X-rays in the Solar System

Introduction

Solar system: 8 planets, $\sim$100 satellites (=moons), 1000s of comets and planetoids.

Typical planetary temperatures are low (10s–100s K), with only upper atmospheres reaching $\sim$1000 K

$\Longrightarrow$ would not expect X-rays

But there are a few interesting exceptions, mainly found in the past 5–10 years

$\Longrightarrow$ worthwhile to take a brief look:

- X-rays from planetary aurorae,
- X-rays from fluorescence of solar X-rays
- X-rays from thunderstorms
- X-rays from charge-exchange reactions in cometary plasmas.

Recent Review: Bhardwaj et al., 2007, Planetary & Space Science 55(9), 1135–1189

History

Brief historical overview:

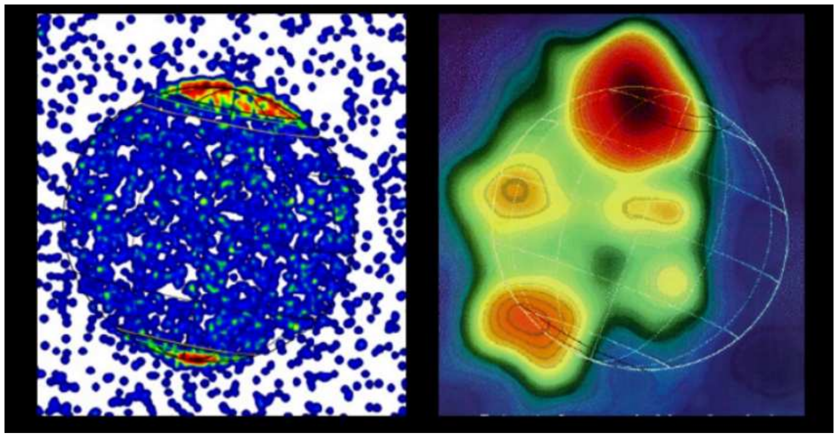
- 1950s: Earth's Aurora glows in X-rays
- 1962: Giacconi et al. unsuccessfully search for the Moon

  ...and find Sco X-1
- 1970s: Apollo missions look at flourescent X-rays from lunar surface
- 1979: *Einstein*-satellite discovers X-rays from Jupiter

$\Longrightarrow$ Up to 1990, there were three X-ray emitting objects known in the solar system (apart from the Sun)

- 1996: *ROSAT* discovers X-rays from comets (completely unexpected)
- today: X-rays discovered from every major and many minor solar system objects.

History



Jupiter with *Chandra* and *ROSAT* (CXC/MPE)

In order to study planets, it is necessary to have a good spatial resolution

$\Longrightarrow$ only possible since $\sim$2000 with *XMM-Newton* and, especially, *Chandra*.

Physical Processes

There are numerous physical processes responsible for X-ray emission in solar system:

1. collisional excitation: excitation of atoms and ions by impact of high-energy electrons $\Longrightarrow$ deexcitation $\Longrightarrow$ (X-ray) line emission
2. bremsstrahlung emission: emission due to motion of electrons in B-fields (gives a continuum spectrum)
3. Thomson scattering of solar X-rays
4. Flourescence emission after inner-shell absorption of solar X-rays
5. Solar wind charge exchange

Jan Curtis / http://www.geo.mtu.edu/weather/aurora/

Physical Processes

2nd main process: solar wind charge exchange

solar wind: highly ionized (mainly fully ionized) particles produced in the solar corona.

Ions can interact, e.g., with hydrogen and electron can get transferred:

$$A^{q+} + M \rightarrow A^{(q-1)+,*} + M^{-} \rightarrow A^{(q-1)+} + M^{-} + h\nu$$

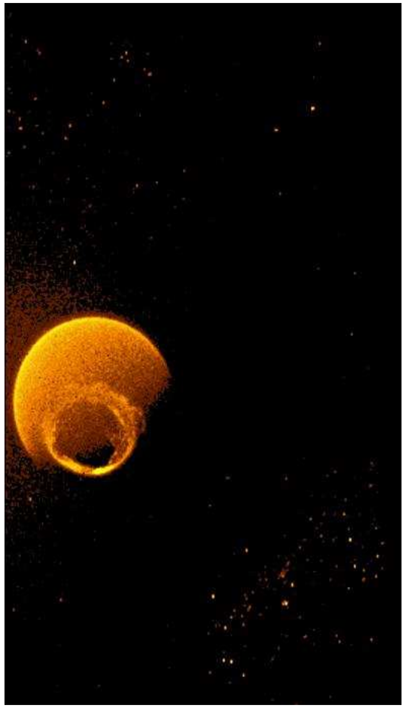
where:

- A^{q+}: highly ionized projectile (e.g., ionized O, C, Fe)
- M: target (e.g., H, H_2O, O)

Deexcitation cascade of A^{*} leads to emission of X-rays.

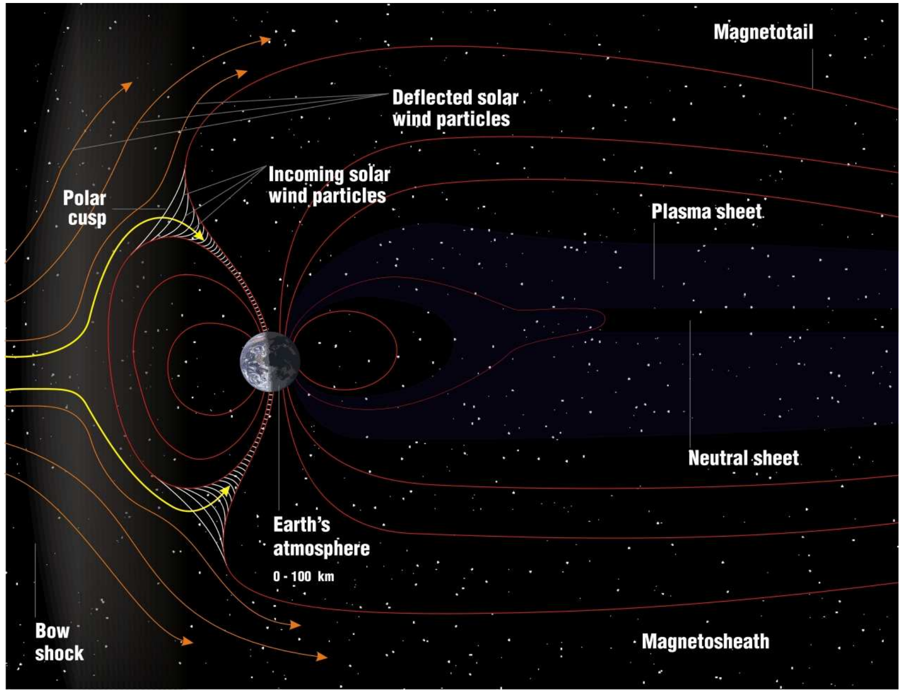
To work, need highly ionized projectiles, found as by-product ($<$0.1%) in the slow component of the solar wind, which comes from the hottest parts of the solar corona.

Aurora seen from Space Shuttle

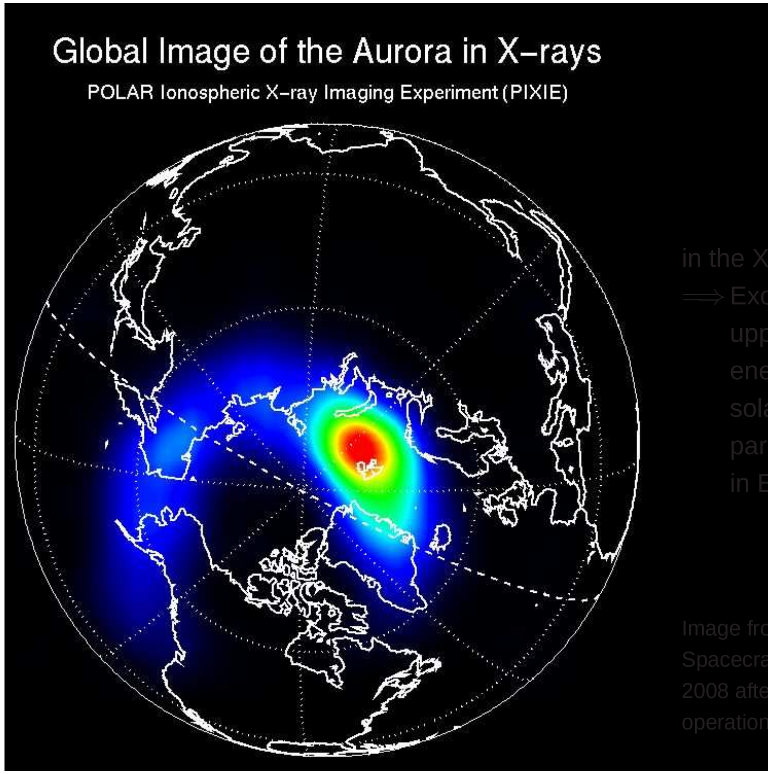


In Vacuum UV: “auroral rings” in polar regions.

NASA/Dynamics Explorer-1 (note Galactic plane!)

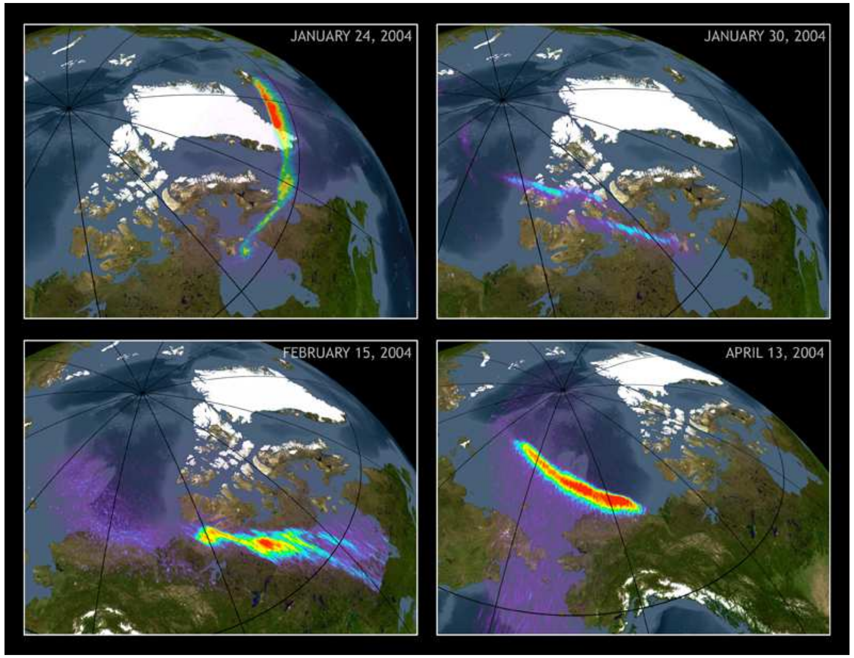


NASA/JPL/Wikipedia



Borealis and Australis are bright in the X-rays $\Longrightarrow$ Excitation of atoms in upper atmosphere by energetic particles in solar wind and particles accelerated in Earth's B-field.

Image from NASA/POLAR – Spacecraft switched off in April 2008 after 12 years of operations

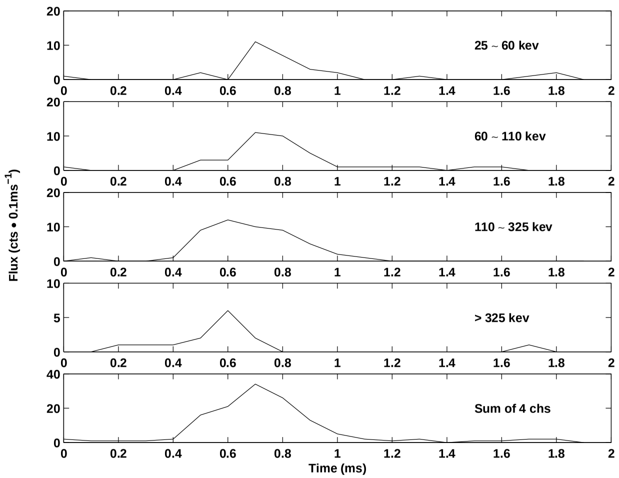


NASA/MSFC/CXC/A. Bhardwaj & R. Elsner, et al.; Earth model: NASA/GSFC/L. Perkins & G.Shirah

Aurora Borealis from *Chandra*: Strong variability depending on solar weather.

courtesy RIKEN

Earth: Thunderstorms, II



Feng et al., 2002, Geophys. Res. Let. 29(3), 6

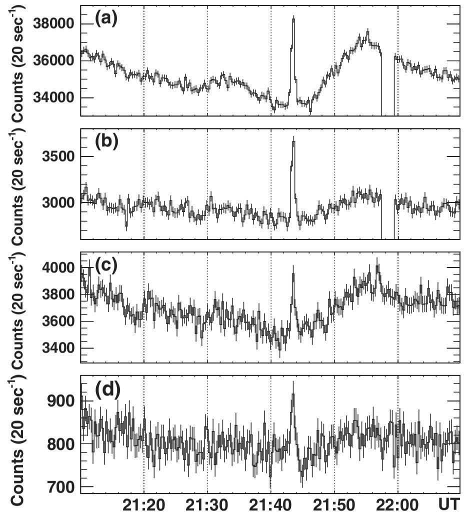
1990s: Short (1 ms) X-ray flashes and Terrestrial Gamma-Ray Flashes in 25 keV–1 MeV discovered from Earth with *Compton Gamma-Ray Observatory*

Fishman et al. (1994); later confirmed with the *RHESSI*-satellite

⟹ Possibly related to sprites and lightning discharges.

Detailed physics not understood yet; several ground-based experiments and also satellite missions in preparation.

Earth: Thunderstorms, III

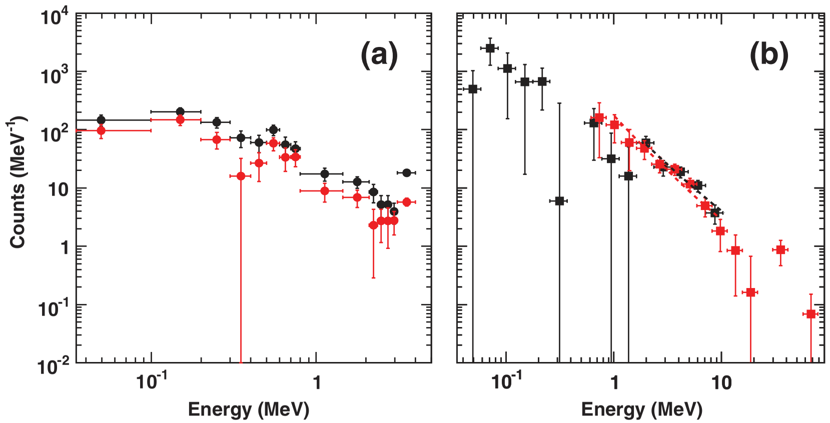


In addition to short flares, also longer, harder flares are observed.

Possible physical explanation for all these phenomena: bremsstrahlung from relativistic electrons accelerated in thunderclouds (typical fields: $100\,\mathrm{kV\,m^{-1}}$ up to $\gtrsim 400\,\mathrm{kV\,m^{-1}}$)

Tsuchia et al., 2007, Phys. Rev. Let. 99, 165002

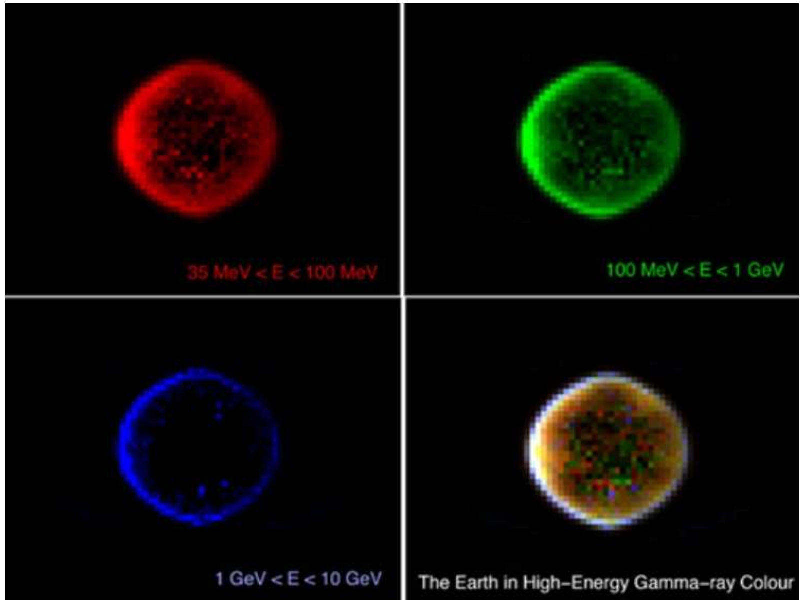
Earth: Thunderstorms, IV



Tsuchia et al., (2007, Fig. 4; data from two different NaI detectors, black: spectrum without BGO anticoincidence, red: spectrum with BGO anticoincidence)

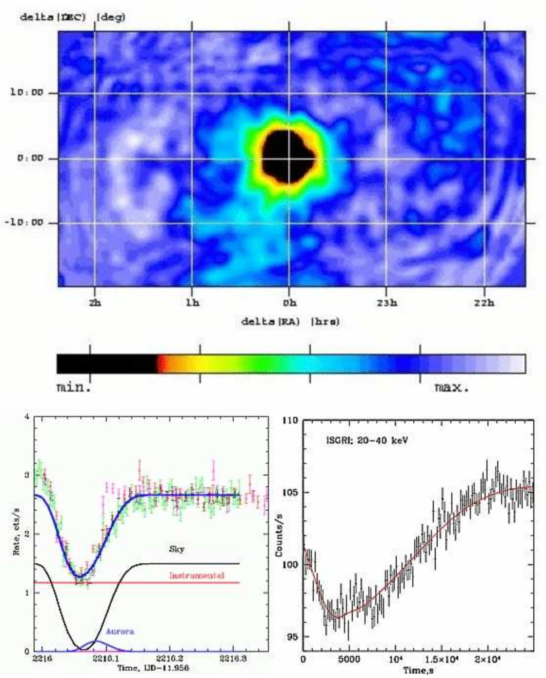
Bremsstrahlung idea has gained further support from first X-ray spectra of flashes measured in 2007 January in Japan.

Spectra from phoswich detector, same design as *Suzaku*-PIN.

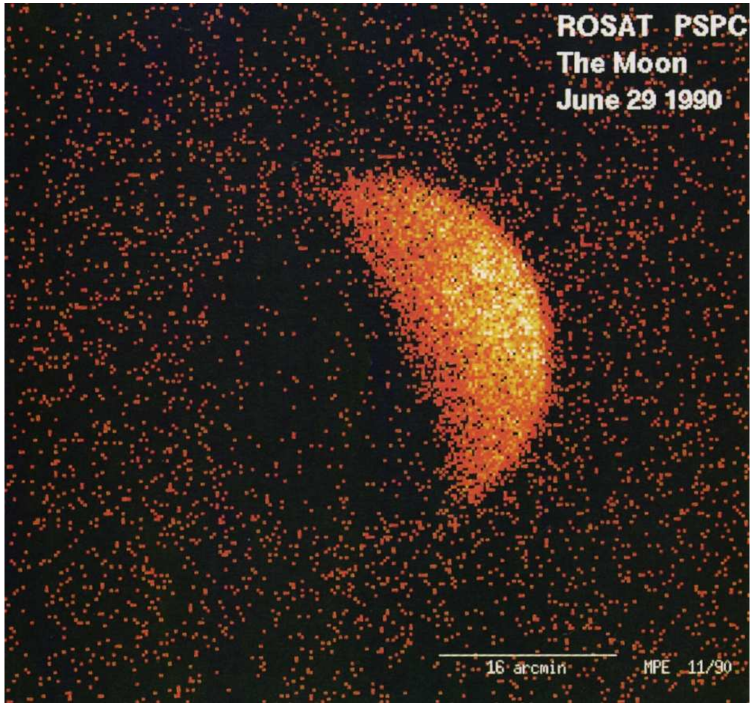


CGRO/MSFC/NASA

Earth in the gamma-rays: radiation produced by cosmic ray interactions in the upper atmosphere. Typically forward scattering $\Longrightarrow$ bright ring around the Earth.



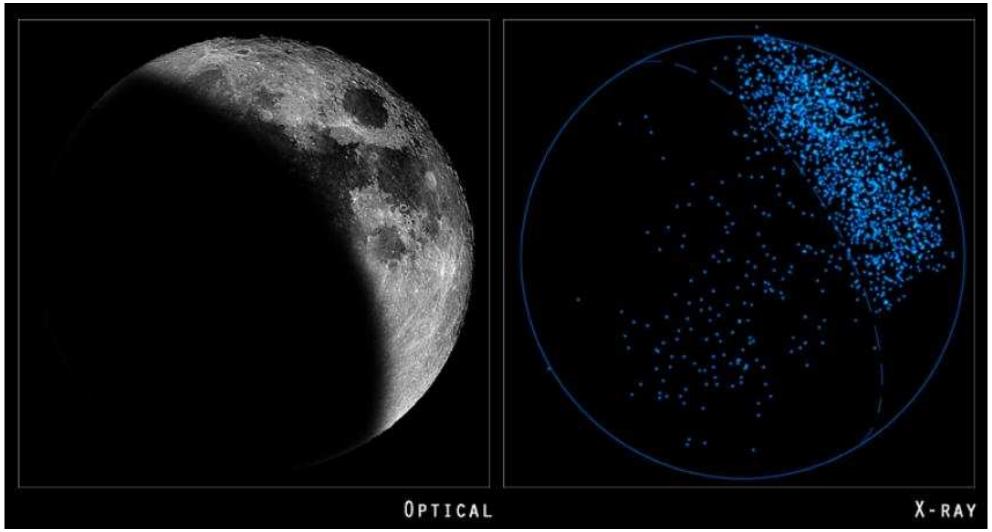
Recent *INTEGRAL* observations confirm earlier *CGRO* results and show possible contribution of aurora.



Moon's surface glows in the soft X-rays: flourescence triggered by solar X-rays

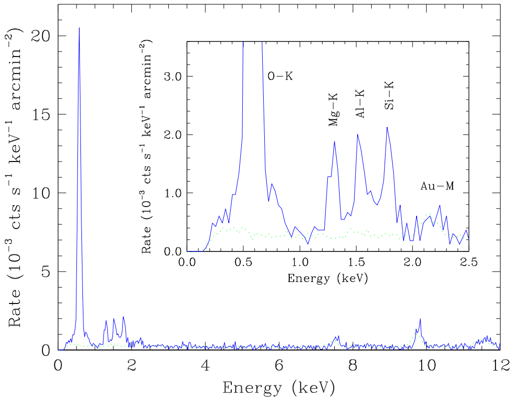
Note X-ray background and emission from unlit side of Moon

Schmitt et al. 1991, Nature, 349, 583



CXC

Moon

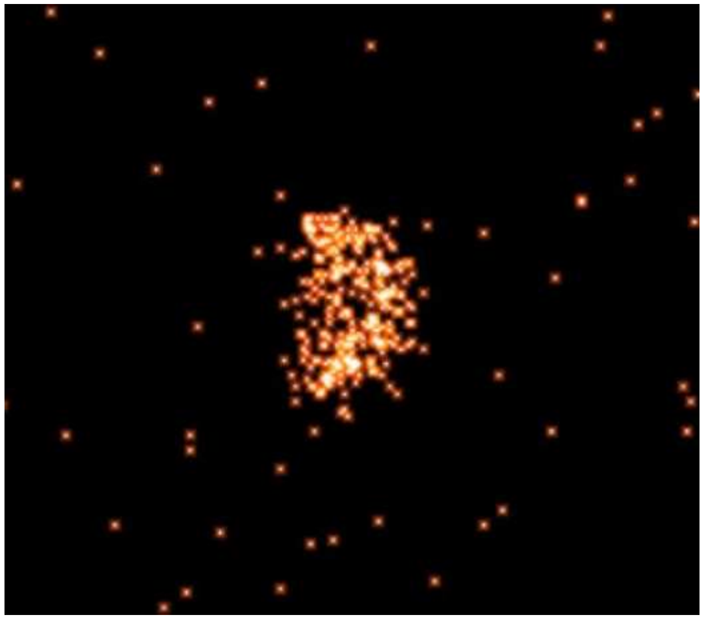


(Wargelin et al., 2004)

Emission from unlit side of moon was originally thought to be due to solar wind electron impact excitation, but *Chandra* spectroscopy reveals strong flourescent emission lines

⟹ Emission is due to geocoronal X-rays caused by solar wind charge exchange with ions located between the Earth's magnetosphere and the Moon

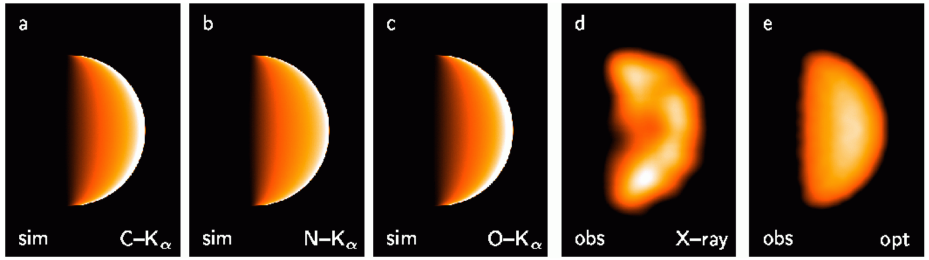
(measurements were made while *Chandra* was outside of the magnetosphere)



(Dennerl et al., 2002)

Venus: X-ray detection of Venus phase with *Chandra*

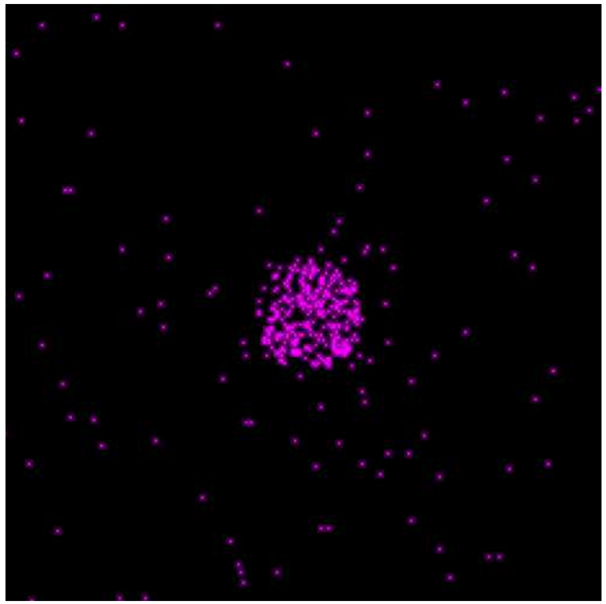
Inner Planets



(Dennerl et al., 2002, Fig. 8)

Image (and also spectrum) of Venus are consistent with solar X-rays scattered in the upper atmosphere of the planet.

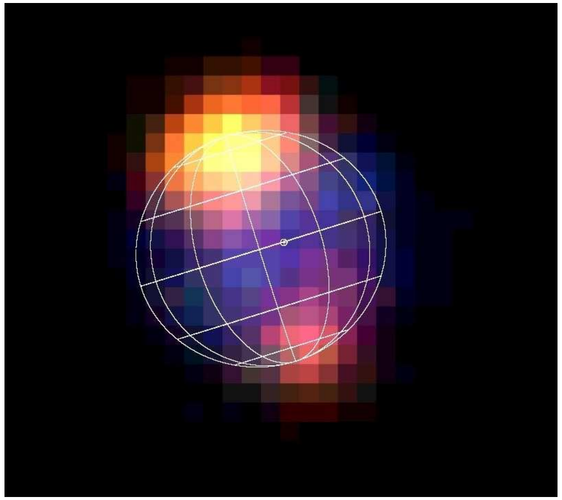
(this suggestion is also confirmed by correlated X-ray variability of the planet and the Sun)



(Dennerl, 2002)

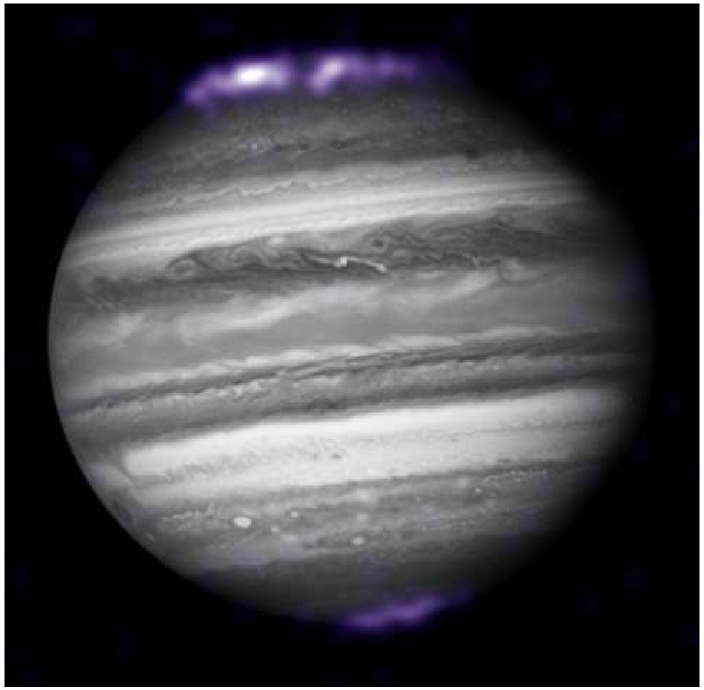
Similar to Venus, Mars low X-ray emissivity (∼4 MW) is also consistent with scattering in the tenuous atmosphere of the planet

Jupiter, I



X-ray color image of Jupiter (*XMM-Newton*):
red: soft X-rays,
green: medium energy X-rays,
blue: high energy X-rays
$\Longrightarrow$ Most X-rays come from Jupiter's aurora.

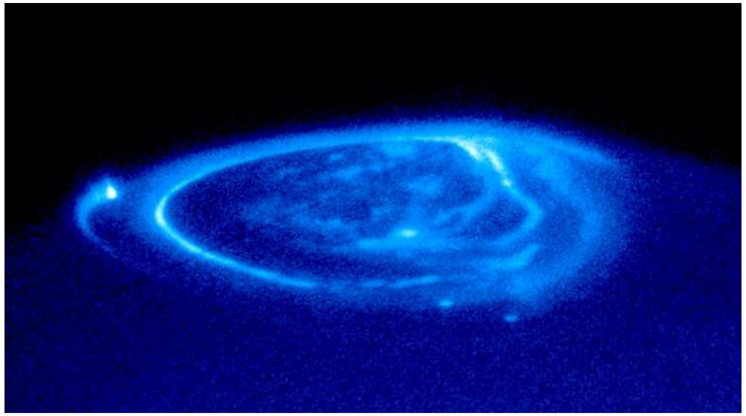
G. Branduardi-Raymont (MSSL) & ESA



Optical and X-ray image of Jupiter

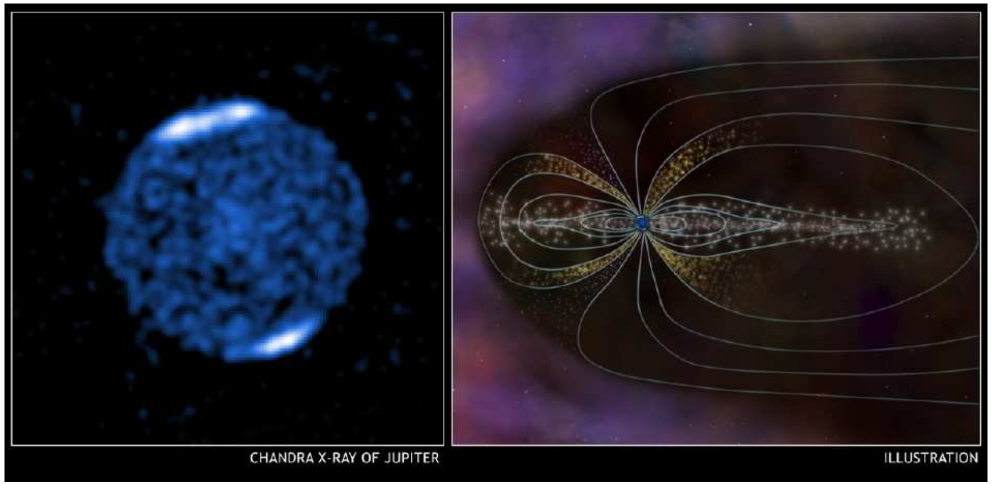
NASA/CXC/STScI

Jupiter, III



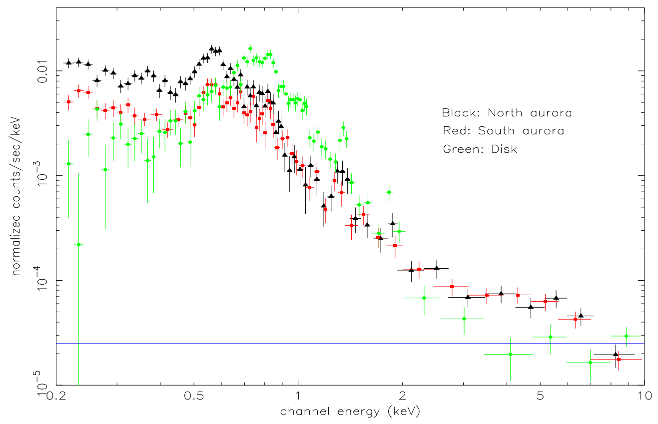
UV-Image of Jupiter from HST (NASA/ESA/John Clarke [U. Michigan])

Aurorae of Jupiter have "hot spots" which are magnetically linked to the Galilean Moons.



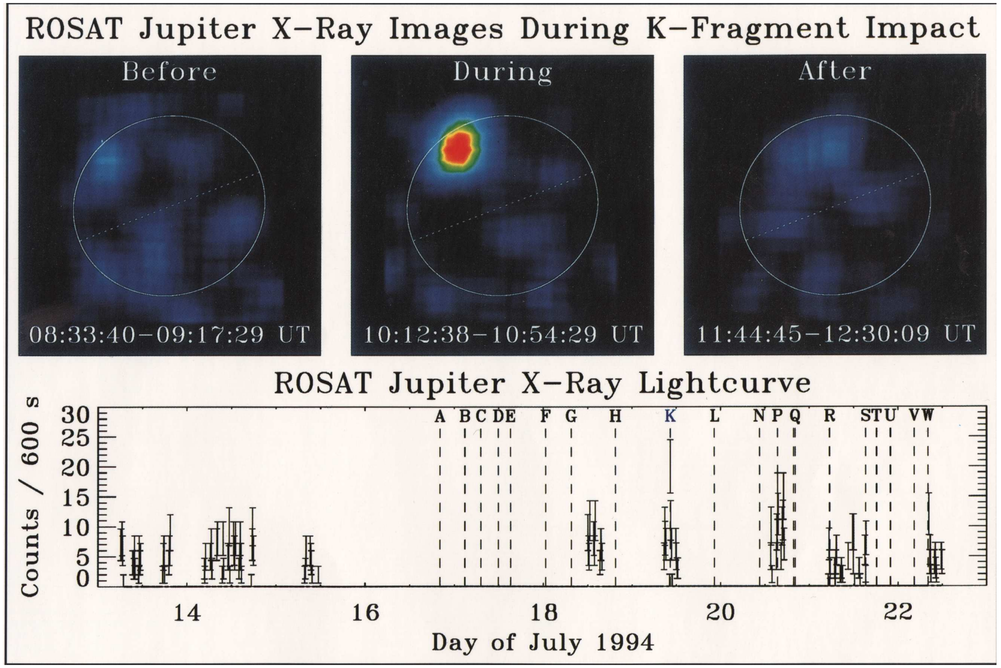
CXC

Jupiter, V

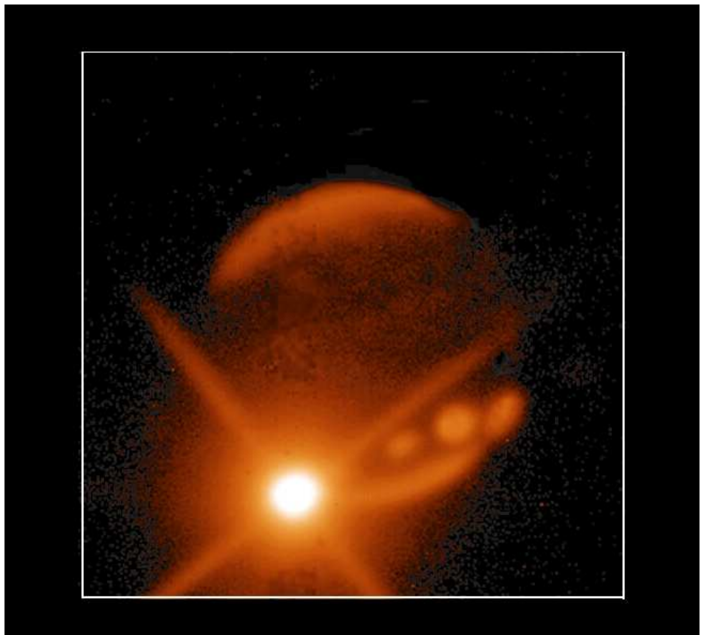


(Branduardi-Raymont et al., 2007)

Spectrum of Jupiter has strong emission lines from He-like O, possibly caused by charge exchange reactions with Sulfur (from Io).

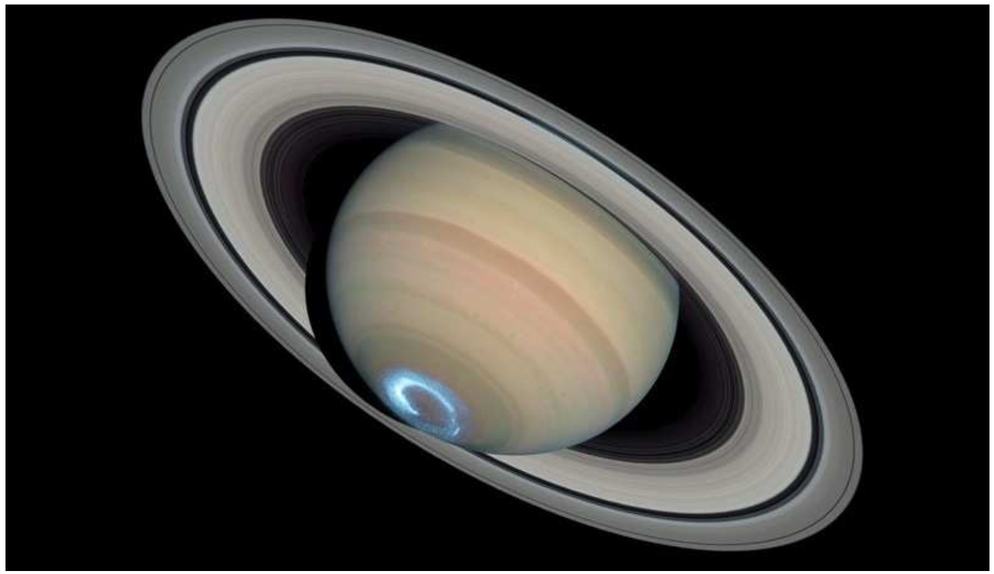


Impact of P/Shoemaker-Levy on Jupiter



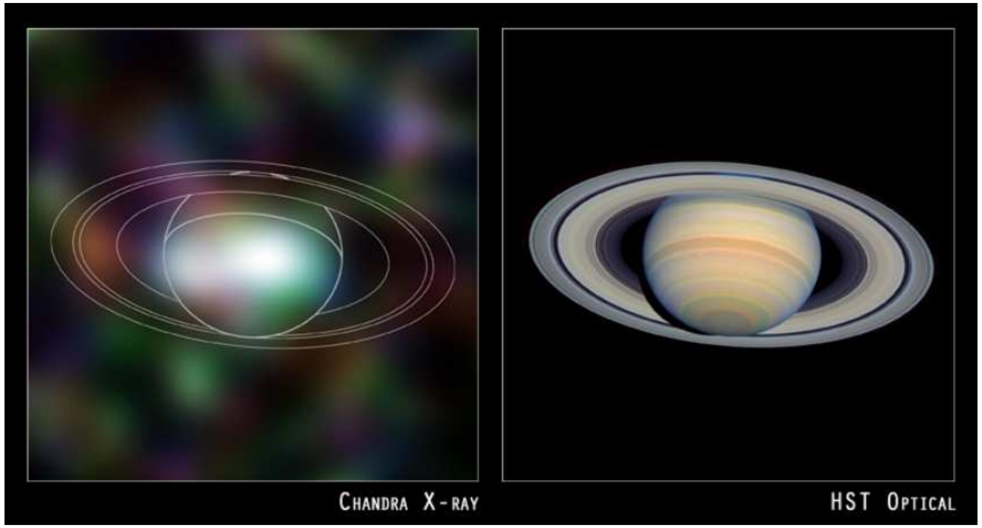
Impact of Fragment K of Comet Shoemaker-Levy on Jupiter.
The scars of three previous impacts can be seen on the planetary disk.

Image from Peter McGregor and Mark Allen, ANU 2.3m telescope.
Instrument: CASPIR at 2.34μm. Colour image Mt Stromlo Observatories.



Boson University and NASA

Saturn has aurorae similar to Jupiter ⟹ expect similar behavior

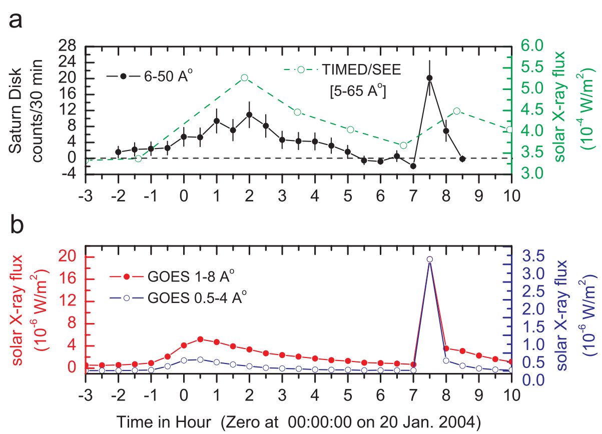


J.U. Ness

Saturn detected in 2002 October with *XMM-Newton* and in 2003 April with *Chandra*

Initially no emission from poles detected.

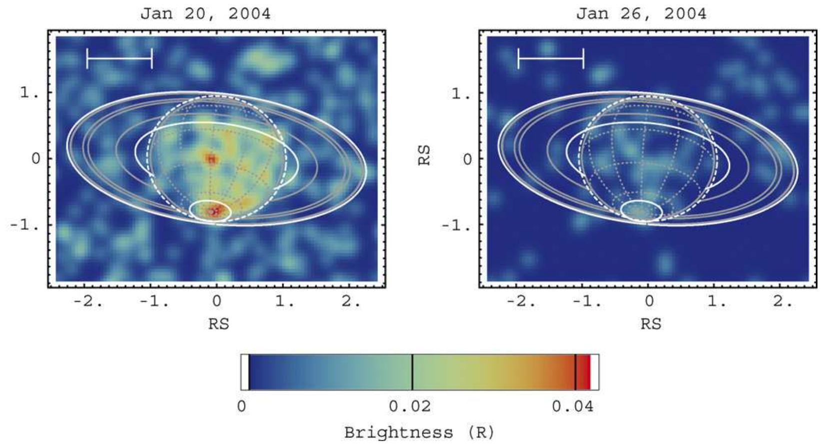
Saturn, III



Bhardwaj et al., 2005

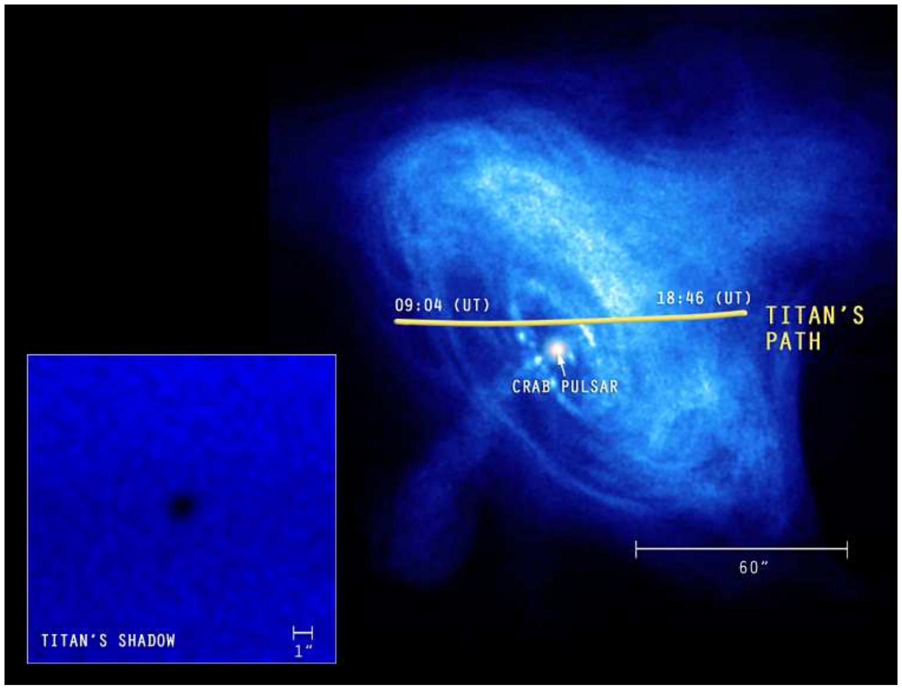
Correlated variability of Saturn's X-rays and solar X-rays points towards reprocessing as the main source of X-ray emission.

Saturn, IV



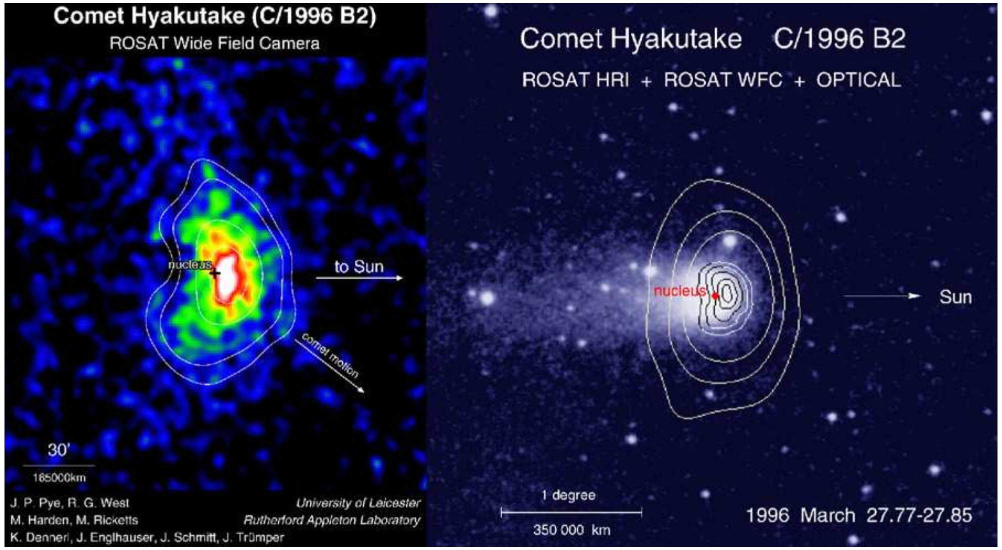
Bhardwaj et al., 2005

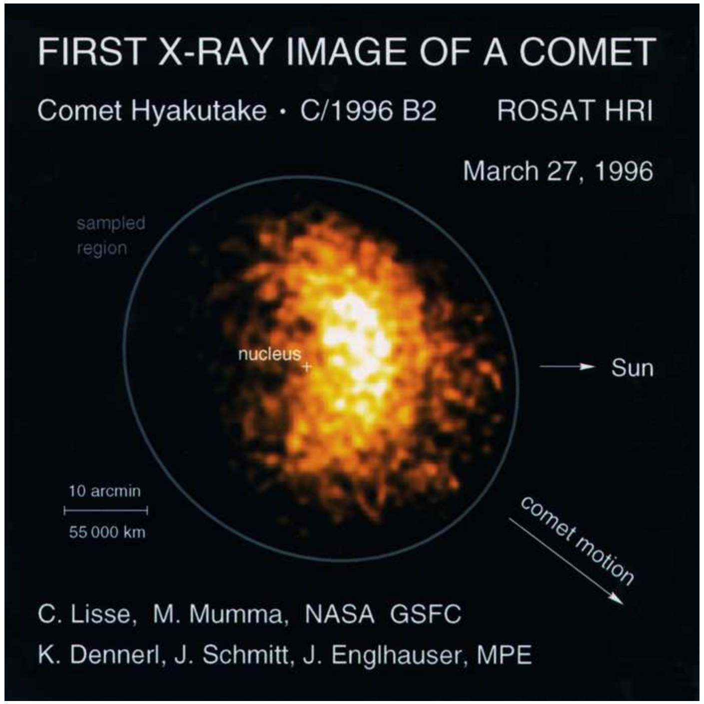
Later some auroral emission detected, but very strongly variable.



CXC

Comet Hyakutake, T. Hunter/CfA





Discovery led to suggestion of the solar wind exchange mechanism.

X-ray spectra show prominent line emission from hydrogen-like oxygen (emission line at $\sim$0.5 keV).

Branduardi-Raymont, G., et al., 2007, A&A, 463, 761

Dennerl, K., 2002, A&A, 394, 1119

Dennerl, K., Burwitz, V., Englhauser, J., Lisse, C., & Wolk, S., 2002, A&A, 386, 319

Wargelin, B. J., Markevitch, M., Juda, M., Kharchenko, V., Edgar, R., & Dalgarno, A., 2004, ApJ, 607, 596