X-ray views of the solar system

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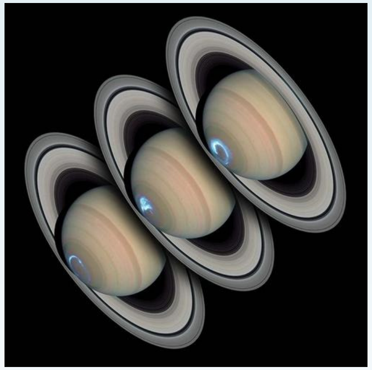
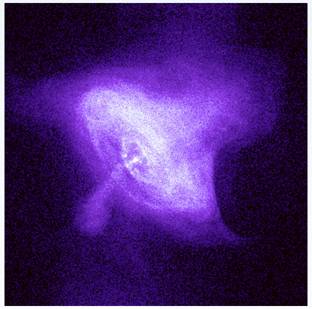
'The X-ray Universe 2008', Granada
27 May 2008

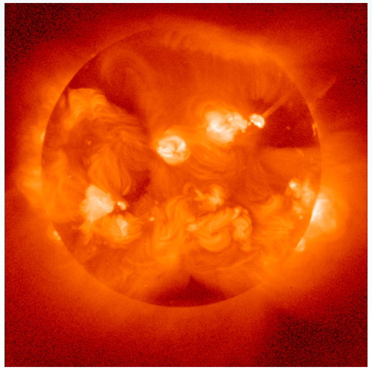
X-ray studies of the solar system

- Reached maturity thanks to *Chandra* and *XMM-Newton* (X-ray imaging + medium and high resolution spectroscopy)

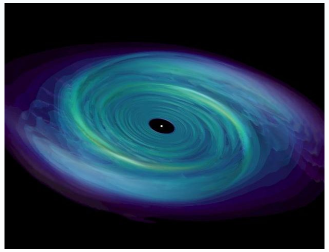


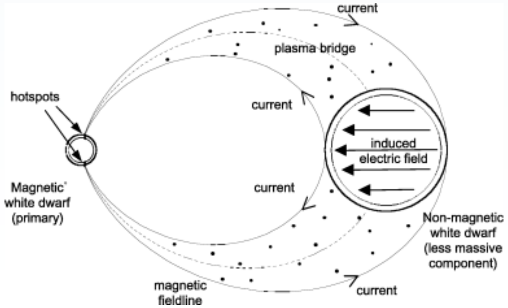
- Processes involve highly energetic plasmas, particle acceleration, powerful magnetic fields, fast rotating bodies, reprocessing of solar radiation





- '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.

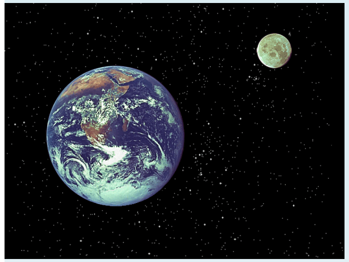
  $$H_2 + O^{7+} \rightarrow H_2^{+} + O^{6+} + h\nu$$

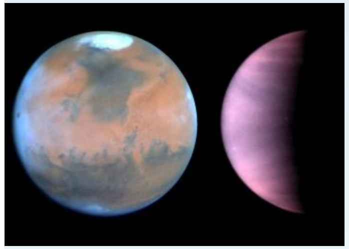
  Low energy solar wind heavy ions (C, O, Ne - SWCX) :
  Comets, heliosphere, Earth geocorona, Venus and Mars exospheres
  Very energetic ambient heavy ions (low-charge ions accelerated, highly charged by stripping, CX): Jupiter's aurorae

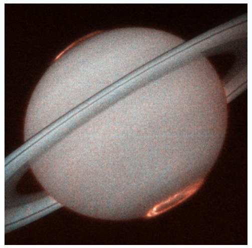
- Electron bremsstrahlung

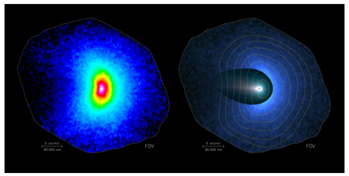
- Elastic and K-shell fluorescent scattering of solar X-rays in planetary atmospheres and on surfaces

(Bhardwaj et al. 2007)









X-rays from the solar system

Object	Auroral	Disk	Other
Venus		S	Exosphere (SWCX)
Earth	E.I. + Brem	S	Geocorona (SWCX)
Moon		S	
Mars		S	Exosphere (SWCX)
Jupiter	CX + Brem	S	
Io, Europa		IPT ion impacts	
Io Plasma Torus	-	-	Brem + OVII
Saturn		S	Rings (S)
Comets			Coma (SWCX)
Asteroids		S	
Heliosphere	-	-	SWCX

Brem = Electron bremsstrahlung E.I. = Electron impacts

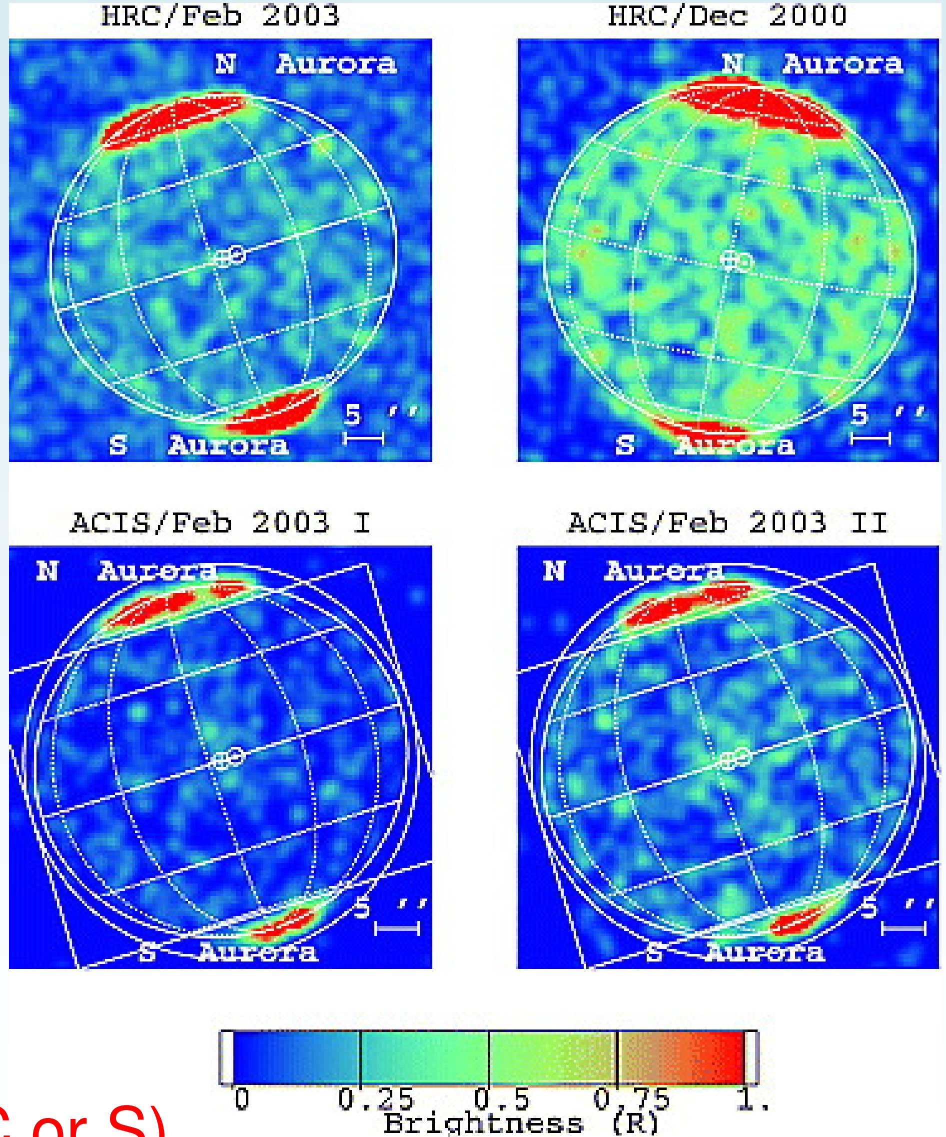
S = Elastic and/or K-shell fluorescent scattering of solar X-rays

X-rays from **Jupiter**

The *Chandra* view

(Bhardwaj et al. 2006) →

Aurorae + disk
X-ray emission



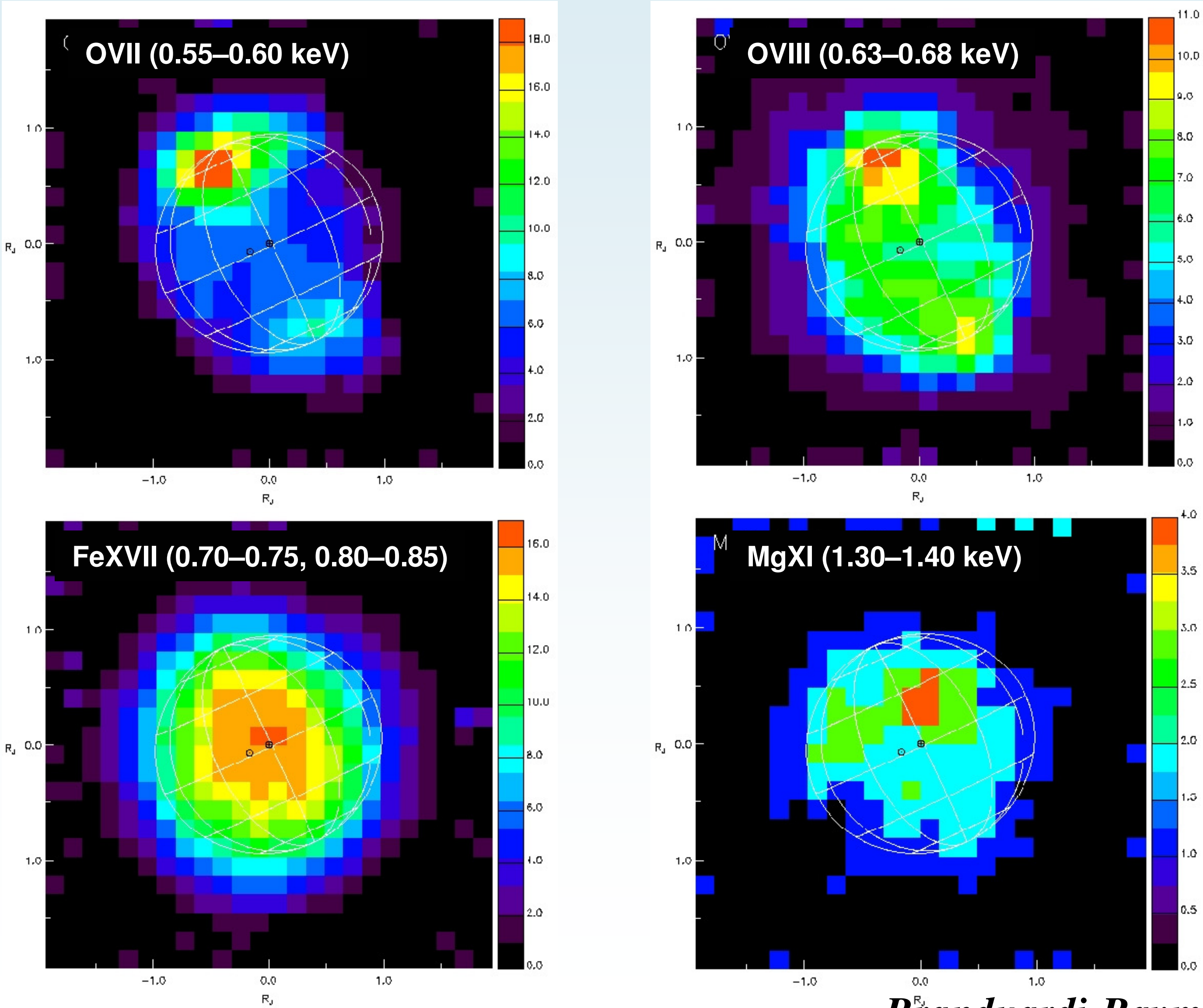
Auroral soft X-rays
K-shell line emission from charge exchange, by energetic ions from > 30 R_J, precipitating along magnetic field lines, e.g.

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

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

Jupiter

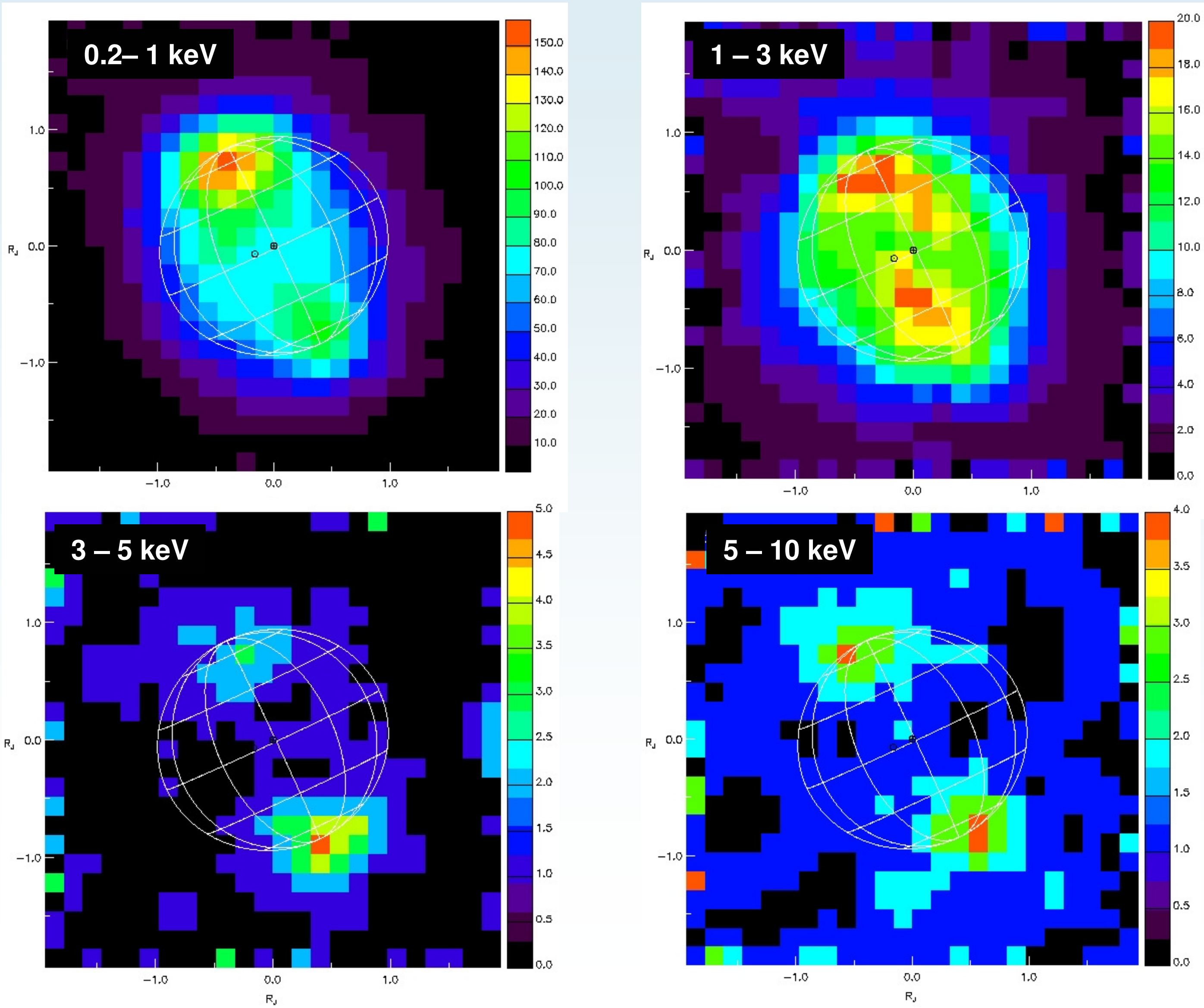
XMM-Newton – Nov. 2003: EPIC



Branduardi-Raymont et al. 2007

Jupiter

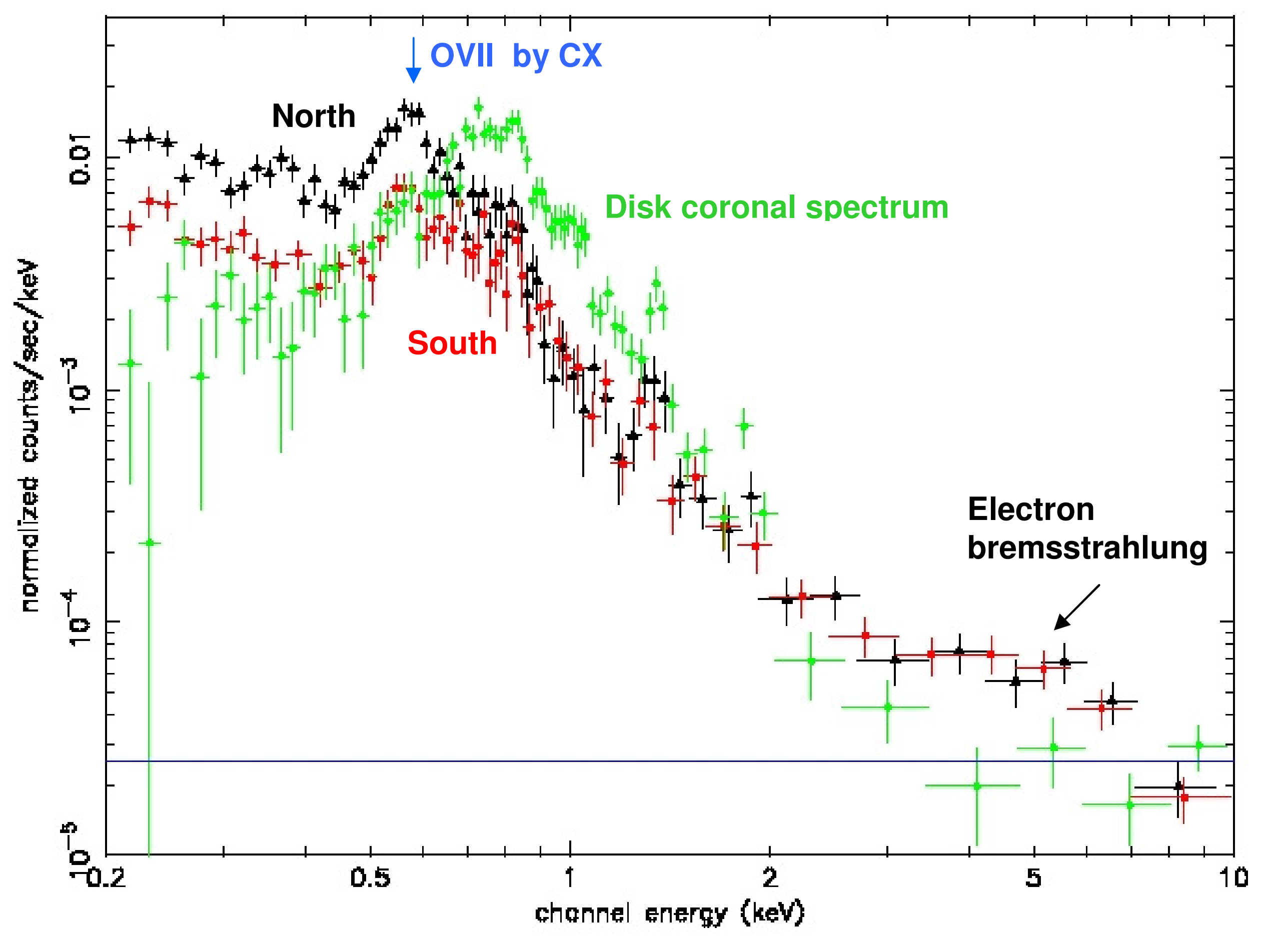
XMM-Newton – Nov. 2003: EPIC



Jupiter

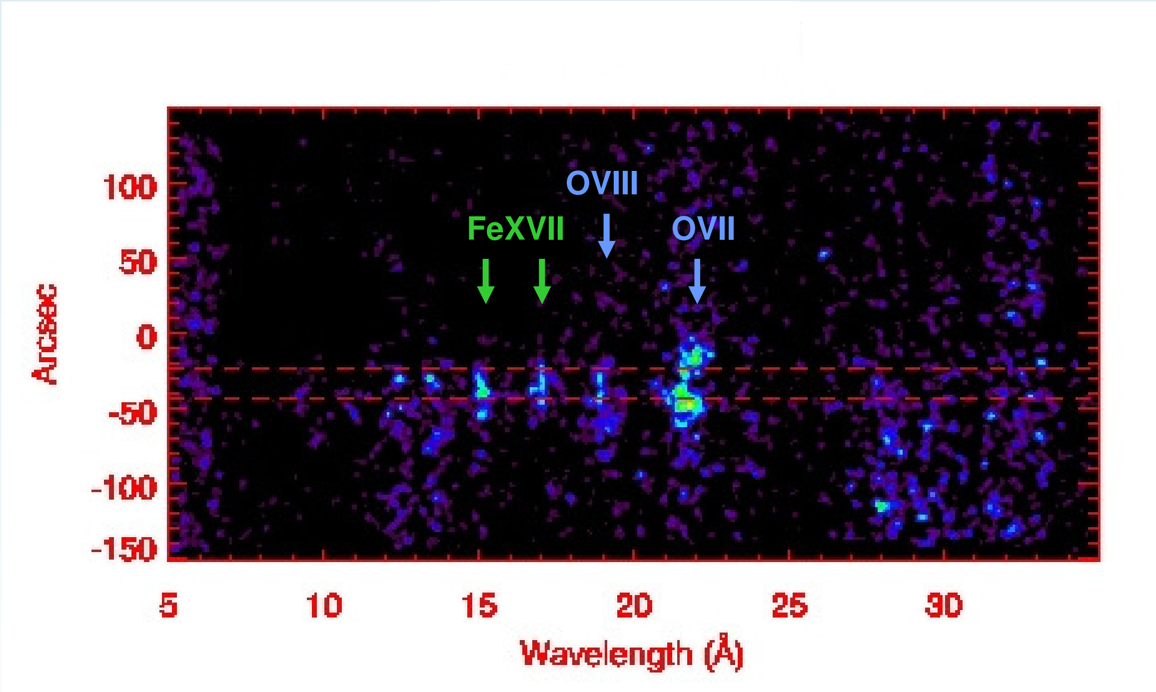
XMM-Newton – Nov. 2003: EPIC

Auroral and disk spectra



Jupiter

XMM-Newton – Nov. 2003: RGS



RGS clearly resolves auroral CX from disk emission lines

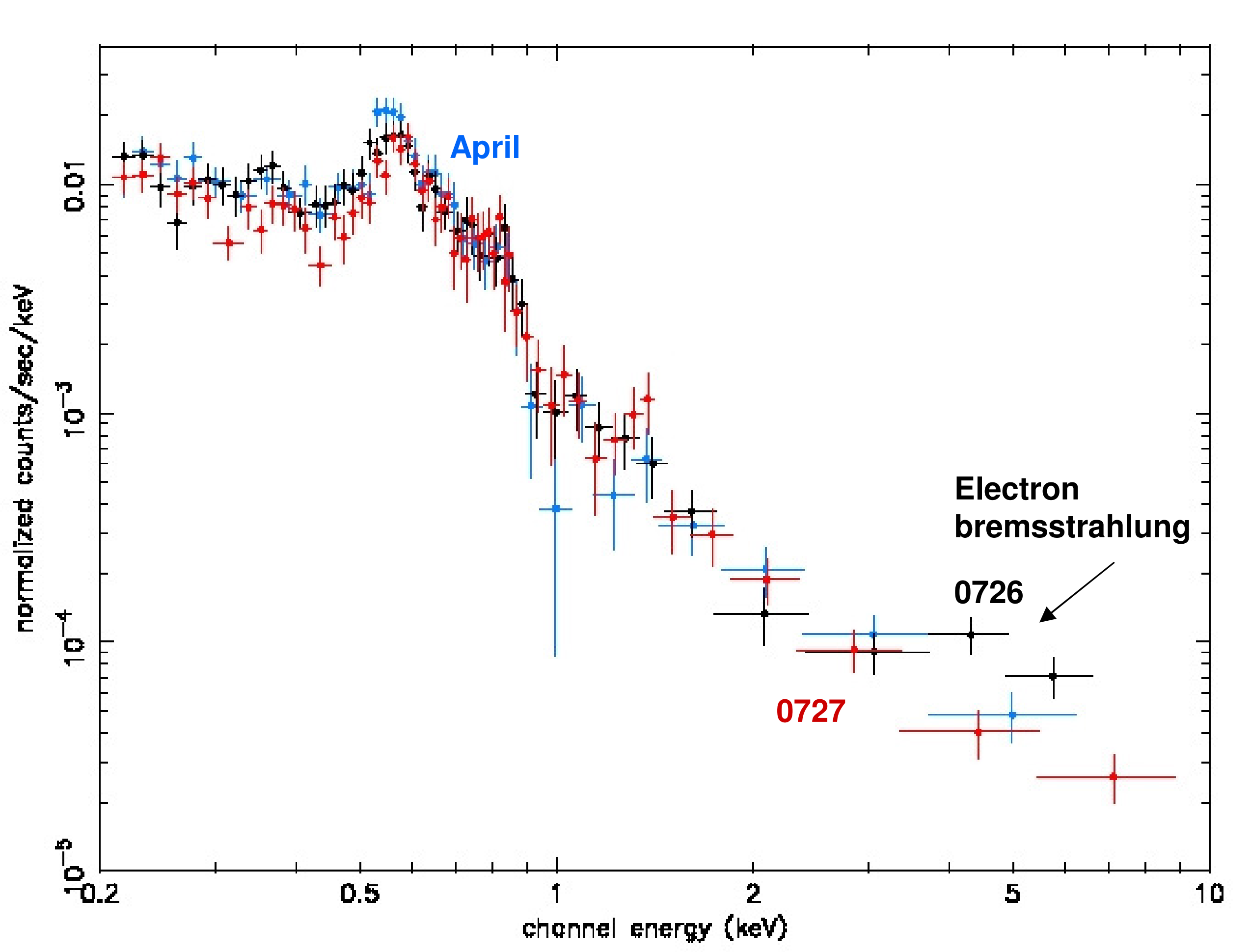
Line broadening → velocities → few MeV energy for O ions, consistent with aurora model predictions

Branduardi-Raymont et al. 2007

Jupiter

XMM-Newton – Apr. & Nov. 2003: EPIC

North aurora spectra

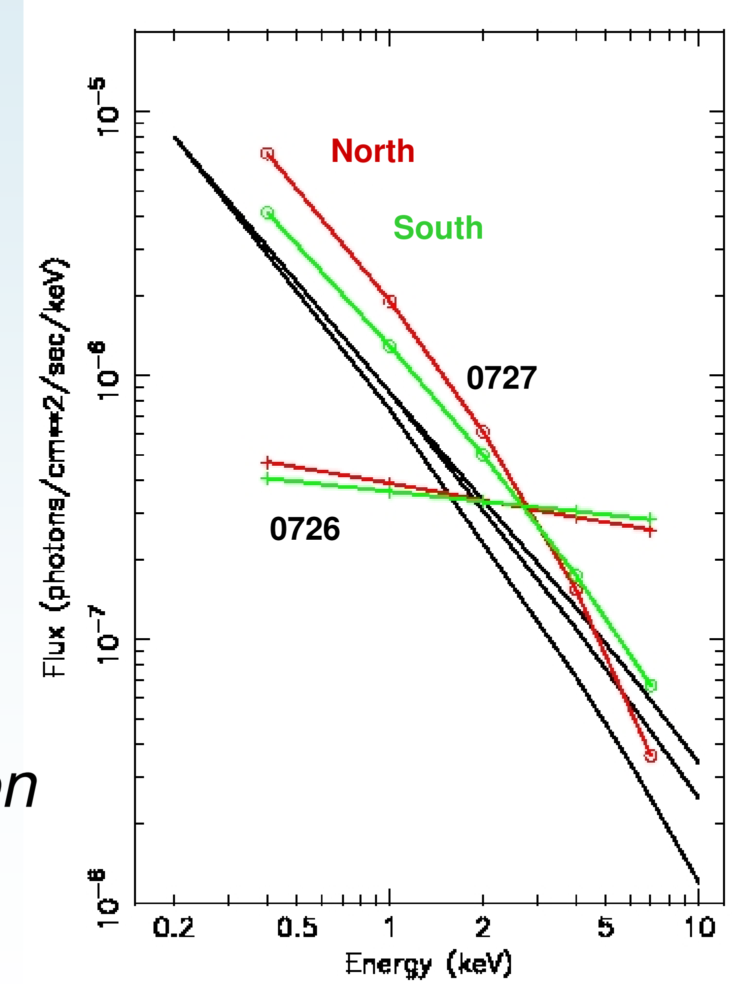


MSSL UCL

Jupiter

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)

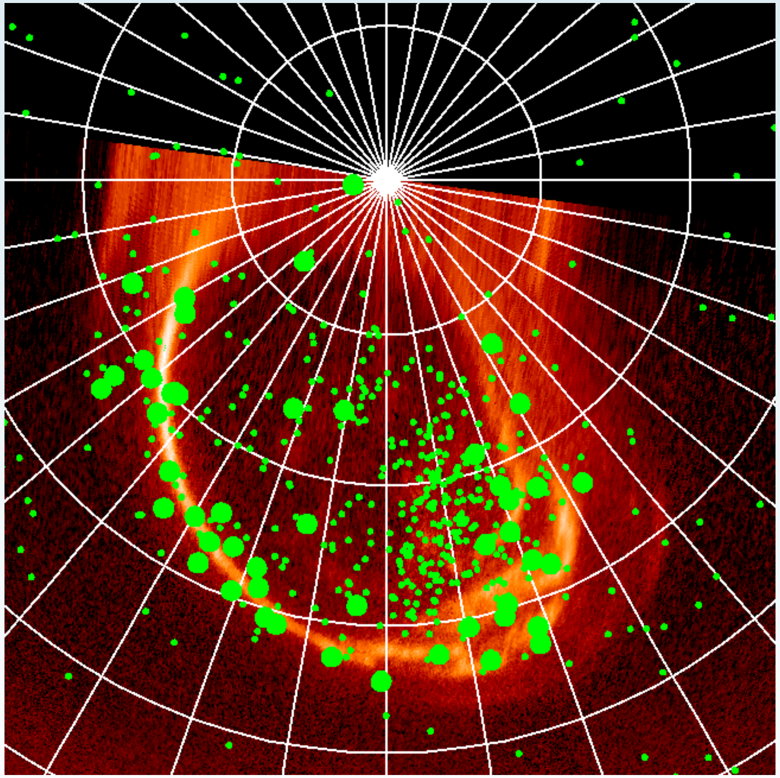
Branduardi-Raymont et al. 2007

Jupiter

Chandra and *Hubble* STIS – Feb. 2003

Chandra ACIS reveals different spatial morphology of soft (ion CX) and hard (electron bremsstrahlung) X-ray events

Simultaneous Hubble STIS images show > 2 keV events coincide with FUV auroral oval and bright features (FUV from excitation of atmospheric H_2 and H by 10 - 100 keV electrons)

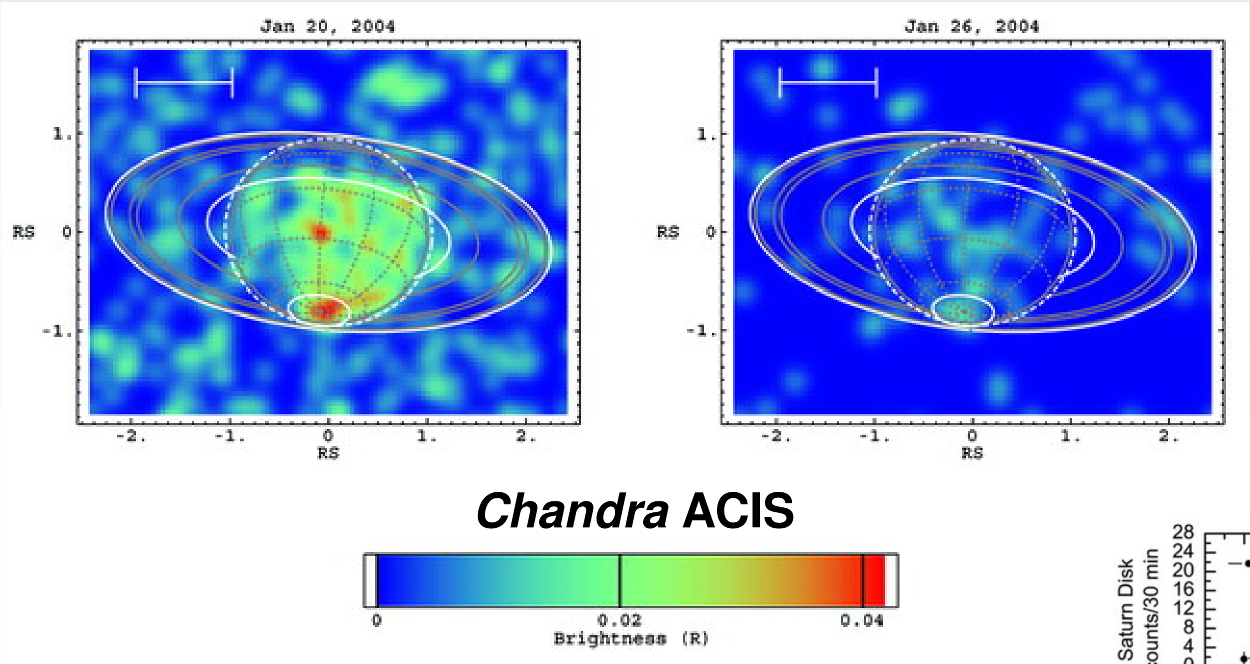


Branduardi-Raymont et al. 2008

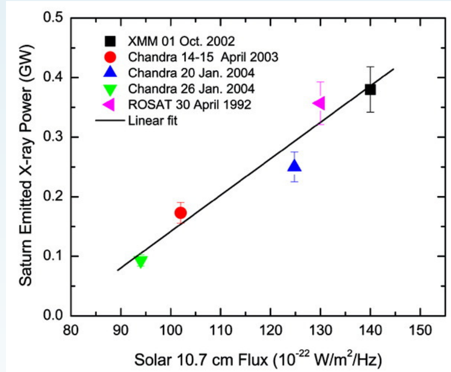
→ Same energetic electrons population likely to be responsible for both, X-ray bremsstrahlung and FUV emission of aurorae

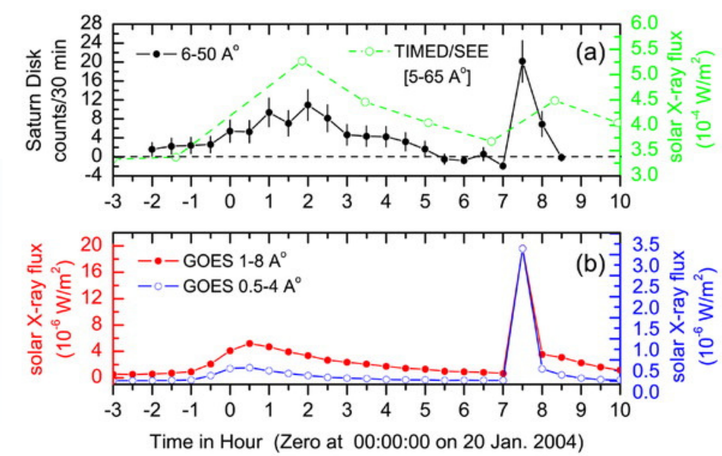
On Saturn …

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



Bhardwaj et al. 2005a



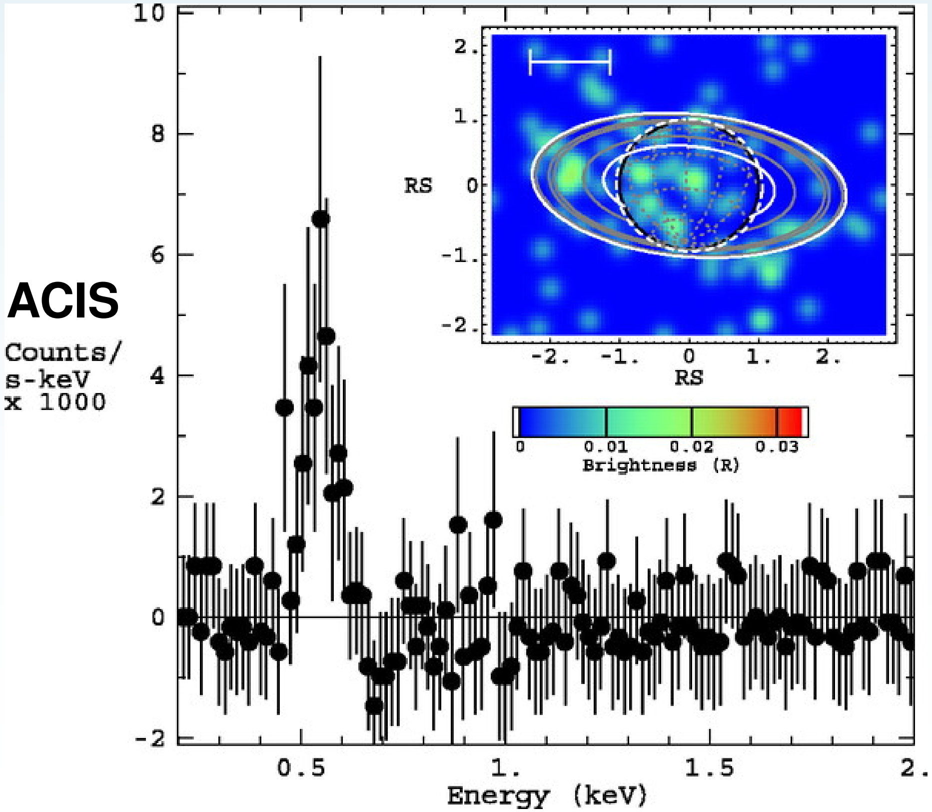


- Flux variability suggests X-ray emission is controlled by the Sun

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

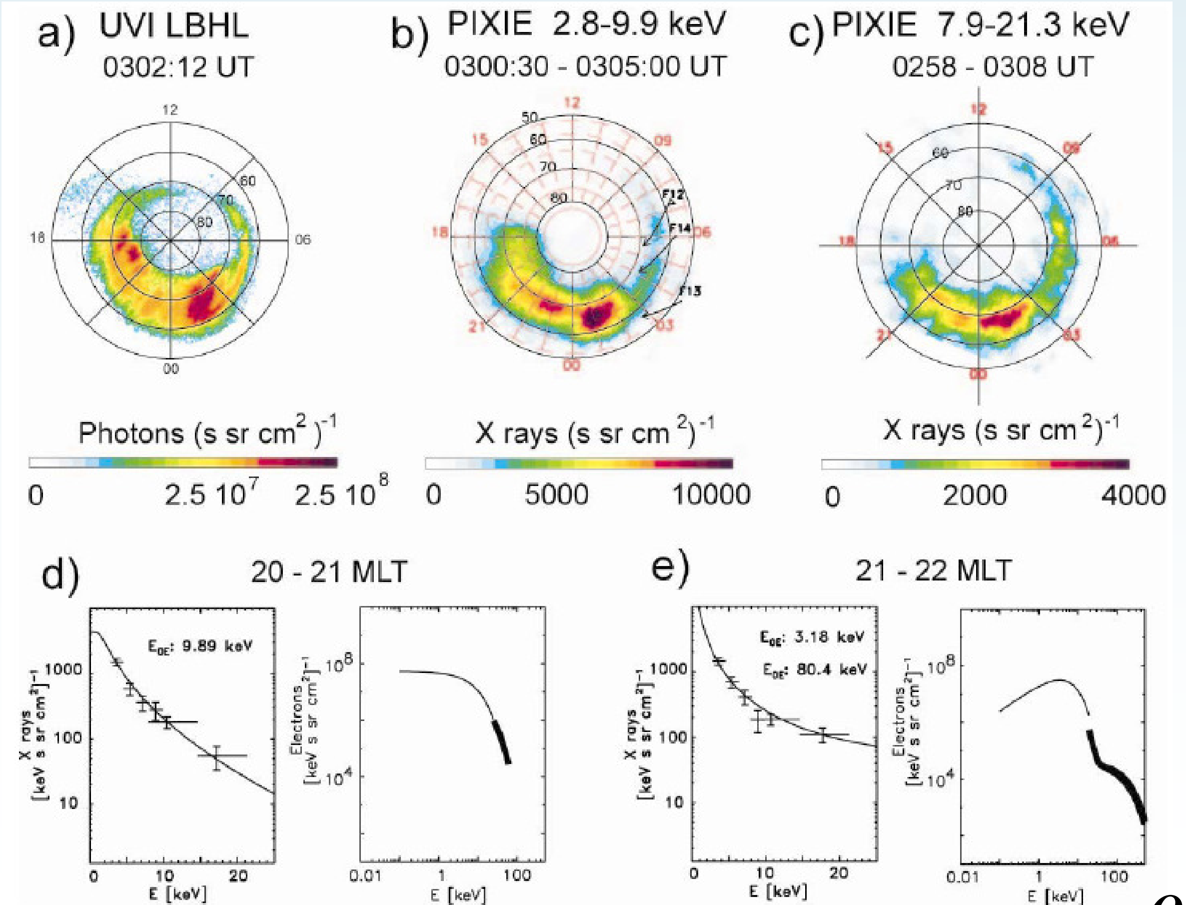
***Chandra* ACIS**



Bhardwaj et al. 2005b

Earth's aurorae: high X-ray energies

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



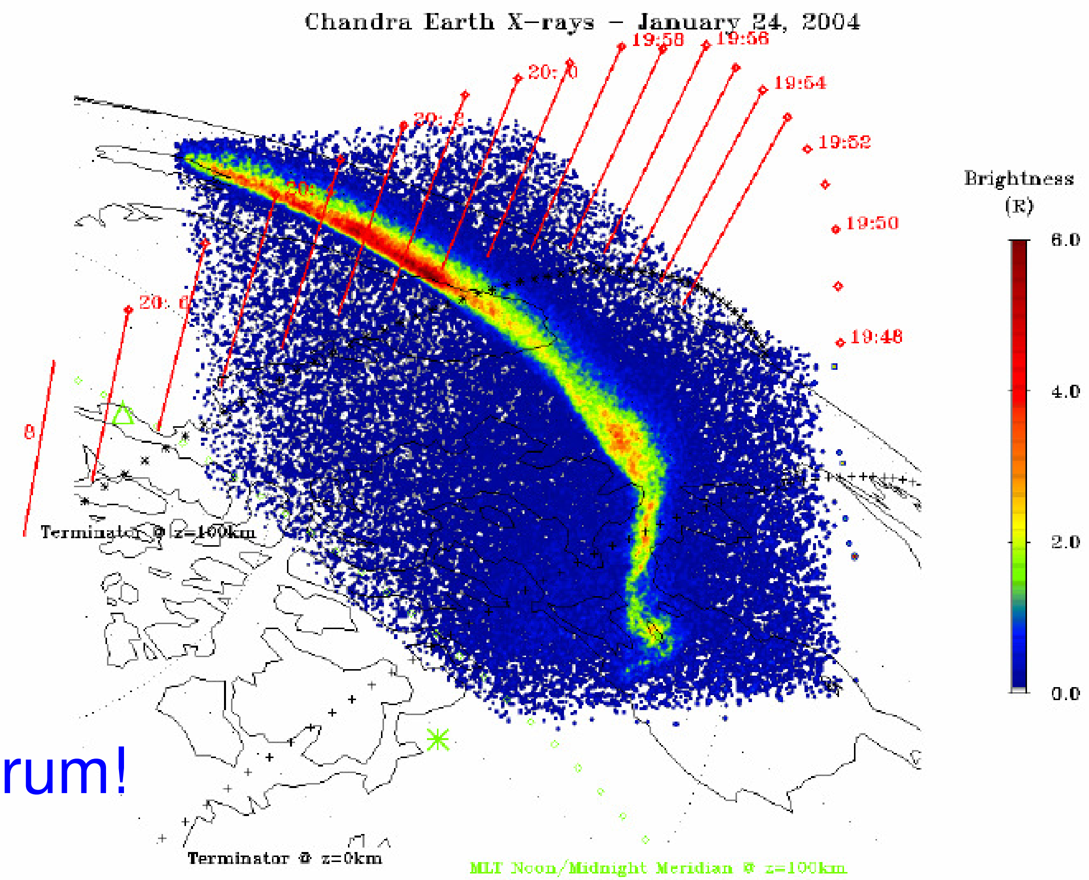
Ostgaard et al. 2001

Earth's aurorae: low X-ray energies

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

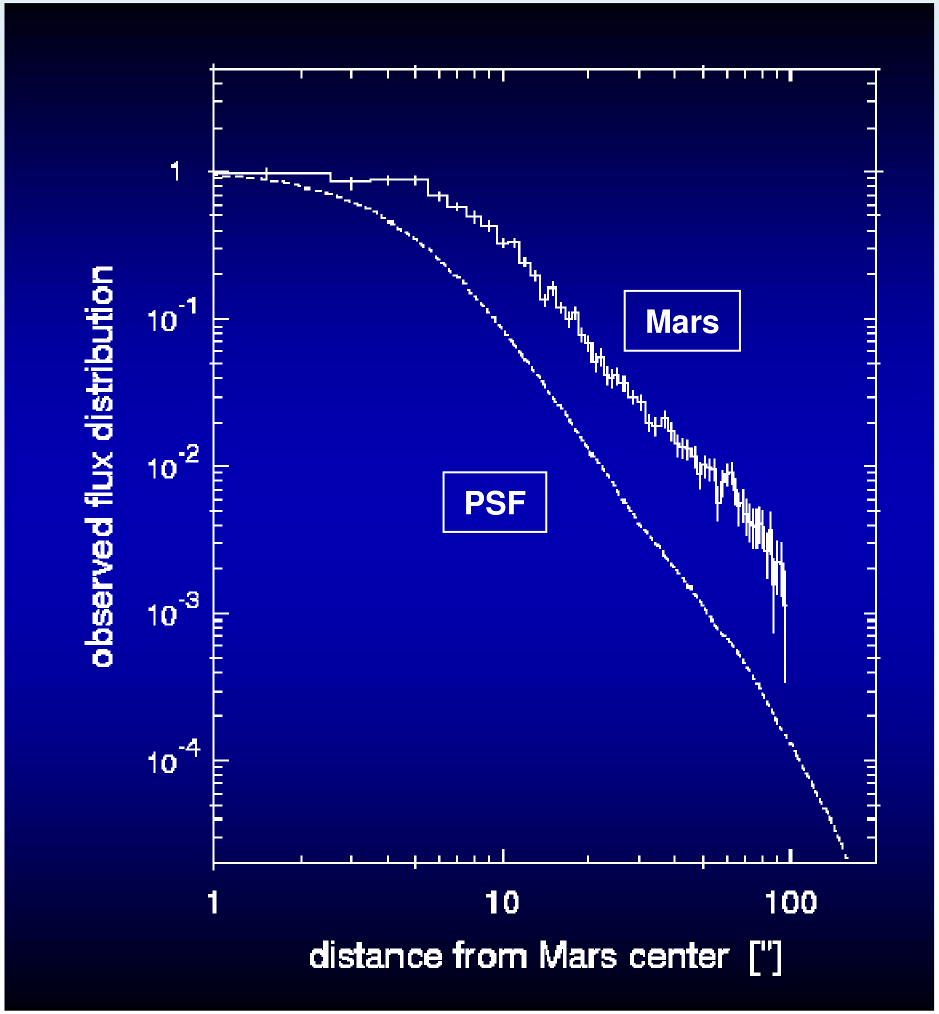
- Aurora very variable, with intense arcs and patches ***(Bhardwaj et al. 2006)***

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

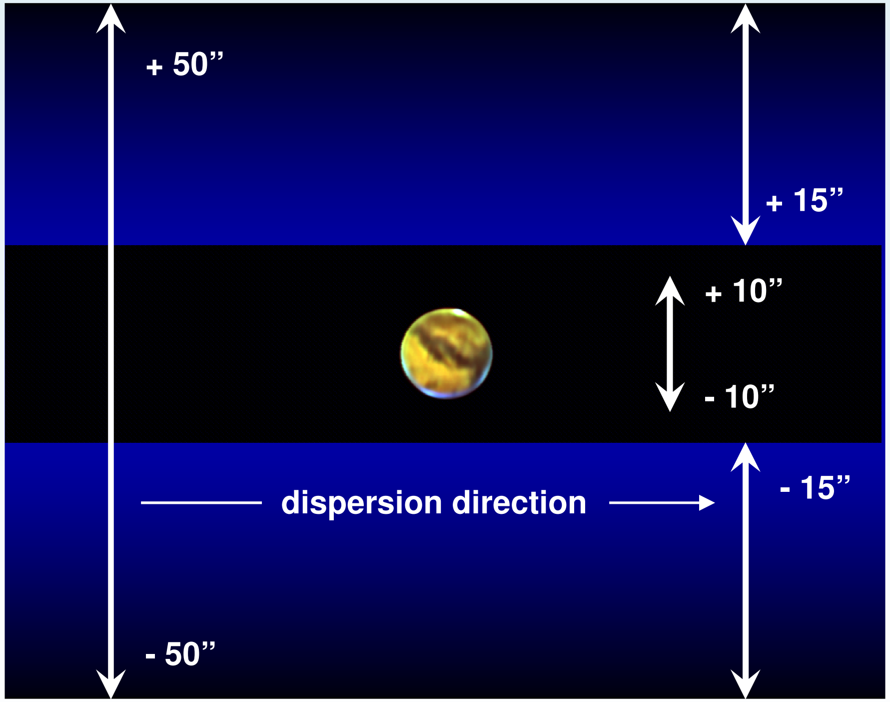


Mars disk and exosphere (halo)

XMM-Newton EPIC



... and RGS strategy

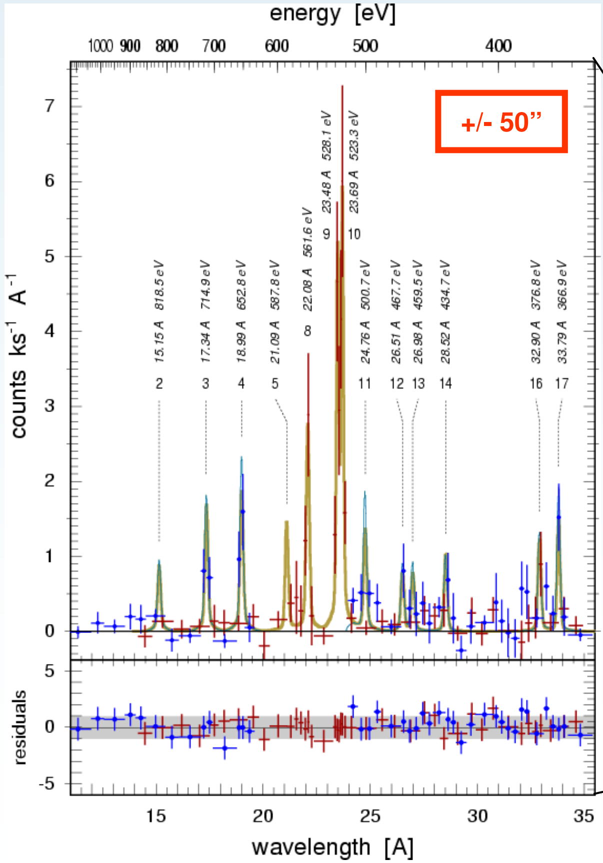


Dennerl et al. 2006

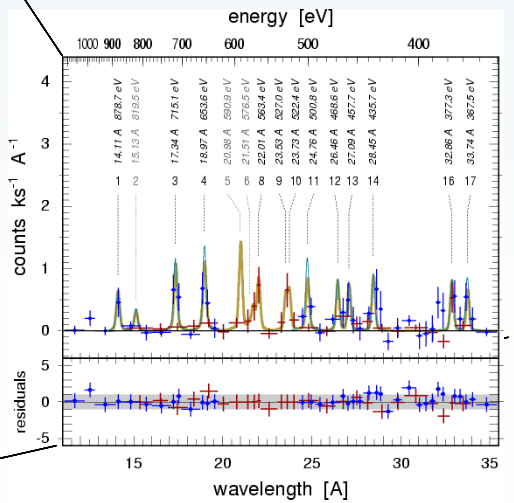
Dennerl et al. 2008

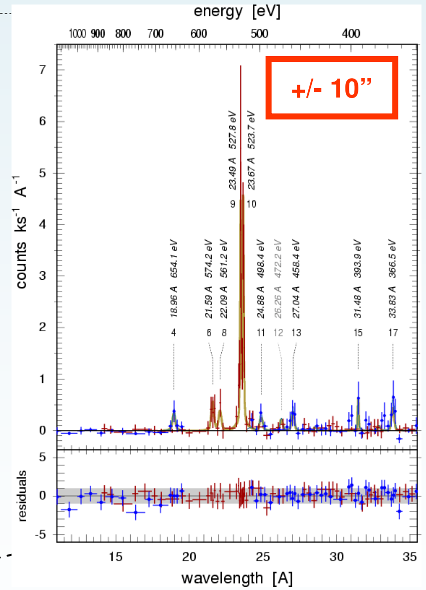
Mars disk and exosphere (halo)

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



- 50” to - 15” and + 15” to + 50”



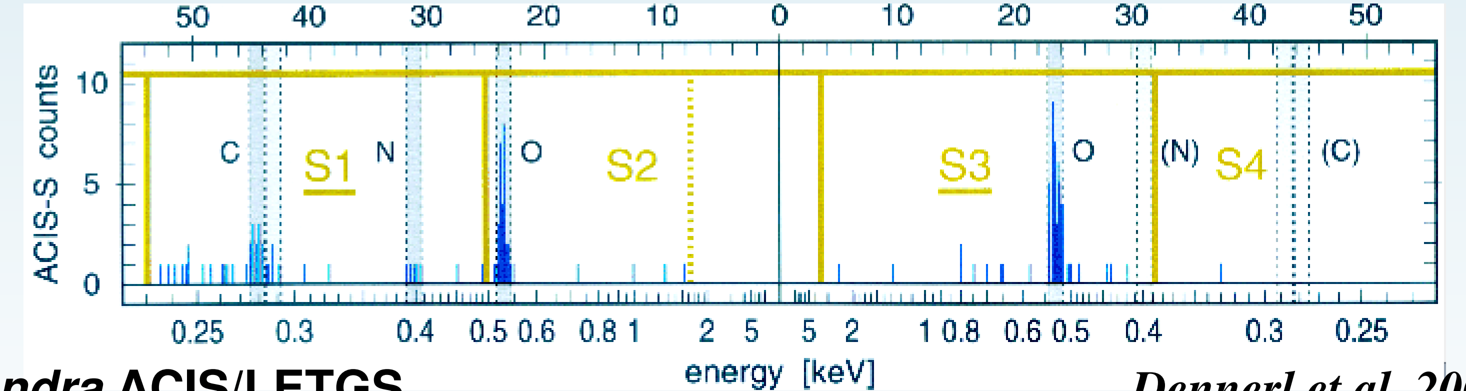


Dennerl et al. 2006

***XMM-Newton* RGS**

X-rays from Venus at solar maximum (2001)

- 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*

- Venus exosphere more condensed than Mars
  → SWCX radiation closer to limb
  → should be easier to detect at solar minimum

X-rays from Venus at solar minimum (2006)

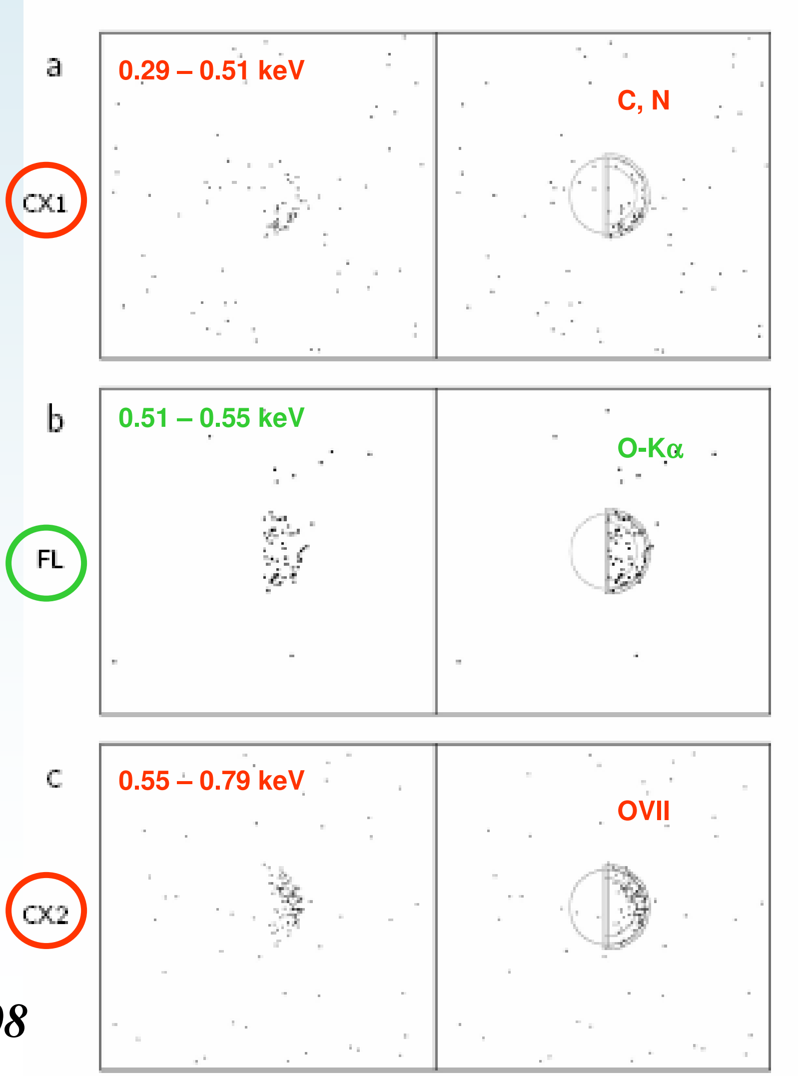
- First evidence of exosphere X-rays from SWCX at the sunward limb

- O-Kα fluorescence of solar X-rays uniformly distributed over illuminated disk

- Spectra from the two regions are indeed different

Dennerl et al. 2008

Chandra ACIS

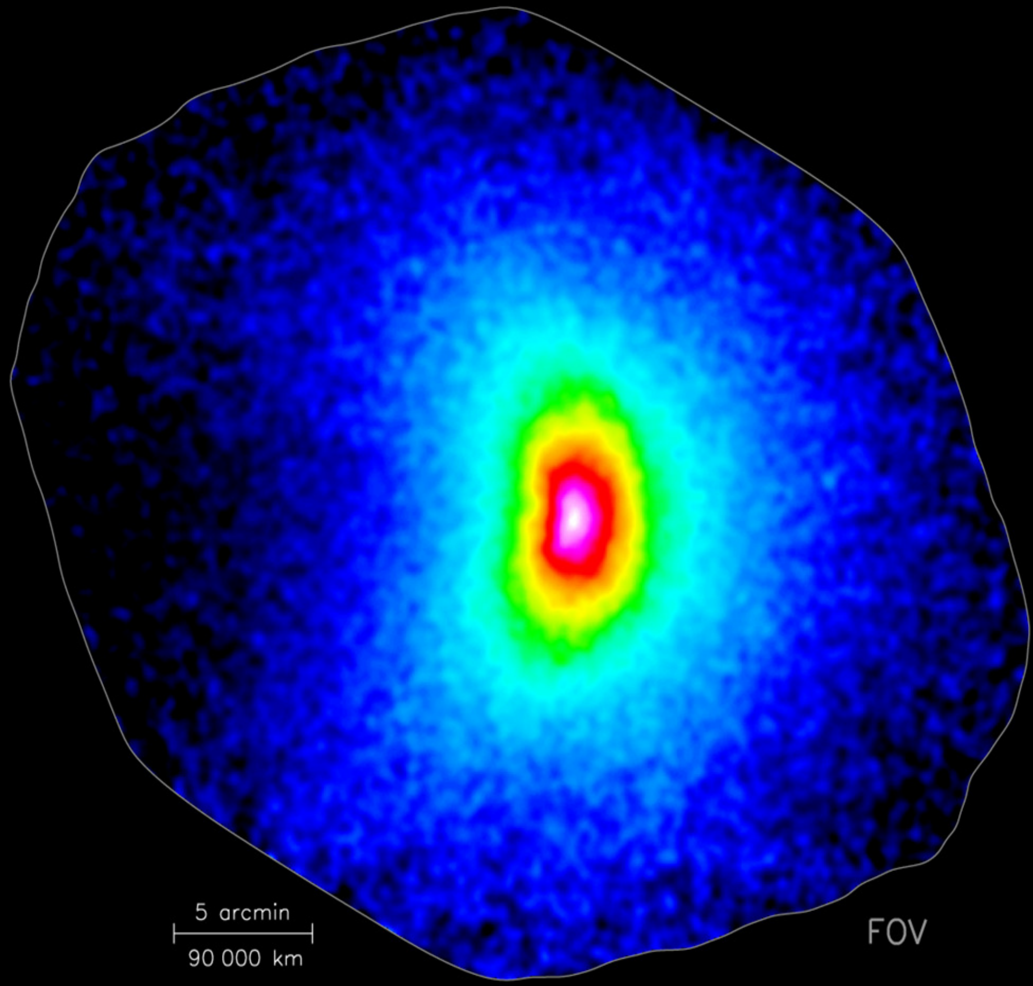


Comet C/2000 WM1, 2001 Dec. 13 – 14

Optical

Dennerl et al. 2003

Comet C/2000 WM1, 2001 Dec. 13 – 14

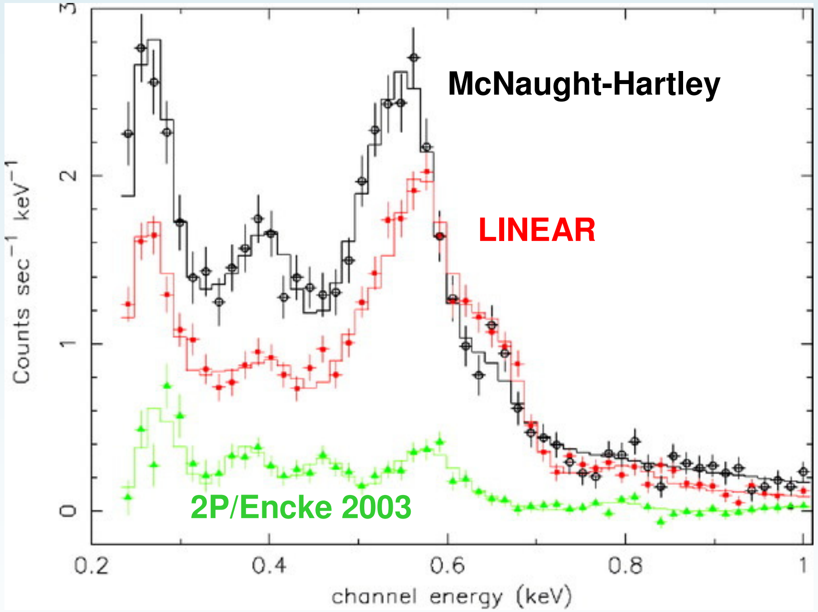


XMM-Newton

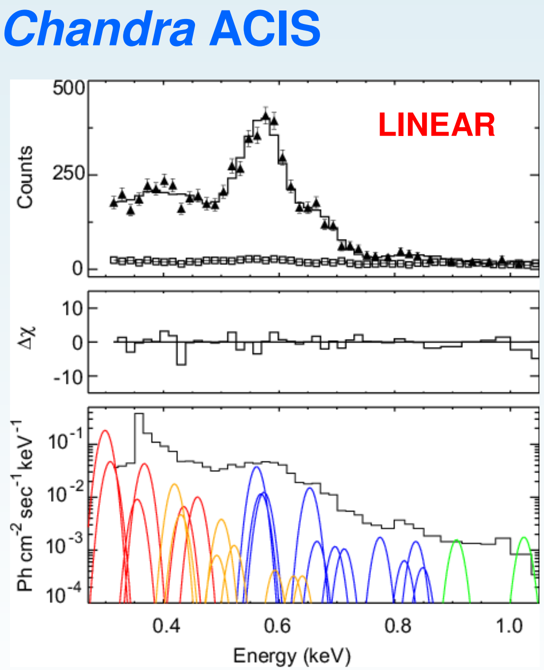
Dennerl et al. 2003

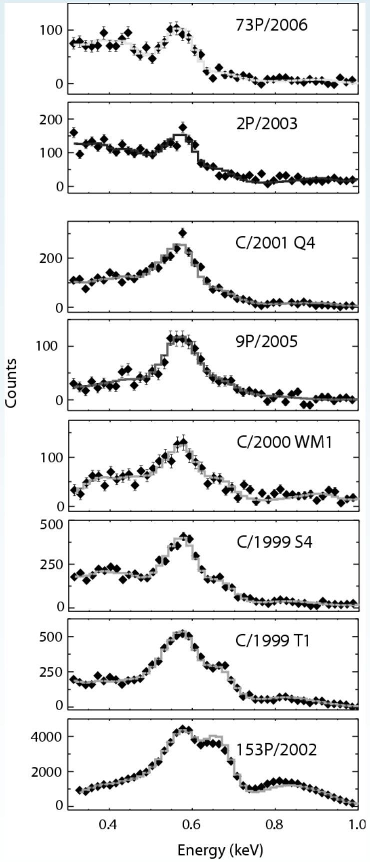
Cometary X-rays

• SWCX with coma neutrals well established emission process



Lisse et al. 2005





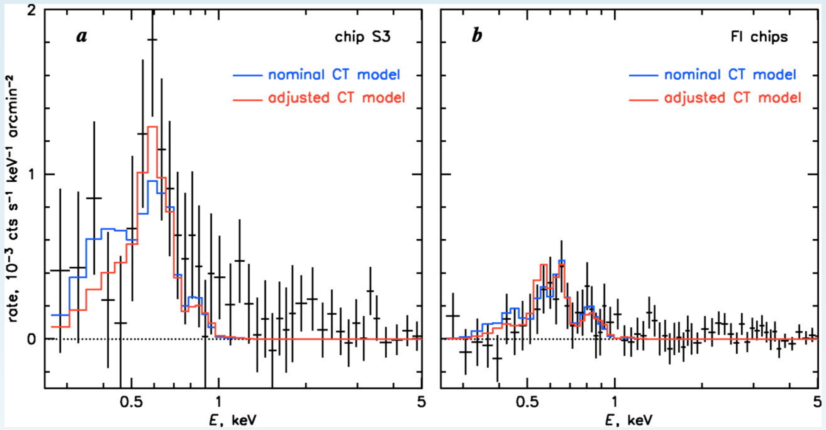
Bodewits et al. 2007

• Cometary spectra reflect state of SW →
first global exploration of comet environs and SW conditions

The Earth's geocorona

- Time variable oxygen emission lines on the dark side of the Moon

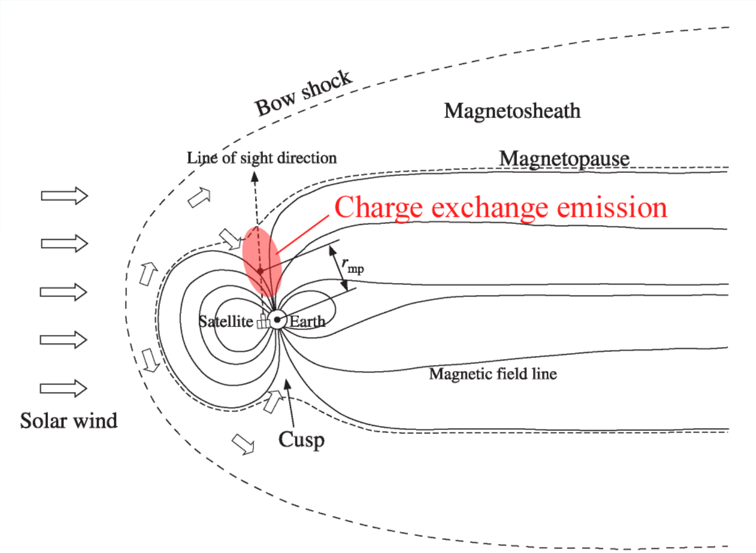
***Chandra* ACIS**



Wargelin et al. 2004

Correlation with solar wind flux → SWCX in Earth's geocorona

- *Suzaku* observations of the NEP
  → Increase in soft X-ray lines correlated with solar wind proton flux
  → See poster by Carter et al., systematic study with *XMM-Newton*



Fujimoto et al. 2007

Solar system X-rays: The future

Learning about the Universe at large, by studying the worlds next door (X-ray, FUV and particle diagnosis)

- Direct response to solar activity and to the conditions of the solar wind → more comprehensive understanding of solar - terrestrial relationships

- Search for elusive Saturn's X-ray aurorae (and those on Uranus, Neptune, Io, Ganymede, Titan?)

→ Synergy of spectroscopy, at high resolution and high throughput, with high spatial resolving power

XMM-Newton ⟺ *Chandra*

Thank you!