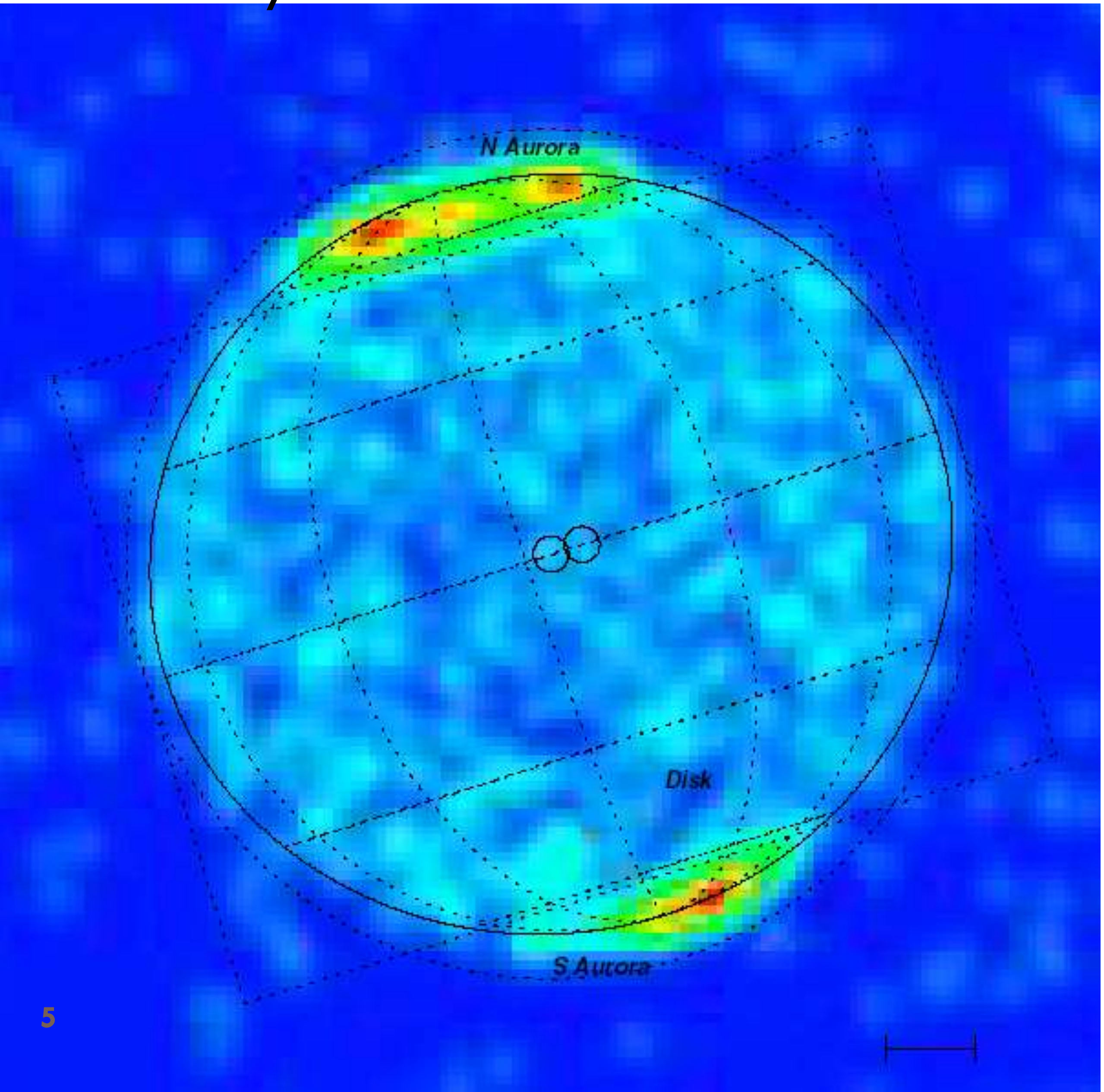
NASA and J. Clarke (University of Michigan) • STScI-PRC00-38

Polar UV (auroral) Flare (*Waite et al. 2001*)



possible association with “active” region (*Pallier and Prange, 2001, 2003*; *Grodent et al., 2003*, …)

CXO Image of Jupiter: Feb. 2003 (*Elsner et al., 2005*)
X-Ray Emission



*Auroral Emission

≈ 1 GW in x-rays

Polar Caps

*Disk emission:

≈ 1 GW in x-rays

scattering and

Fluorescence of solar

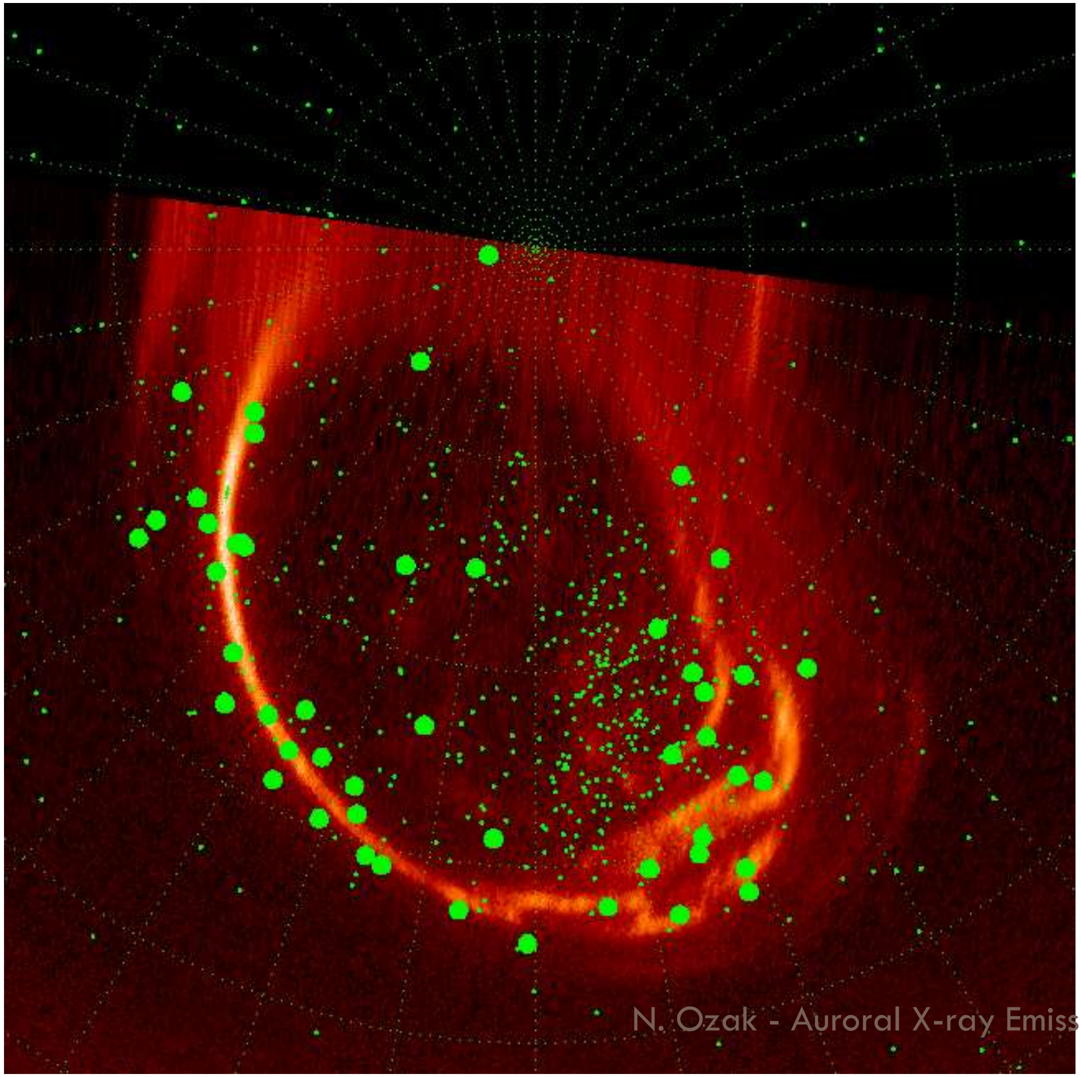
x-rays

(*Maurellis et al., 2000; Cravens et al., 2005*)

Recent Auroral X-ray Observations

- Spectrum of auroral x-ray emission by CXO and XMM - sulfur and oxygen lines and maybe carbon -- outer magnetosphere ions and acceleration (*Elsner et al., 2005; Branduardi-Raymont et al. 2004, 2005, 2007, 2008*).
- Spectrum of auroral x-ray emission by XMM-Newton -- possible solar wind ion precipitation (*Branduardi-Raymont et al., 2004*).
- Grating spectrum of auroral x-ray emission by XMM-Newton -- - Doppler broadened oxygen emission (*Branduardi-Raymont et al., 2007*).

Bremsstrahlung x-ray emission observed from the Jovian aurora (E > 1 keV photons) with a distinct spatial morphology (*Branduardi-Raymont et al., 2007, 2008*).



- Simultaneous HST – CXO observation on Northern aurora in 2003.
- FUV and x-rays overplotted
- Large dots: E > 2 keV (bremsstrahlung) Small dots: E < 2 keV
- Co-located with bright FUV auroral region

Time Variation

- ~45 min pulsation period of x-ray hot spot observed by CXO in 2000 (*Gladstone et al. 2002*)
- Similar periodicity as high latitude radio and energetic electron bursts observed by Ulysses --- QP 40 bursts (*MacDowall et al. 1993*) 5 R_J accel. electrons. source
- No periodicity match when compared to solar wind or interplanetary magnetic field
- At later time (2003), the 45 min variation was absent from XMM-Newton and CXO observations (*Elsner et al. 2005, Branduardi-Raymont et al. 2004, 2005*)
  - Character of the variability may change from organized to chaotic

Characteristics of the X-ray Emissions

Elsner et al. (2005)

CXO Feb. 2003

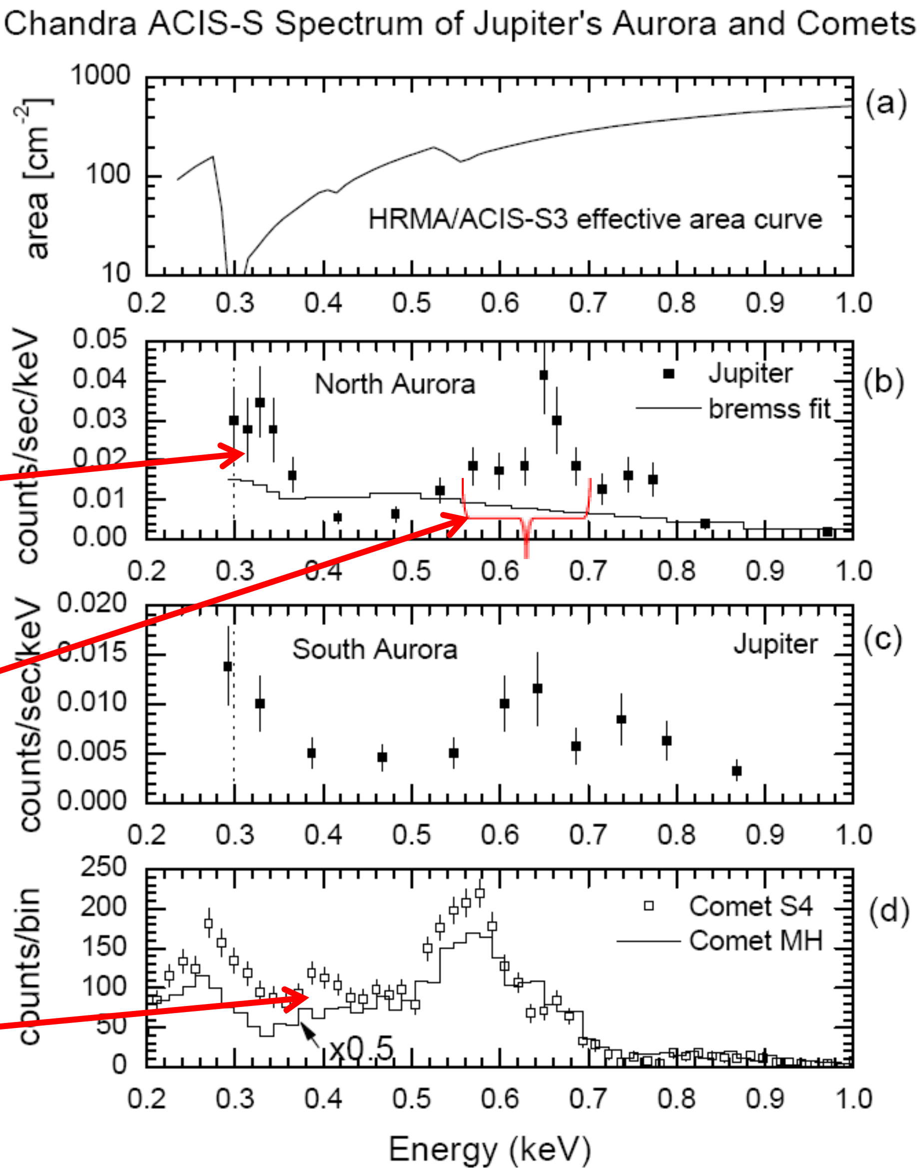
ACIS-S Spectra

S^{9+},S^{10+} lines

O^{6+}, O^{7+} lines

C^{5+} lines

Comet



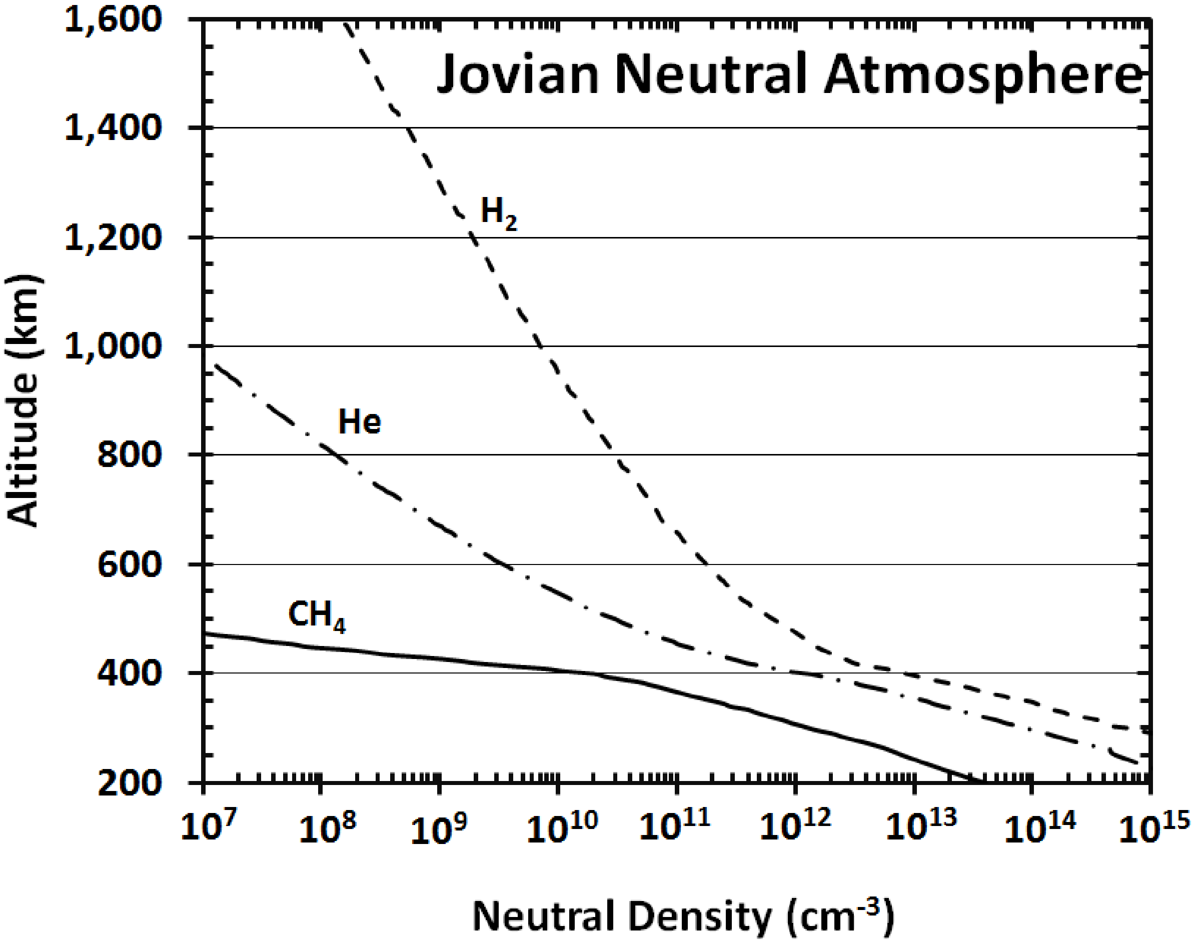
Why is ion precipitation necessary?

- Observations by CXO and XMM-Newton confirmed that the x-ray emissions originating at high latitudes on Jupiter are line emissions from sulfur, oxygen and maybe carbon (K-shell emissions) and NOT bremsstrahlung
- Need ions not electrons!
- Spectrum of Jovian auroral x-rays modeled with sulfur, oxygen, and carbon lines (*Kharchenko et al, 2007; Hui et al., 2009, 2010a*; ***Ozak et al., 2010***) using new complete set of cross sections (*Schultz et al., 2011 in prep*).

Possible Explanations for X-ray Mechanism (*Cravens et al.* 2003)

- 1. Accelerated (200 keV) solar wind heavy ions in the cusp region (the SWCX mechanism)
  - However no evidence of carbon in the spectrum to indicate solar wind origin
- 2. Accelerated (≈ 10 MeV) S and O ions in the outer magnetosphere.
  - Low charge state ions with high energies will strip the electrons and become highly charged
  - Highly charged ions will charge exchange, become excited and release an x-ray photon as they decay to ground state

Jovian Ion Precipitation Model



Ozak et al. (2010)

Monte Carlo model with altitude-dependent effects like opacity and quenching.

Follow low state ions with different initial energies as they penetrate the atmosphere

Collision Processes

- Electron stripping process:

$$O^{(q-1)+} + H_2 \longrightarrow O^{q+} + H_2 + e^-$$

- Charge transfer collisions:

$$O^{q+} + H_2 \longrightarrow O^{(q-1)+*} + H_2^+$$

- X-ray emission:

$$O^{(q-1)+*} \longrightarrow O^{(q-1)+} + h\nu \text{ (X-ray)}$$

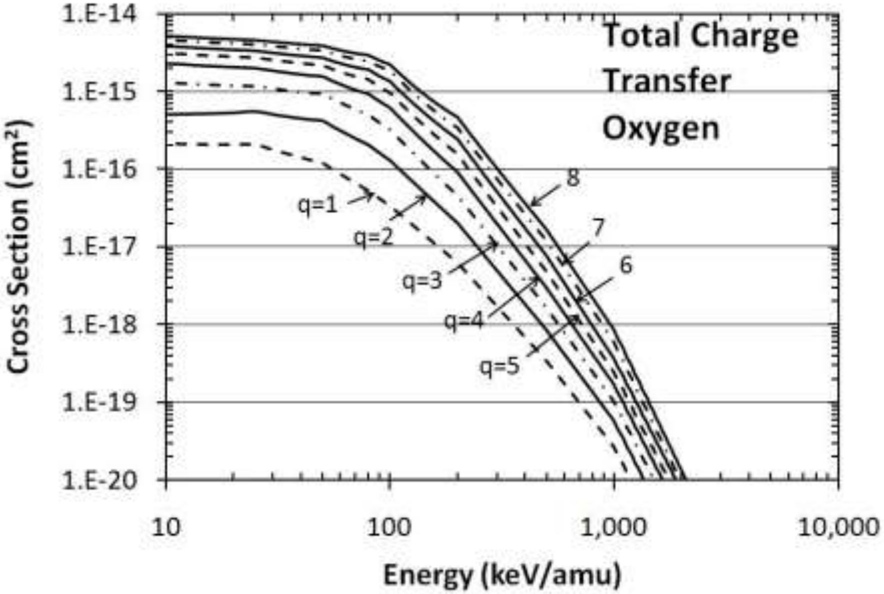
- Ionization:

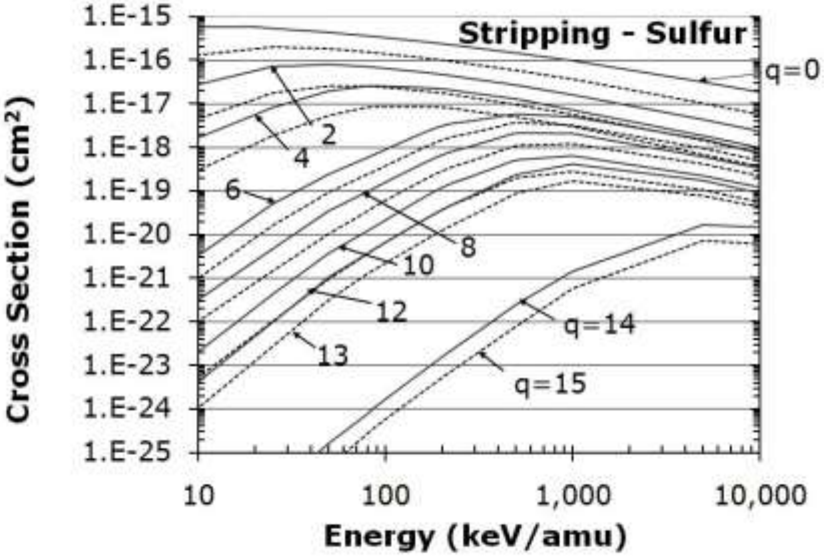
$$O^{q+} + H_2 \longrightarrow O^{q+} + H_2^+ + e^-$$

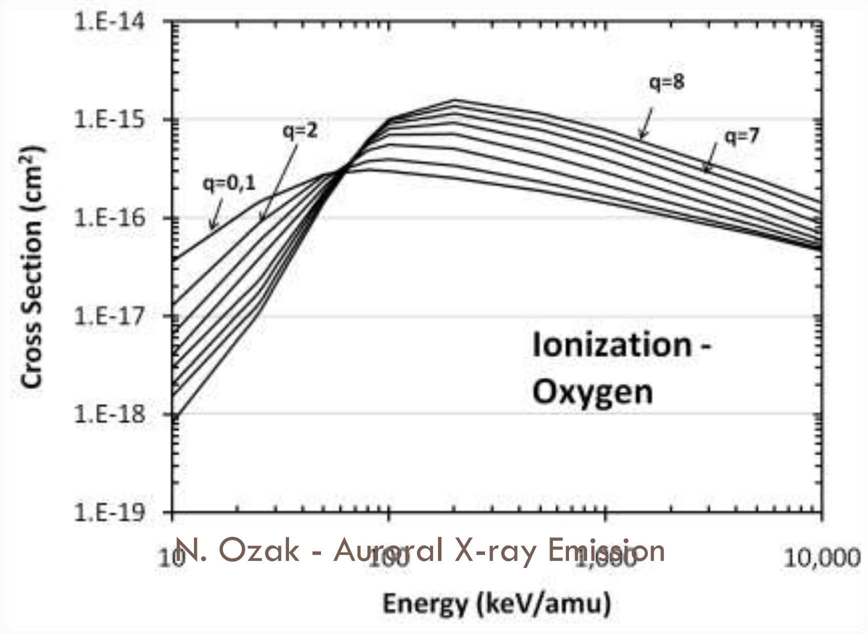
- Excitation:

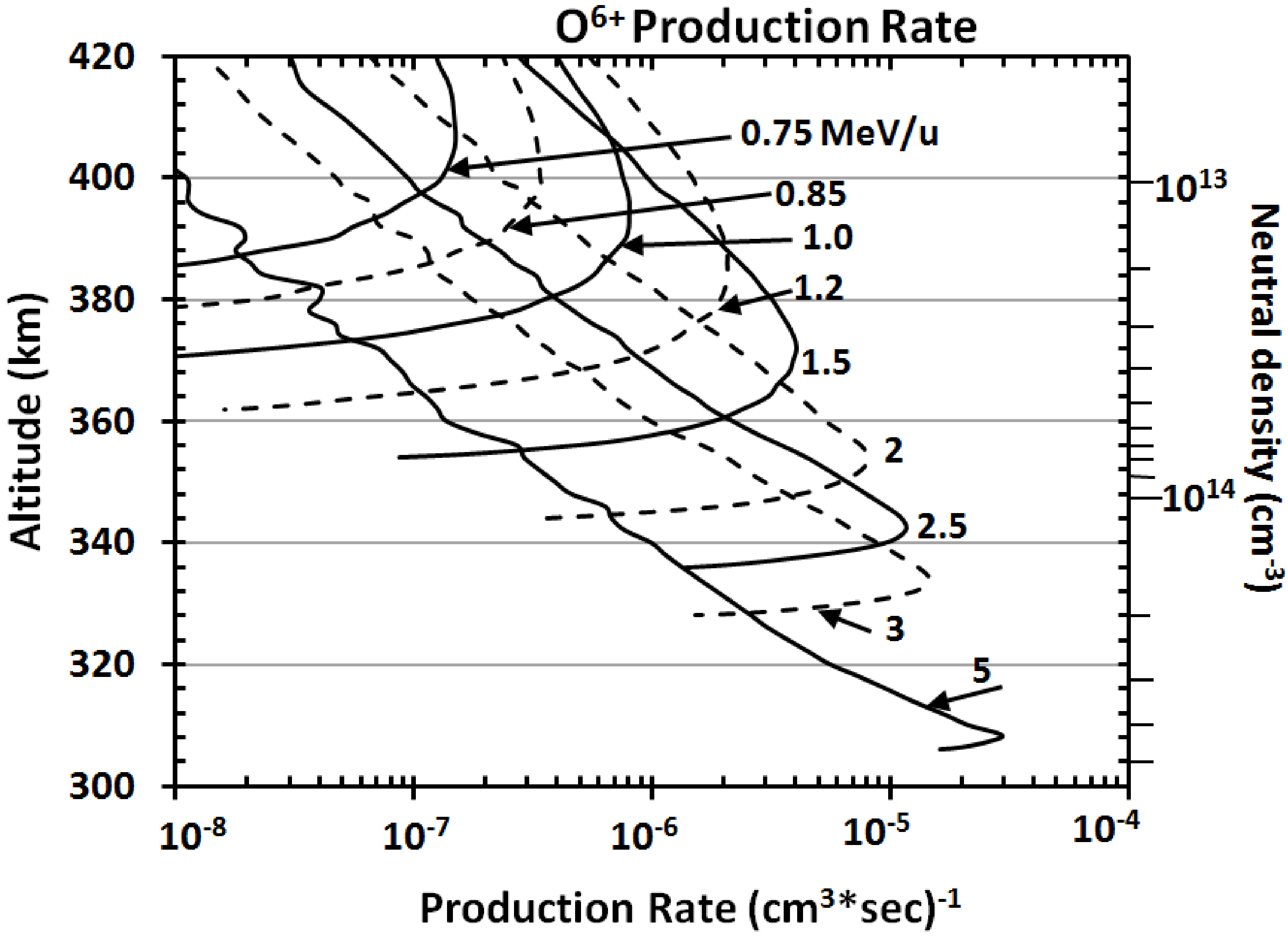
$$O^{q+} + H_2 \longrightarrow O^{q+} + H_2^*$$

Cross Sections *(Ozak et al. 2010, Schultz et al. in prep)*



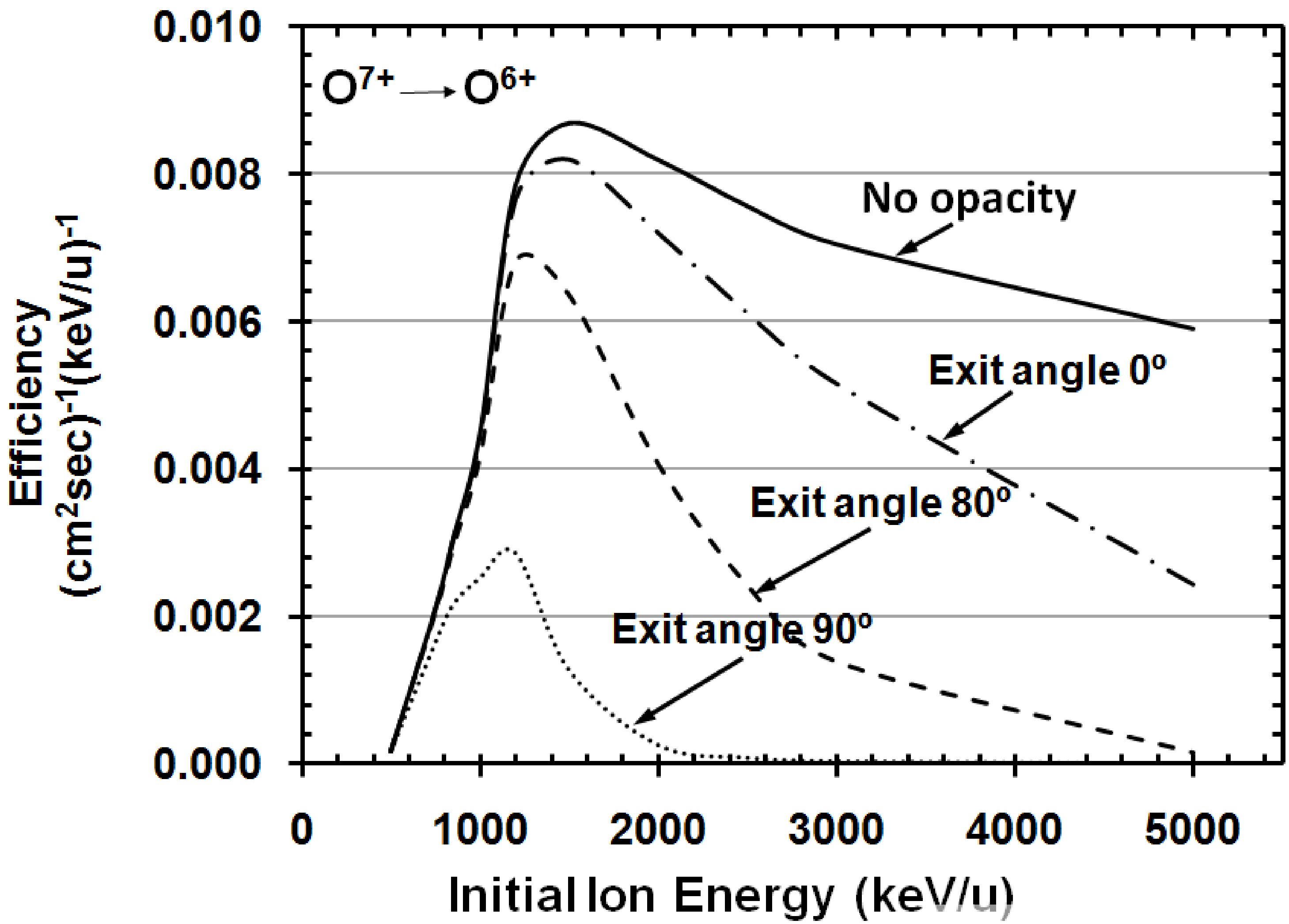






Ozak et al. (2010)

Peak X-ray emission efficiency for E ≈ 1.5 MeV/u



Ozak et al. (2010)

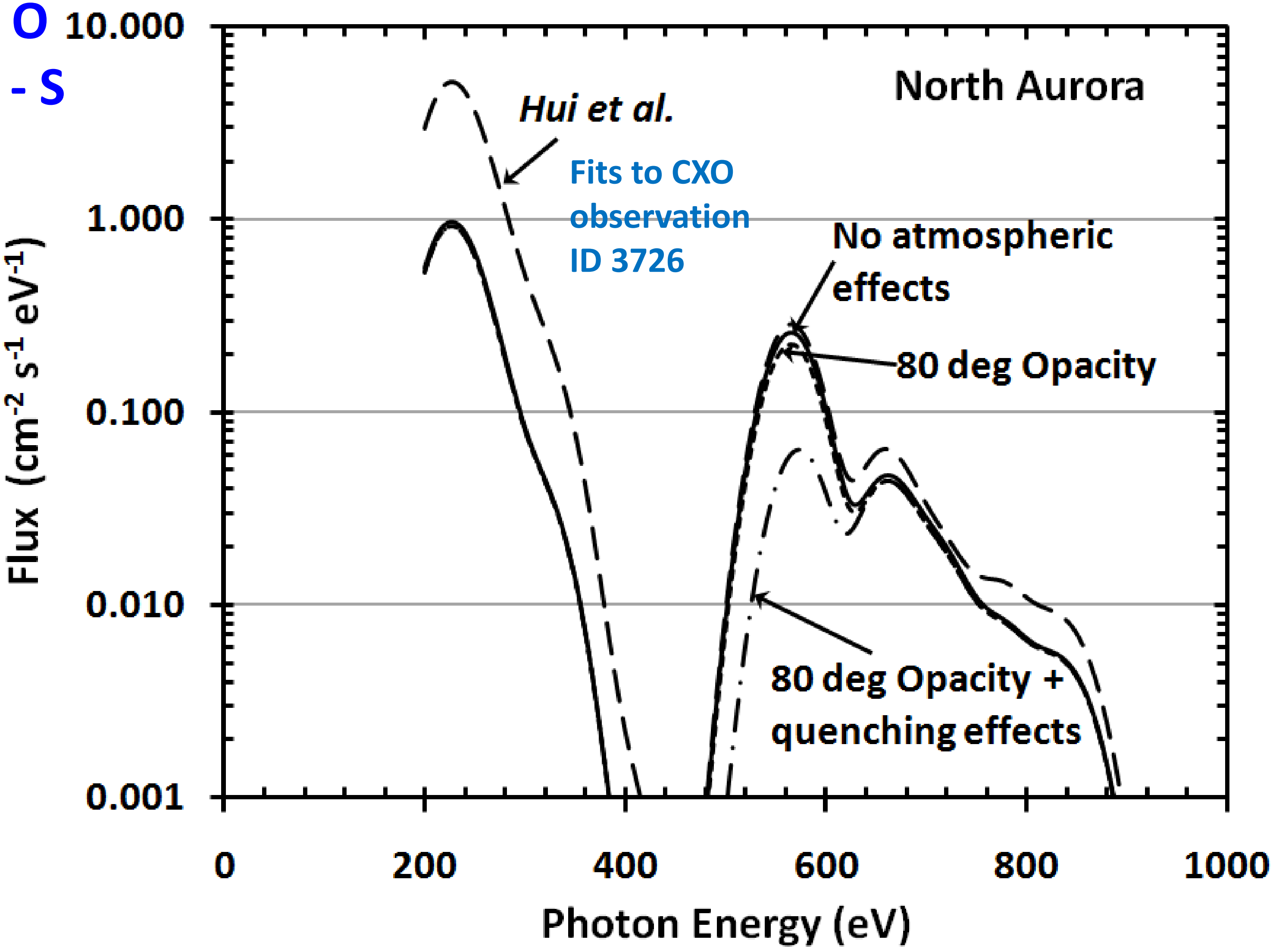
$$4\pi I = \int_{z_0}^{\infty} P(z(s))e^{-\tau(s)}ds$$

Initial Energies:

1.2 MeV/u - O

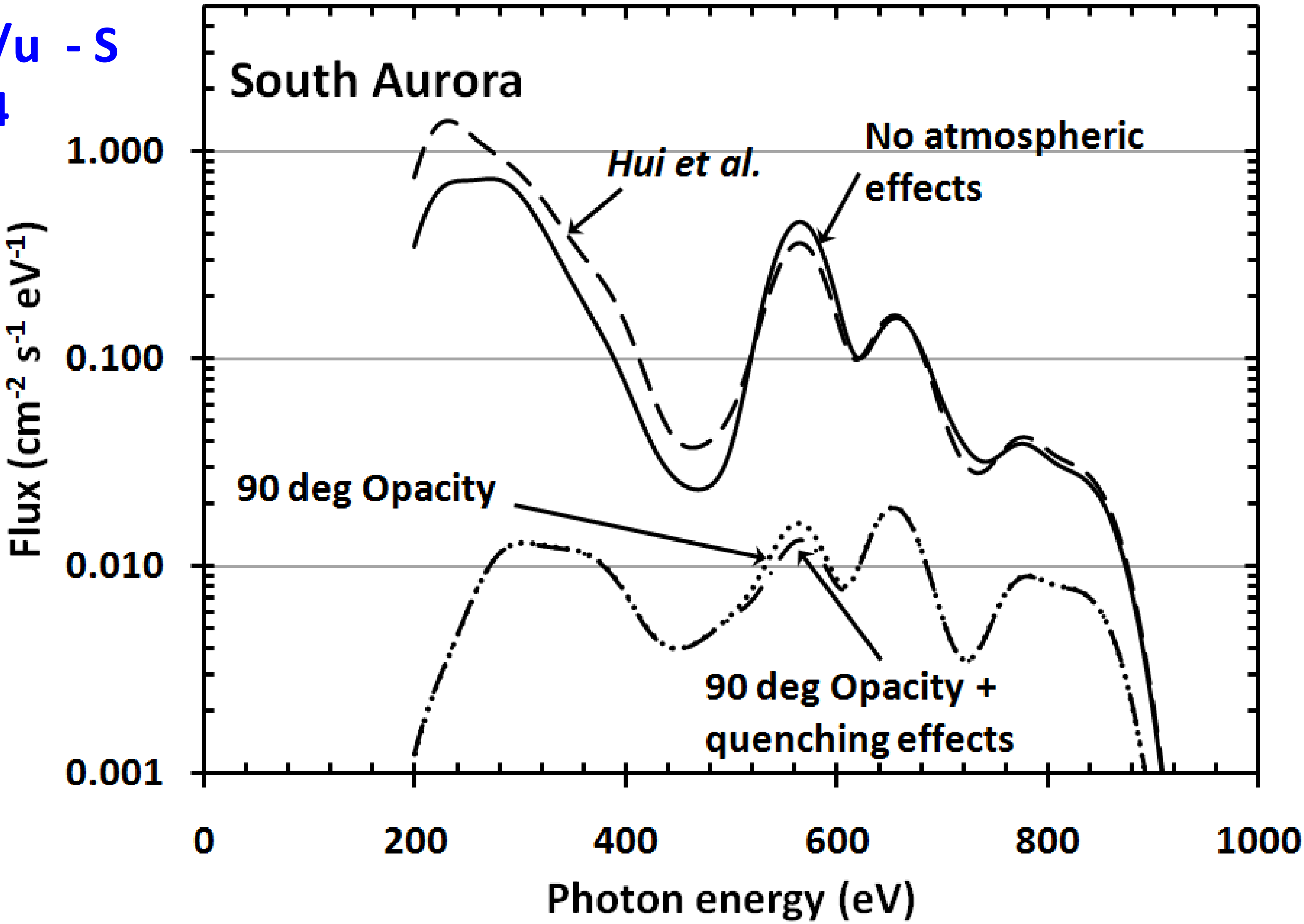
0.51 MeV/u - S

S/O = 204



Ozak et al. (2010)

Initial Energies:
2.0 MeV/u - O
1.86 MeV/u - S
S/O = 0.94



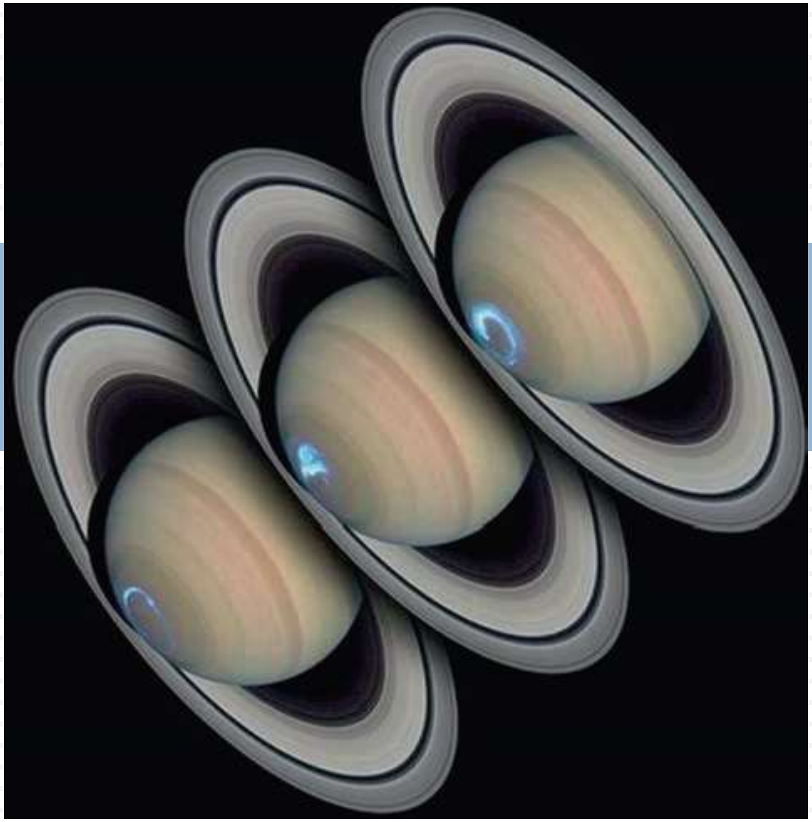
Ozak et al. (2010)

Summary of X-Ray Model Comparisons

- **Sulfur** and **Oxygen** lines are sufficient (no Carbon *Hui et al. 2010a*) -- magnetospheric ions and *not* *solar wind ions.*
- 1.5—2 MeV/u oxygen ions and 1-2 MeV/u sulfur ions are **most efficient** in producing X-rays
- **Quenching and Opacity** effects need to be included (and hence some details of the neutral atmosphere matter) (*Ozak et al. 2010*). Could explain some N-S spectral differences (more work needed).

X-Ray Emission - Parallel Acceleration

- Magnetospheric ion populations are not adequate - in flux or energy (50 keV).
- One solution is to accelerate these ions parallel to the magnetic field - this not only energizes them but increases the flux to the atmosphere by filling the loss cone (Knight mechanism). Otherwise, most charged particles in the magnetosphere magnetically mirror before reaching the atmosphere.
- Is this "x-ray" current (*Cravens et al. 2003*) the main oval return current (Vasyliunas cycle) or is it linked to the magnetopause (Dungey cycle)(*Bunce et al. 2004*)?

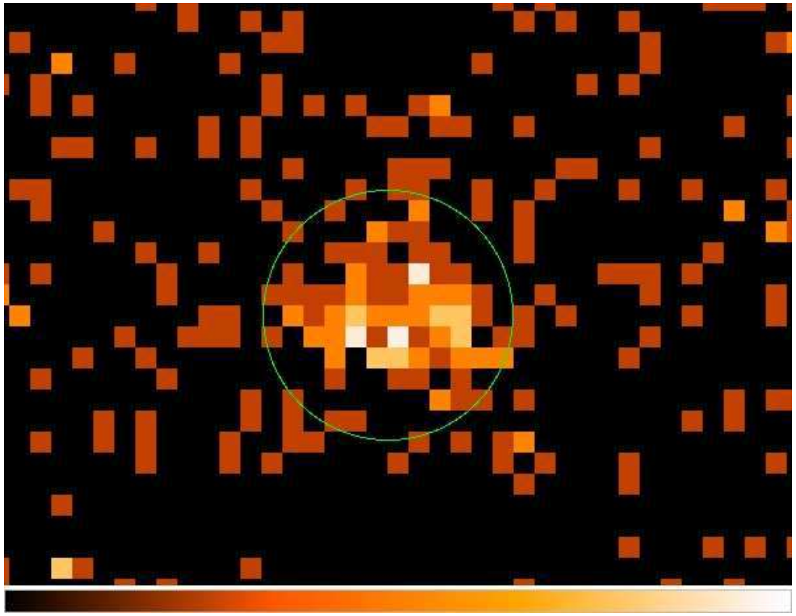


What about Saturn?

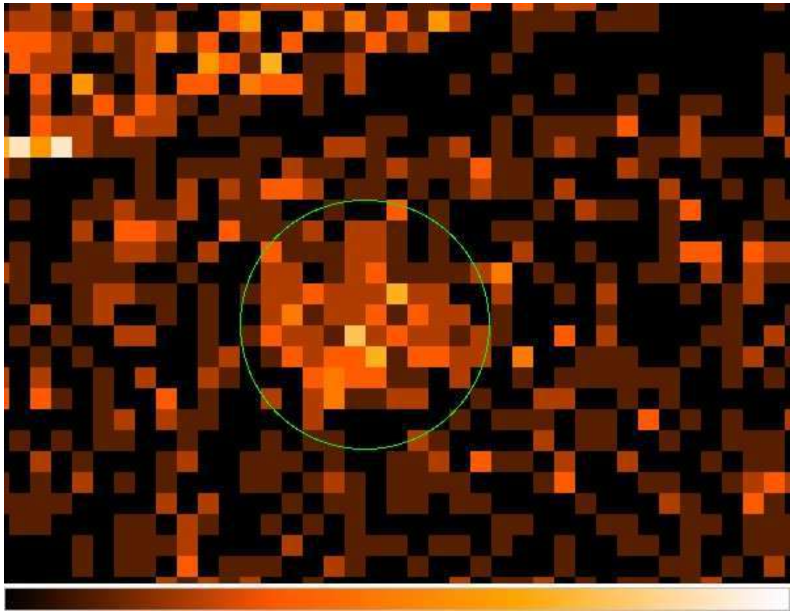
Kurth et al. 2009

No Auroral X-rays Observed!

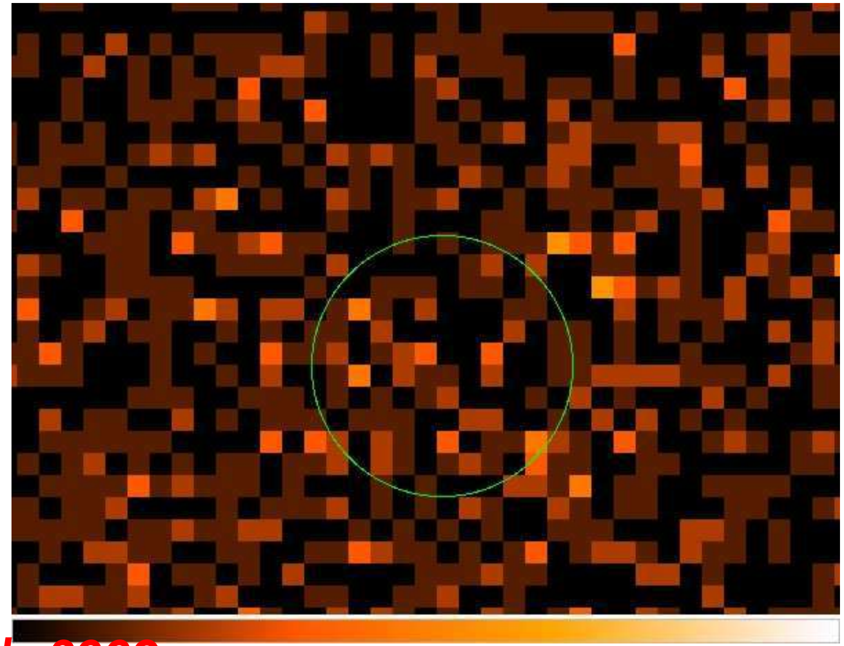
- There is x-ray emission, BUT it is concentrated at non-polar latitudes
  - Large temporal variability
  - Correlated to the solar x-ray flux
- Saturn: Auroral x-ray emission are *not* observed (upper limit on luminosity: 2% of Jupiter, 1GW vs. 8 - 24 MW)
- Analysis of *absence of Saturnian auroral x-rays* (*Branduardi-Raymont et al., 2009; Hui et al., 2010b*).
- Estimates of possible x-ray luminosity are orders of magnitude below observational limit.



Oct. 2002



Apr. 2005



Oct. 2005

Branduardi-Raymont et al., 2009

Summary

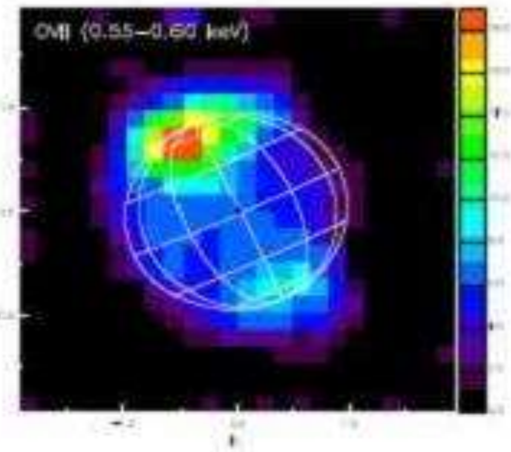
- Jovian X-ray emission is caused by precipitation of oxygen, sulfur and maybe (although not likely) carbon
- It is a diagnostic of downward Birkeland currents due to ions in the outer magnetosphere or magnetopause region, just as electron precipitation is a diagnostic of upward currents.
- The ion precipitation is probably powered by magnetic reconnection and can be a valuable tool in understanding M-I coupling at this planet.
- Saturn: lack of x-ray emission - inadequate field-aligned potentials generated and/or cusp entry of solar wind ions

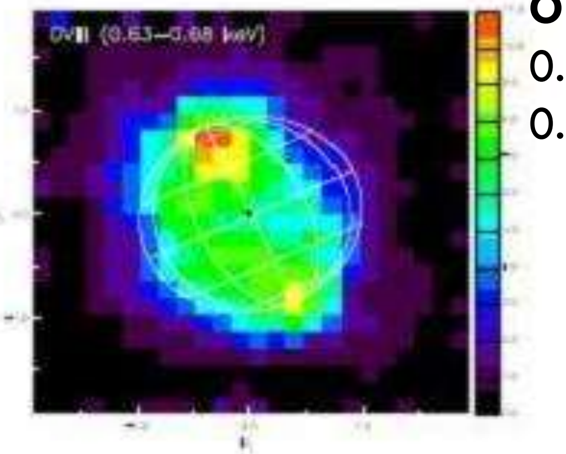
Thank you!

I would like to acknowledge NASA Planetary Atmospheres Program and thank Tom Cravens and our collaborators for their help on this work.

Polar Emission vs. Disk Emission

OVII
0.55 –
0.60 keV



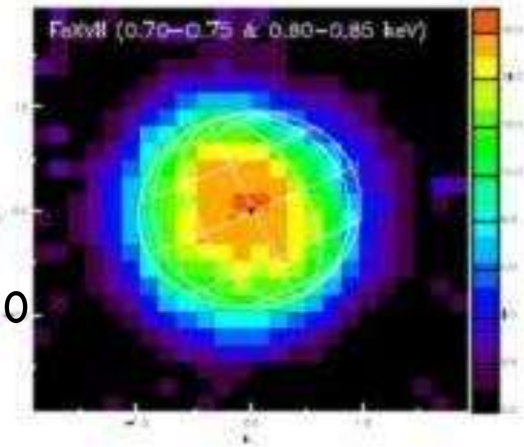


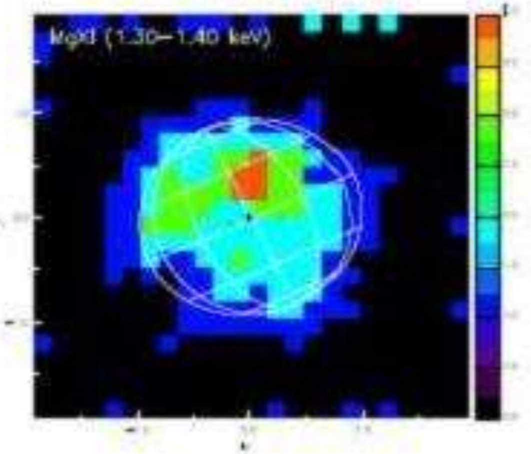
OVII
0.63 -
0.68 keV

(Branduardi-Raymont et al. 2007)

XMM-Newton Nov. 2003

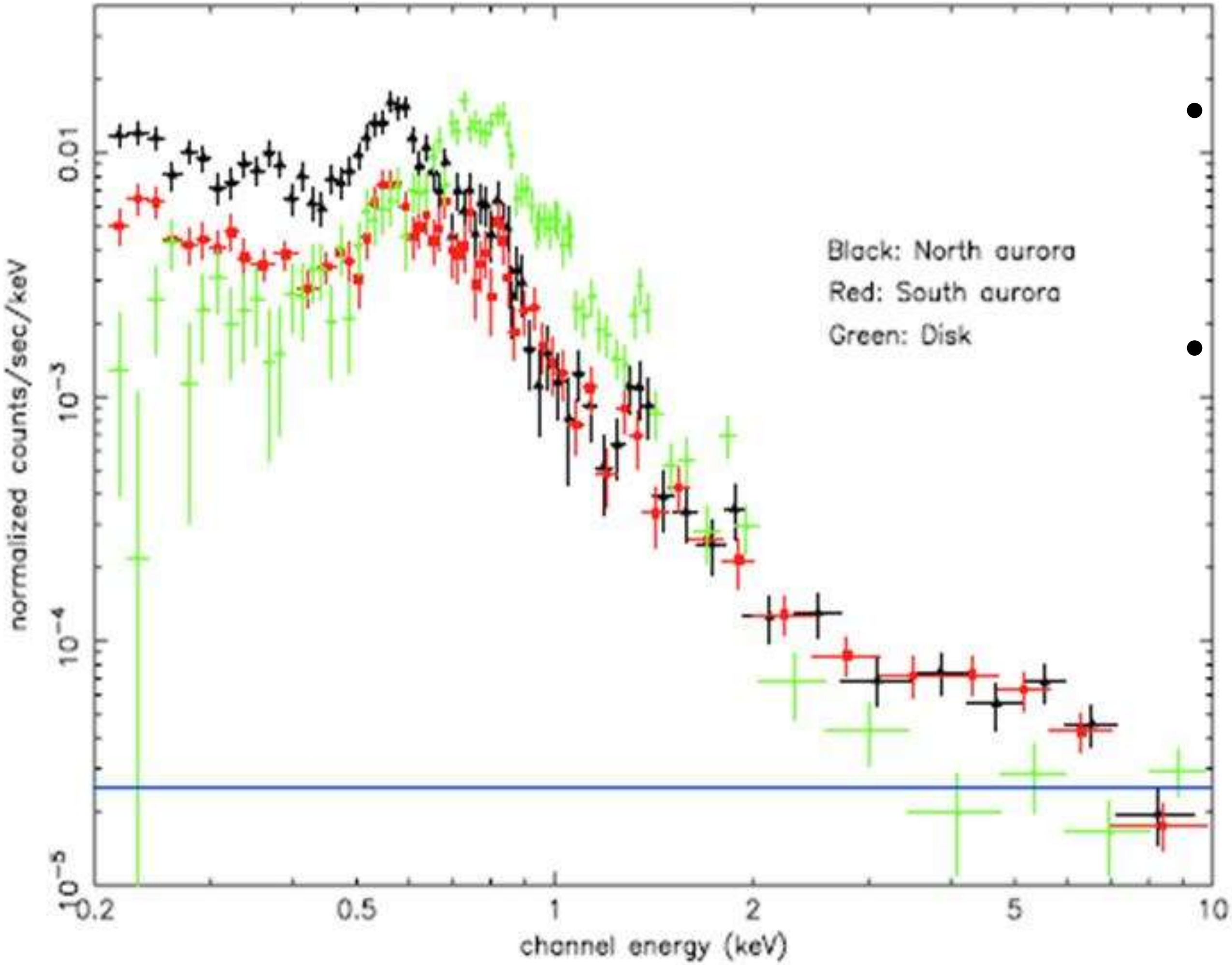
FeXVII
0.70
and 0.80
keV





MgXI
1.30 –
1.40 keV

Differences in Spectral Shape Between High Latitude Emissions and Disk



- (*Branduardi-Raymont et al. 2007*)
- XMM-Newton Nov. 2003

Charge Exchange Mechanisms for X-ray Emission

- Magnetospheric or solar wind ion M^{q+} (O, S, C..)
- ☐ Charge state q = 6, 7, 8 for O or q = 8, 9, 10, 11, 12… for S produces x-ray emission
- Charge transfer excitation collisions:

$$M^{q+} + H_2 \text{--->} H_2^{+} + M^{(q-1)+*}$$

$$M^{(q-1)+*} \text{----->} M^{(q-1)+} + h\nu$$

Monte Carlo Model (MCM)

- Takes into account the charge history of the precipitating ions.
- O^{2+} and S^{+} ions are chosen as initial charge states, since they are common in the outer magnetosphere.
- Each ion initially has an arbitrarily chosen energy and a randomly chosen pitch angle.
- Calculate the probability of a having a collision and with this the displacement of each ion into the atmosphere in terms of the column density: $\Delta N = -\mathrm{Ln}(\mathrm{Prob}) / \sigma_{tot}$
- Choose collision type from different processes:
  - $p_0 = \sigma_{ioniz} / \sigma_{tot}$, $p_+ = \sigma_{strip} / \sigma_{tot}$, $p_- = \sigma_{cx} / \sigma_{tot}$
- Calculate energy loss using empirical power.
- Repeat until ion runs out of energy.

Jovian X-Ray Emission Mechanism - Magnetospheric Ion Precipitation

- X-ray emission is from high charge state O and S ions, yet only low charge state ions are seen in the magnetosphere (O^+, O^{++}, S^+, S^{++}, S^{+++}).
- High charge state ions (and x-rays) can be produced by collisions of high energy ions (E > 1 MeV/amu) with atmospheric targets.
- But the X-ray emission is from very high latitudes (that is, the outer magnetosphere - $r > 50\ R_J$) and the energetic ion populations are not sufficient to give the observed x-ray power (or the energies) – (*Mauk et al. 2004*).