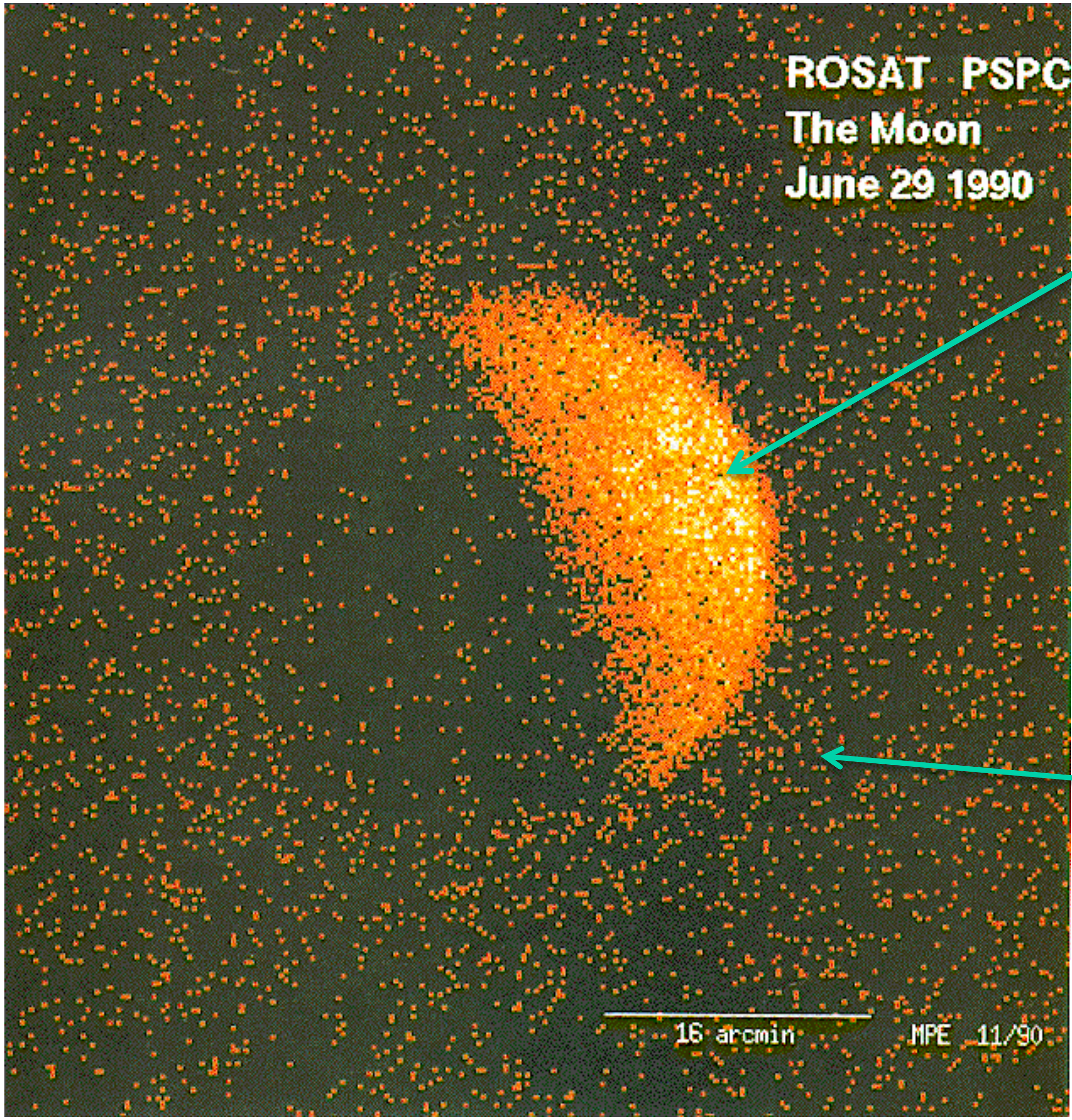
The X-ray view of Solar System Objects


ROSAT PSPC
The Moon
June 29 1990
16 arcmin
MPE 11/90
Interaction with solar particles
X-ray background

A new picture of the Solar System

Facts

- X-rays are almost ubiquitous in the solar system, the Sun being the main "actor" of the observed X-ray radiation

- Their detections is mostly matter of instrument sensitivity

- Scarce knowledge only for the most distant planets of the solar system

AND

- X-rays emission generally associated with hot plasma, whereas most of the solar system bodies contain no hot gas

- Typical temperatures are 30K-1000K in the comets/upper atmosphere of the planets

Chronology of detections of X-rays in the Solar System

- 1949: weak X-ray emission from the solar corona (Geiger counter, V-2 rocket)
- 1957: discovery of terrestrial X-rays from the auroral regions (but first image in 1996 by the Polar satellite)
- 1962: first "attempt" to detect X-rays from the Moon (instead, detection of Sco X-1 and consequent birth of X-ray Astronomy)
- Early 1970s: Apollo 15-16 studied fluorescently scattered X-rays from the Moon
- 1979: Einstein detected X-rays from Jupiter
- Situation in early 1990s: detection of X-rays from the Sun, Earth, Moon and Jupiter. Data still incomplete, but many scientists doubted on the presence of significant X-ray emission from other bodies of the Solar System
- 1996: ROSAT detected X-ray emission from comets (unexpected)

The *Chandra* and XMM-*Newton* era

• Detected X-ray emission (mainly below 2 keV) from Venus, Mars and its halo, Saturn and its rings, Io, Europa and Ganymede, and the Io plasma torus. The geocorona is emitting in X-rays and contributes to soft XRB. Recent detection of X-ray emission from Pluto.

• Consequence: "new" physics and models required to explain the observed properties in the X-ray band

Table 1
Classes of solar system objects detected in X-rays

Class	Object(s)
Star	Sun
Planets	Venus, Earth, Mars, Jupiter, Saturn
Satellites	Moon, Io, Europa, Ganymede, [Titan][a]
Minor Bodies	Comets, Asteroids
Planetary coronae (exospheres)	Geocorona, Martian Halo (corona)
Extended objects (around planets)	Io Plasma Torus, Rings of Saturn
Large cavity	Heliosphere

[a]X-rays from Titan have not been observed, but in a rare celestial event captured by the Chandra X-ray Observatory on January 5, 2003, Titan passed in front of the Crab Nebula. The X-ray shadow cast by Titan allowed astronomers to make the first X-ray measurement of the extent of its atmosphere (Mori et al., 2004).

Bhardwaj et al. 2007
(review)

Table 2. Summary of the characteristics of soft X-ray emission from solar system bodies

Object	Emitting Region	Power Emitted[a]	Special Characteristics	Possible Production Mechanism
Earth	Auroral atmosphere	10-30 MW	Correlated with magnetic storm and substorm activity	Bremsstrahlung from precipitating electrons, and characteristic line X-rays
Earth	Non-auroral atmosphere	40 MW	Correlated with solar X-ray flux	Scattering of solar X-rays by atmosphere
Jupiter	Auroral atmosphere	0.4-1 GW	Pulsating (~20-60 min) X-ray hot spot in north polar region	Energetic ion precipitation from magnetosphere and/or solar wind + electron bremsstrahlung
Jupiter	Non-auroral atmosphere	0.5-2 GW	relatively uniform over disk	Resonant scattering of solar X-rays + possible ion precipitation from radiation belts
Moon	Dayside Geocoronal (Nightside)	0.07 MW	Correlated with solar X-rays Nightside emissions are ~1% of the dayside	Scattering and fluorescence due to solar X-rays by the surface elements on dayside. SWCX with geocorona
Comets	Sunward-side coma	0.2-1 GW	Intensity peaks in sunward direction ~10^5-10^6 km ahead of cometary nucleus	SWCX with cometary neutrals
Venus	Sunlit atmosphere	50 MW	Emissions from ~120-140 km above the surface	Fluorescent scattering of solar X-rays by C and O atoms in the atmosphere
Mars	Sunlit atmosphere exosphere	1-4 MW 12 MW	Emissions from upper atmosphere at heights of 110–130 km emissions extend out to ~8 Mars radii	Fluorescent scattering of solar X-rays by C and O atoms in the upper atmosphere SWCX with Martian corona
Io	Surface	2 MW	Emissions from upper few microns of the surface	Energetic Jovian magnetospheric ions impact on the surface
Europa	Surface	1.5 MW	Emissions from upper few microns of the surface	Energetic Jovian magnetospheric ions impact on the surface
Io Plasma Torus	Plasma torus	0.1 GW	Dawn-dusk asymmetry observed	Electron bremsstrahlung + ?
Saturn	Sunlit disk	0.1-0.4 GW	Varies with solar X-rays	scattering of solar X-rays + Electron bremsstrahlung ?
Rings of Saturn	Surface	80 MW	Emissions confined to a narrow energy band around at 0.53 keV.	fluorescent scattering of solar X-rays by atomic oxygen in H_2O ice + ?

+ X-rays from Asteroids (EROS, Itokawa)

Bhardwaj et al. 2010 (review)

What produces the X-ray emission

Main mechanisms possibly involved

- Collisional excitation of neutral species and ions by charged particle impacts (mostly electrons), followed by line emission
- Electron collisions with neutral species and ions producing bremsstrahlung emission
- Solar photon scattering from neutral species in planetary atmospheres, acting as diffuse mirrors (elastic scattering and K-shell fluorescent scattering)
- Charge Exchange (CX) of solar wind ions of low energy with neutral species, followed by X-ray emission
- X-ray production from Charge Exchange of energetic heavy ions of planetary magnetospheric origin with neutral species or by direct excitations of ions in collisions with neutral species

Fundamental principles of the Charge Exchange

Main mechanisms possibly involved

- CX (or charge-transfer ionization) is a reaction between an ion and an atom or molecule in which a charge is transferred. CX cross sections at solar wind ion energies are large ($\approx 10^{-15}$ cm^2)

$$A^{+} + B \rightarrow A + B^{+}$$

$$A^{q+} + B \rightarrow A^{(q-1)+*} + B^{+}$$

e^-

A=projectile (e.g., O, C, Fe)
q=projectile charge (e.g., q=5,6,7)
B=target neutral species (e.g., H_2O, O, H)
$A^{(q-1)+*} \Rightarrow A^{(q-1)+}$ +hv: the product ion de-excites by emission of a photon (or radiative cascade), i.e., the electron moves into a tighter orbit

$$O^{8+} + H \rightarrow O^{7+*} + H^{+}$$

fully stripped oxygen + atomic hydrogen reaction

The X-ray Sun

• The solar corona emits X-rays, far from being symmetric (loops, sub-structures, etc.)

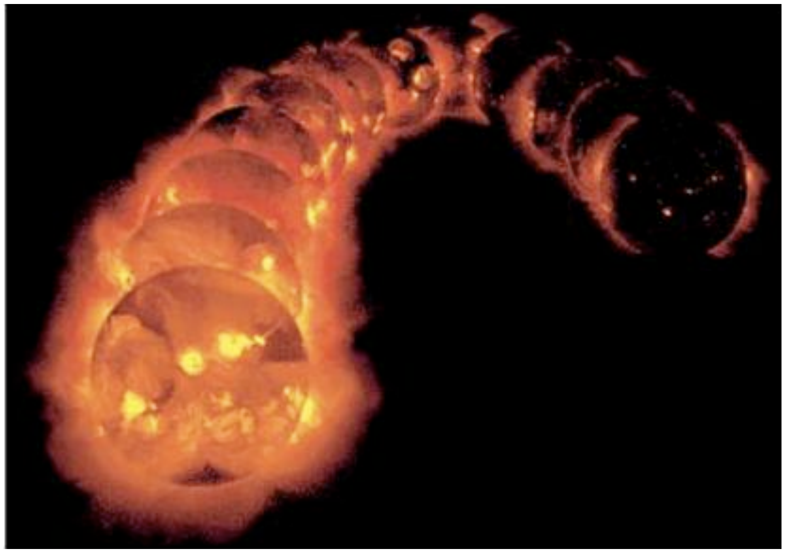
• Temporal variability on essentially all time scales, the longest ones being associated to the solar cycle (two orders of magnitude difference)

• T>10^6 K, mostly soft X-rays, 1 part over 10^6 of the energy budget emitted in X-rays ➔ feeling that it could be hard to detect extra-solar coronae (not true!)

• Magnetic activity is responsible for X-ray corona emission (magnetic dynamo in the convection zone), as in cool stars

Yohkoh observations
of the sun throughout its cycle

$L_{\text{soft X-ray}} \approx 4 \times 10^{27}$ erg/s



The Sun's overall structure

Core:

- Nuclear reactions fuse hydrogen atoms into helium.

Radiation Zone:

- Photons bounce around in the dense plasma, taking millions of years to escape the Sun.

Convection Zone:

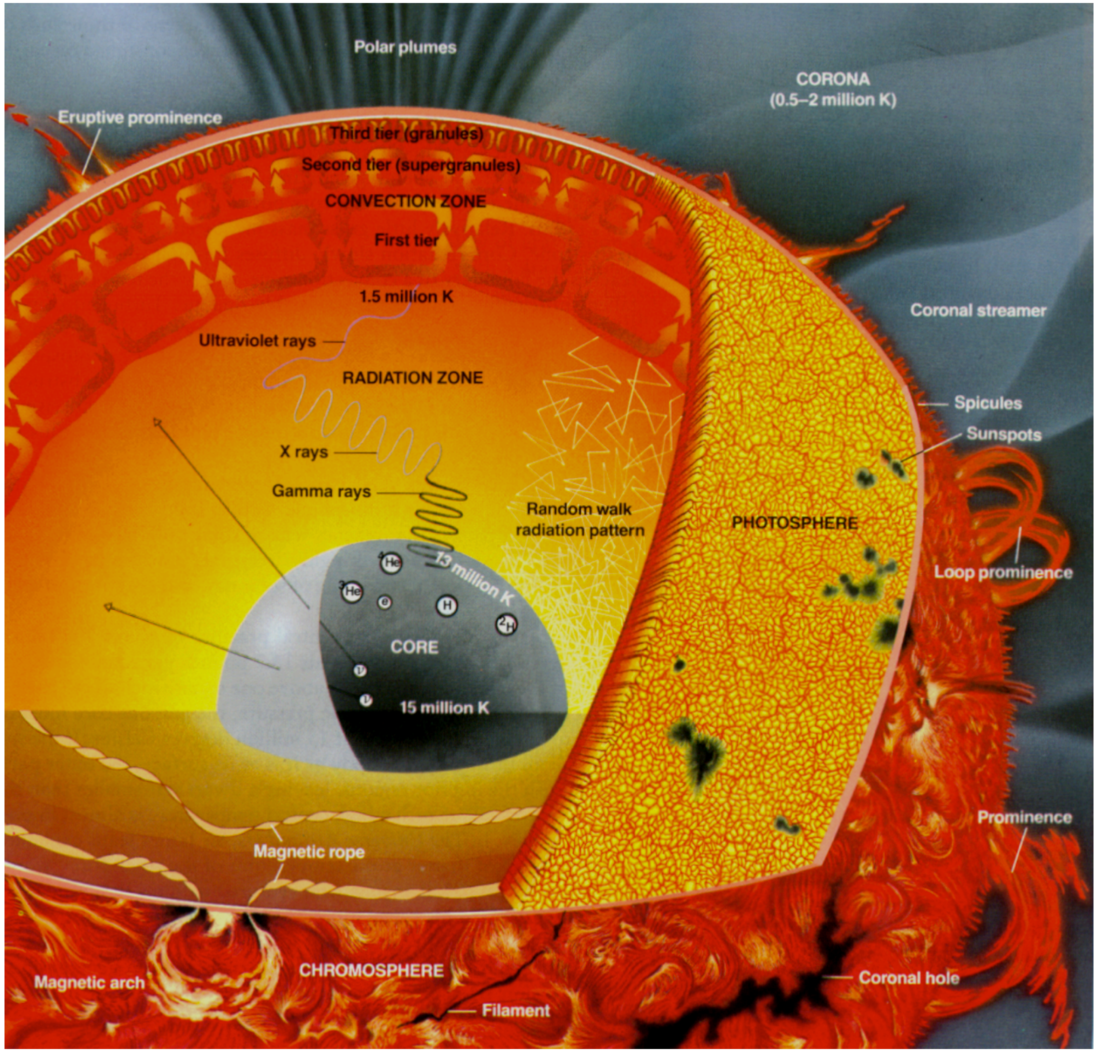
- Energy is transported by boiling, convective motions.

Photosphere:

- Photons stop bouncing, and start escaping freely.

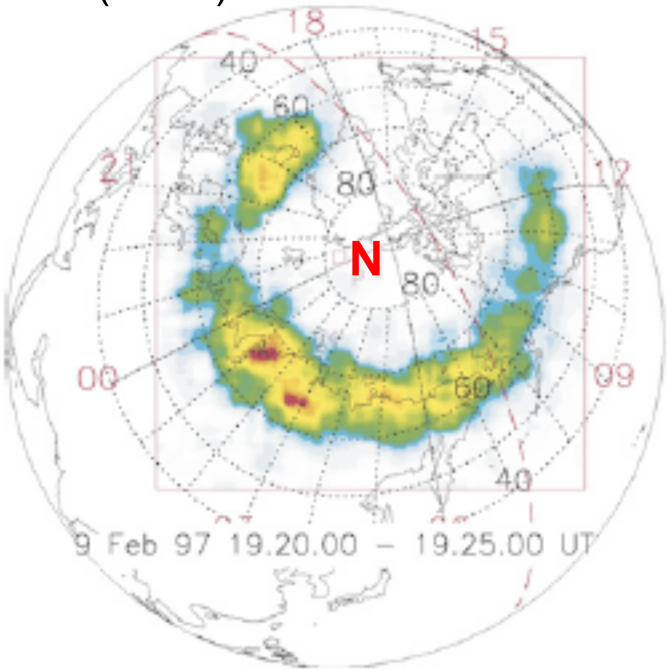
Corona:

- Outer atmosphere where gas is heated from ~5800 K to several **million** degrees!

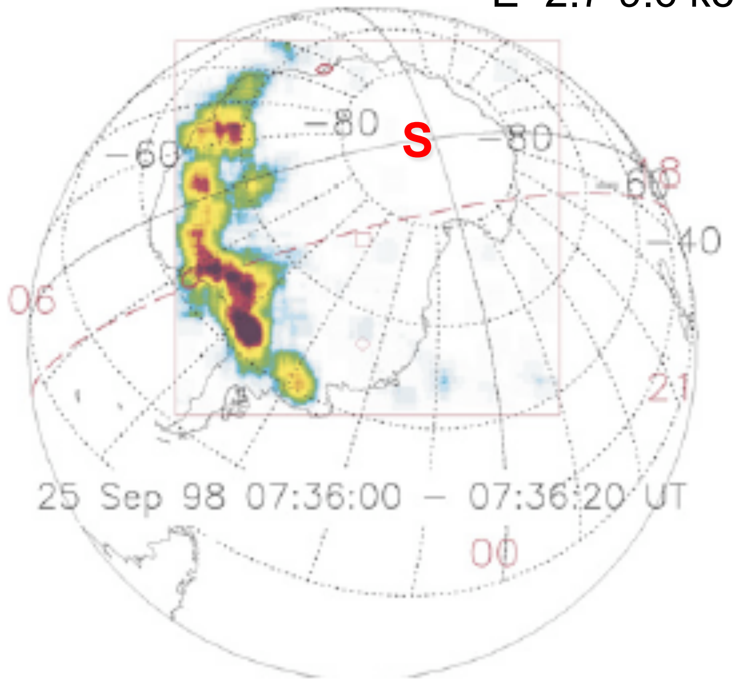


Imaging X-ray emission from the Earth

E=8.1-19.7 keV (5 min)



E=2.7-9.6 keV (20 s)



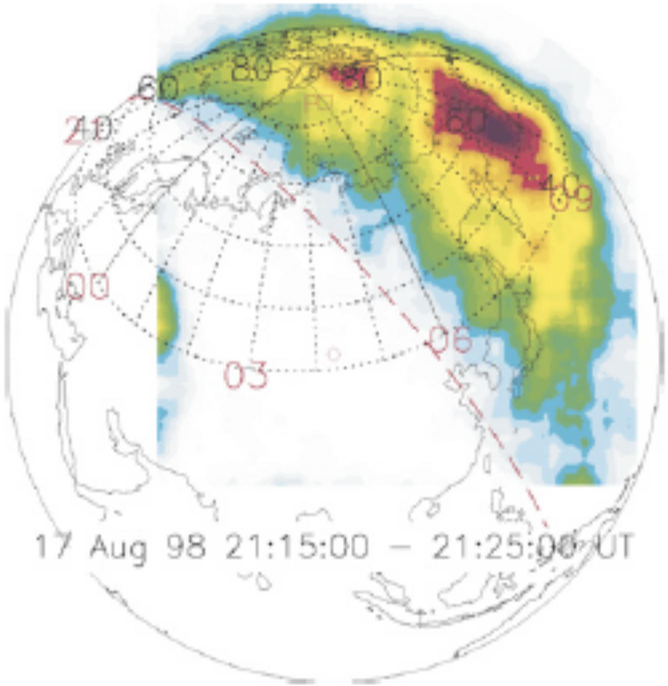
Auroral X-ray images of the Earth from the Polar PIXIE (700 km spatial resolution)

Charged particles (electrons and protons) from the magnetosphere precipitate into the ionosphere and deposit their energy by *ionization*, *excitation*, *dissociation*, and *heating of the neutral gas* (as a result of the dynamic processes in the magnetosphere and the close coupling between magnetosphere and ionosphere) ➔ visible, UV, and X-rays

+ X-ray emission lines + bremsstrahlung (dominant at E>3-4 keV)

Not only auroral X-ray emission

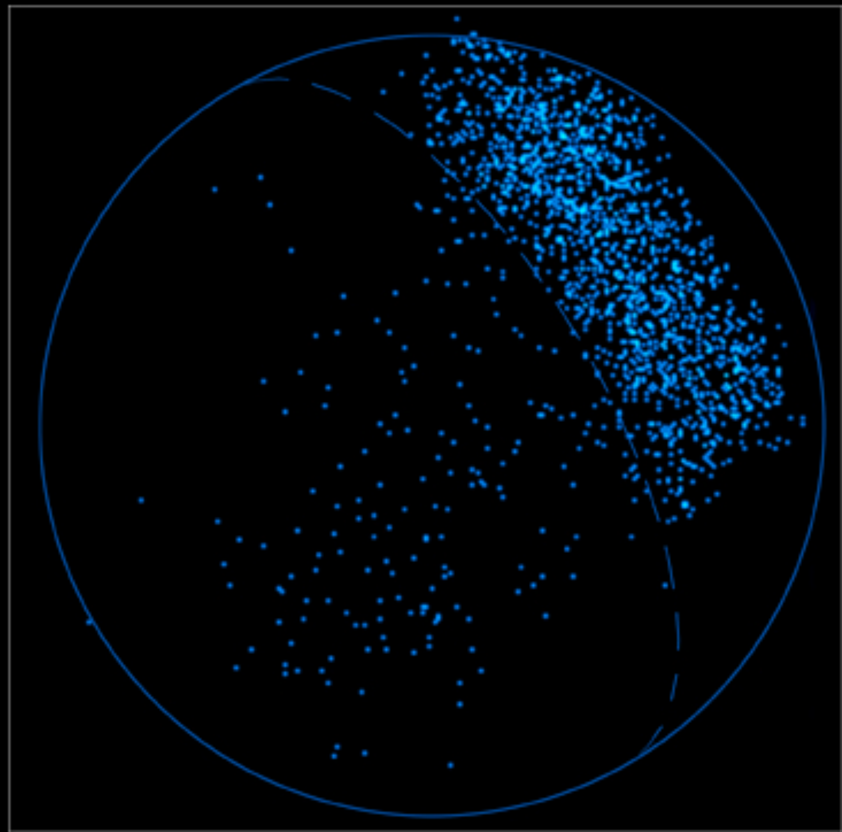
E=2.9-10.1 keV, solar flare
(PIXIE)



- Non-auroral X-ray emission at E>2 keV negligible except during solar flares.
- Observed E<2 keV radiation from the sunlit Earth's atmosphere also during 'quiet-Sun' conditions: (a) **Thomson scattering** (solar X-rays vs. electrons in the atomic/molecular constituents of the atmosphere); (b) **fluorescence** - absorption of solar X-rays followed by K-lines (N, O, Ar).
- X-ray brightness can be comparable to that of a moderate aurora.

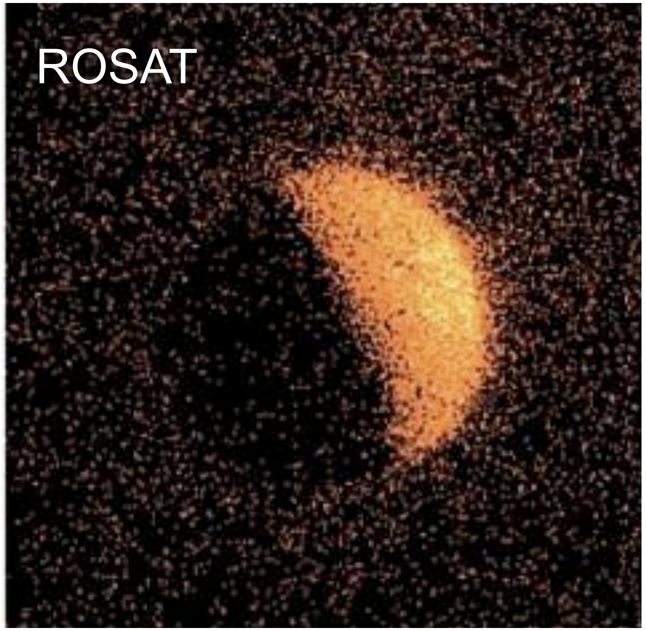
The Moon

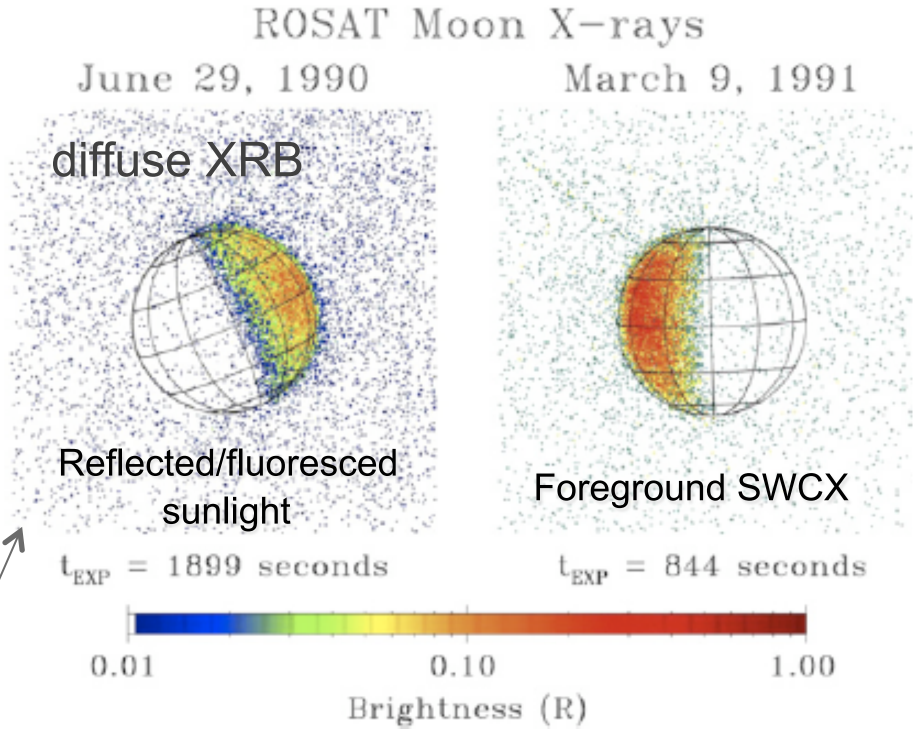
OPTICAL



X-RAY

Lunar X-rays

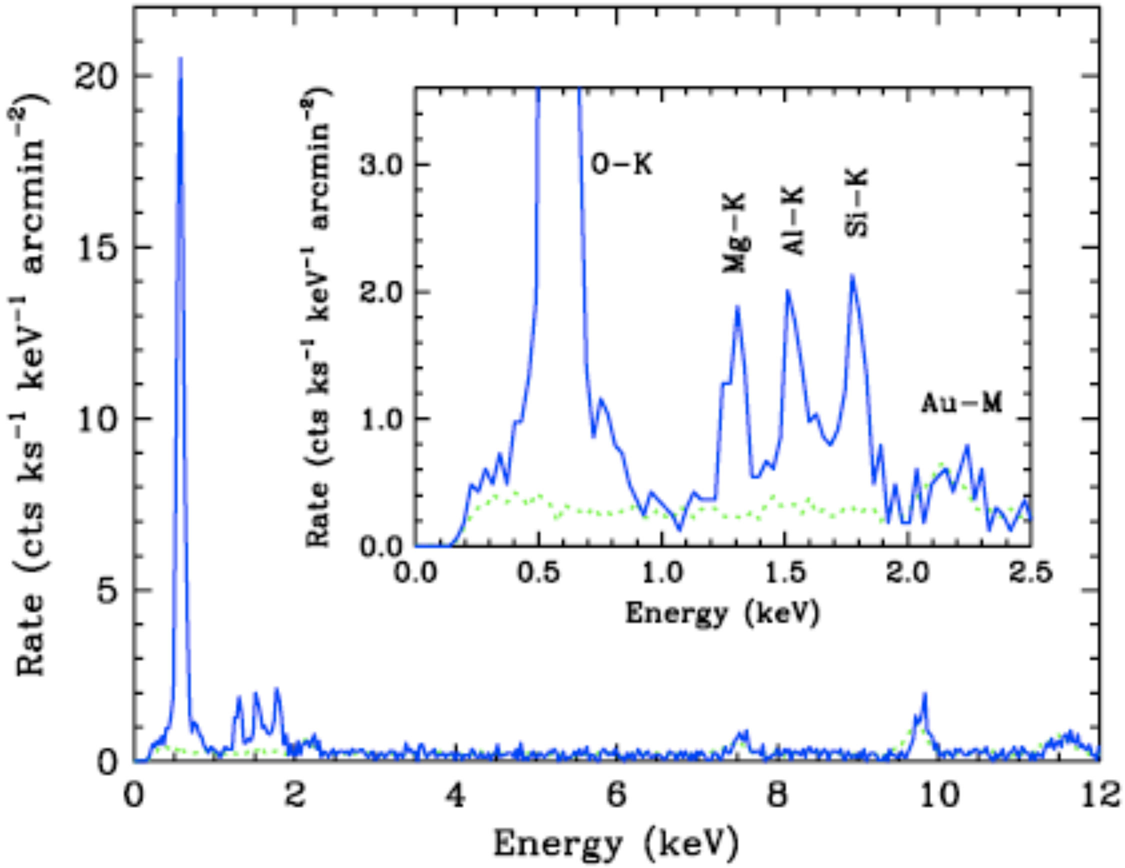




• Mechanisms in action: (a) very low level of bremsstrahlung from solar wind electrons impacting the surface; (b) **scattering of solar radiation**; (c) **fluorescence of sunlight by the surface** ➔way to map the elemental composition of the lunar surface

• Night-side X-ray emission (100x fainter): **CX of heavy atoms (C, O, Ne) in the solar wind with geocoronal H atoms** located between the Earth and the Moon (outside the magnetosphere) ➔ foreground X-ray emission

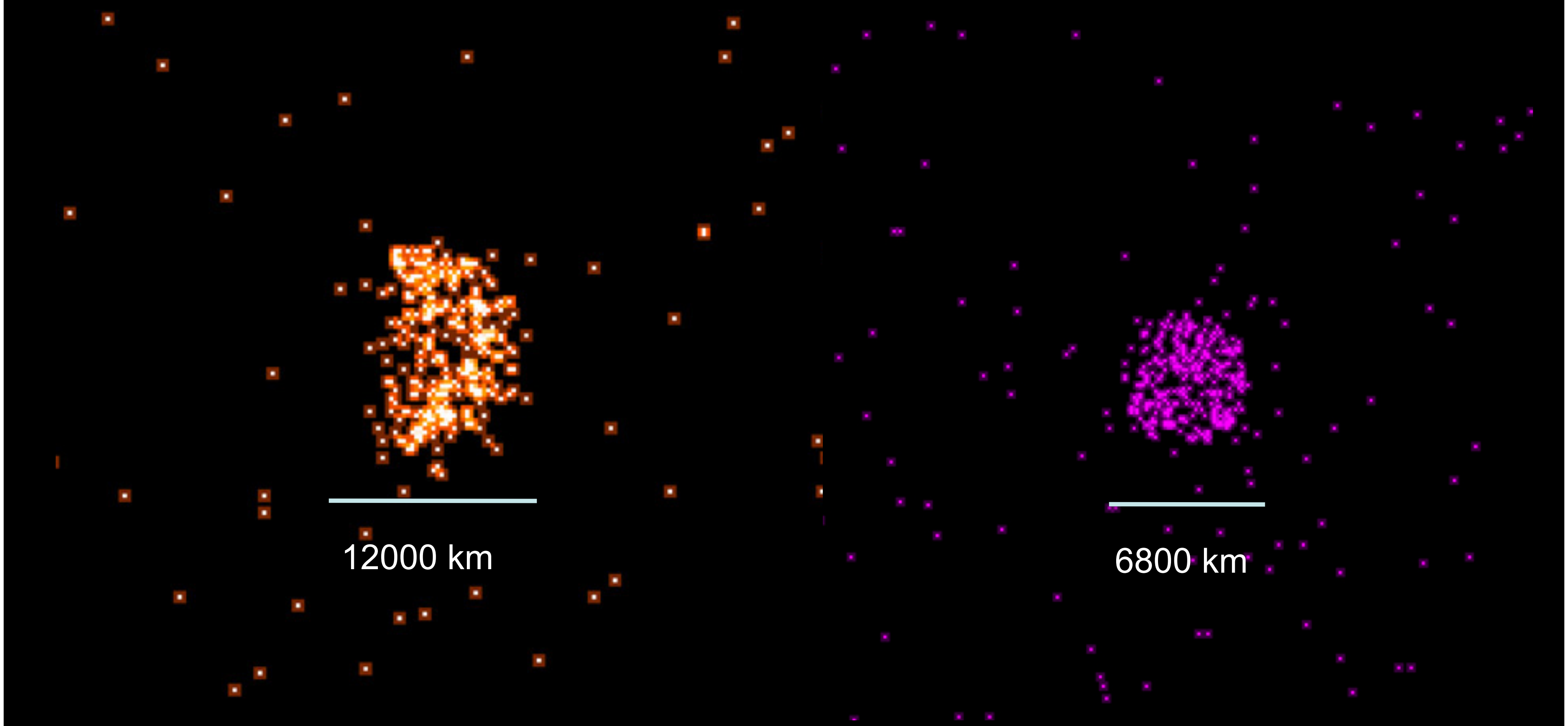
The bright side of the Moon



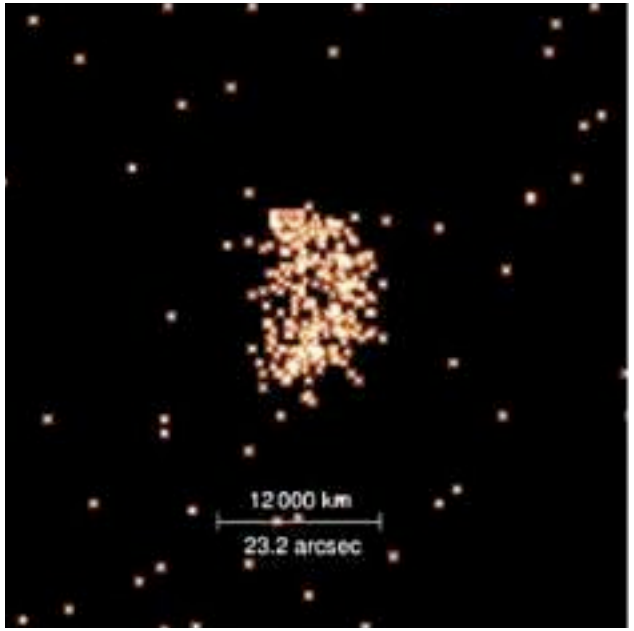
Chandra spectrum of the bright side of the Moon.

Lines are due to K-shell fluorescence

Venus & Mars

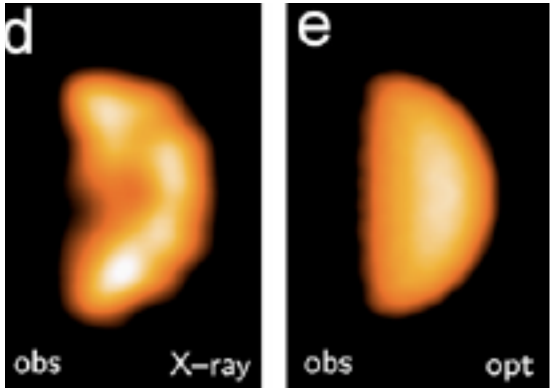


Venus in X-rays



Chandra first image of Venus (radius≈6050 km)

X-ray dominated by oxygen emission; optical emission reflected from clouds at h=50-70 km

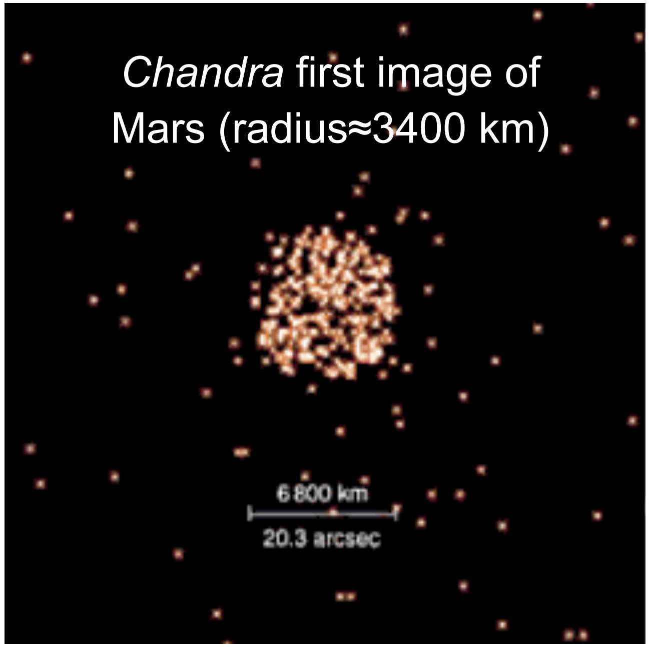


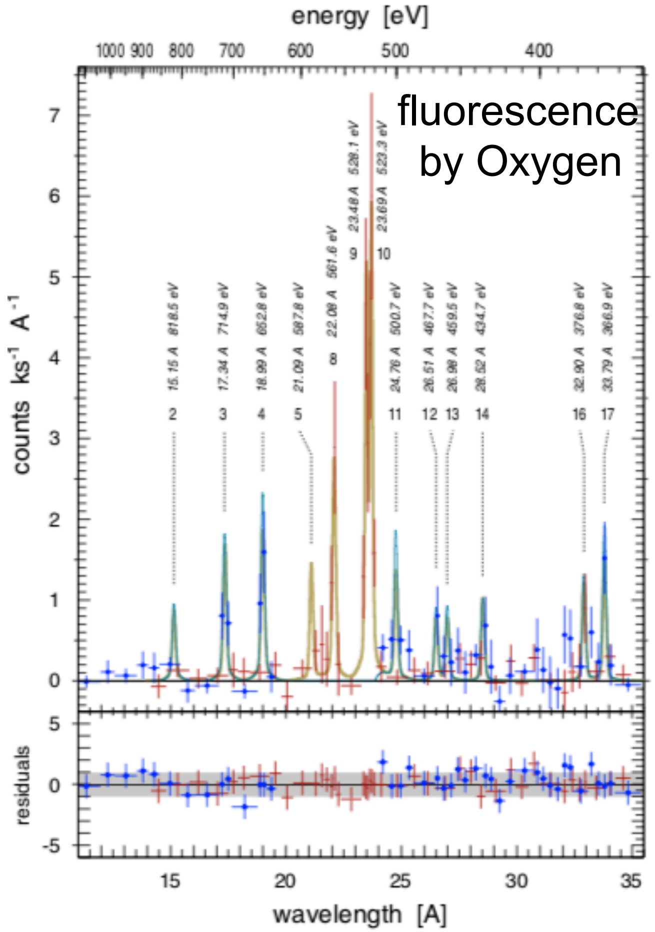
• X-rays due to **fluorescent scattering of solar X-rays** on C and O *in the upper atmosphere* of Venus (not the surface, as for the Moon), at heights of 120-140 km. Good agreement with simulations.

• X-ray variability over time scales of minutes.

• 1 X-ray photon per 5×10^{11} photons from Venus.

X-ray observations of Mars





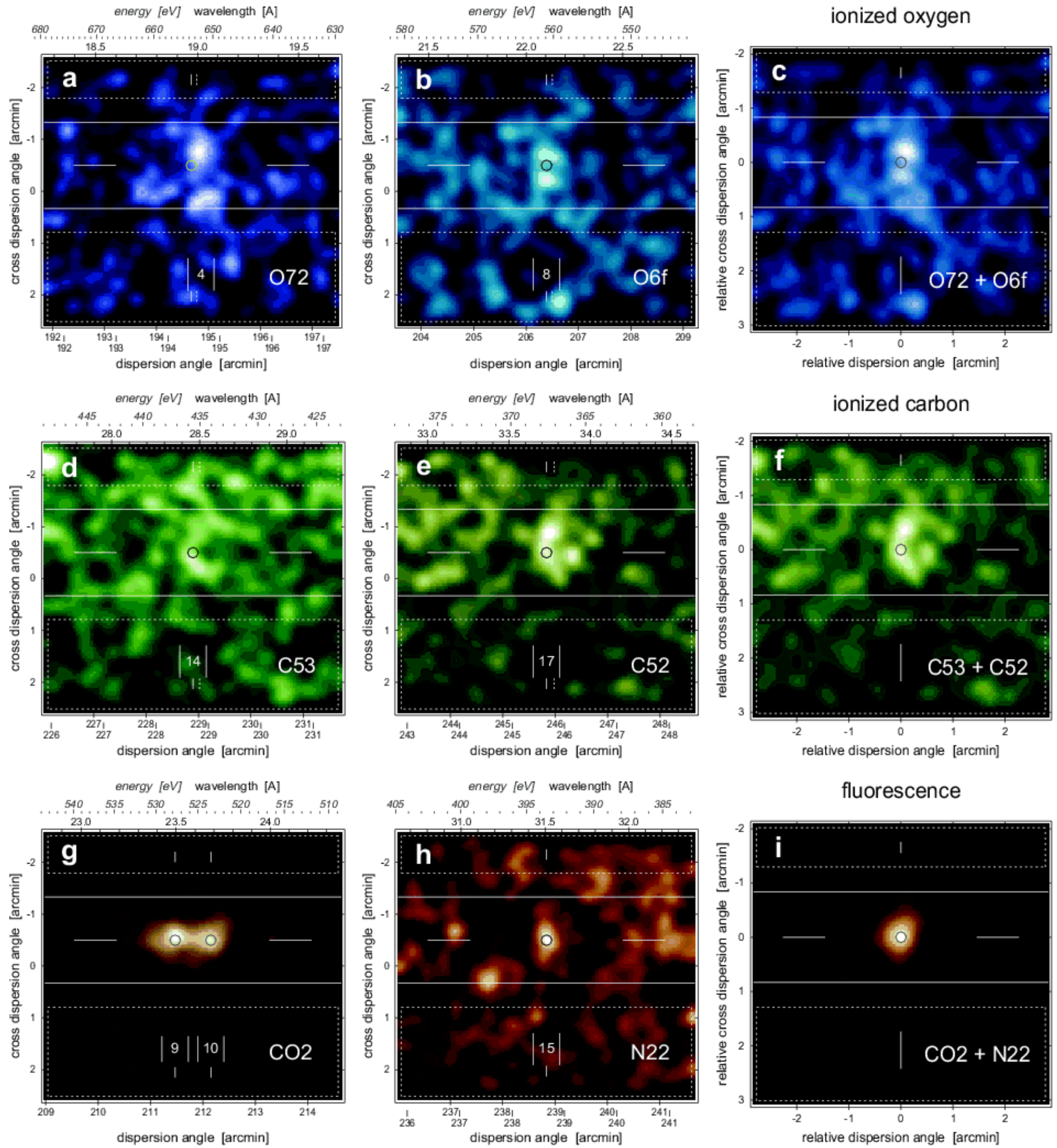
Dennerl et al. (2006)

• ROSAT sensitivity too low to detect X-ray emission from Mars.

• X-rays due to **fluorescent scattering of solar X-rays** on C and O in the upper atmosphere of Mars, similarly to Venus, at heights of 110-130 km.

• Some extra emission from the Martian exosphere (halo, 1-3 R_{mars}, **CX interactions** between highly charged heavy ions in the solar wind and neutrals in the Martian exosphere), confirmed by XMM-*Newton*.

• Variability, when present, is associated to the solar X-ray flux.



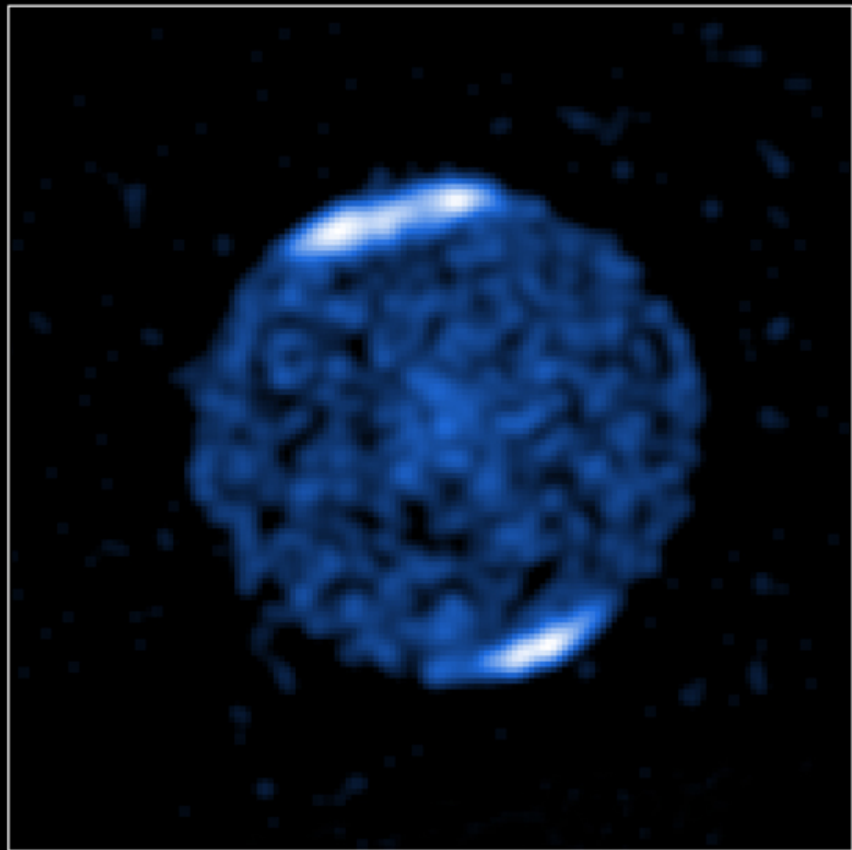
Ionized oxygen

Ionized carbon

CO_2 and N_2 molecules

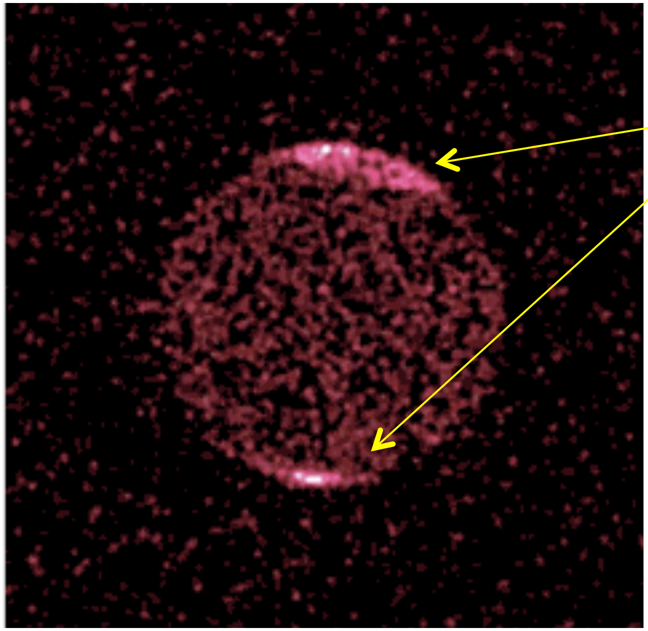
XMM-*Newton*/RGS observations of Mars and its halo

Jupiter

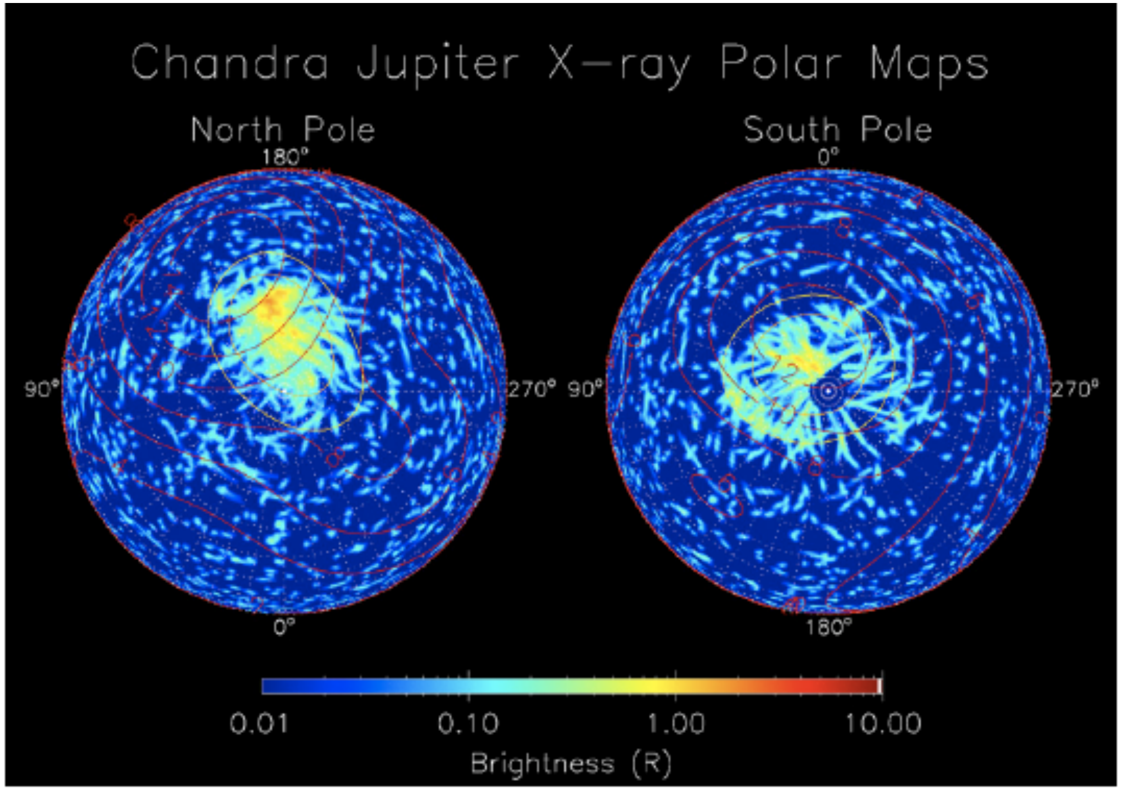


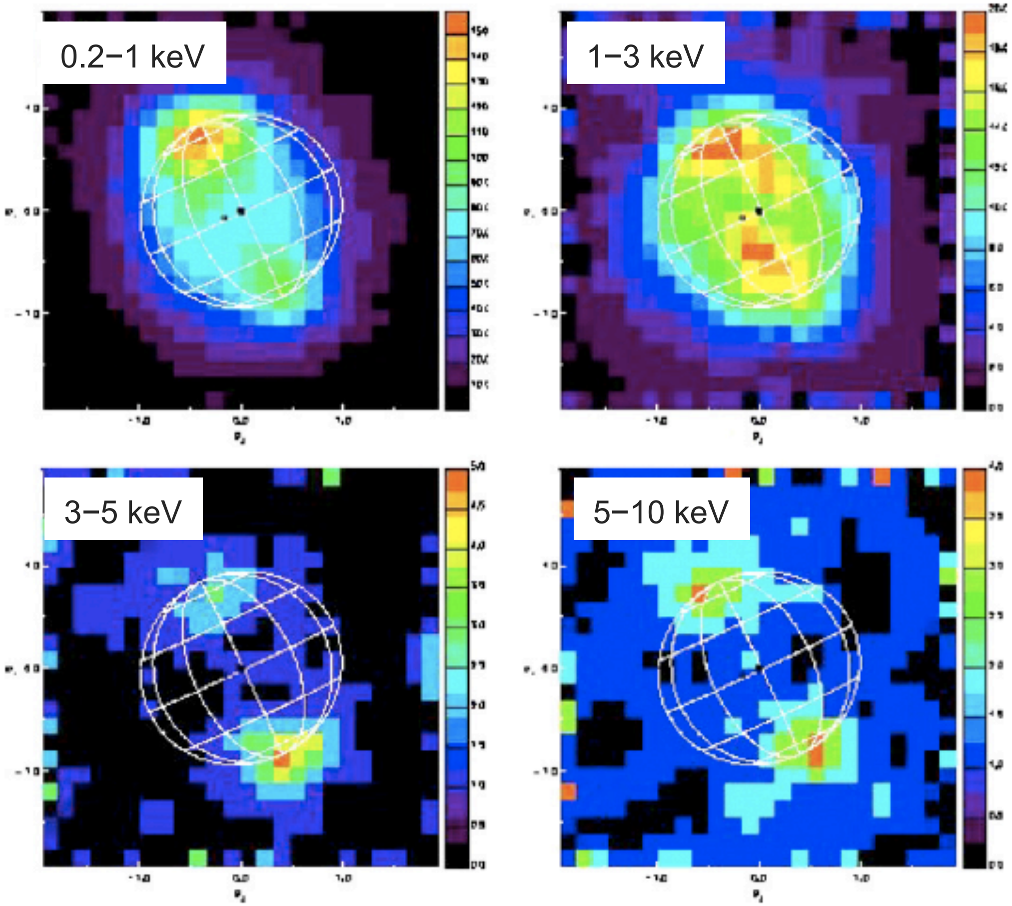
CHANDRA X-RAY OF JUPITER

X-rays from Jupiter: the aurorae



Chandra image of Jupiter and its highly structured auroral regions

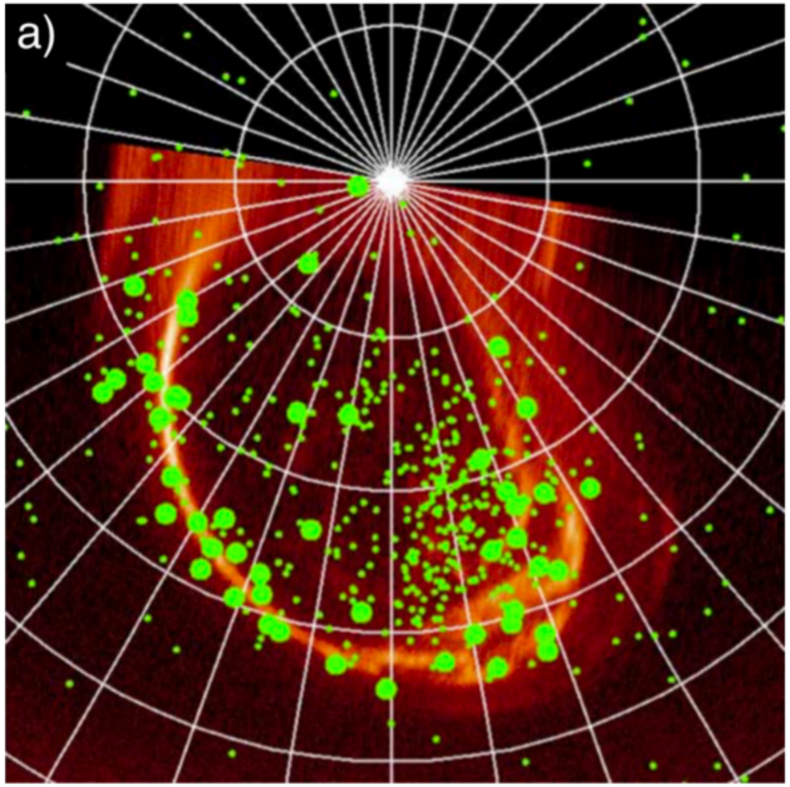




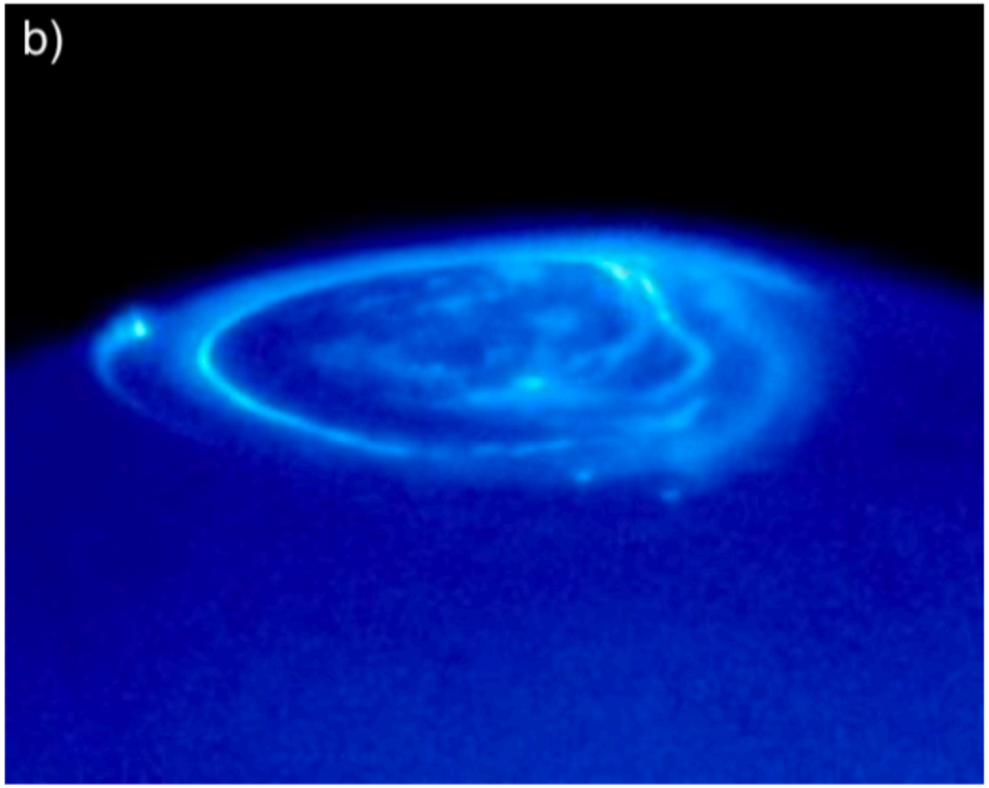
XMM-*Newton:* presence of a high-energy component in the aurorae.

- Former X-ray detection of Jupiter by *ROSAT*, but with poor angular and spectral resolution.
- X-ray aurorae not located in the UV auroral zone but are more polar (higher latitude)
- 40-m pulsation not present in all observations, reminiscent of quasi-periodic radio bursts.
- Presence of X-ray flares.
- Origin of the auroral emission (according to the current understanding): precipitation of highly ionized oxygen and sulfur from the outer magnetosphere into the polar regions plus their interaction with the upper atmosphere, and some electron precipitation. Elements from Io? SW? Electron bremsstrahlung?
- Other X-ray emission: scattering of solar X-rays (plus heavy ion precipitation).
- Further modeling required.

Branduardi-Raymont et al.(2008) – *Chandra* + *HST*



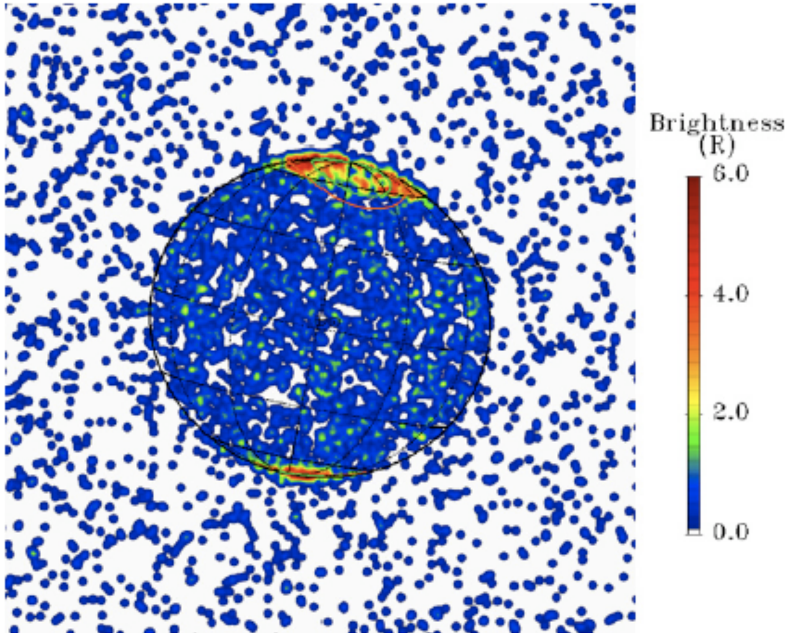
Clarke et al. (2004) - *UV*



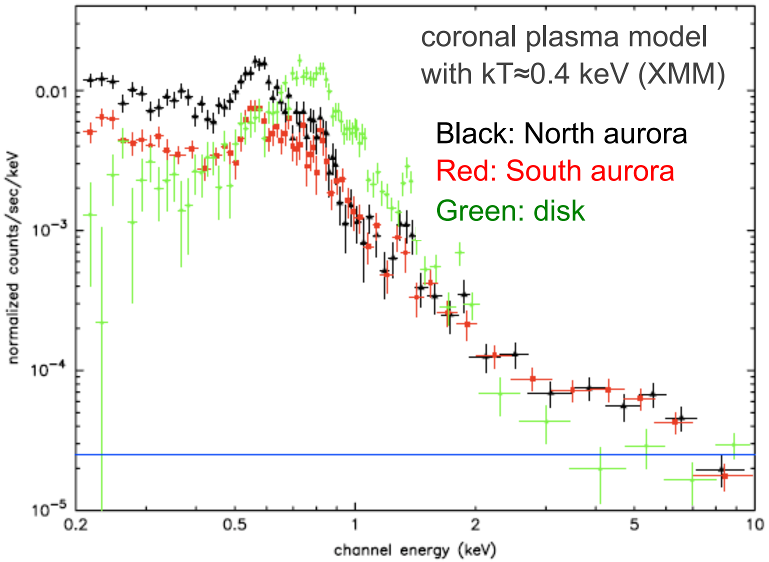
Green: X-rays from bremsstrahlung emission + CX

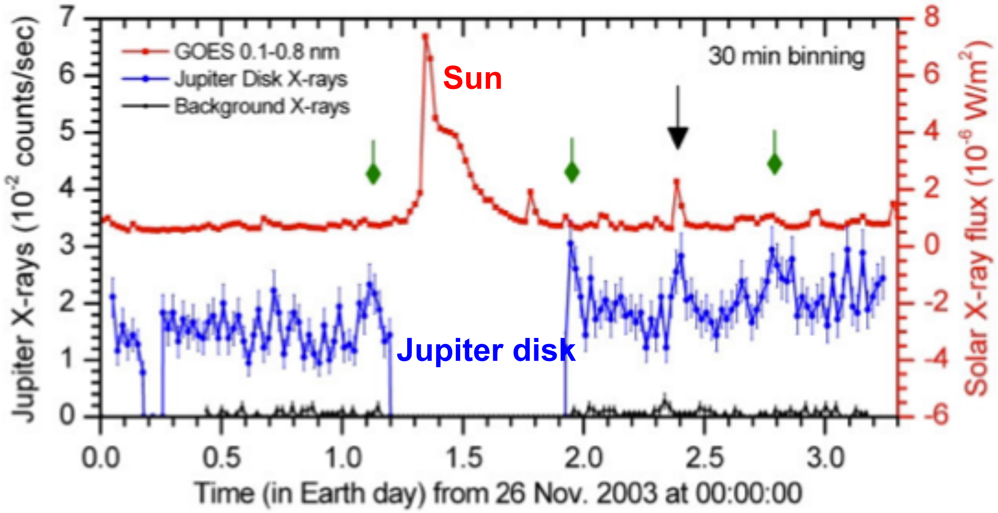
Blue: UV auroral emission: H excitation from electron collisions in the atmosphere

X-rays from Jupiter: low-latitude disk emission

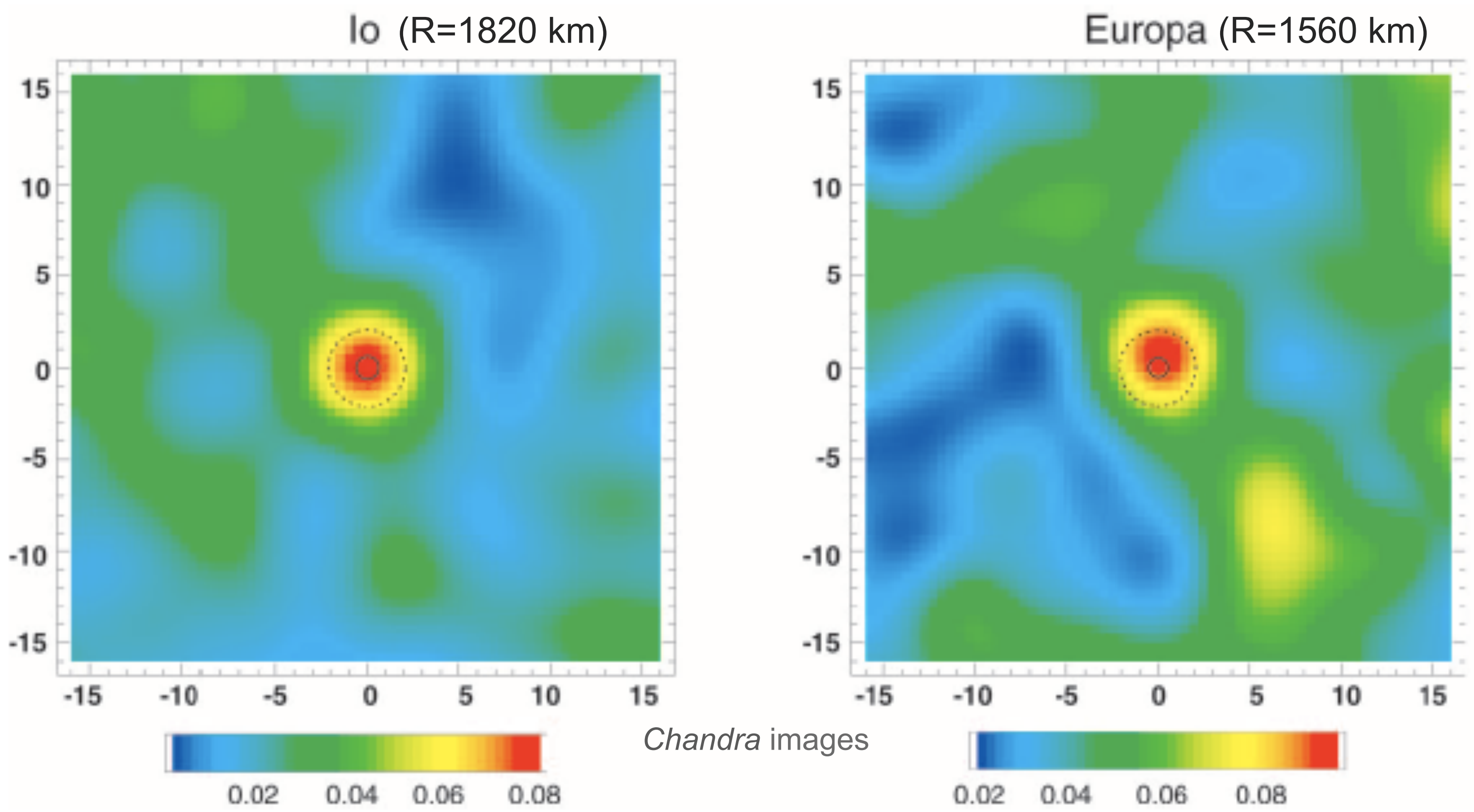


- Former X-ray detection of disk emission by *ROSAT*.
- No hard X-ray component in the Jupiter disk emission.
- No X-ray variability on time scales of 10-100 min.
- Emission mainly due to **scattered solar X-rays**, supported by the fact that a strong solar X-ray flare was found to have a corresponding feature in the Jupiter X-ray emission.





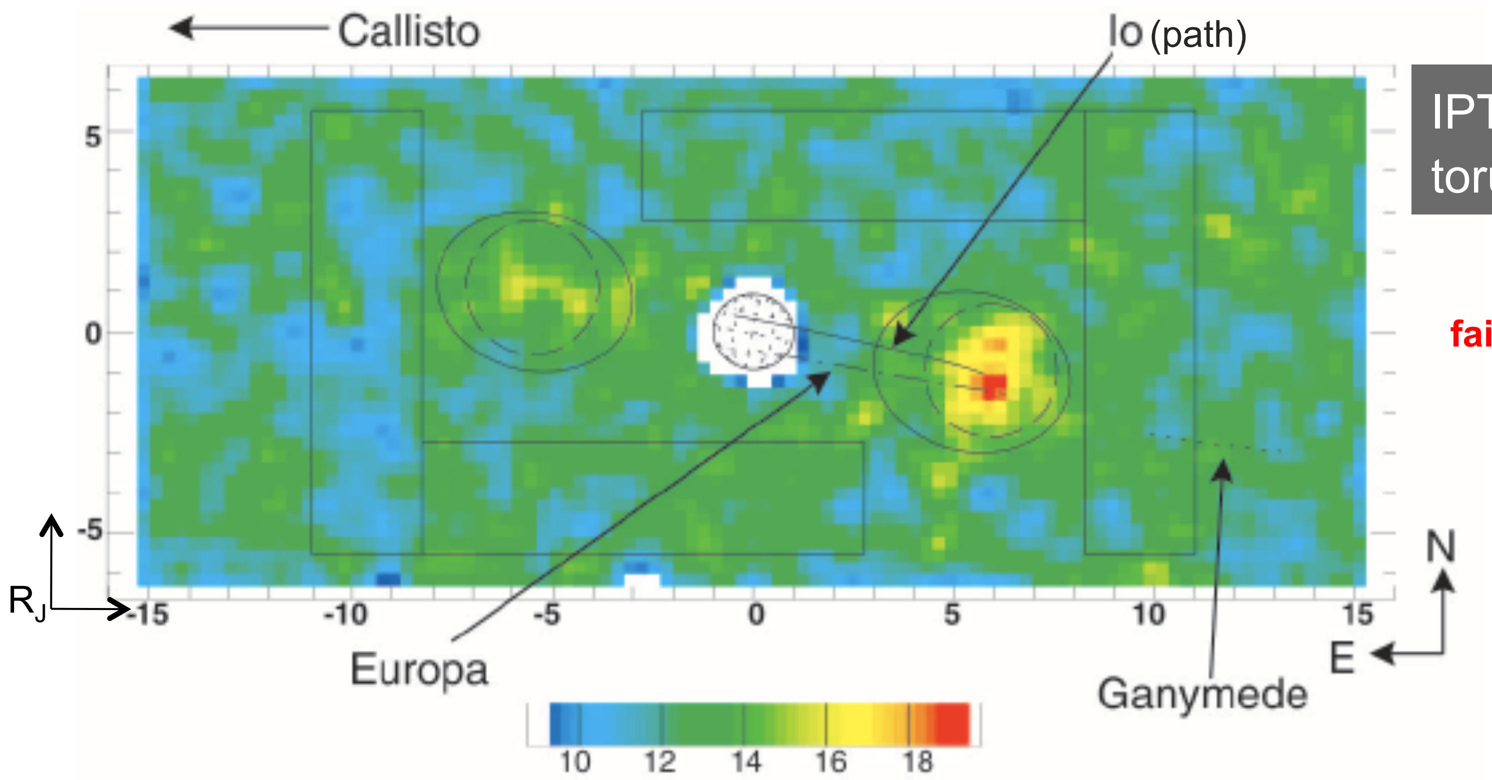
Galilean satellites and Io plasma torus (IPT)



Elsner+06

• X-ray emission from Io and Europa (10 photons each, 86ks observation), tentative emission from Ganymede and Callisto.

• The emission is due to the bombardment of the satellite surface by energetic H, O, and S atoms and ions, with subsequent **fluorescent emission**.



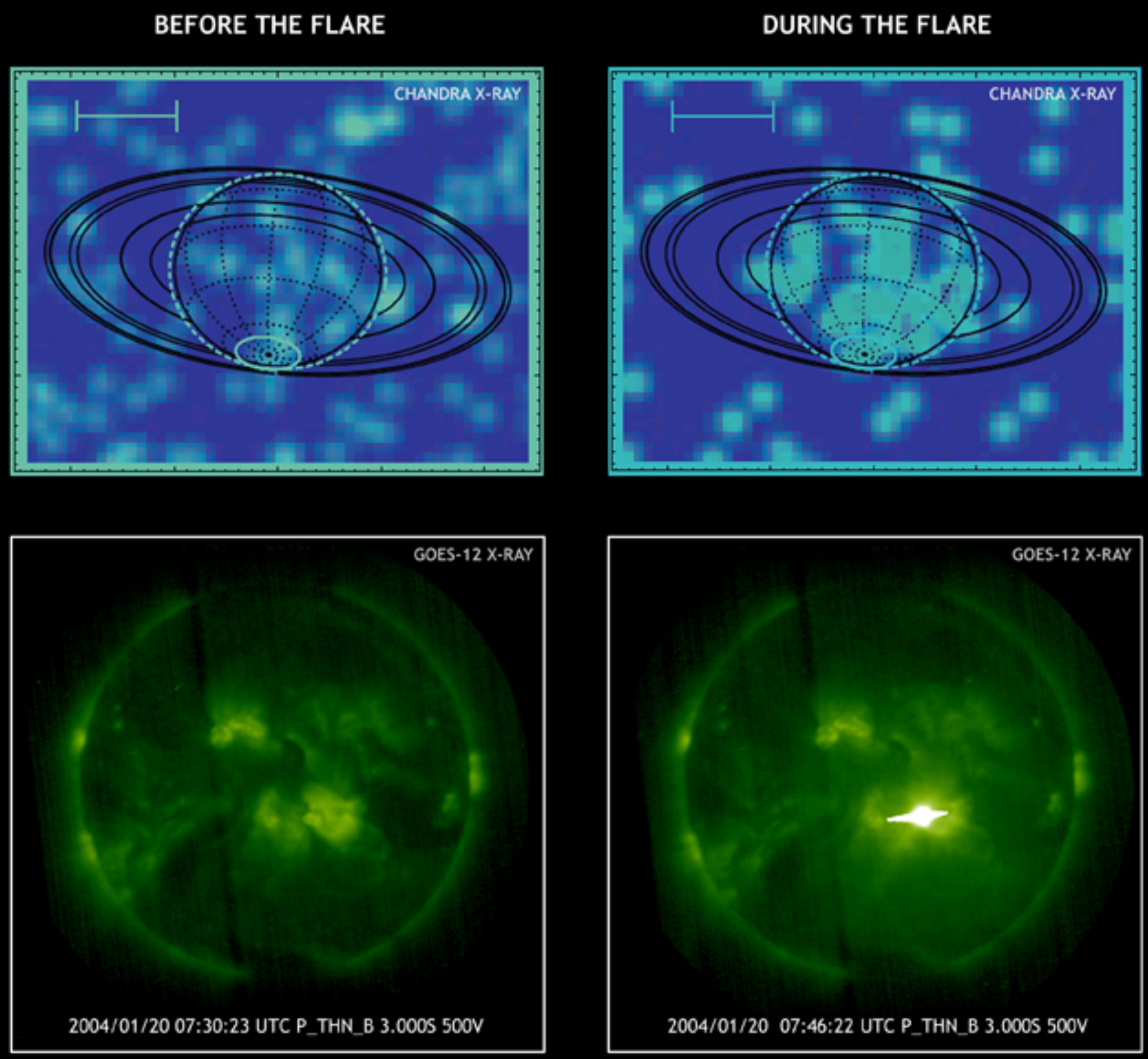
IPT=ion plasma torus

IPT is a faint soft X-ray emission

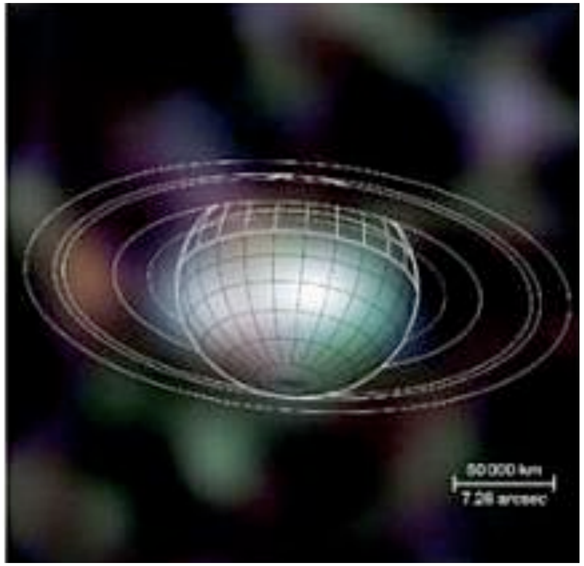
• IPT is defined by optical emission from O and S ions, mapped from ground-based telescopes. Elements likely coming from Io's volcanic activity. Atoms spewed into space, then ionized and trapped by Jupiter's magnetic field

• *Chandra* HRC image of the IPT (due to photoionization and CX in low-density plasma and neutral environment). X-ray emission due to bremsstrahlung from non-thermal electrons?

Saturn


BEFORE THE FLARE
DURING THE FLARE
CHANDRA X-RAY
CHANDRA X-RAY
GOES-12 X-RAY
2004/01/20 07:30:23 UTC P_THN_B 3.000S 500V
GOES-12 X-RAY
2004/01/20 07:46:22 UTC P_THN_B 3.000S 500V

X-rays from Saturn



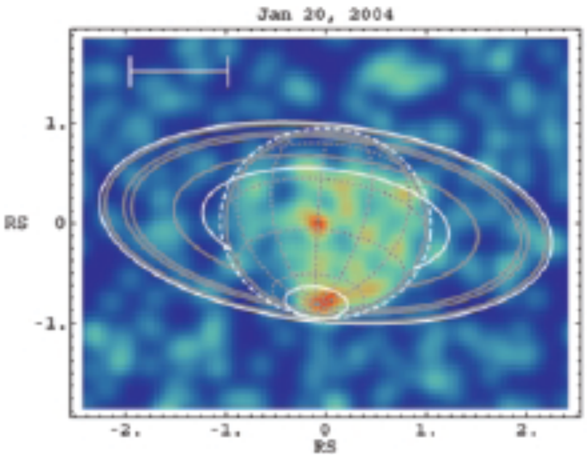
First X-ray image of Saturn (*Chandra*)

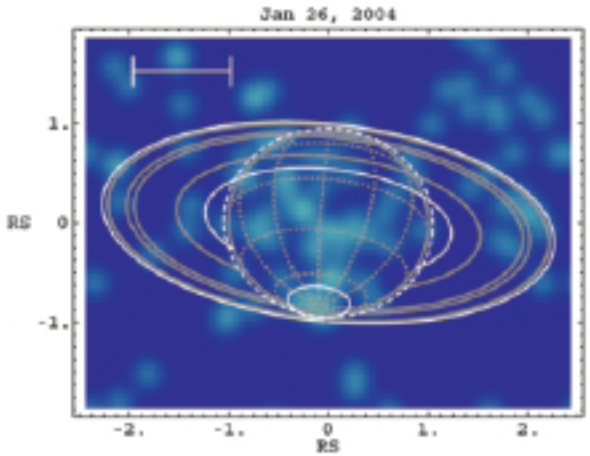
• First X-ray image from *Chandra*: low-latitude emission similar to that in Jupiter (**scattering of solar X-rays**), no auroral emission at the South Pole (North Pole not visible).

• Emission ¼ of that of Jupiter (because of distance).

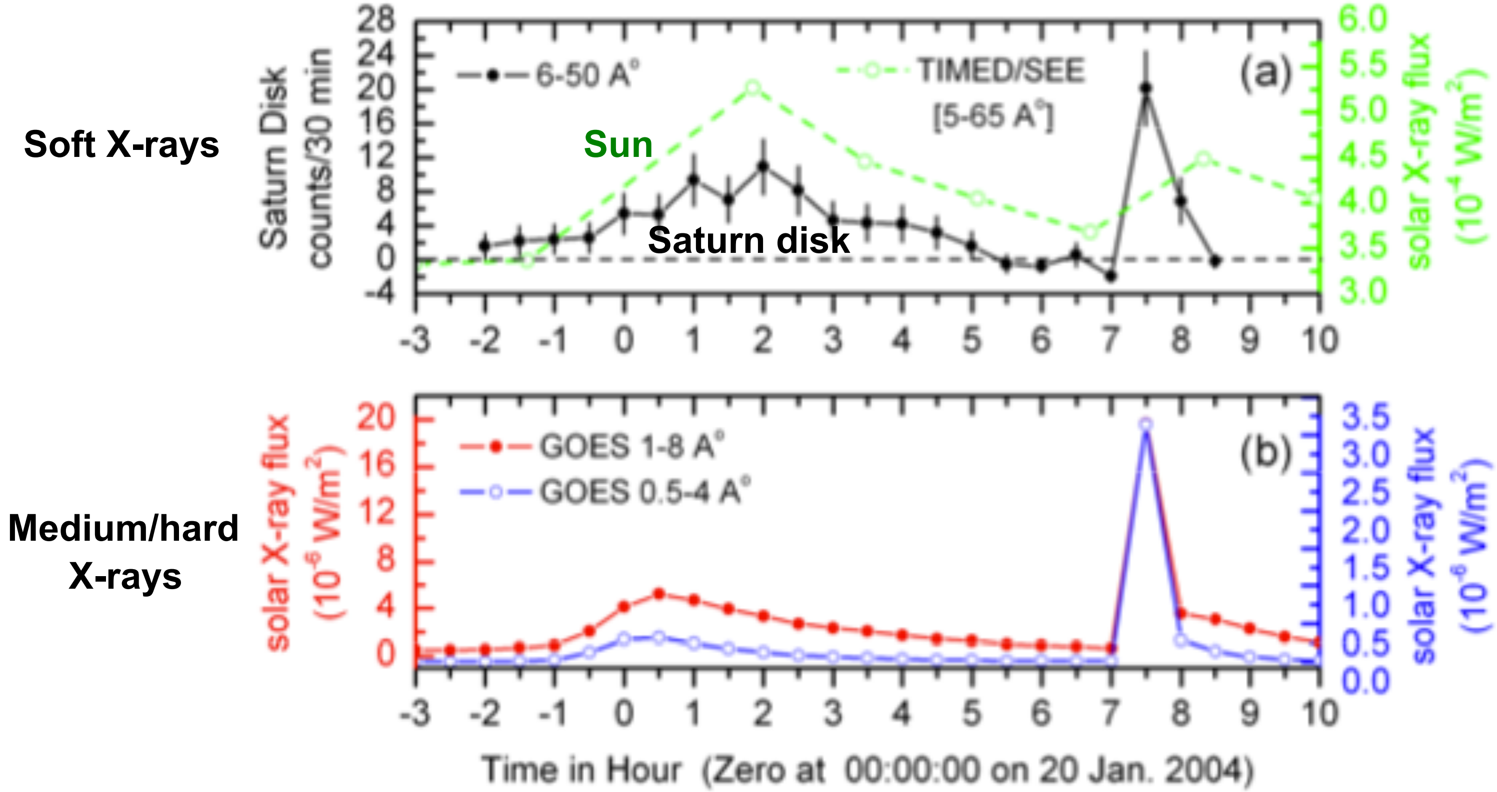
• Subsequently, possible X-ray emission from the south polar cap but emission too different (softer) from that of Jupiter. Extended X-ray emission from the disk?

• Variable X-ray emission (≈factor 2-4 over one week).



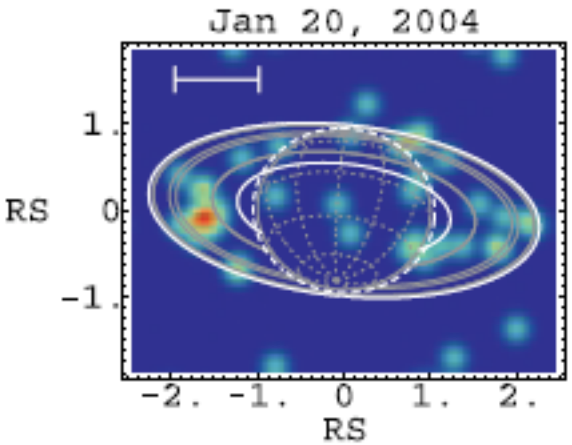


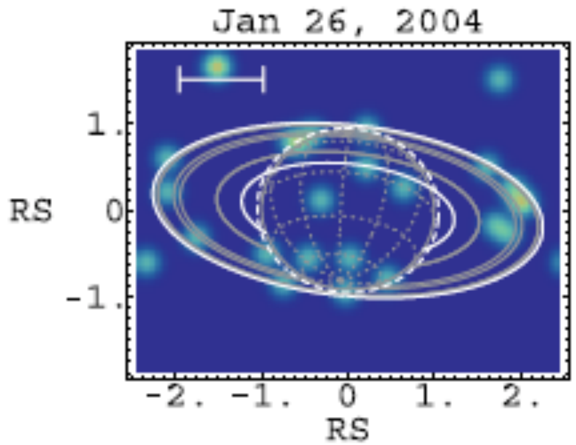
Chandra 0.2-2 keV images of the Saturn disk taken one weak apart



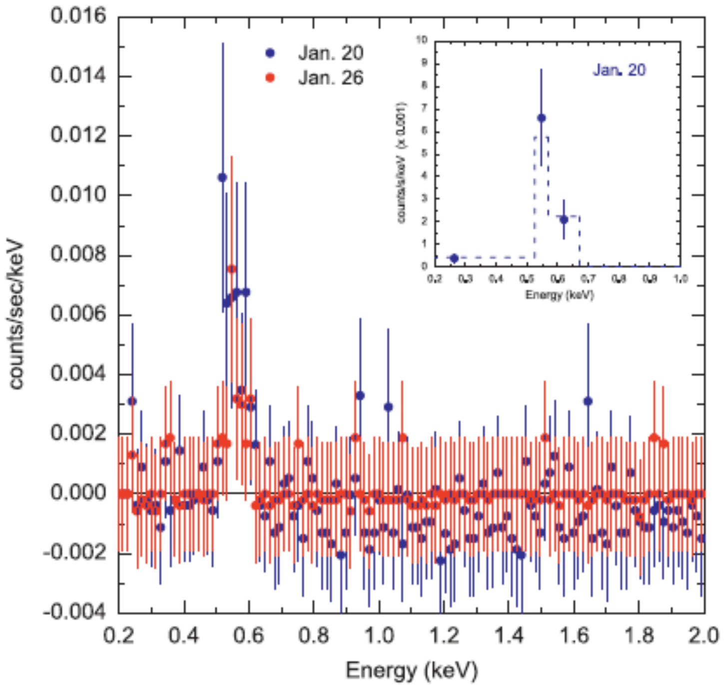
Solar flare and then Saturn disk flare: scattering of solar X-rays

and X-rays from the rings





Chandra 0.49-0.62 keV images to mazimize the prominence of oxygen emission (low emission from the disk)

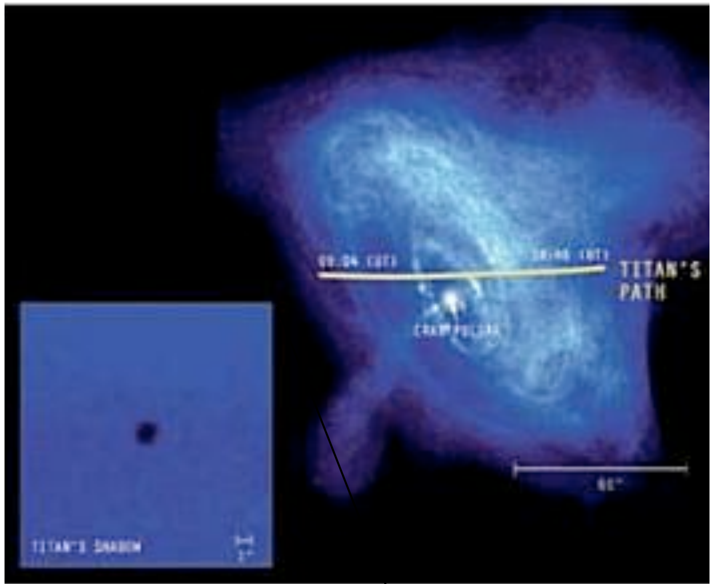


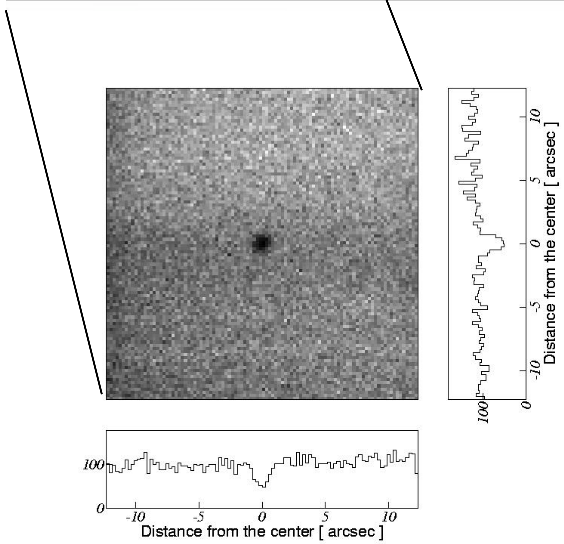
• Ring emission: **fluorescent scattering of solar X-rays** on oxygen atoms in the tenuous oxygen atmosphere and ionosphere over the rings and $H_2$0 icy ring material (one photon/10 min).

• All emission in the ≈0.49-0.62 keV energy range, where O Kα is present (E=0.53 keV).

• The emission is highly variable.

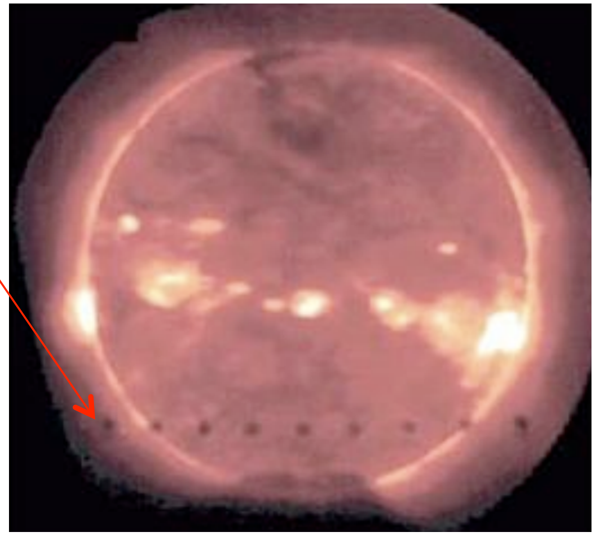
The “indirect” X-ray view of Titan

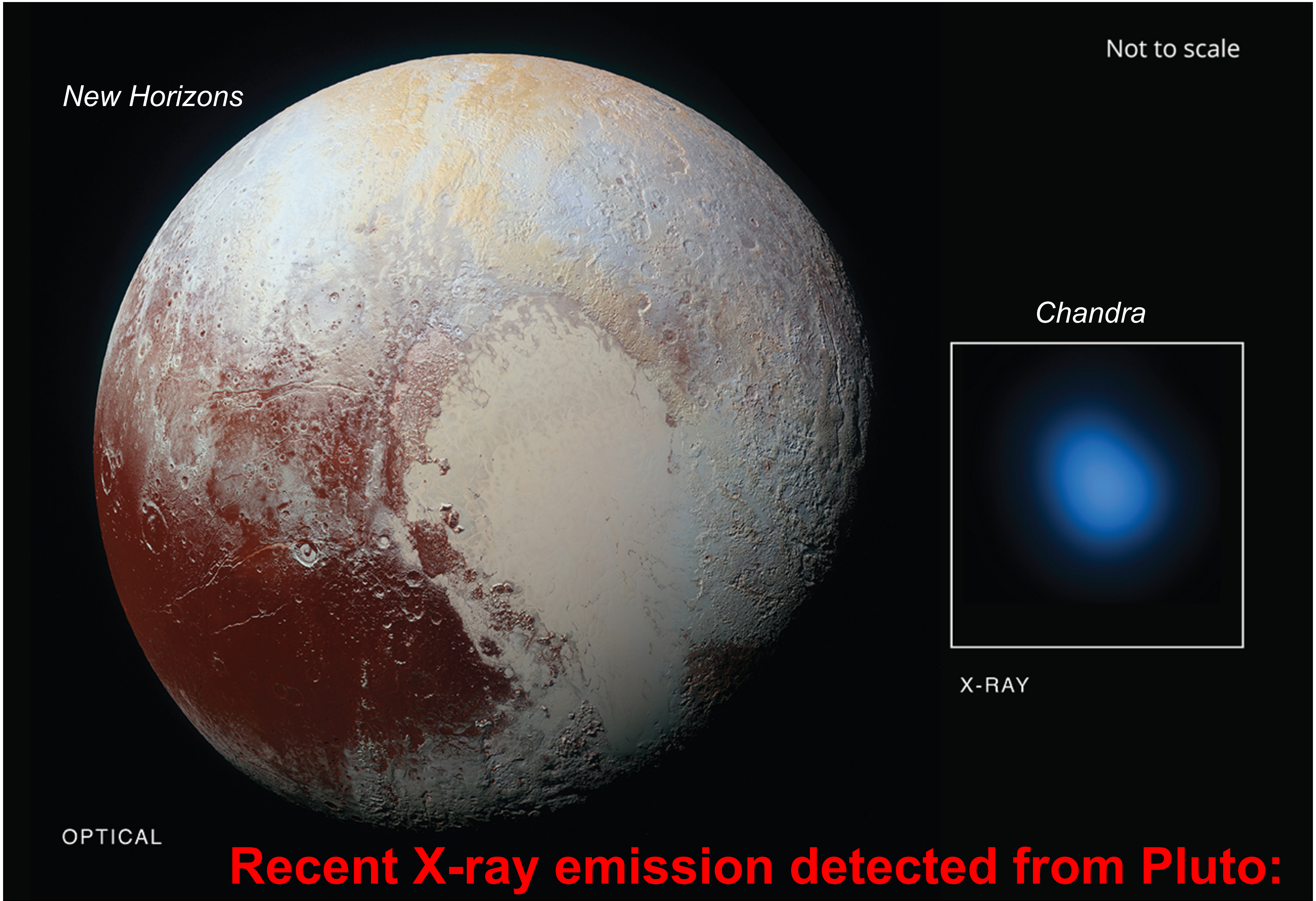




- Titan was observed in absorption in front of the Crab nebula (background, bright and extended X-ray source).
- First measurement of the Titan’s atmospheric extent at X-ray wavelengths.
- No X-ray emission from the Titan’s atmosphere (95% N – 5% NH_4).
- Size≈880 km±60 km

“Transit technique” adopted also for the study of Venus

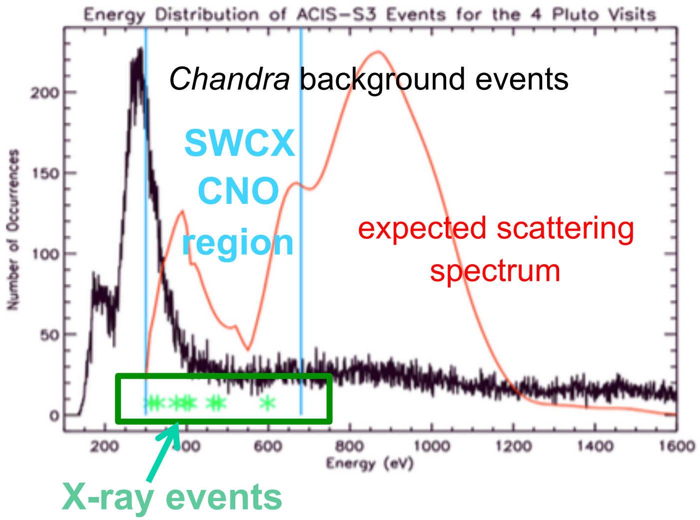


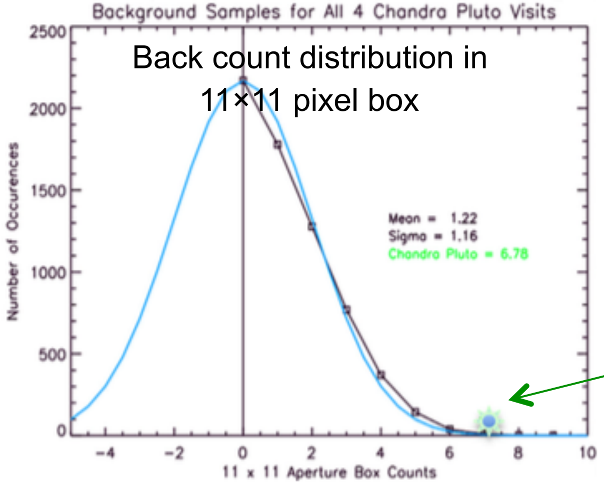


Recent X-ray emission detected from Pluto:
Chandra at its best

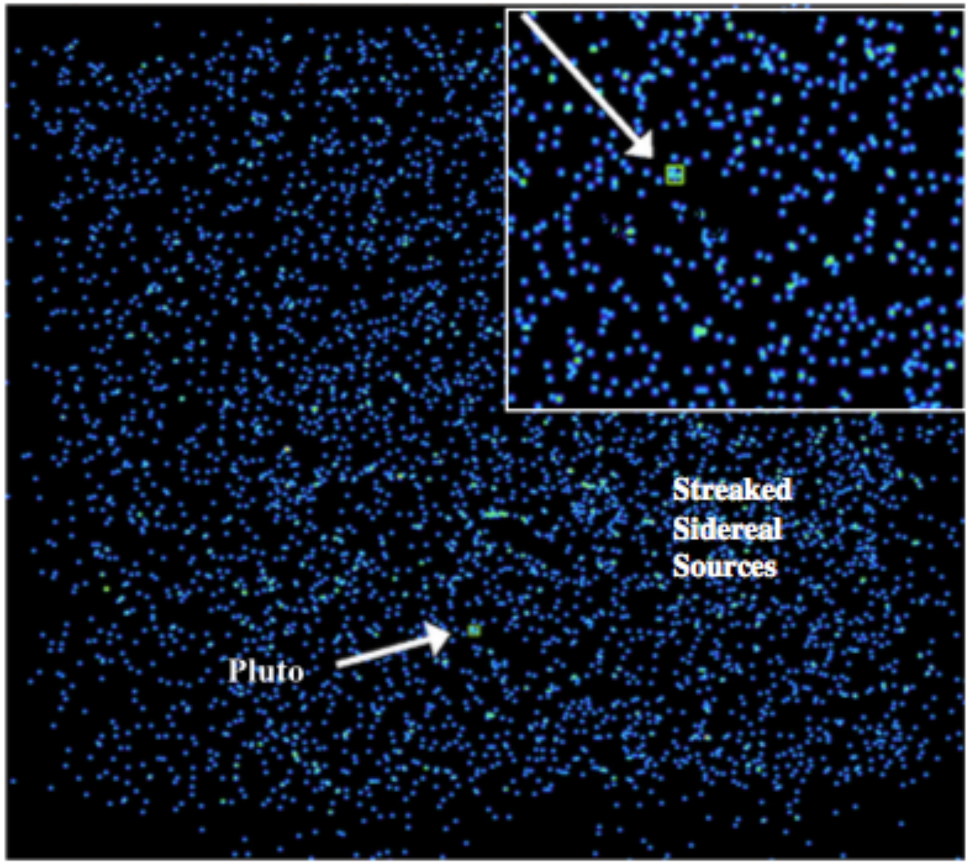
X-ray emission from Pluto

- T=174 ks
- N (net counts)=6.8 [0.3−0.6 keV], probability of being a random fluctuation of the background being $<5\times10^{-4}$ ➔ $L_X \approx 2\times10^{15}$ erg/s





Significance of the *Chandra* detection



Lisse+16

Possible causes of X-ray emission:

- ❑ Precipitation of solar wind or magnetospheric energetic ions into planetary atmosphere

- ❑Fluorescence scattering of solar X-rays

- ❑Charge exchange of energetic solar wind or magnetospheric energetic ions with cometary or planetary neutral atoms

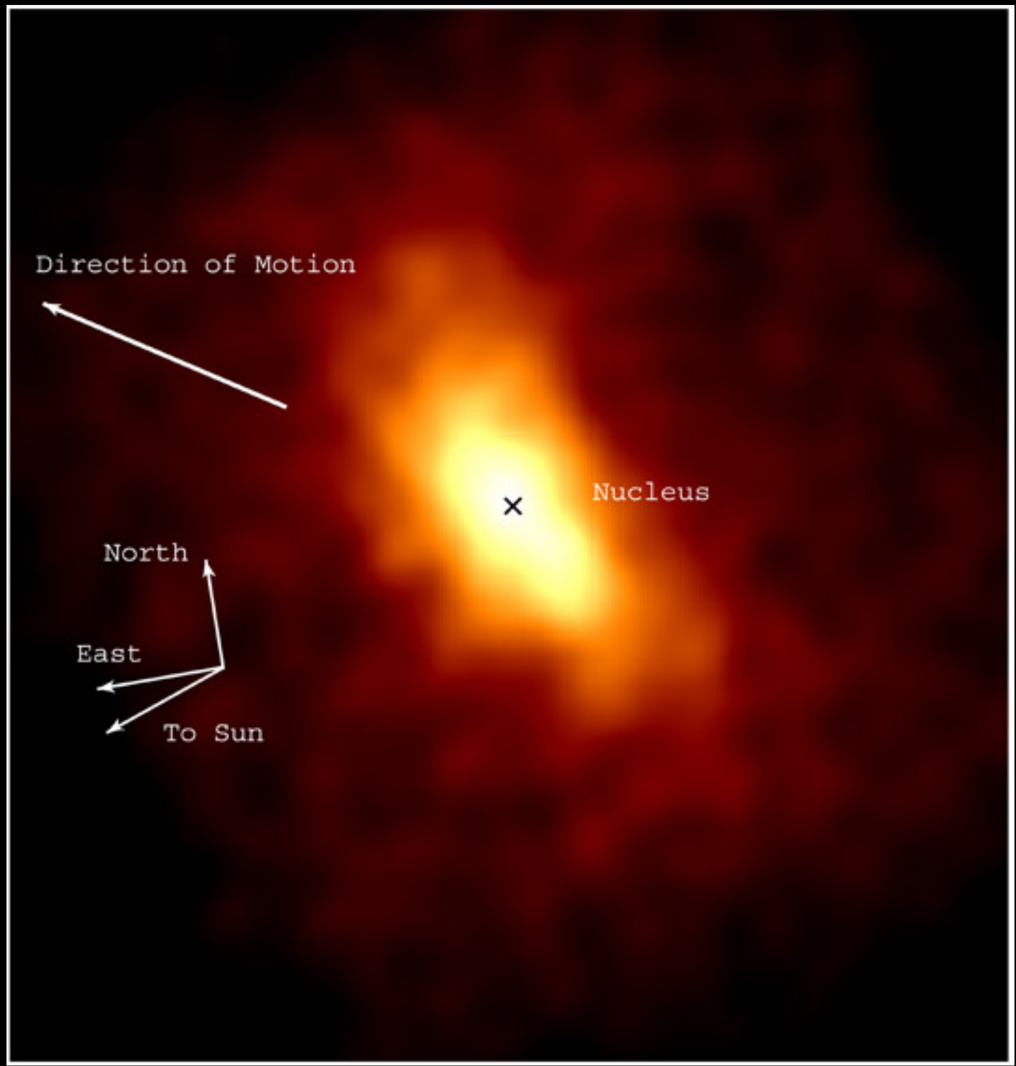
However:

a. No significant intrinsic magnetic field observed in Pluto, hence no aurora effects

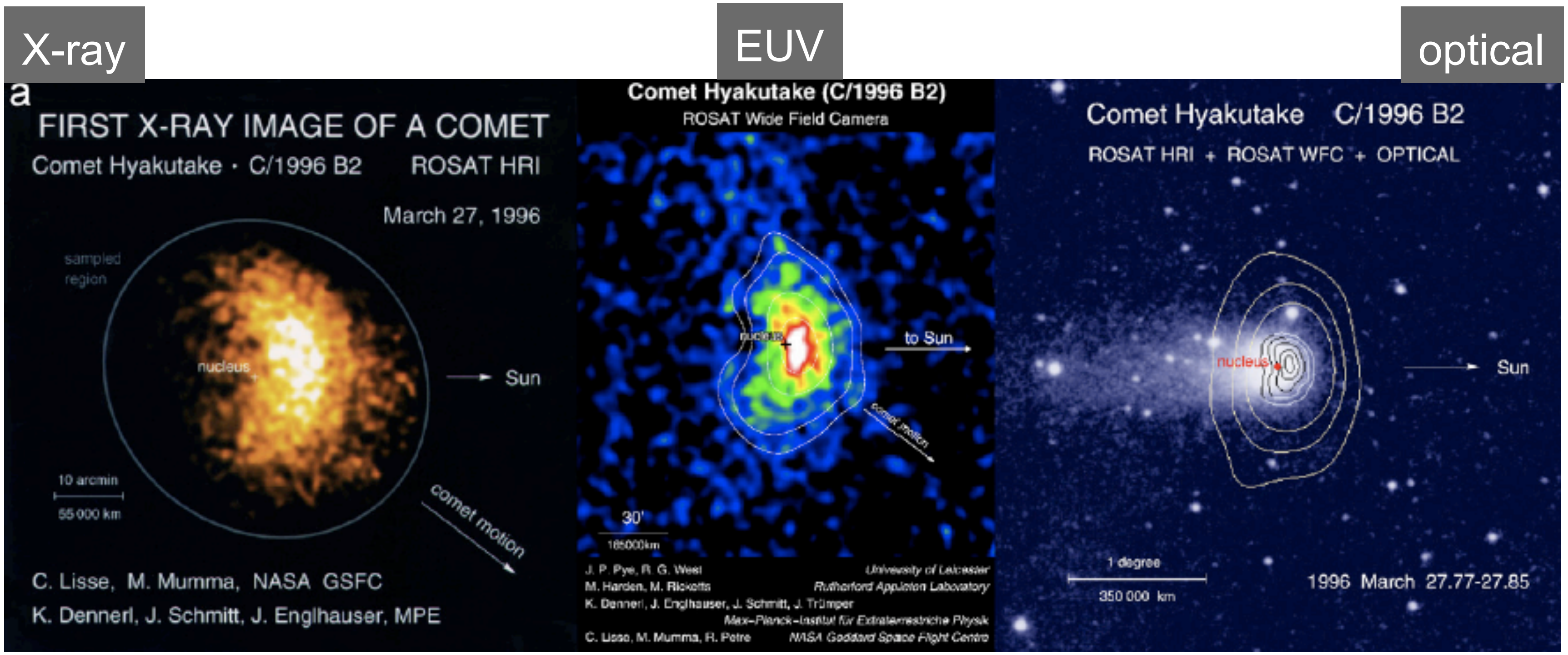
b. Unlikely the presence of scattering (because of the observed photon distribution – photons expected at ≈0.6−1.0 keV and the expected count rates being ≈3 orders of magnitude lower than measured, assuming Martian measurements)

SW minor CNO ion **charge exchange** and neutral gas species (mainly CH4) escaping from Pluto appears the most reasonable explanation

Comets



X-rays from comets



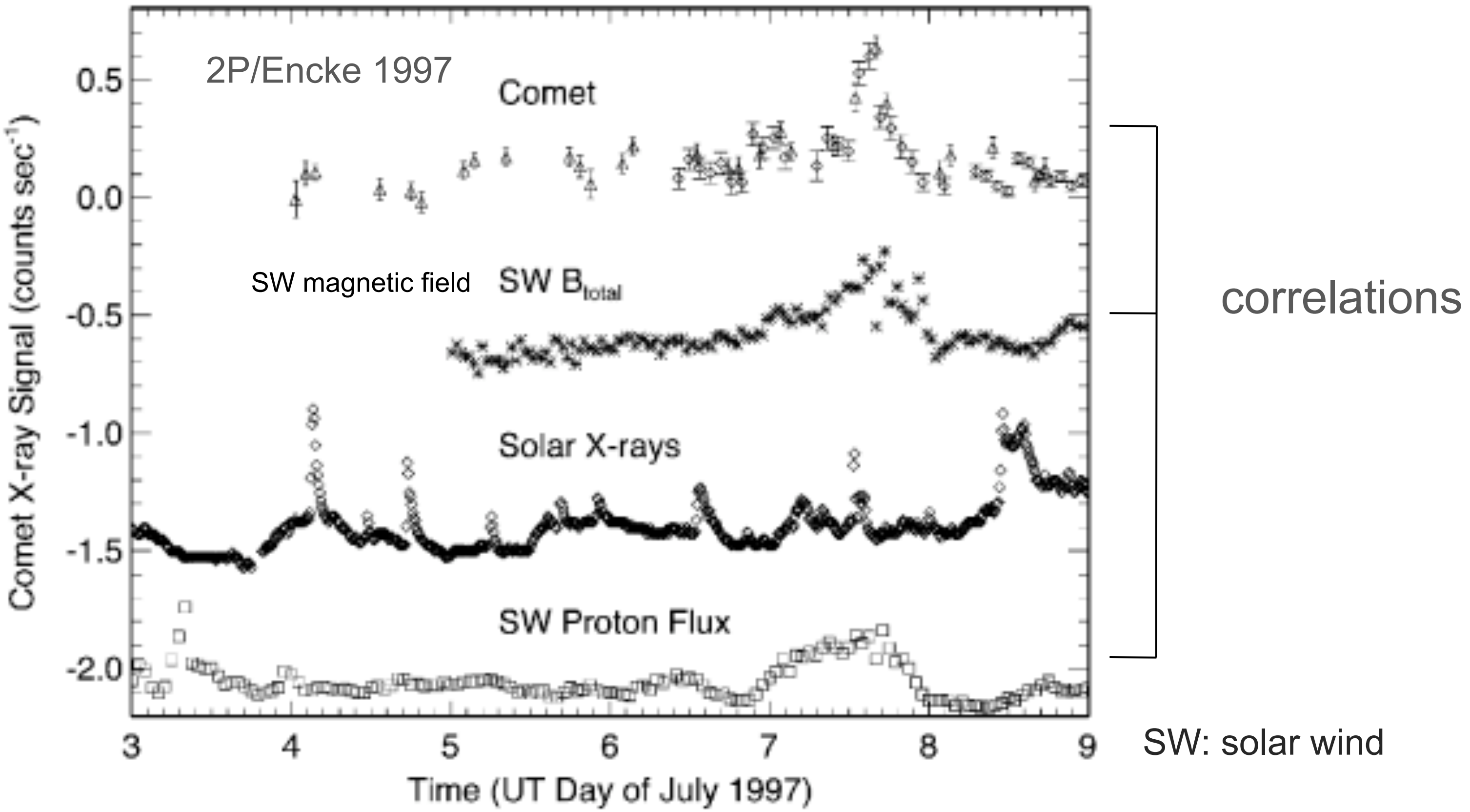
• 1996: first X-ray pointed observation and detection of emission from a comet (Hyakutake, *ROSAT*).

• X-rays from interaction of solar wind with comet's atmosphere (**CX emission** between highly charged solar wind ions with cometary neutral species).

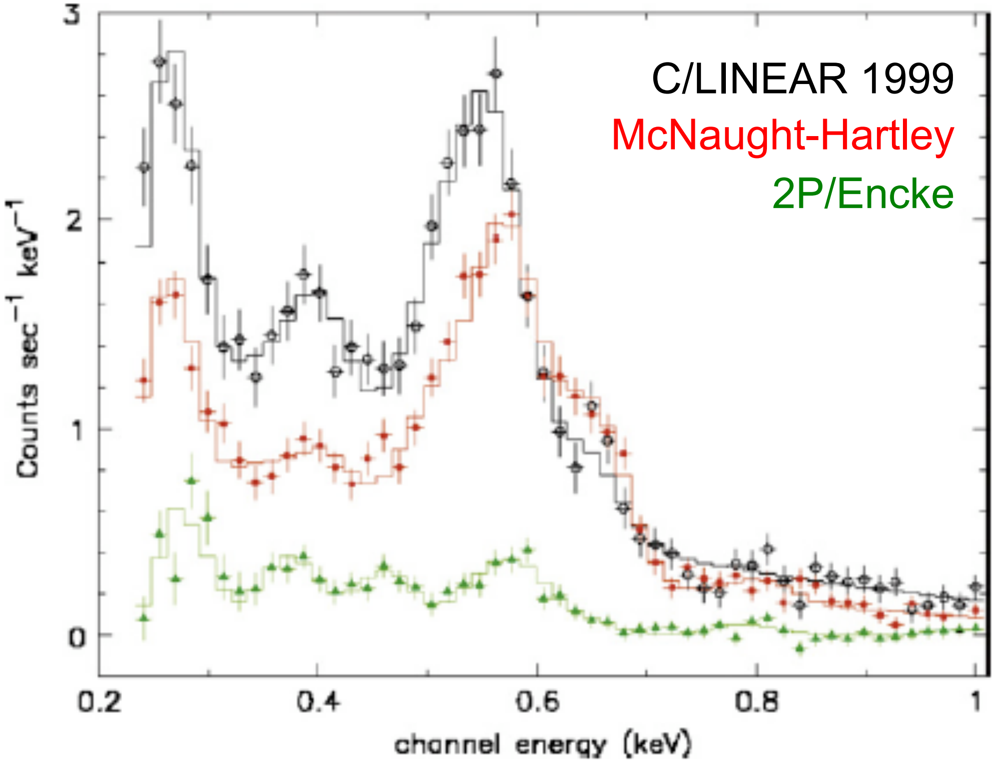
• X-ray brightness profile decreases as r^{-1}, where r is the cometocentric distance (up to 10^6 km).

• $L_x = 4\times10^{15}$ erg/s for Hyakutake – L_x prop. to L_{opt} and gas production rate.

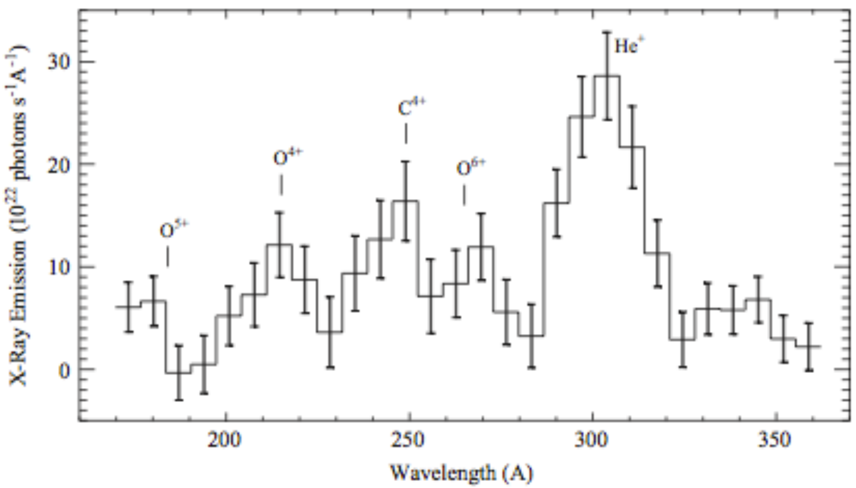
• No significant X-ray emission from the tails of comets.



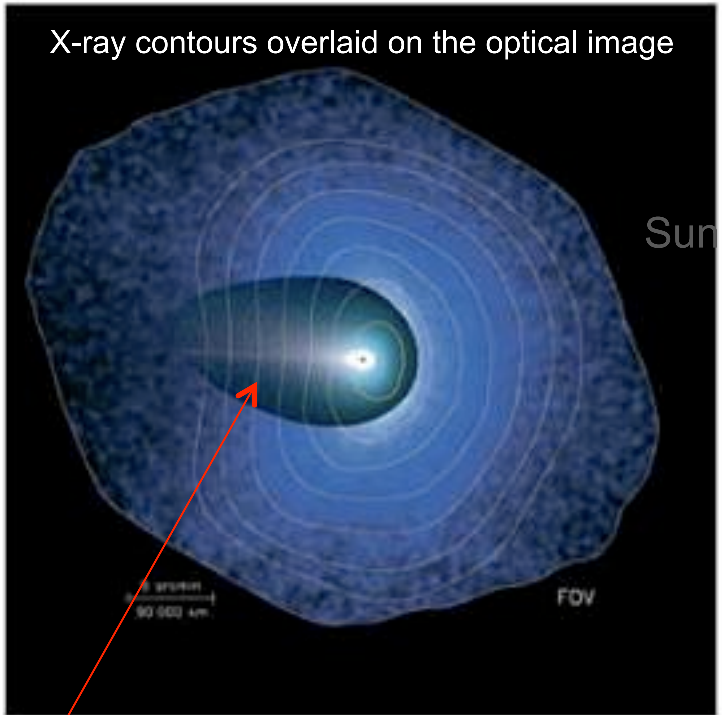
Comets are a typical example of charge exchange (**CX**) in action because of the large **cross section** (**≈3×10^{-15} cm^2**) of such process. It works between the highly excited ions from the solar wind (**SW**) and the gas in the cometary coma and tenuous comet's atmosphere. UV and X-rays are thus produced.

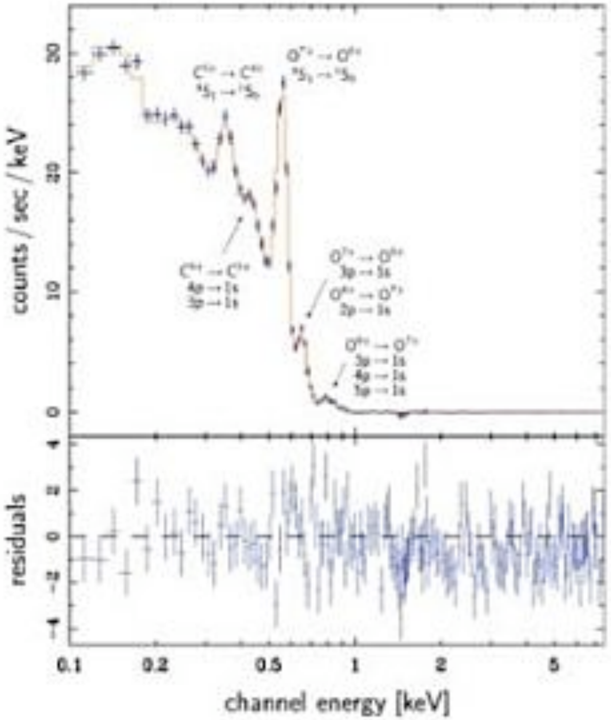


CX lines as bulk of the emission
C, O, N, and Ne
+ some bremsstrahlung
continuum emission



XMM-*Newton* image of the LINEAR comet.
CX transitions (mainly oxygen), no X-rays above 1 keV. Highly charged ions from the Sun, producing CX in the Coma. Then the increasing density of electrons reduces the ionization state of the ions. No X-ray emission from the comet's tail





Mostly, soft X-ray spectrum + CX lines

Shadow region = outer coma emission (projection effects)

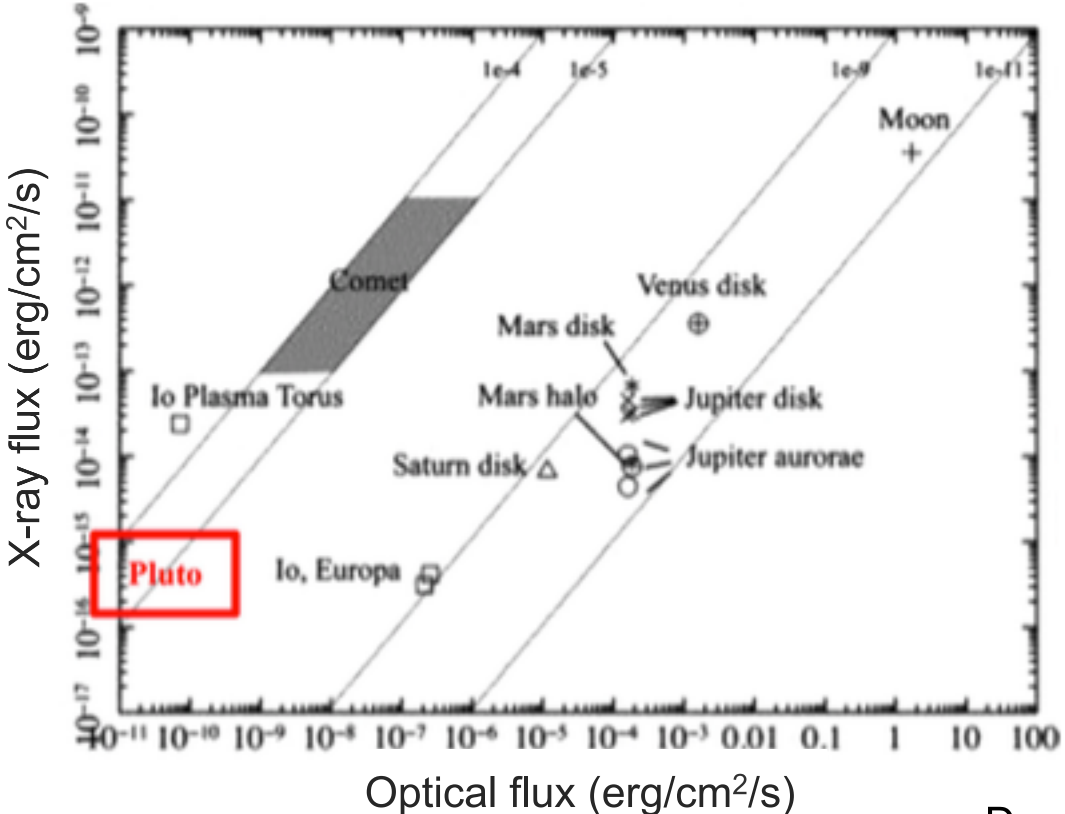
$$O^{7+} + H_2O \ \ (OH) \rightarrow O^{6+*} + (molecule - outer \ \ e^{-})$$

$$\downarrow$$

then de-excites to the ground state

$$\Downarrow$$

Direct information about the heavy ion content of the solar wind and on its different states [fast, cold wind – slow, warm wind - disturbed, fast and hot winds associated with interplanetary coronal mass ejections]



Dennerl+12, Lisse+16