X-ray spectroscopy of solar system objects

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X-ray studies of the solar system

- Reached maturity thanks to *Chandra* and *XMM-Newton* (medium and high resolution spectroscopy)
- Processes involve highly energetic plasmas, particle acceleration, powerful magnetic fields, fast rotating bodies, reprocessing of solar radiation
- ‘Next door’ examples of widespread astrophysical phenomena

X-ray production in the solar system

- Charge exchange (CX) process

  Highly ionised heavy ions collide with neutrals/molecules
  → excited following electron capture ('charge exchange')
  → de-excitation produces X-ray line emission, e.g.

  $$H_2 + O^{7+} \rightarrow H_2^{+} + O^{6+} + h\nu$$

  Low energy solar wind heavy ions (C, O, Ne - SWCX) :
  Comets, heliosphere, Earth geocorona, Mars halo
  Very energetic ambient heavy ions (low-charge ions accelerated, highly charged by stripping, CX): Jupiter aurorae

- Electron bremsstrahlung

- Elastic and K-shell fluorescent scattering of solar X-rays in planetary atmospheres and on surfaces

(Bhardwaj et al. 2007)

X-rays from the solar system

Object	Auroral	Disk	Other
Venus	No	Yes[*]	
Earth	Yes[++]	Yes[*]	Geocorona[+]
Moon		Yes[*]	
Mars	No	Yes[*]	Exosphere[+]
Jupiter	Yes[^,++]	Yes[*]	
Io, Europa			particle impacts
Io Plasma Torus			[++], OVII Heα?
Saturn	No	Yes[*]	Rings[*]
Comets			[+]
Asteroids			[*]
Heliosphere			[+]

[+] SWCX [^] CX [++] Electron bremsstrahlung
[*] Elastic and/or K-shell fluorescent scattering of solar X-rays

X-rays from Jupiter

First detection with the *Einstein Observatory* ***(Metzger et al. 1983)***

Earth analogy → e^- bremsstrahlung of auroral origin expected

Alternative: K-shell line emission from CX of energetic S and O ions, precipitating along magnetic field lines

ROSAT spectrum consistent with recombination line emission

(Waite et al. 1994)

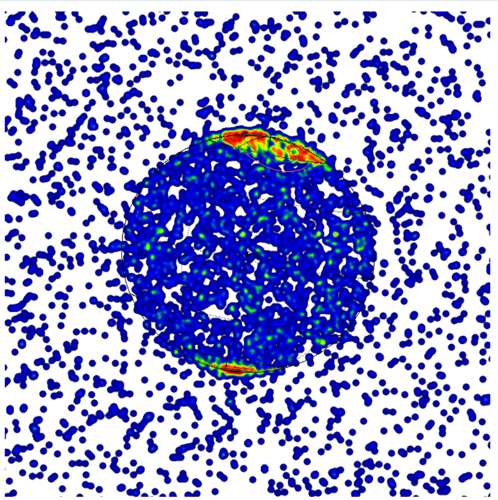
Ions thought to originate in inner magnetosphere (8 – 12R_J)
Dec. 2000 *Chandra* observations point to origin at > 30 R_J

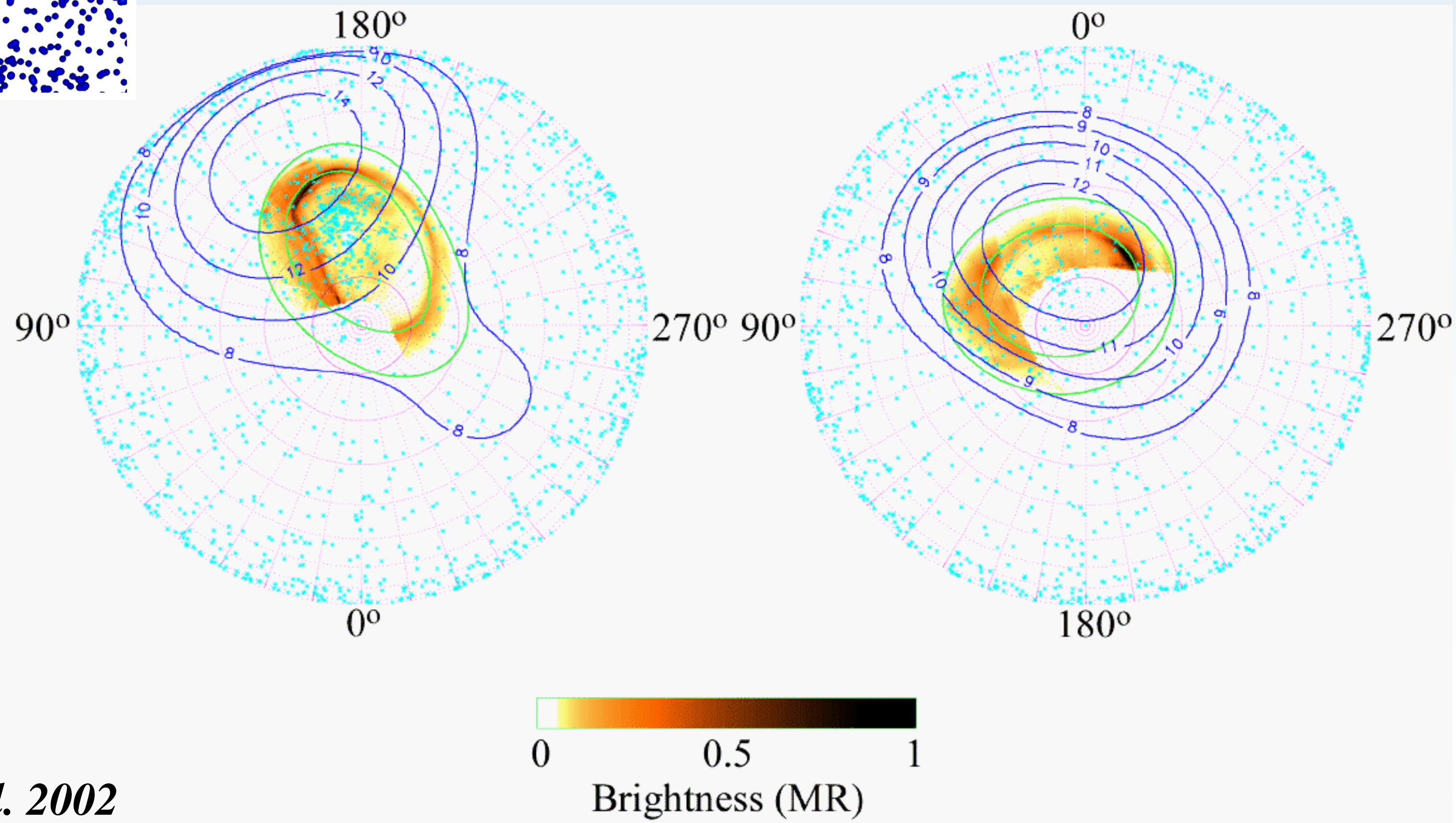
(Gladstone et al. 2002)

→ What are the ion species (C or S)
and thus their origin (SW or magnetosphere)?

Chandra HRC-I polar projections

Jupiter

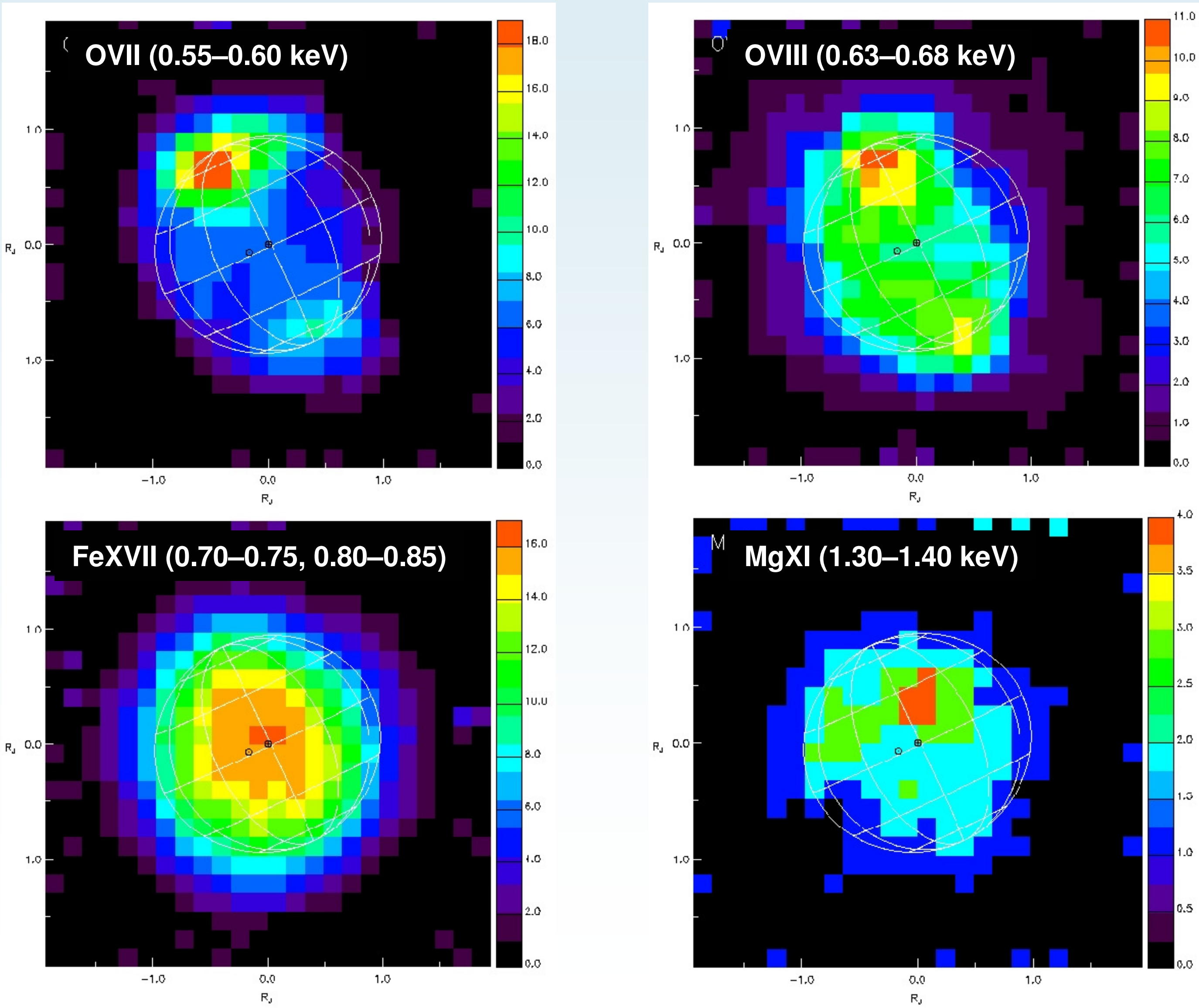




Gladstone et al. 2002

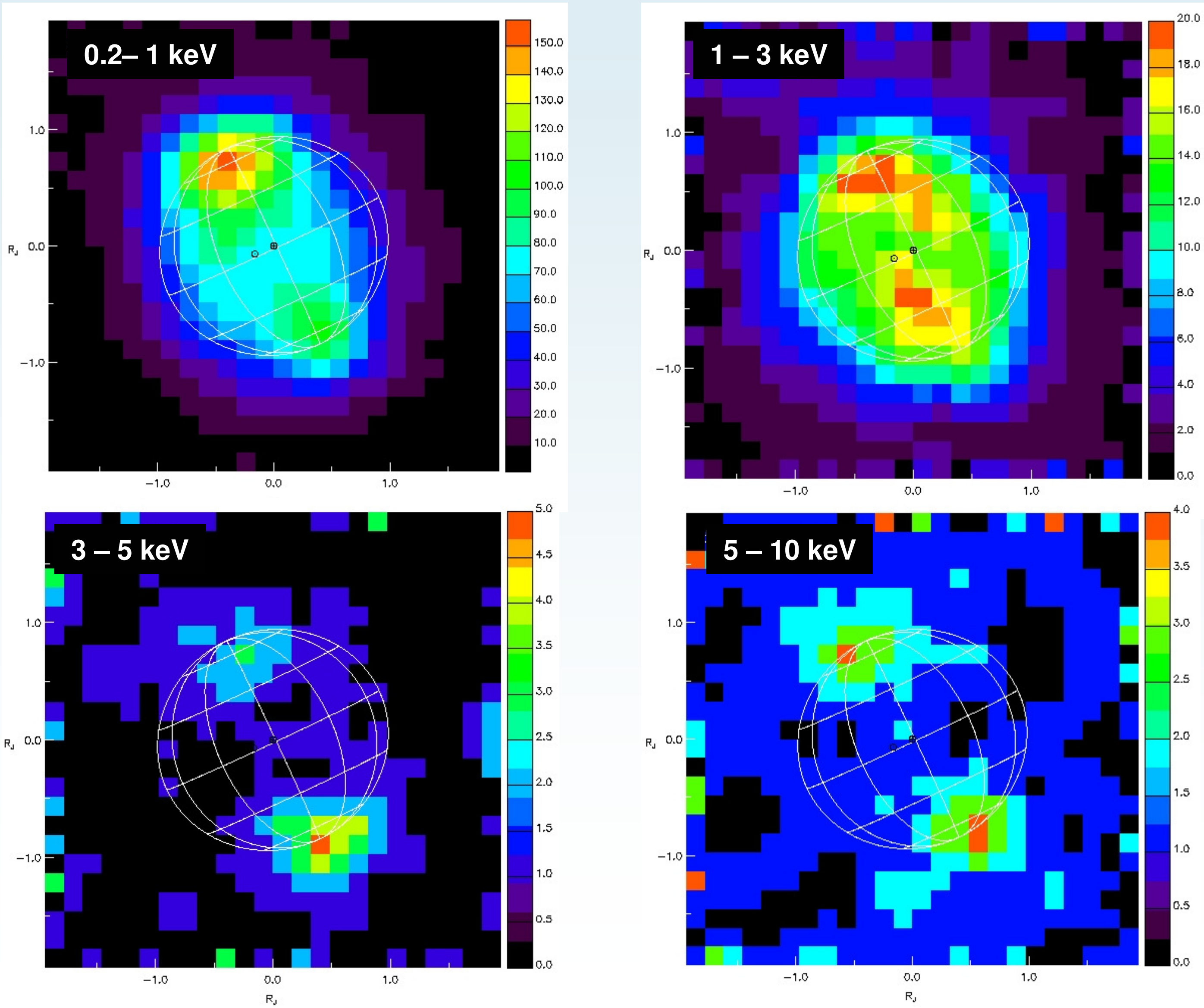
Jupiter

XMM-Newton – Nov. 2003: EPIC



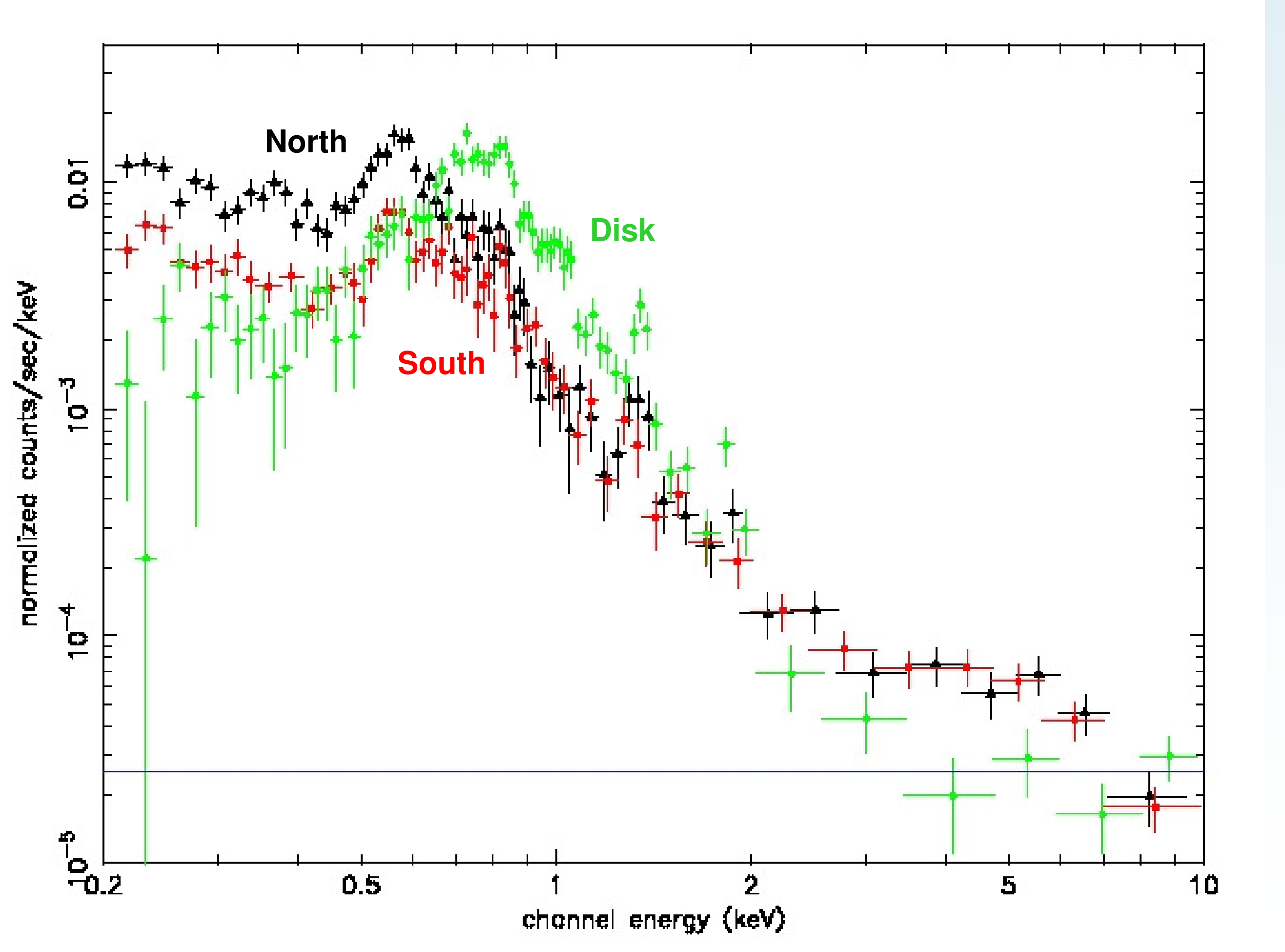
Jupiter

XMM-Newton – Nov. 2003: EPIC



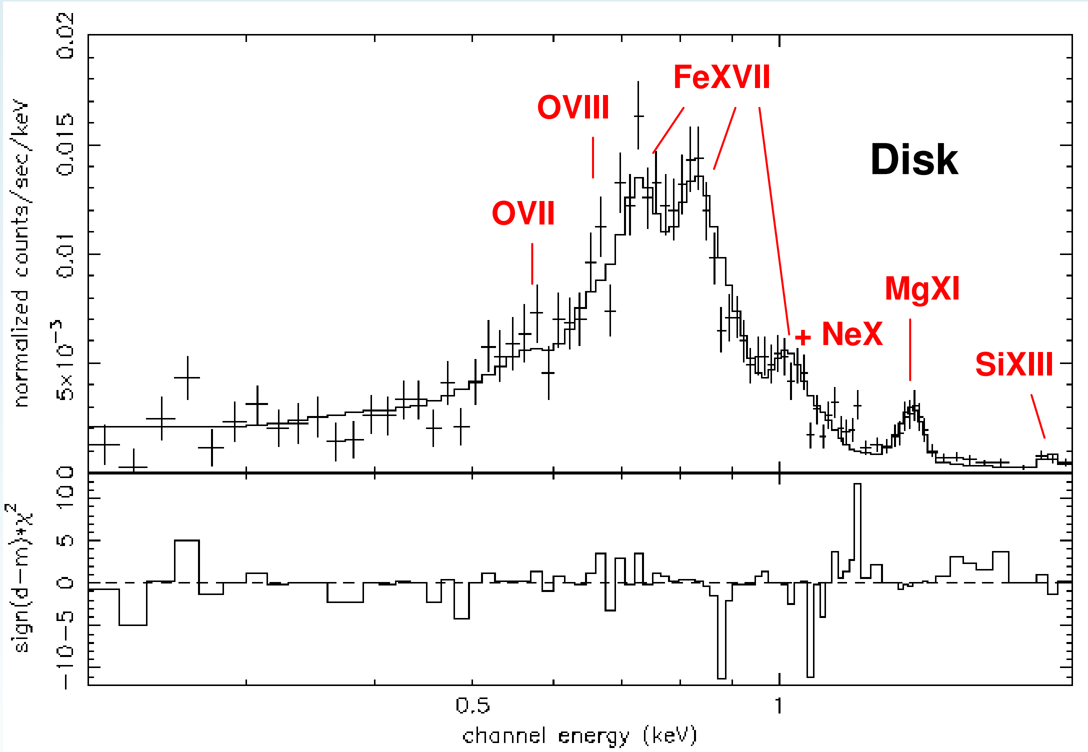
XMM-Newton – Nov. 2003: EPIC

Jupiter's auroral and disk spectra



Jupiter

XMM-Newton – Nov. 2003: EPIC



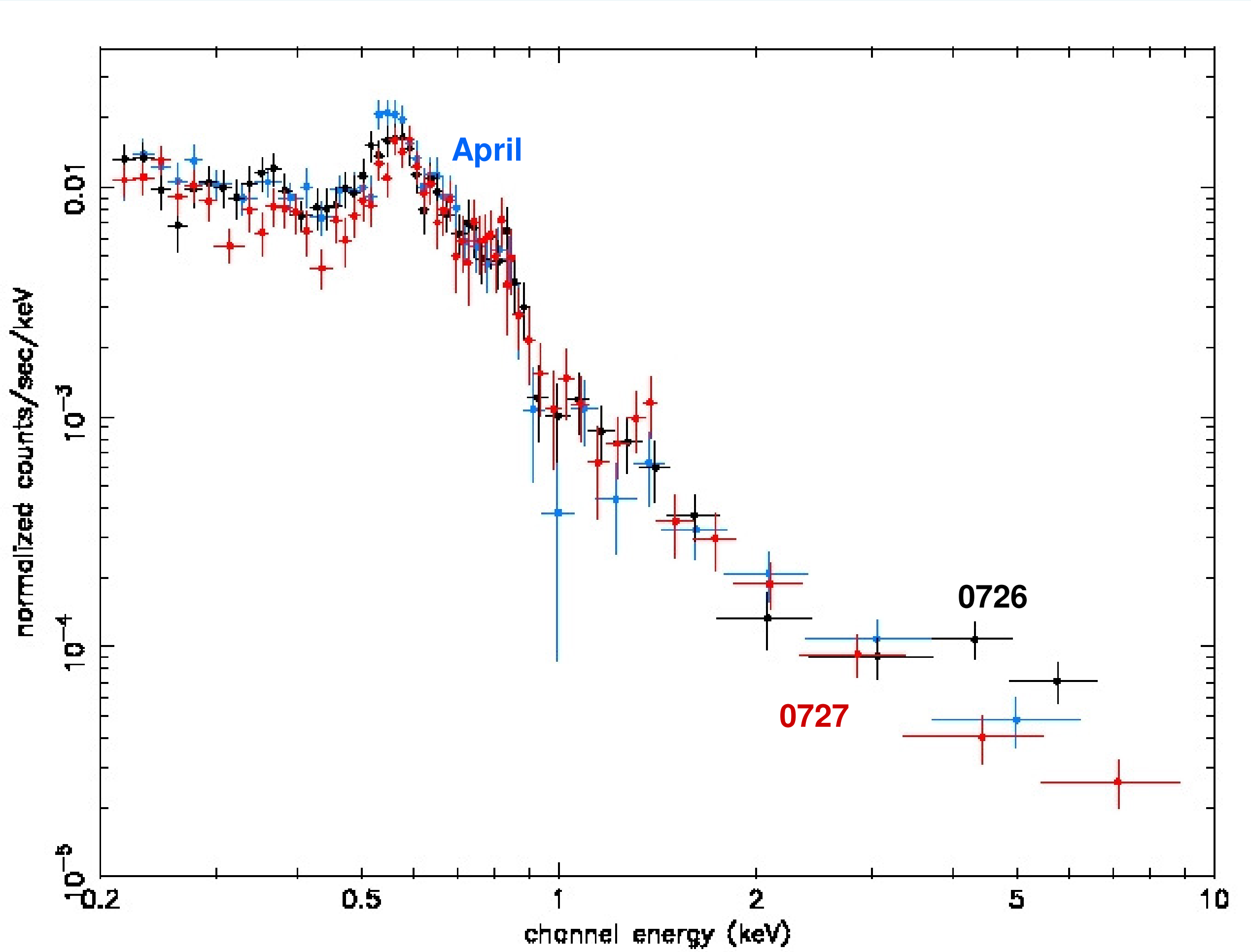
Disk emission well fitted with one ‘mekal’ model (kT = 0.42 +/- 0.02 keV) with solar abundances + line contribution by MgXI and SiXIII (solar activity)

→ Consistent with elastic scattering and carbon K-shell fluorescence of solar X-rays

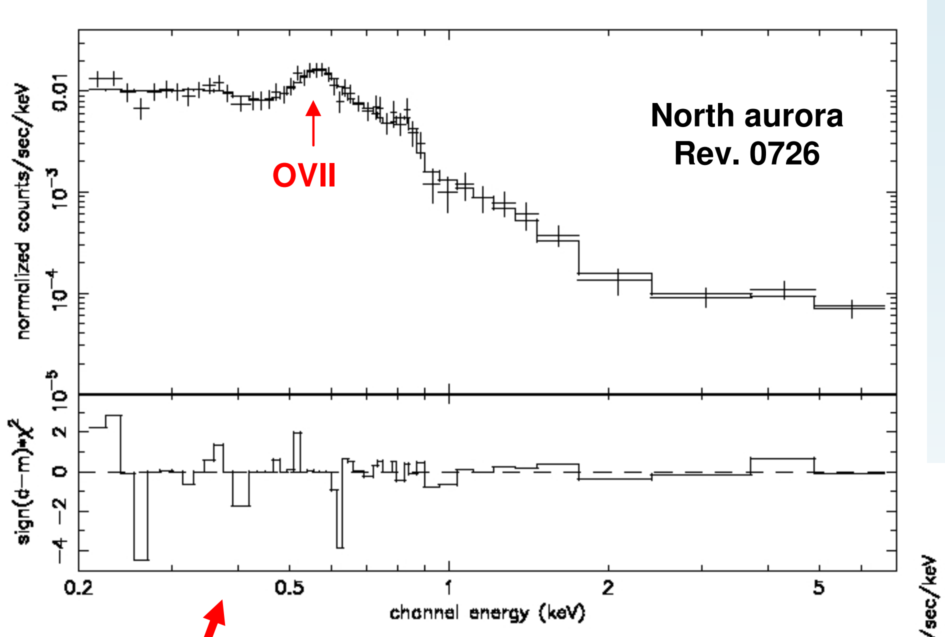
Branduardi-Raymont et al. 2007a

XMM-Newton – Apr. & Nov. 2003: EPIC

Jupiter's North aurora spectra



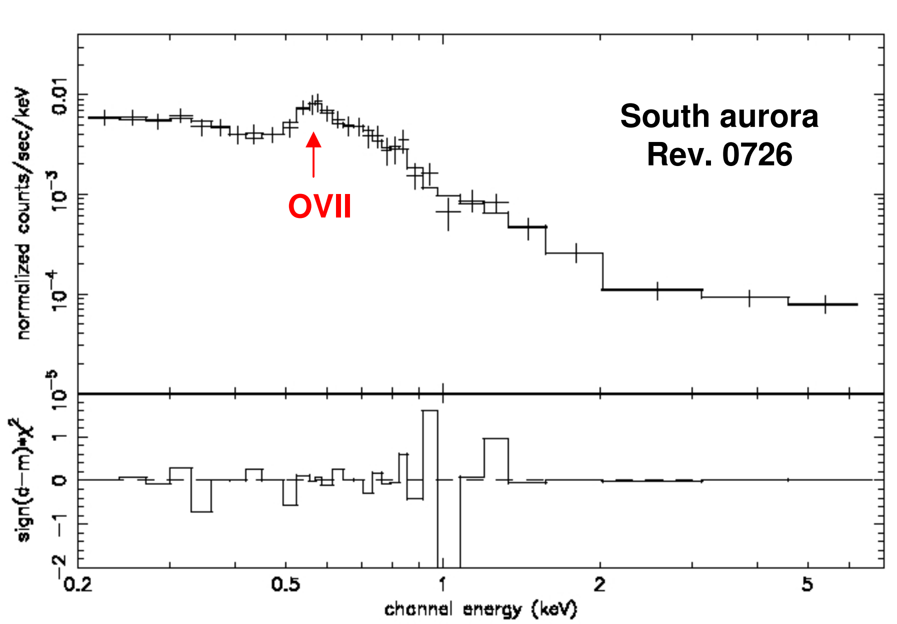
XMM-Newton – Nov. 2003: EPIC



Auroral soft X-ray lines (C/S?, OVII, OVIII) → CX (ion origin?)

Shape of high energy component varies between rev. 0726 and 0727…

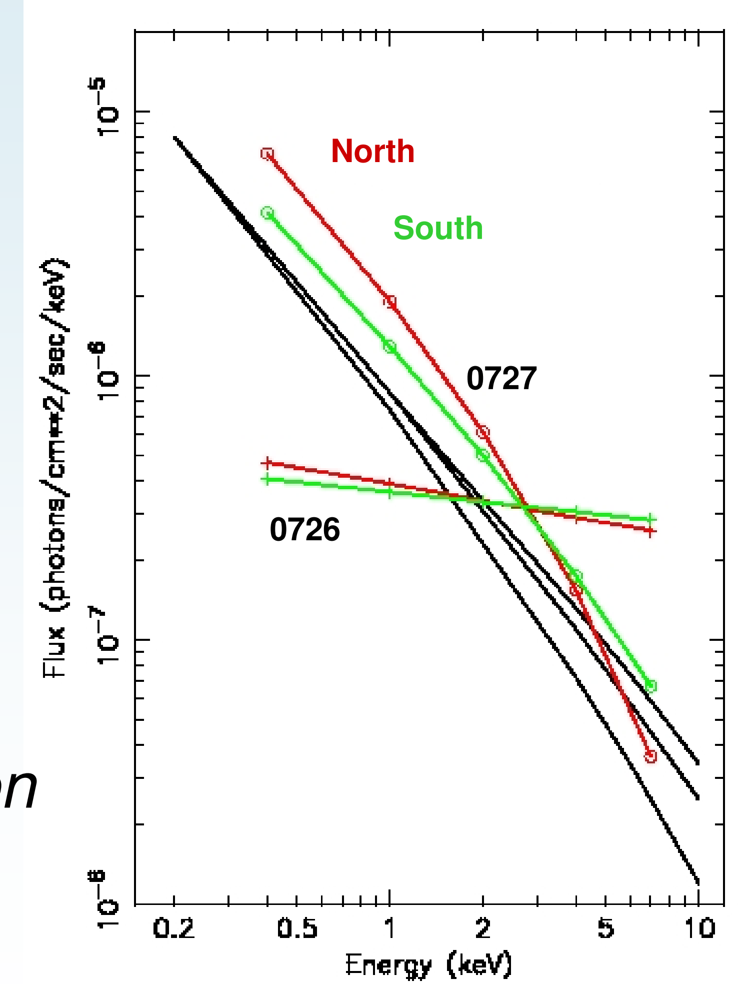
High energy spectral slope best fitted by $\Gamma \sim 0.2$ power law



Branduardi-Raymont et al. 2007b

XMM-Newton – Nov. 2003: EPIC

Singhal et al. (1992) predicted bremss. flux of precipitating electrons with characteristic energies of 10, 30, 100 keV (black)

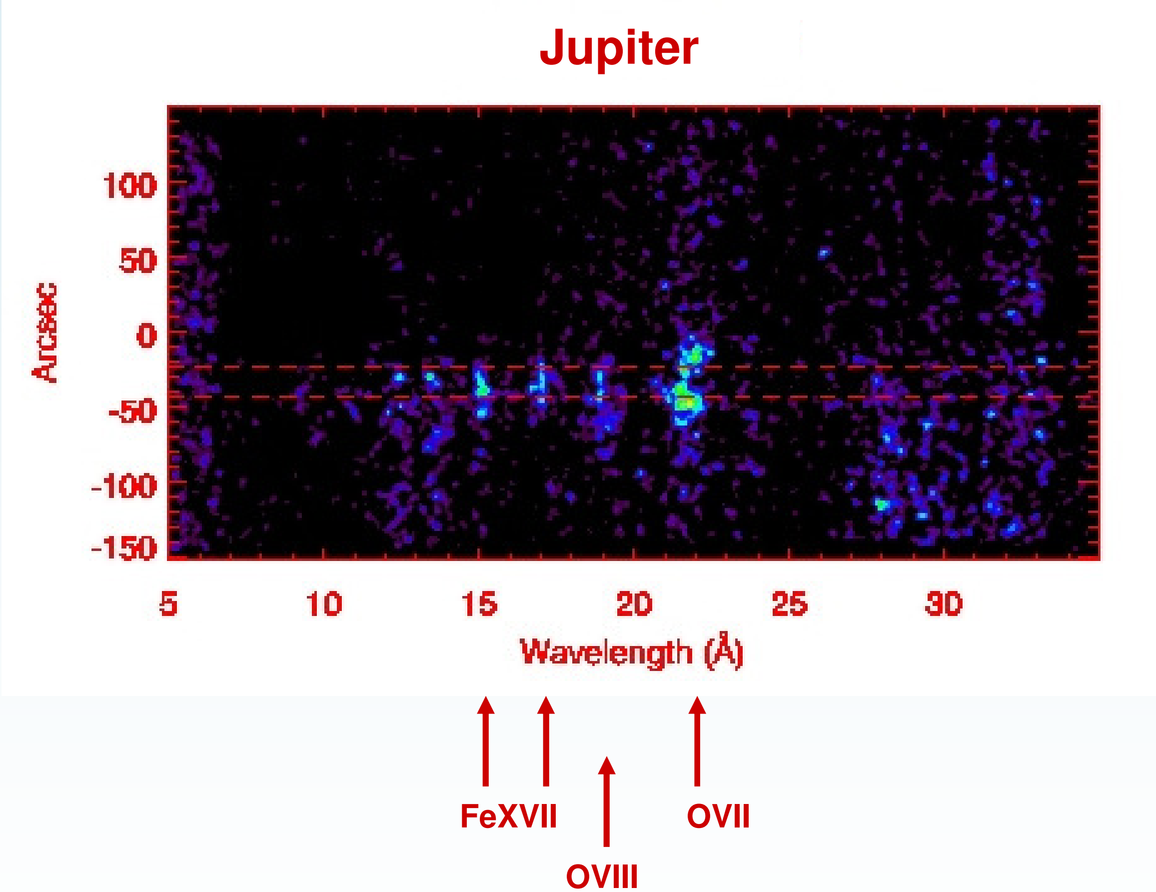


Predicted e⁻ bremss. in Jupiter's aurorae revealed by *XMM-Newton*

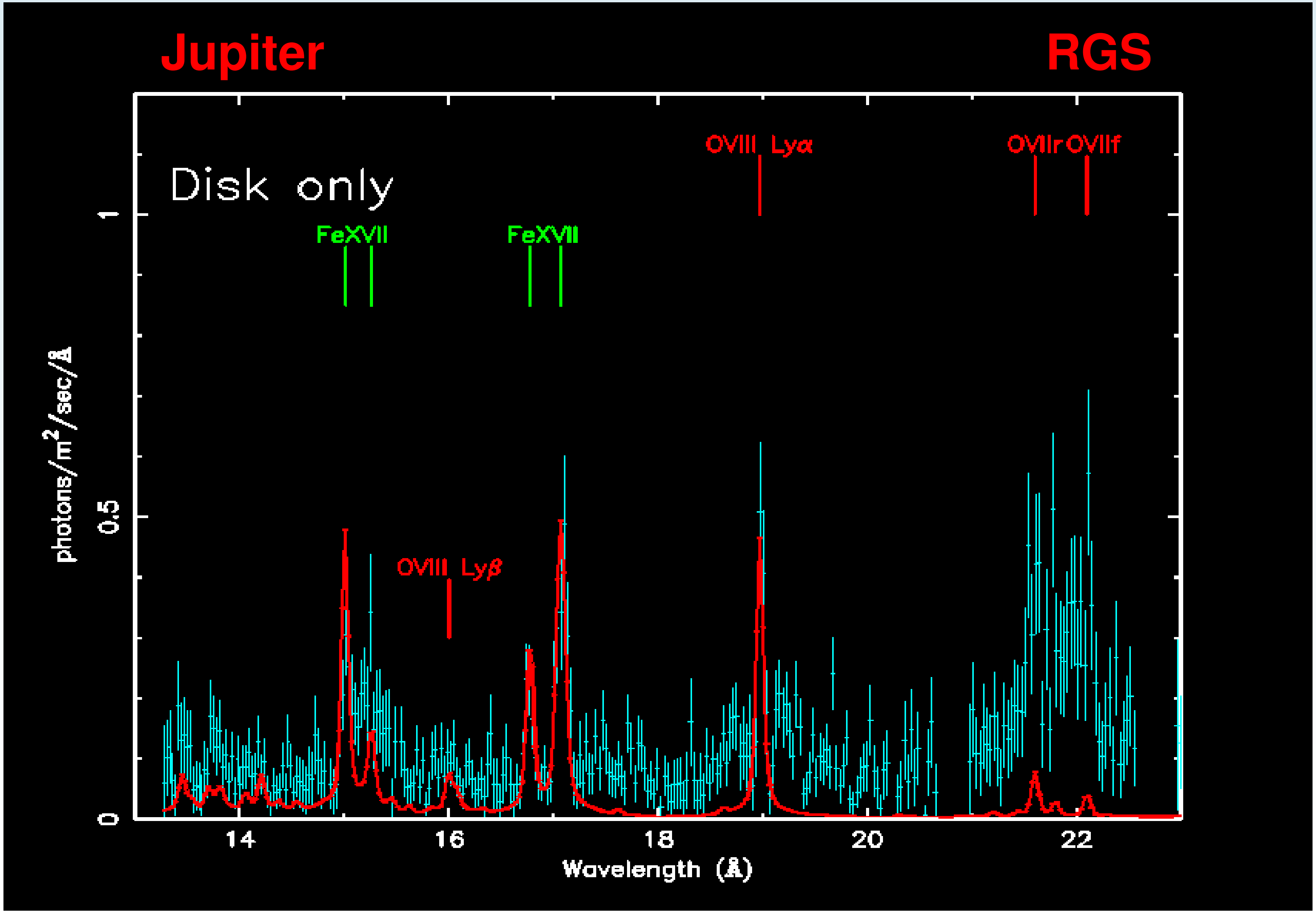
and

shown to be variable in flux and spectral shape (solar activity)

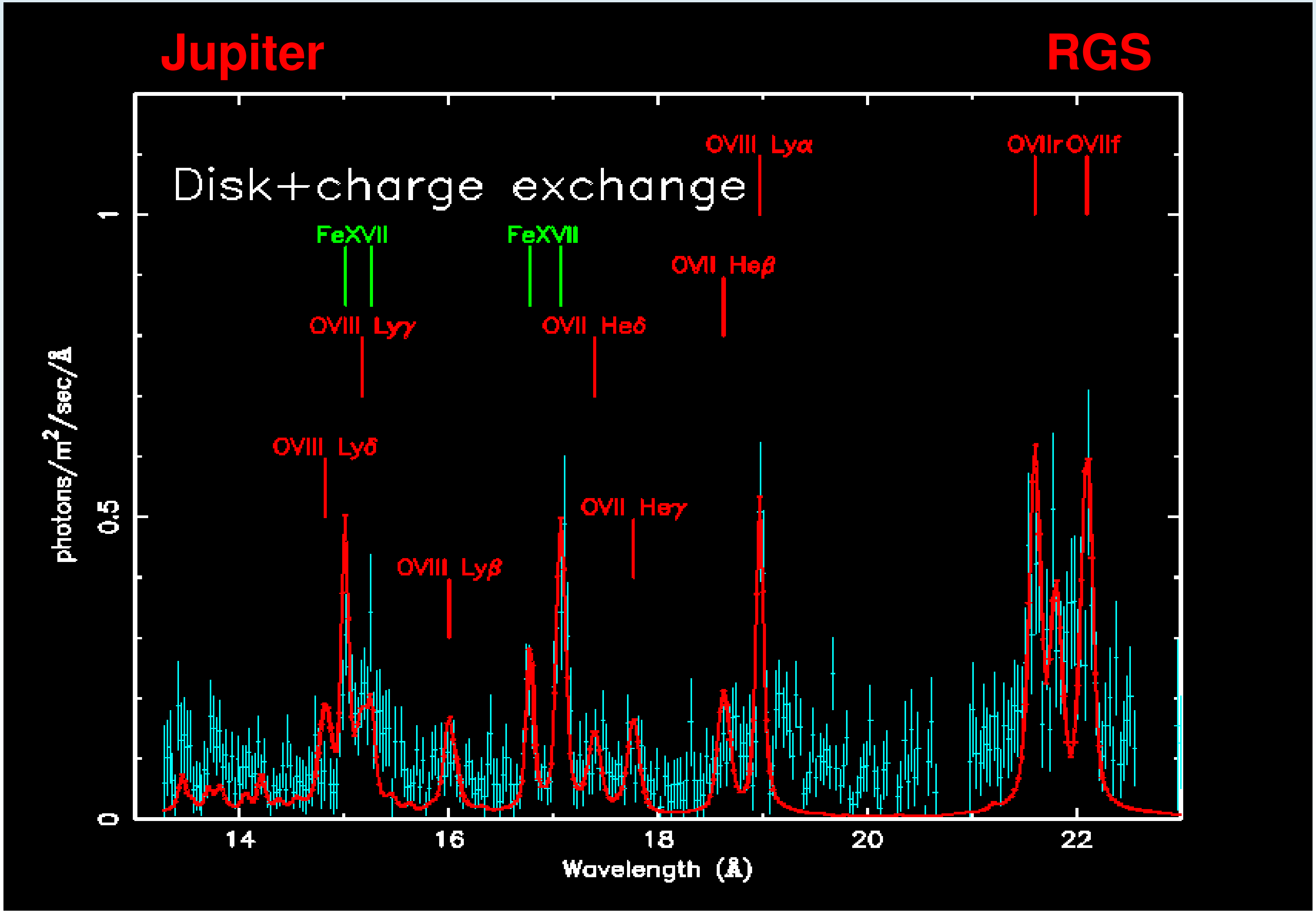
XMM-Newton – Nov. 2003: RGS

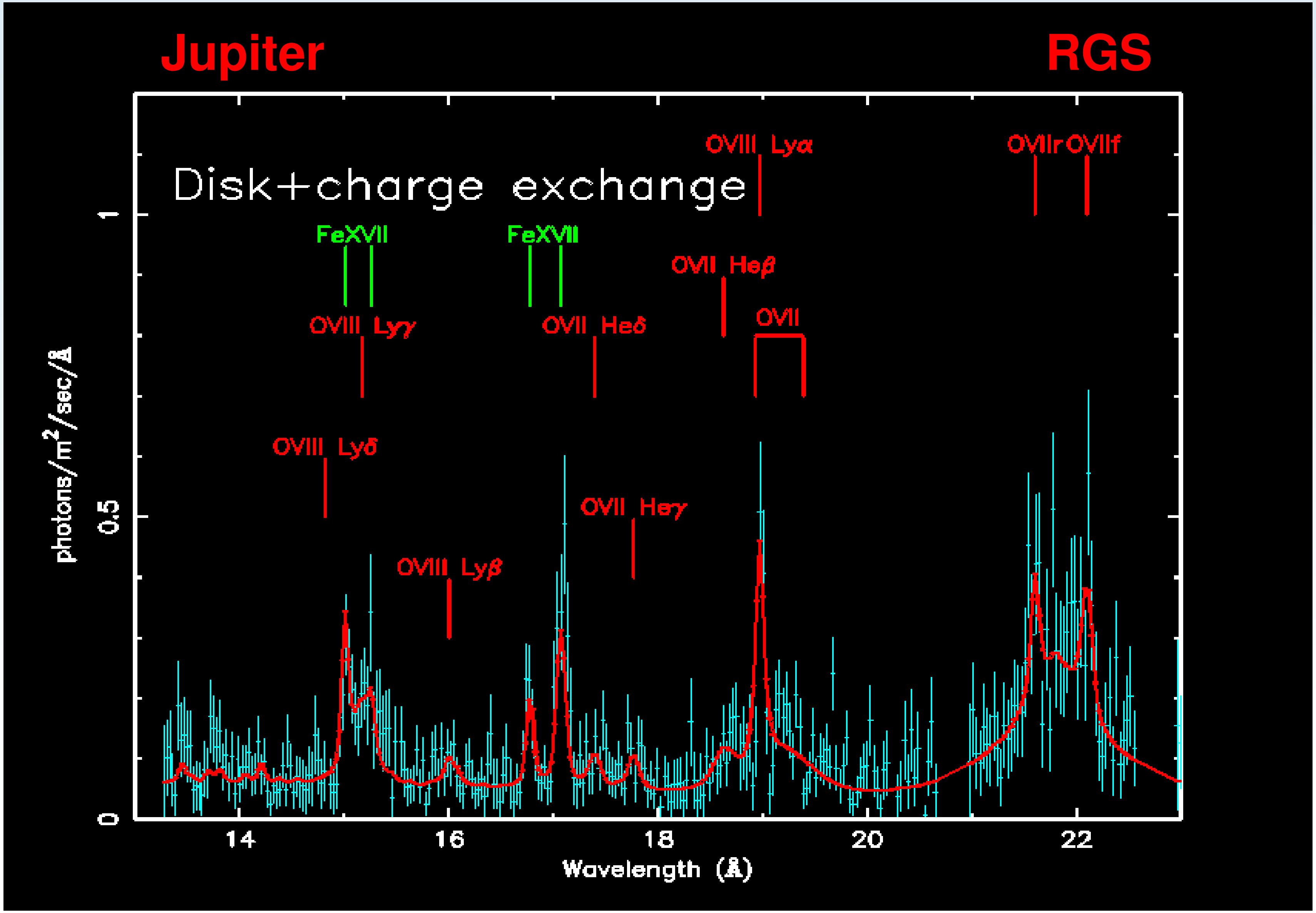


RGS clearly resolves auroral CX emission lines from disk contribution



Jupiter
RGS
Disk only
FeXVII
FeXVII
OVIII Lyα
OVIIr OVIIf
OVIII Lyβ
photons/m²/sec/Å
0
0.5
1
14
16
18
20
22
Wavelength (Å)


Jupiter
RGS
Disk+charge exchange
OVIII Lyα
OVIIr OVIIf
FeXVII
FeXVII
OVII Heβ
OVIII Lyγ
OVII Heδ
OVIII Lyδ
OVII Heγ
OVIII Lyβ
photons/m^2/sec/Å
0
0.5
1
14
16
18
20
22
Wavelength (Å)



Jupiter
RGS
Disk+charge exchange
FeXVII
FeXVII
OVIII Lyα
OVIIr OVIIf
OVII Heβ
OVII
OVIII Lyγ
OVII Heδ
OVIII Lyδ
OVII Heγ
OVIII Lyβ
photons/m²/sec/Å
0
0.5
1
14
16
18
20
22
Wavelength (Å)

Jupiter

XMM-Newton RGS results

- FWHM of broad OVII and OVIII lines imply velocities of +/- 5000 km s^{-1} → energies of ~ 2.5 MeV for O ions

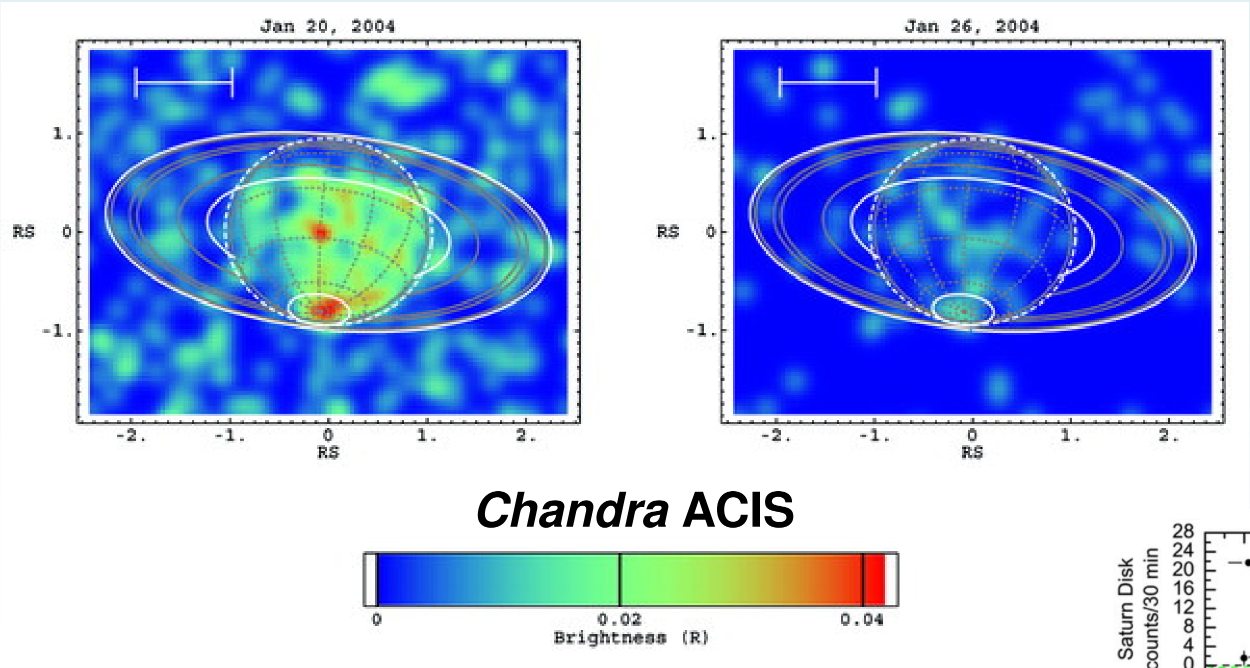
  → consistent with energies required by models
  (Cravens et al., 2003; Bunce et al. 2004):
  1 MeV/amu for magnetospheric ions
  100 keV/amu for solar wind

- Broad OVIII shifted to the red by ~4500 km s^{-1}

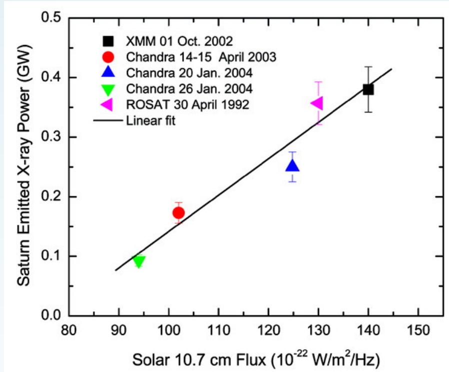
- Wavelength of broad OVII emission consistent with that of the triplet intercombination line

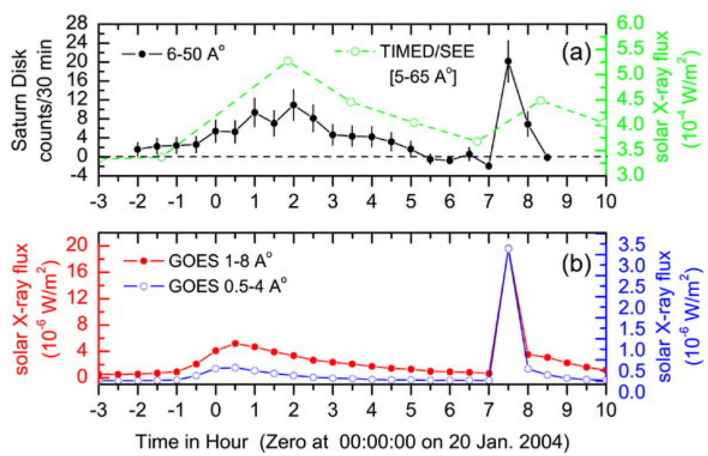
On Saturn …

- Disk and polar cap X-ray emissions have similar coronal-type spectra (unlike Jupiter)



Bhardwaj et al. 2005a



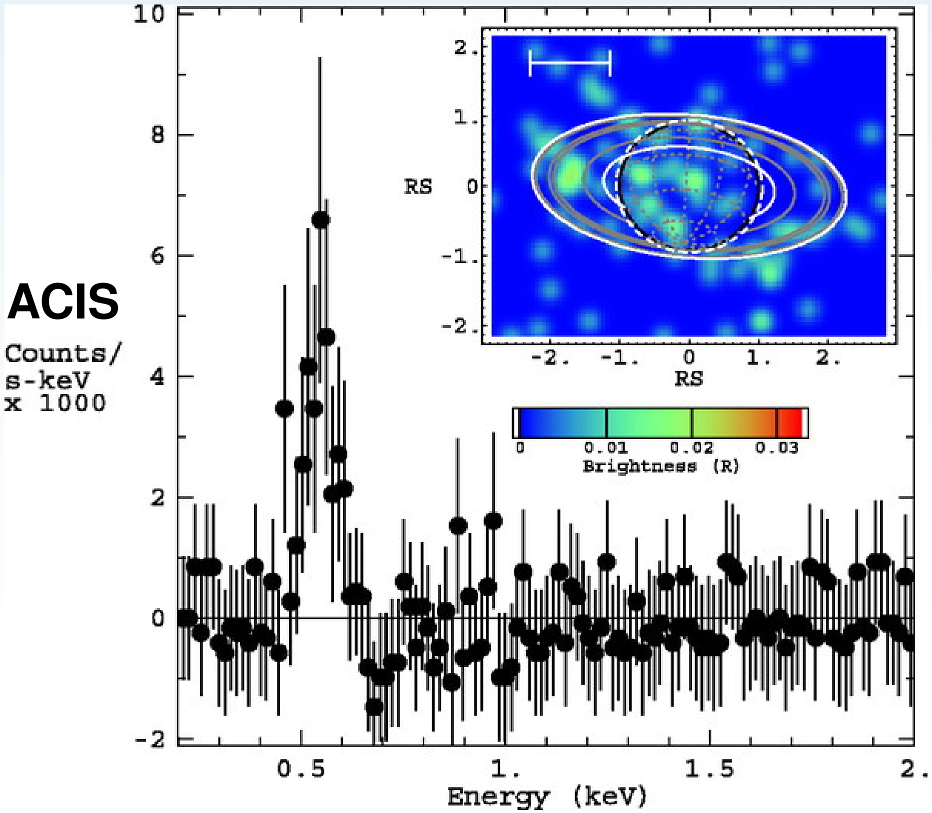


- Flux variability suggests X-ray emission is controlled by the Sun

Saturn's rings

- 0.53 keV O-Kα fluorescent line (~1/3 of disk emission)
- Scattering of solar X-rays on atomic oxygen in H_2O icy ring material (tenuous atmosphere by solar photo-production)

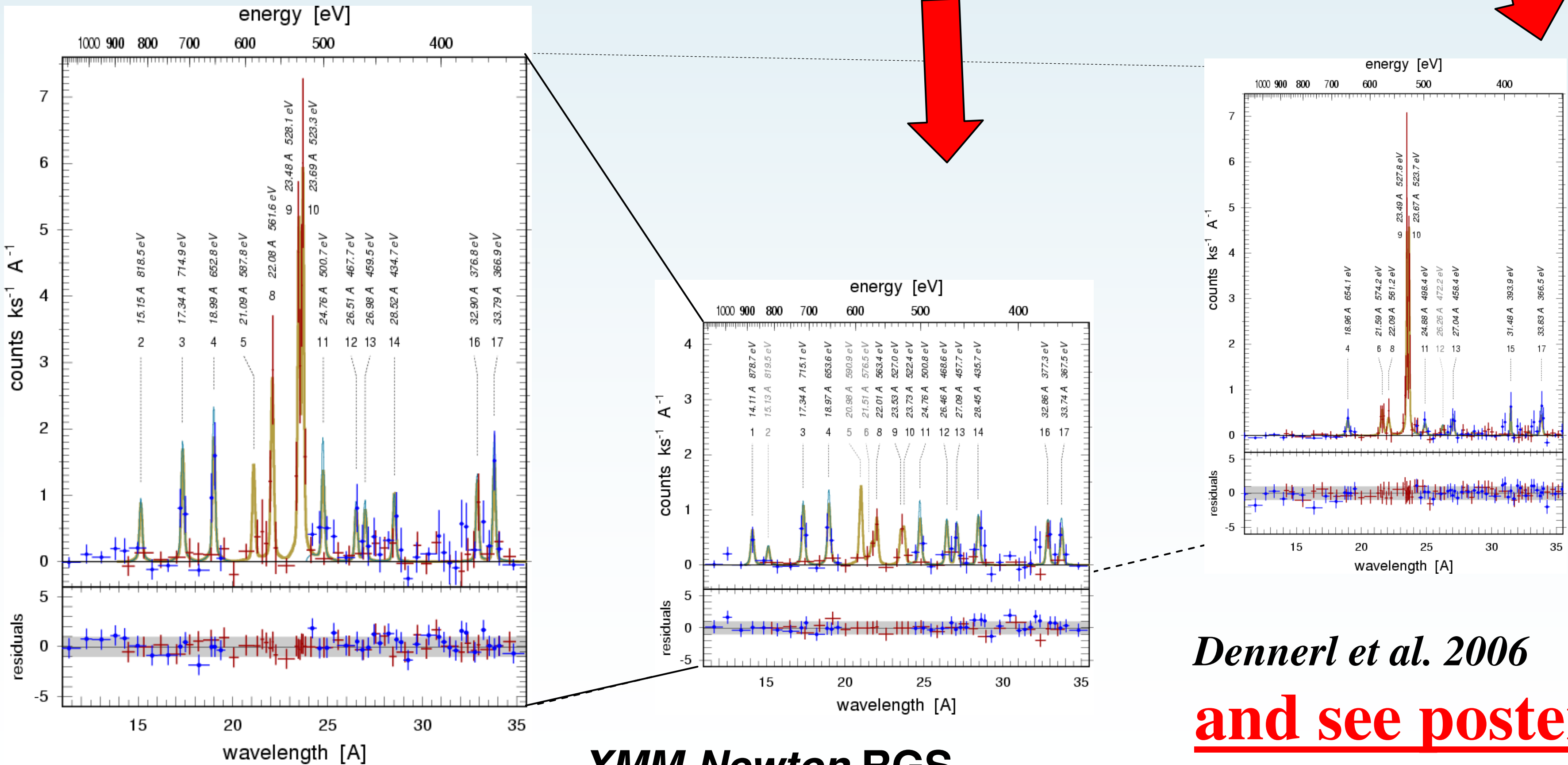
***Chandra* ACIS**



Bhardwaj et al. 2005b

Mars disk and exosphere (halo)

- Fluorescent scattering of solar X-rays in CO_2 atmosphere
- Solar wind charge exchange (SWCX) in the exosphere



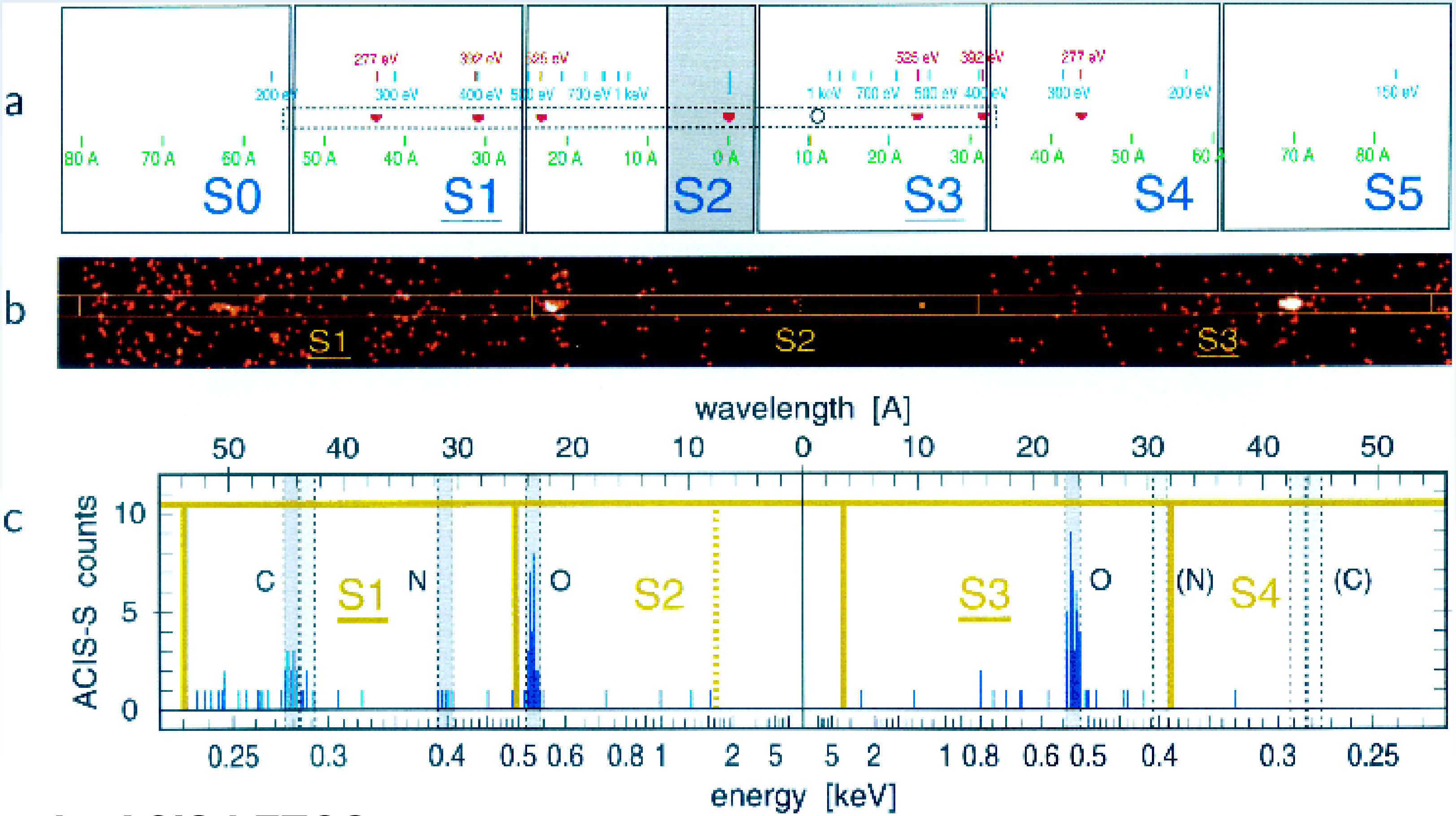
XMM-Newton **RGS**

Dennerl et al. 2006

and see poster!

X-rays from Venus

- Fluorescent scattering of solar X-rays in upper atmosphere
- O-Kα, C-Kα (and N-Kα ?) detected; also CO/CO_2 signature

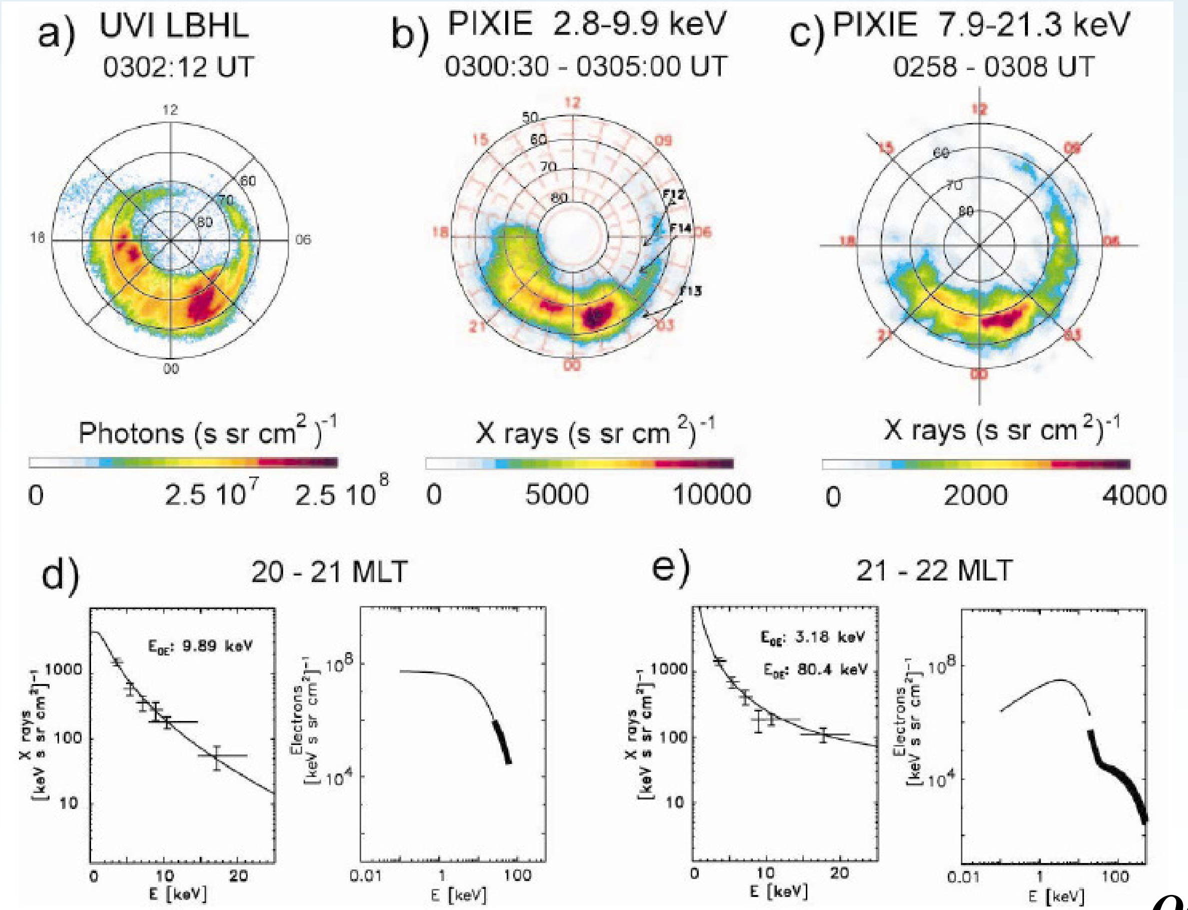


***Chandra* ACIS/LETGS**

Dennerl et al. 2002

Earth's aurorae: high X-ray energies

- Since 1960s hard X-ray observations from balloons (> 20 keV)
- PIXIE experiment on *Polar* : > 3 keV electron bremsstrahlung



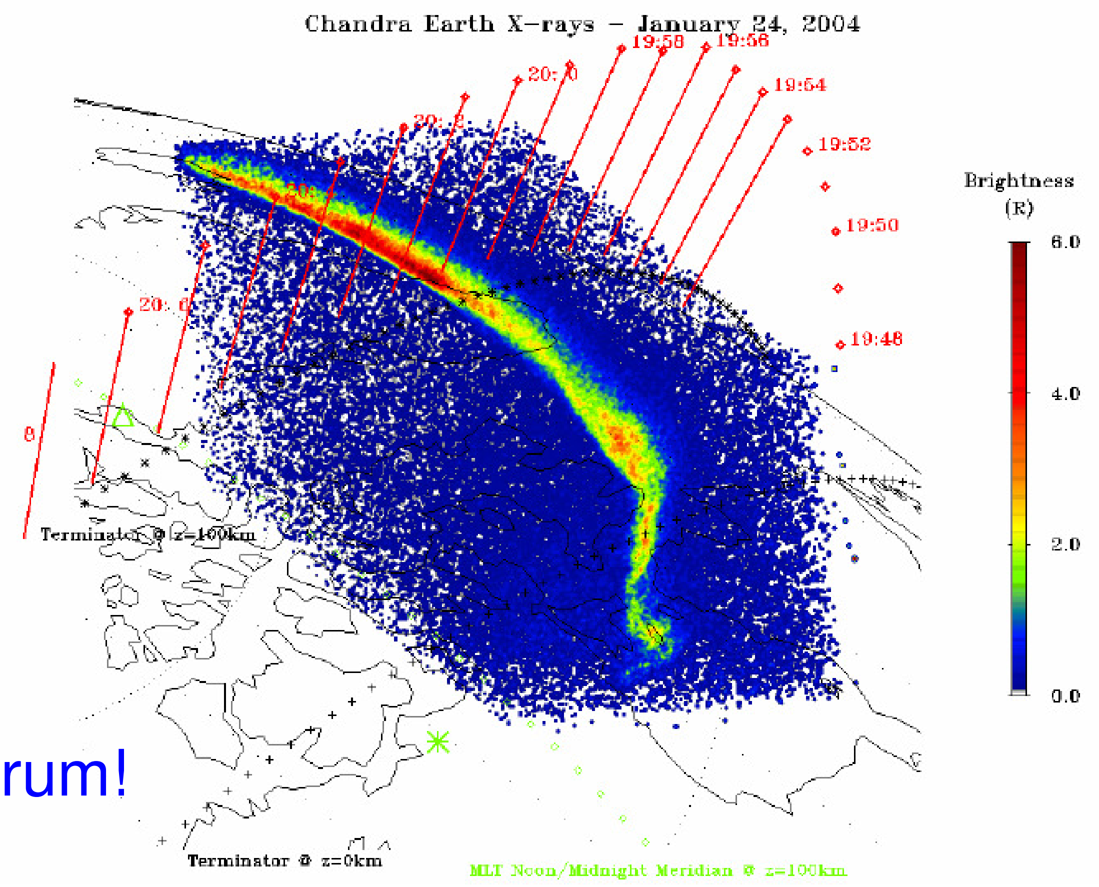
Ostgaard et al. 2001

Earth's aurorae: low X-ray energies

- Evidence for auroral electron bremsstrahlung and N and O line emission <u>below 2 keV</u> from *Chandra* HRC imaging and simultaneous DMSP F13 electron measurements

- Aurora very variable, with intense arcs and patches ***(Bhardwaj et al. 2006)***

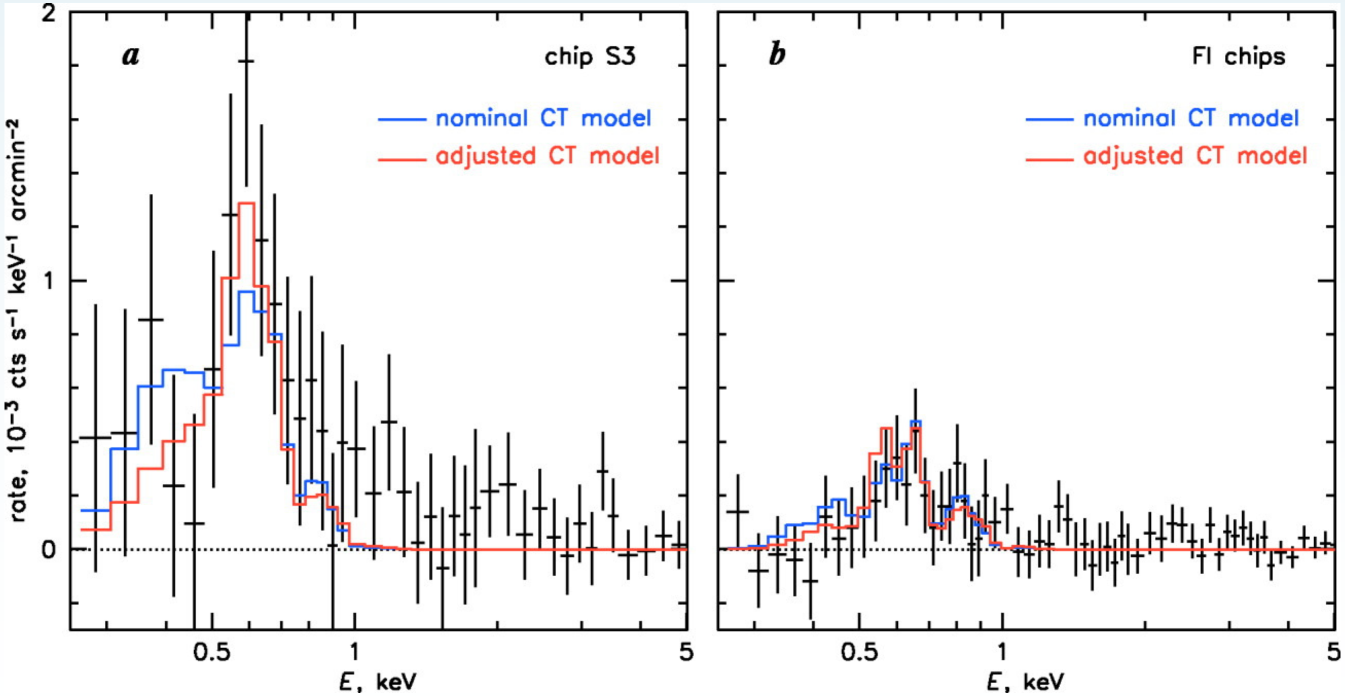
- Not yet shown conclusively that ion precipitation has a part in X-ray production
  → needs high res. spectrum!



Dark side of the Moon

- Time variable oxygen emission lines
- Correlation with solar wind flux → SWCX in Earth's geocorona

***Chandra* ACIS**

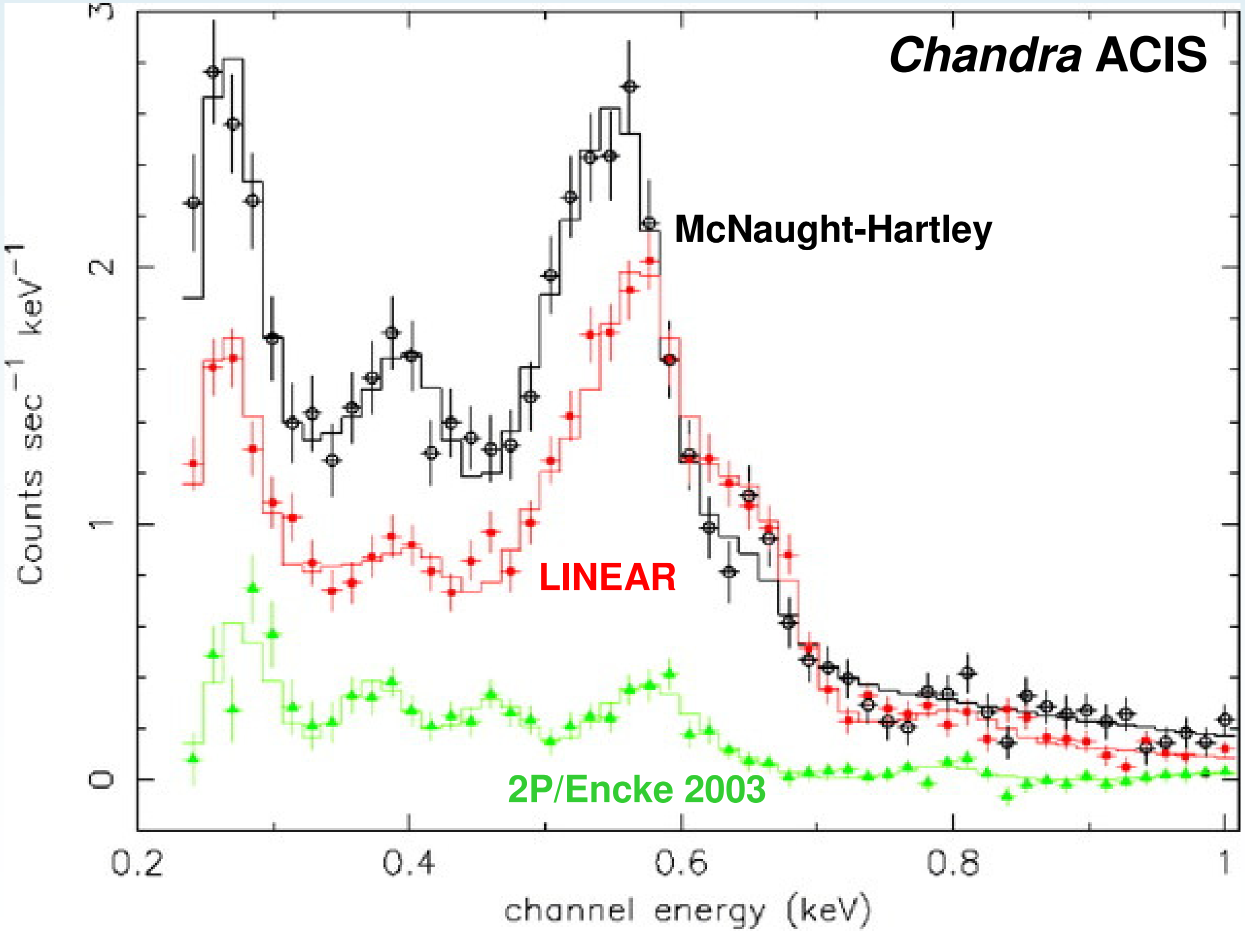


Wargelin et al. 2004

Cometary X-rays

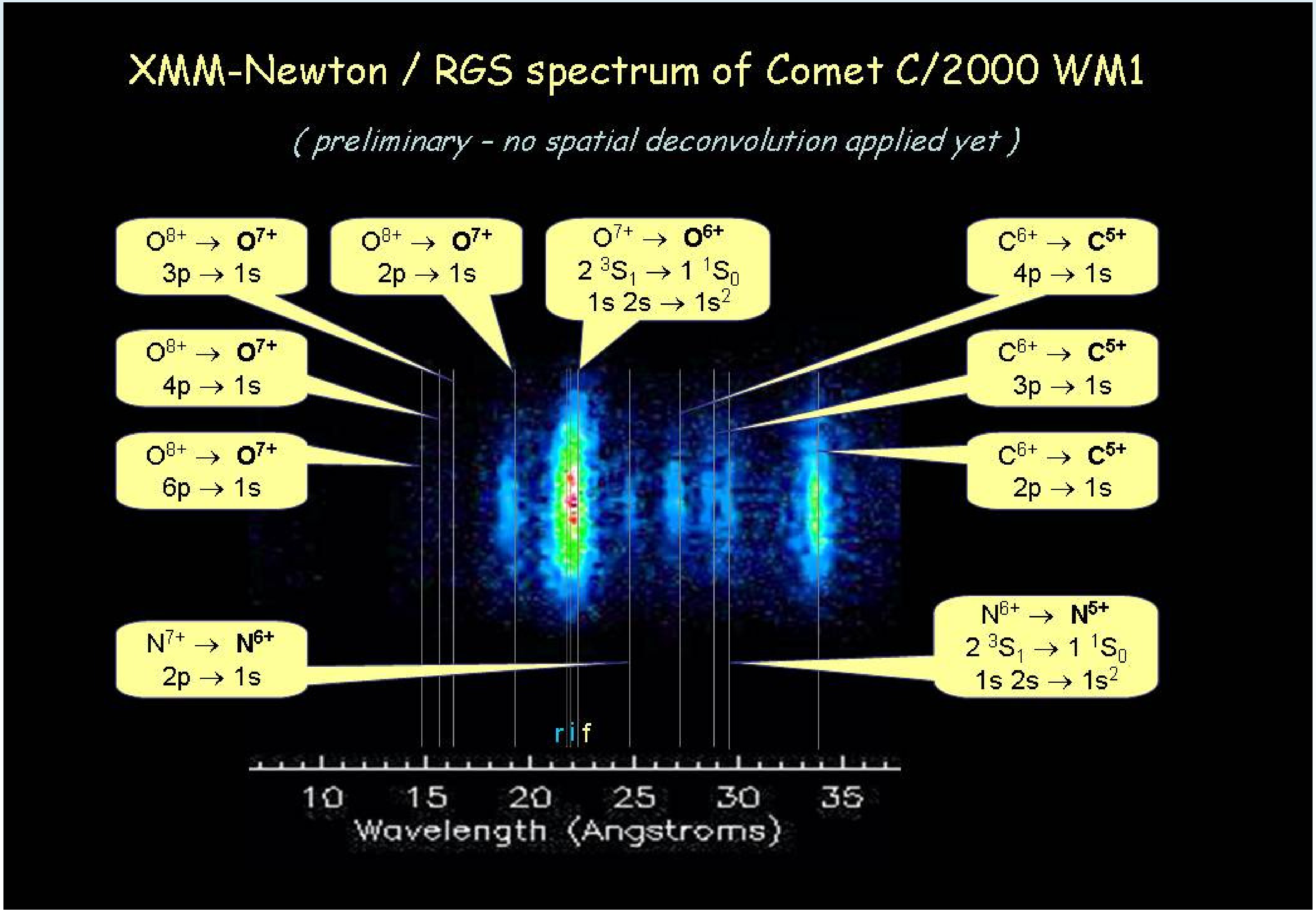
- SWCX with coma neutrals well established emission process
- Cometary spectra reflect state of SW

- Best fit model:
  8 emission lines
  from
  C^{+5}, C^{+6}, N^{+6},
  O^{+7}, O^{+8}, Ne^{+9}



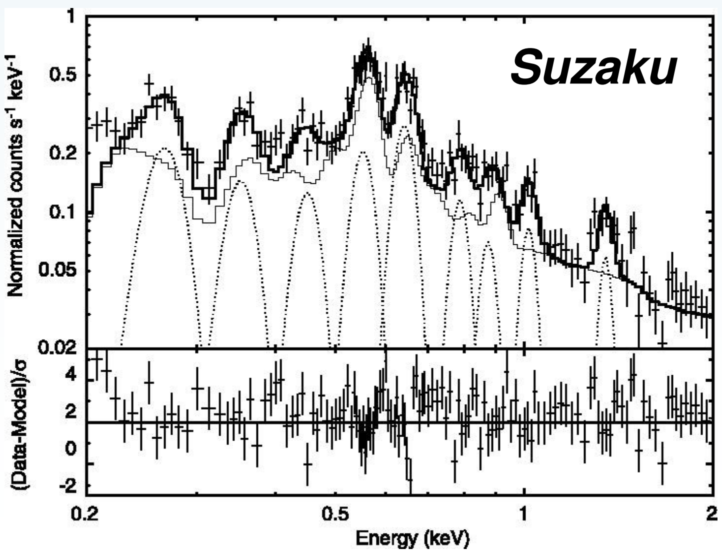
Lisse et al. 2005

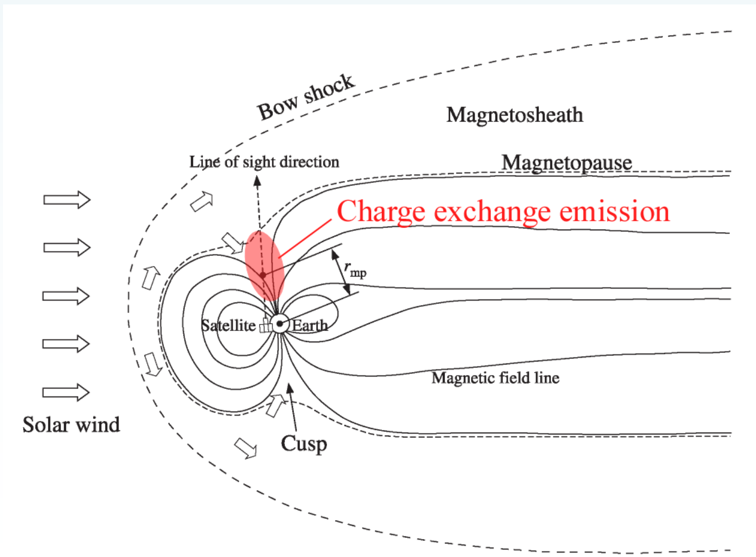
Dennerl et al., in prep.



SWCX and the soft X-ray background

- *Suzaku* observations of the NEP → Increase in soft X-ray lines correlated with solar wind proton flux
- SWCX with neutrals in the Earth's magnetosheath → Half or more of oxygen emission comes from Earth's neighbourood
- SWCX ubiquitous throughout the Universe: solar system, interstellar clouds, galactic winds and galaxy clusters





Fujimoto et al. 2007

Thank you!