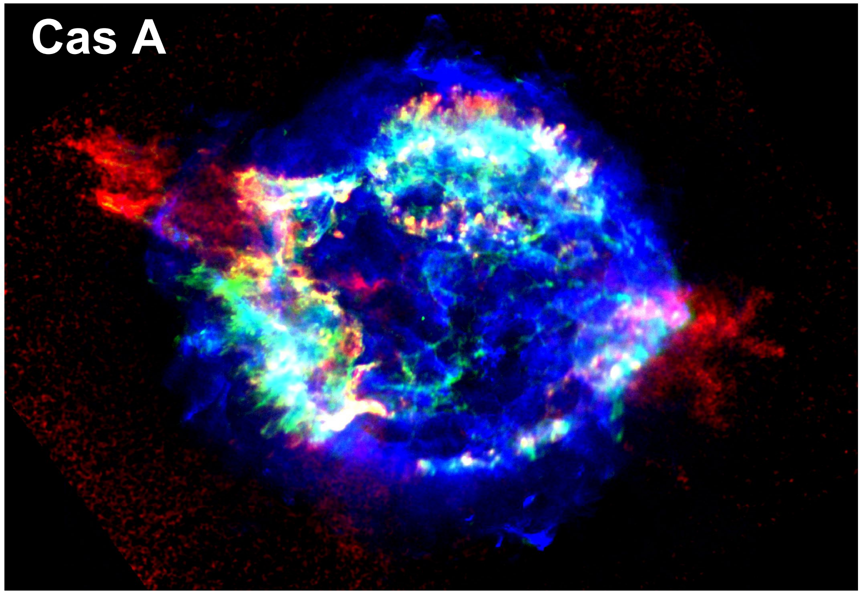
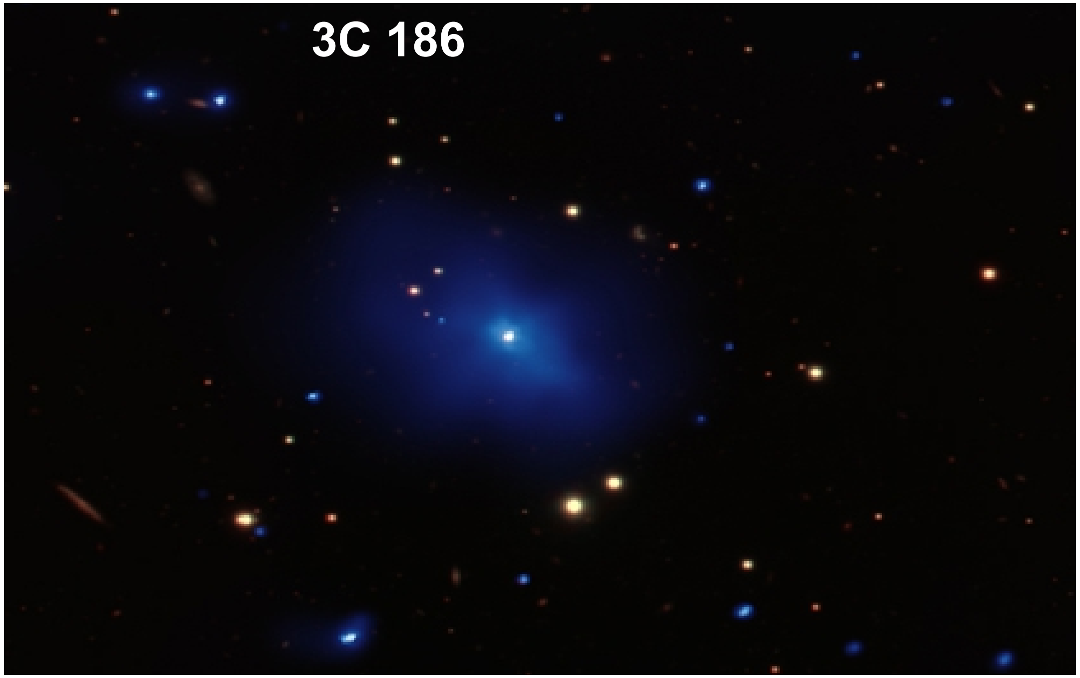
Part 3. **THEORY**

The theory of different emission processes across astrophysical objects:

- Solar system objects
- Nuclear Burning Stars
- White Dwarfs
- Cataclysmic Variables
- Classical Novae
- Pulsars and Isolated Neutron Stars
- Accreting Neutrons Stars and Black Hole binaries
- Supernova Remnants
- Interstellar Medium
- Galactic Center

- Nearby Galaxies
- Active Galactic Nuclei
- Clusters of Galaxies
- Gamma- Ray Bursts
- Cosmic X-ray Background



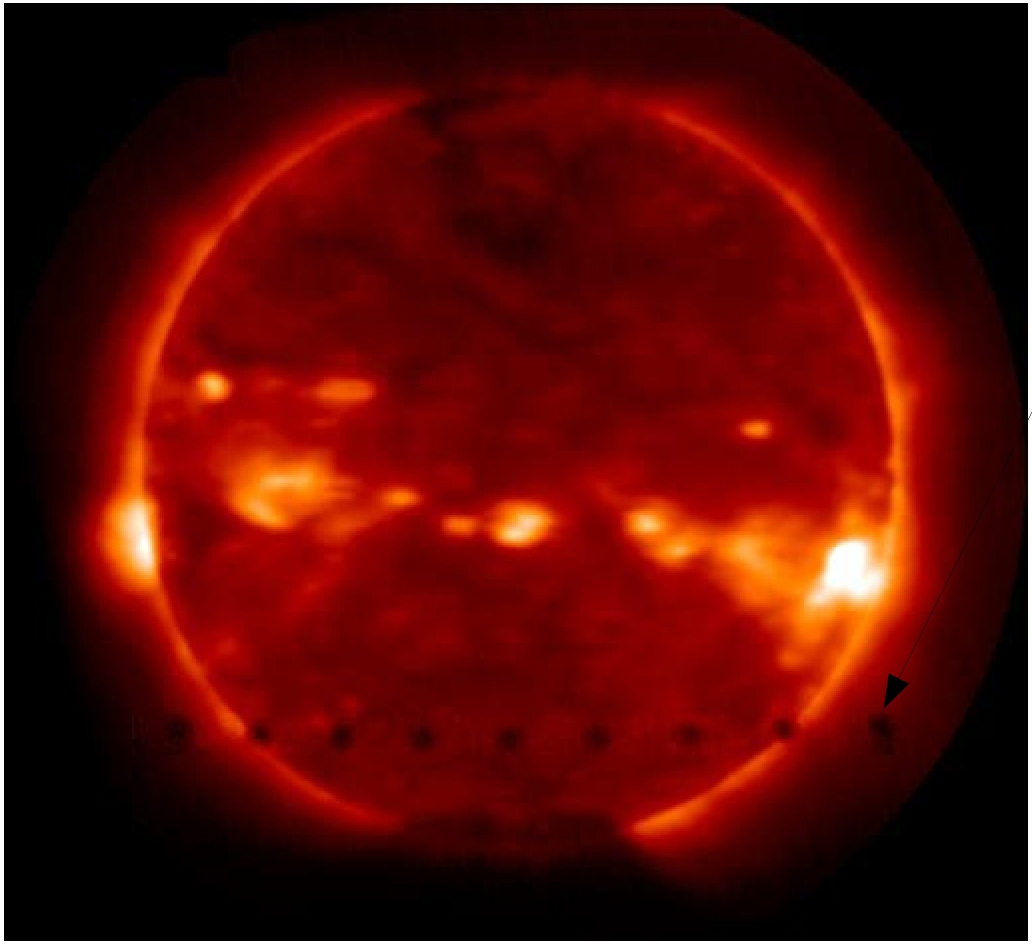


1963 – Riccardo Giacconi with collaborators have made

the first X-ray image of the Sun
using small Wolter telescope
on the board of rocket.

1. Solar System Objects:

The Sun is responsible for practically all of the X-ray radiation found in the Solar System !!!



GOES Solar X-ray Imager:
June 8, 2004

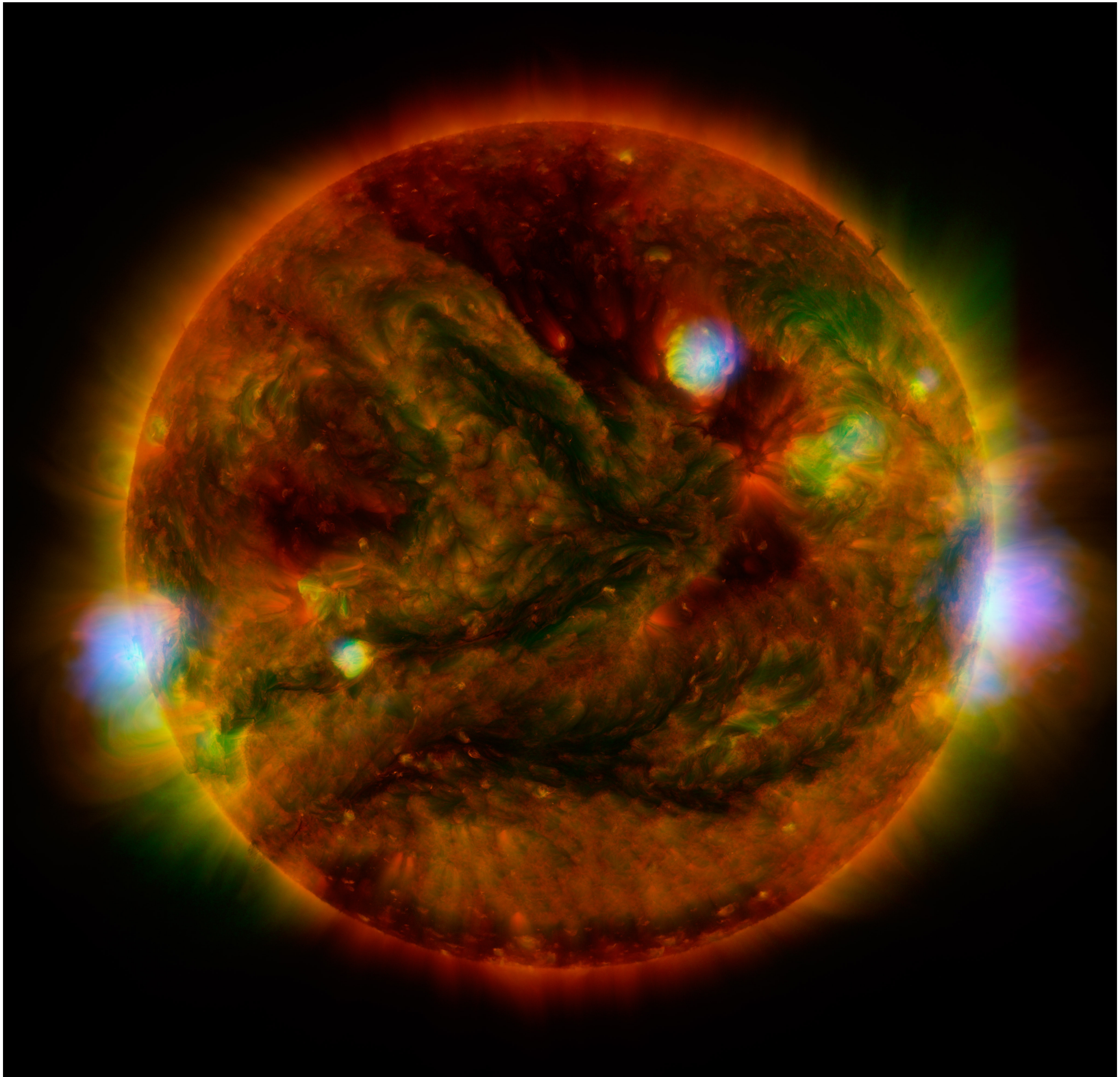
Venus transit.

Solar corona is hot (10^7 K) to emit soft X-rays (1 keV).

Variability on the wide variety of time scales, ranging from minutes, due to solar flares, to decades, due to solar cycle.

X-ray luminosity less than optical luminosity by the factor of 10^7.

NuSTAR hard X-rays 3-6 keV – blue

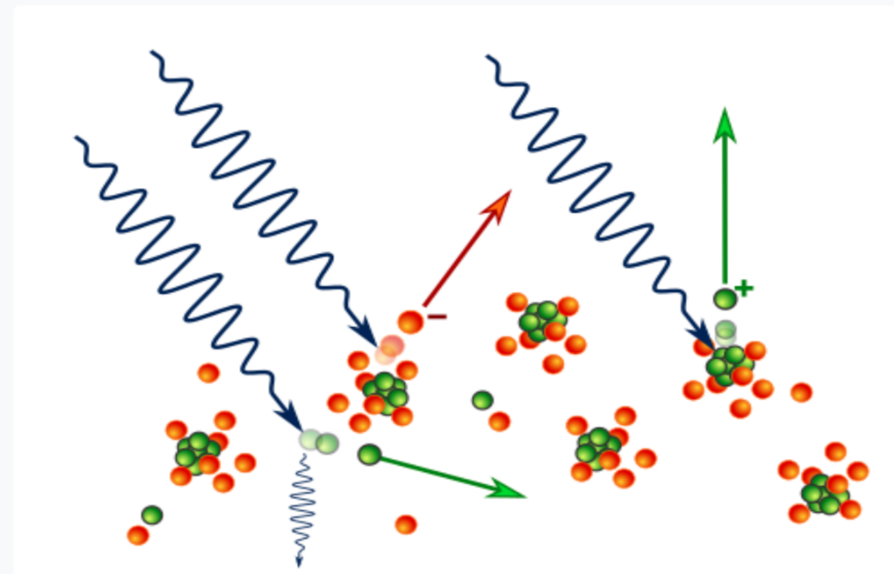


This radiation irradiates other objects. Some photons are scattered elastically or by fluorescence.

Several regimes of scattering:

- energy regime depends if matter is thermalized or not
- usually low-energy means low temperature of matter
- but very often low-energy means low energy of photons

Light–matter interaction



Low-energy phenomena:

Photoelectric effect

Mid-energy phenomena:

Thomson scattering

Compton scattering

High-energy phenomena:

Pair production

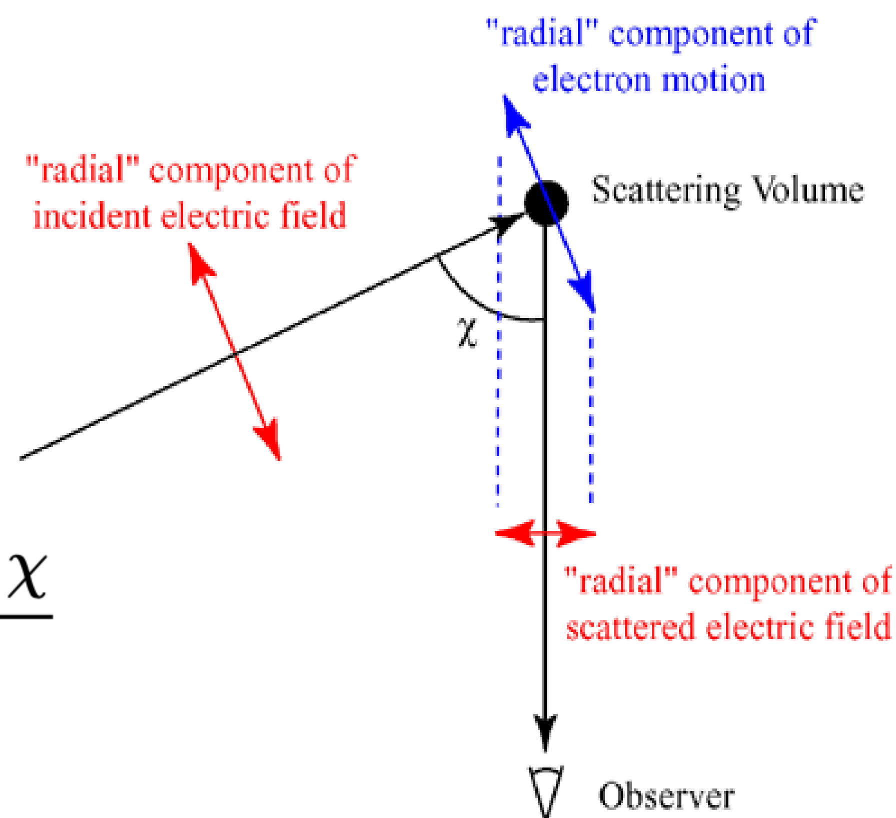
Photodisintegration

Photofission

This radiation irradiates other objects. Some photons are scattered elastically or by fluorescence.

When the matter is relatively neutral (low temperature), elastic scattering depends on albedo and it is similar like for optical light.

In Solar System, when we deal with ions or free electrons in very low density regime – solar wind, scattering is usually elastic in Thomson regime. Un-elastic Compton scattering needs higher densities.



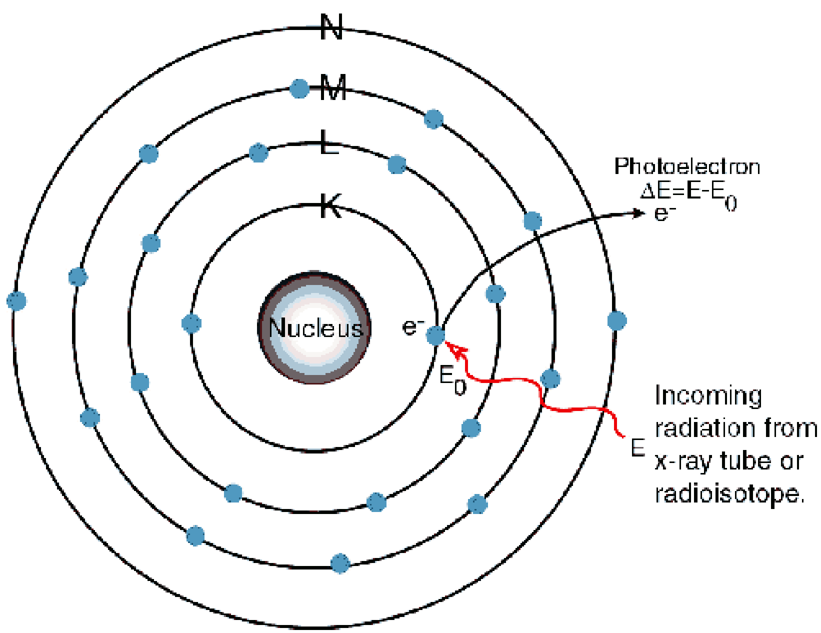
Differential cross section:

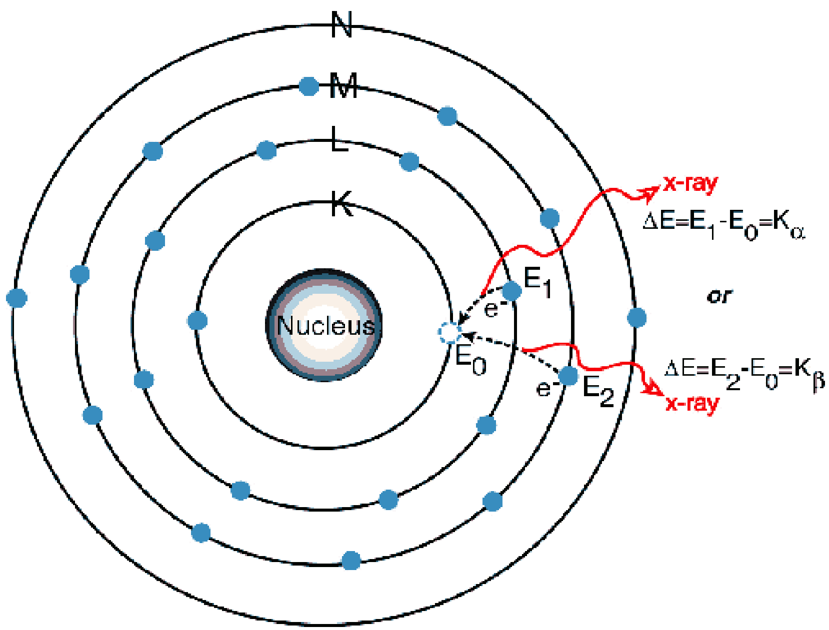
$$\frac{d\sigma_t}{d\Omega} = \left(\frac{q^2}{4\pi\varepsilon_0 mc^2}\right)^2 \frac{1+\cos^2\chi}{2}$$

This radiation irradiates other objects. Some photons are scattered elastically or by fluorescence.

The second is much easier realized for X-rays.

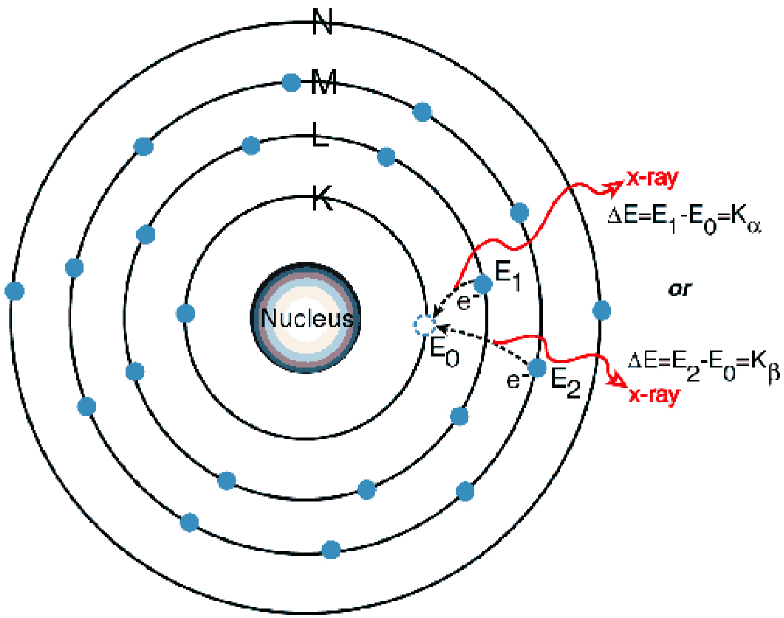
Fluorescence:





The energies of line centroids of many heavy elements for innermost K shell atom orbits belong to the soft X-ray band.
C5 – 0.302 keV; C6 0.367 keV; O7 – 0.568 keV; O8 – 0.653keV

The probability that the emitted photon will escape atom and it will not be absorbed by electrons from higher shells.



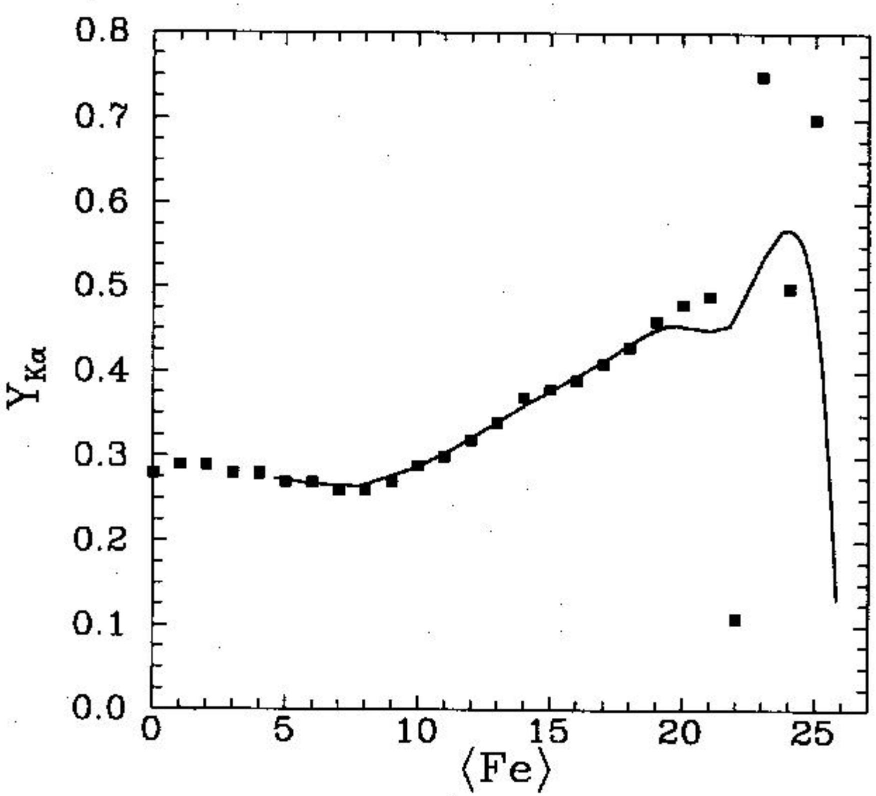
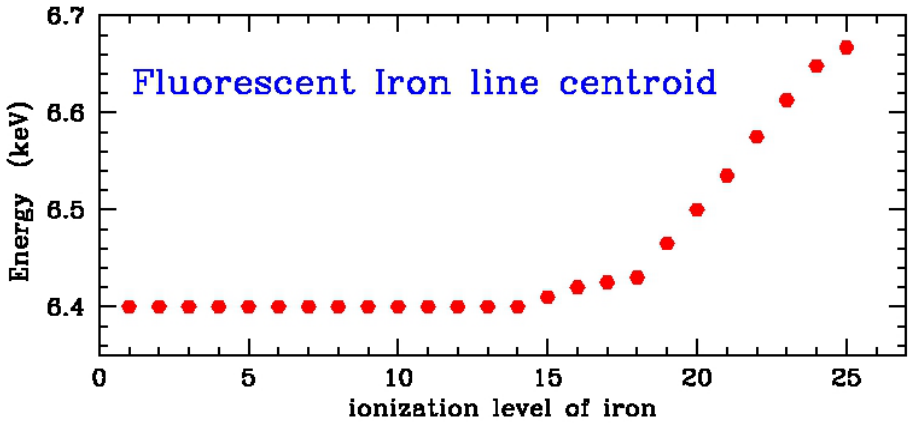


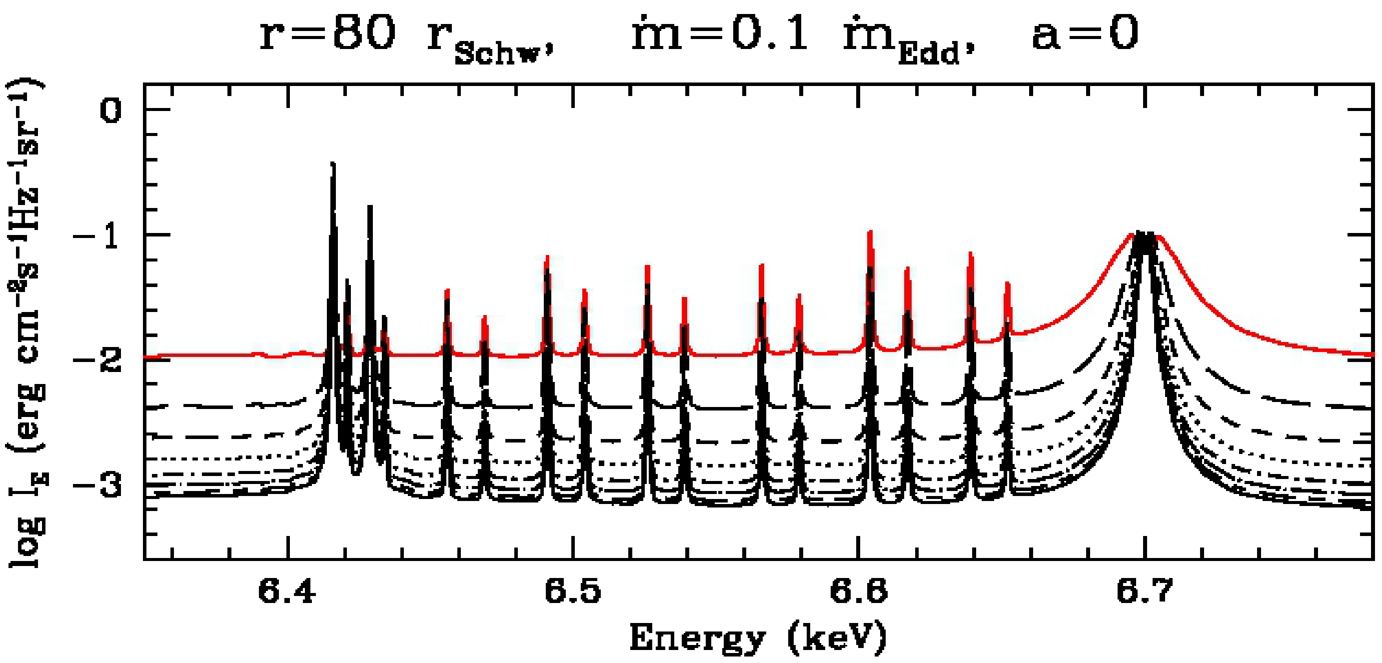
Figure 3. The fluorescent yield of the Kα line. The points mark the values for the iron ions in a single ionization stage (Jacobs & Rozsnyai 1986; Krolik & Kallman 1987). The continuous curve represents the average fluorescent yield for the ion concentrations that result from ionization equilibrium and are characterized by the mean value of the iron ionization stage, ⟨Fe⟩. The coexistence of various ionic species smooths out the large variations in $Y_{K\alpha}$ that occur for highly ionized iron.

Absorption on higher shells – Auger's effect

Energy of the line centroid depends on the level of ionization, for iron:

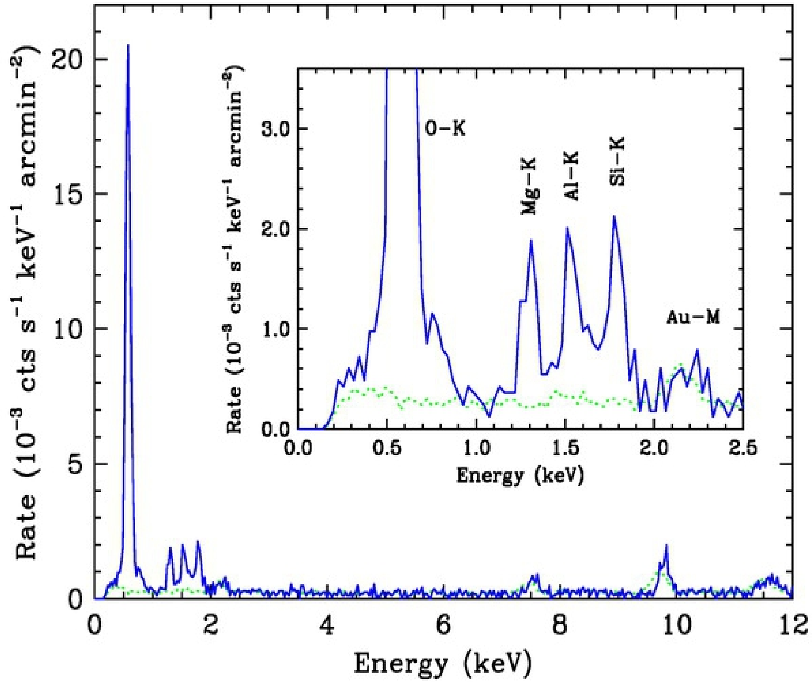


An example of illuminated (an accretion disk) atmosphere:

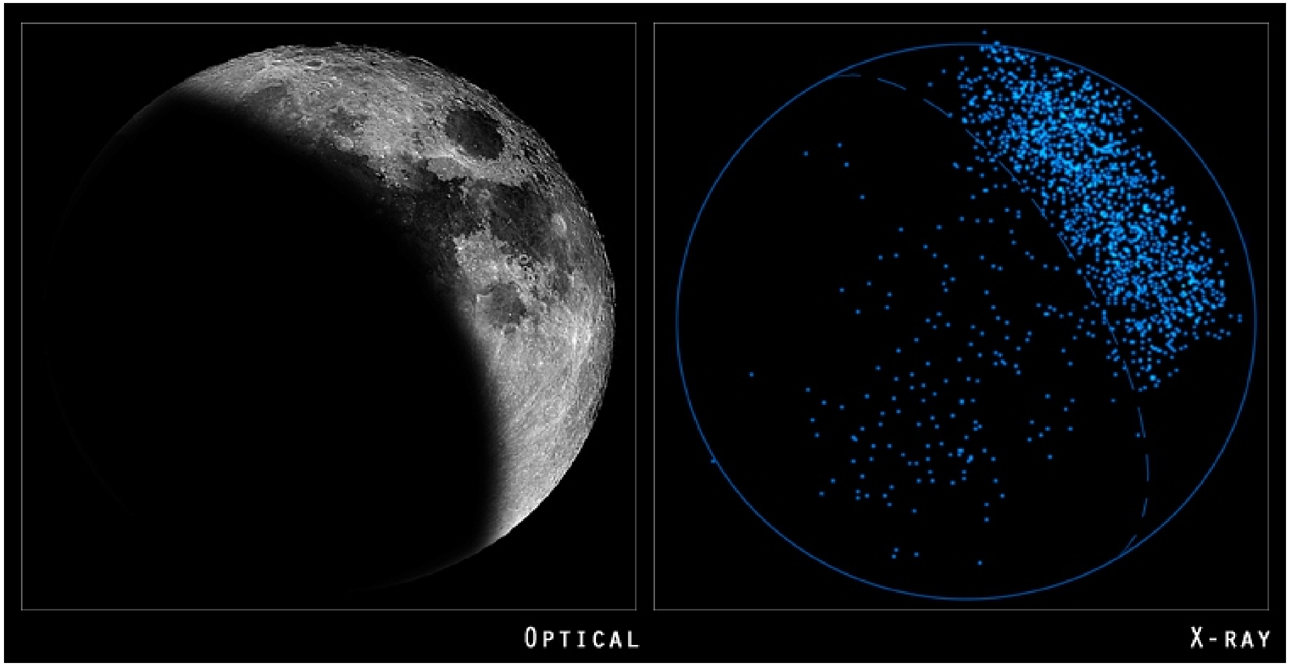


Moon:

From the bright side of the moon we see mostly fluorescence due to heavy elements.

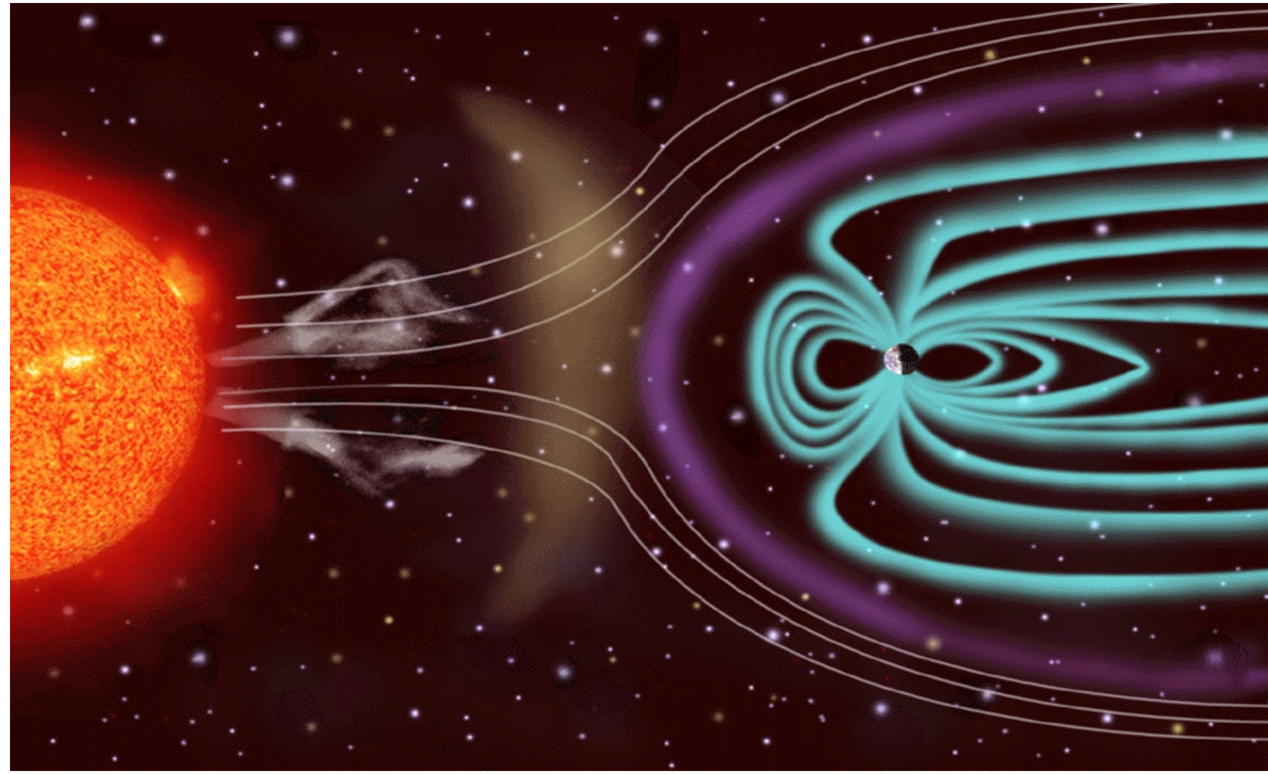


Chandra 2003

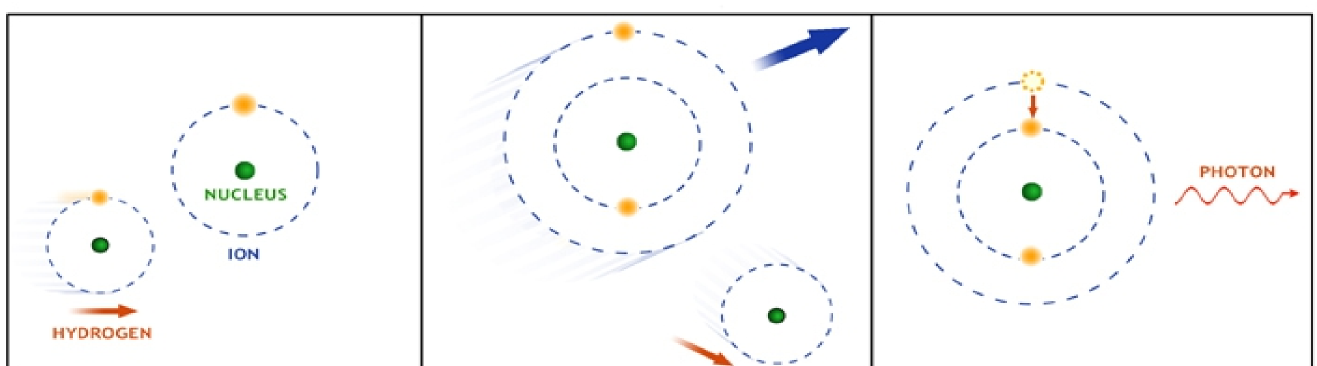


Solar wind:

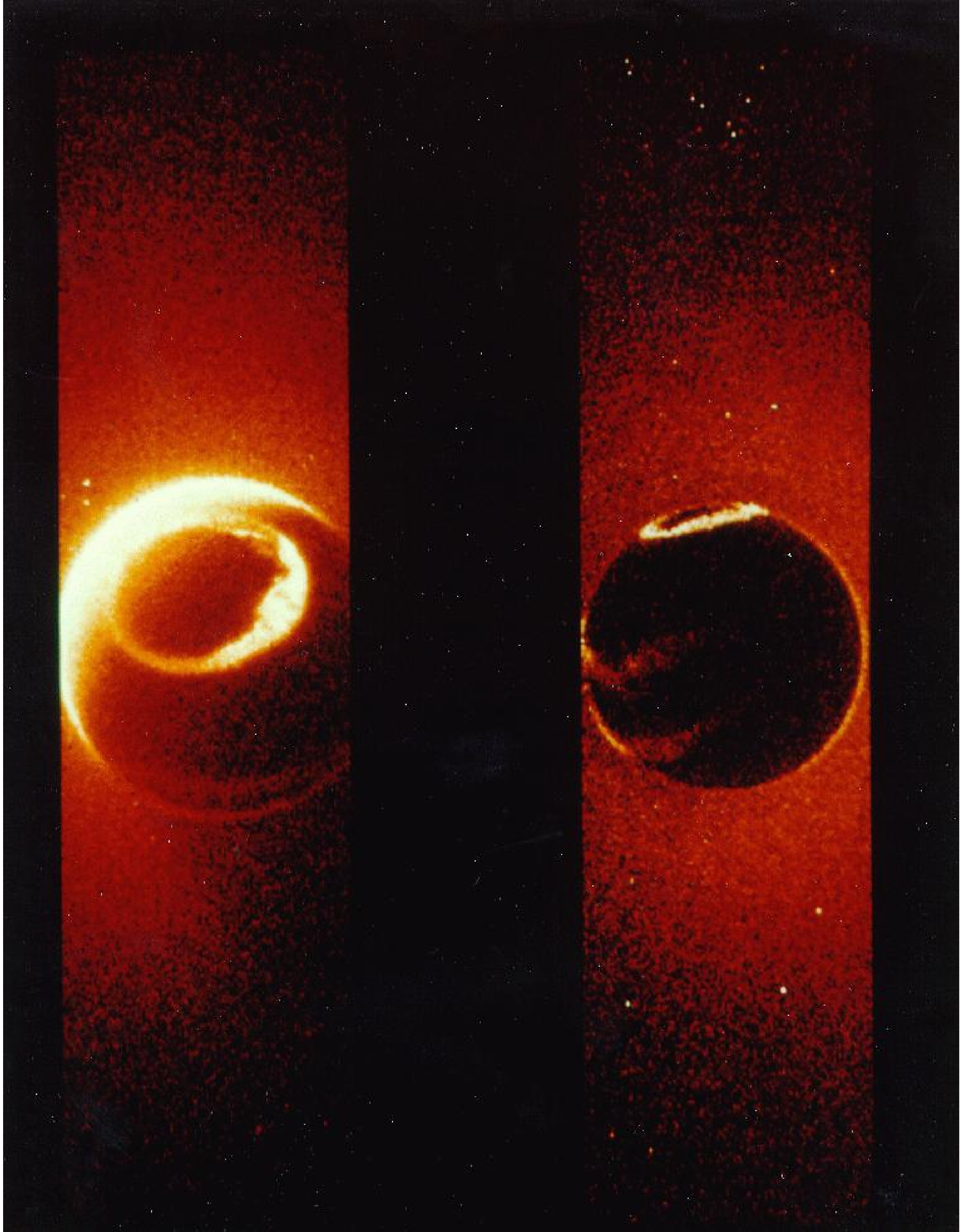
Contains mainly H and He ions and electrons, plus 0.1% of heavy elements highly ionized. Wind is ejected 100 km/s and usually there is no charge to recombine.



But if the density of electrons or neutral H He gas becomes higher, charge transfer (exchange) process becomes important.



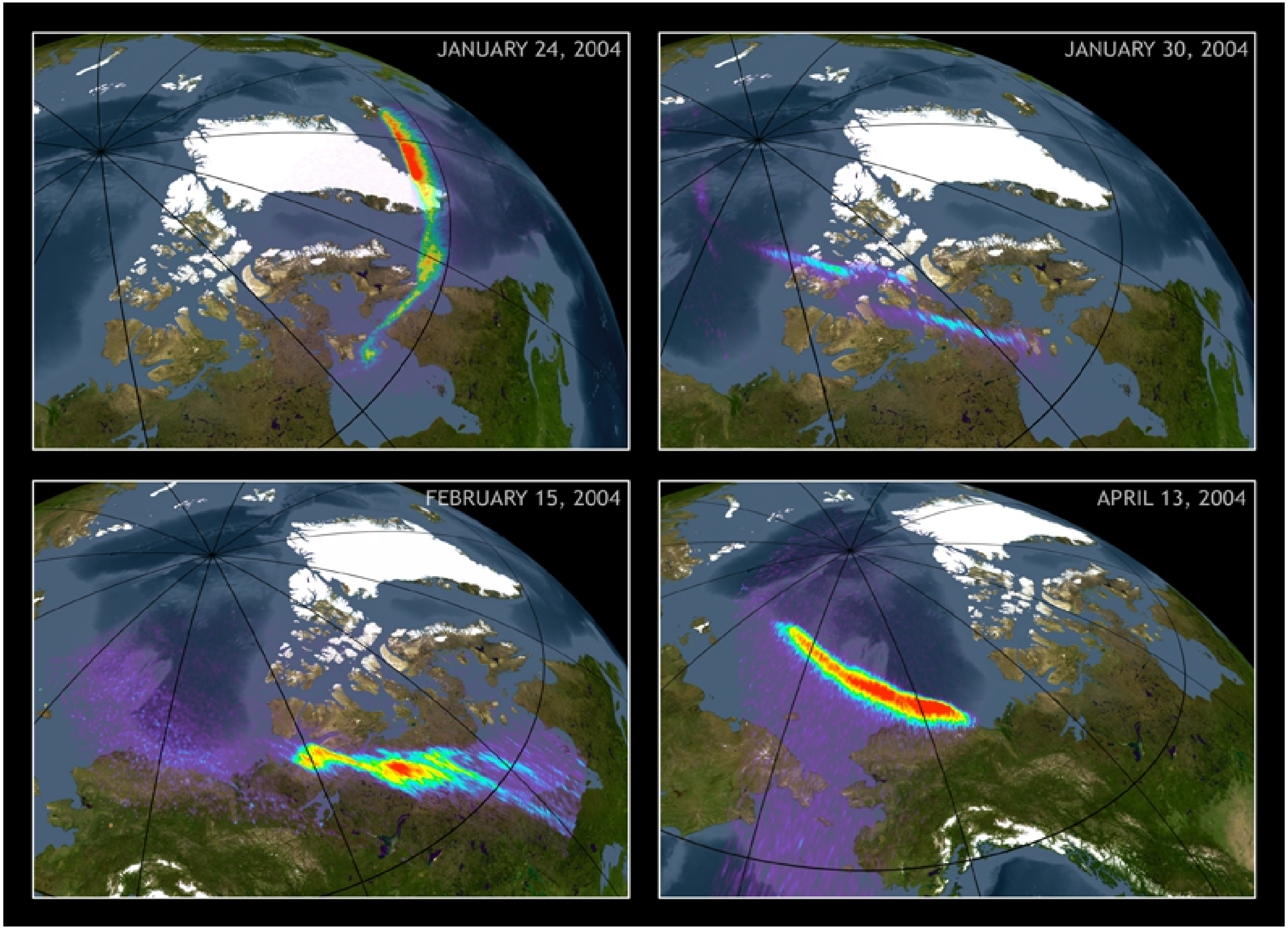
Geocorona – extended tenuous cloud of H around the Earth observed in EUV because of fluorescent L_α scattering of solar EUV radiation:



Three parts constitute X-ray properties of Earth:

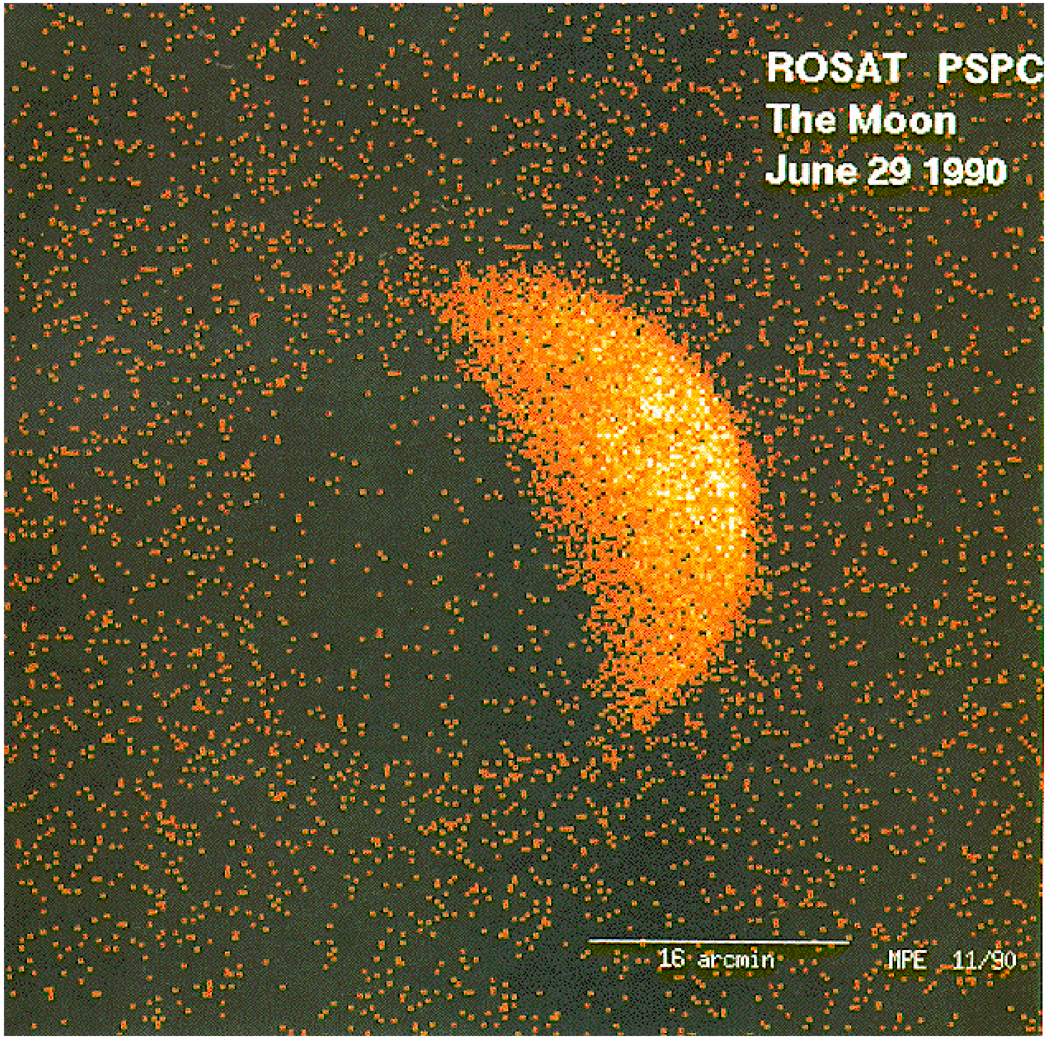
1) auroral oval
2) reflection from the Sun
3) the geocorona.

Aurora seen by Chandra:



Earth magnetic field can accelerate electrons which are decelerated in the planetary atmosphere.

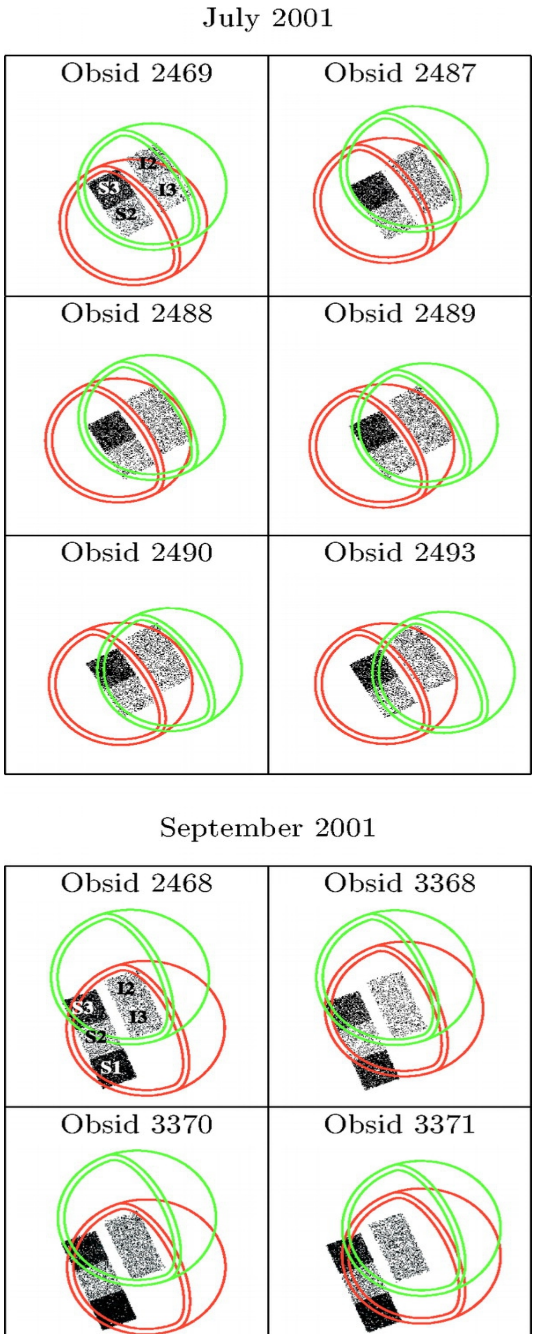
Observing other objects of our Solar System we cannot get out of Earth Geocorona.



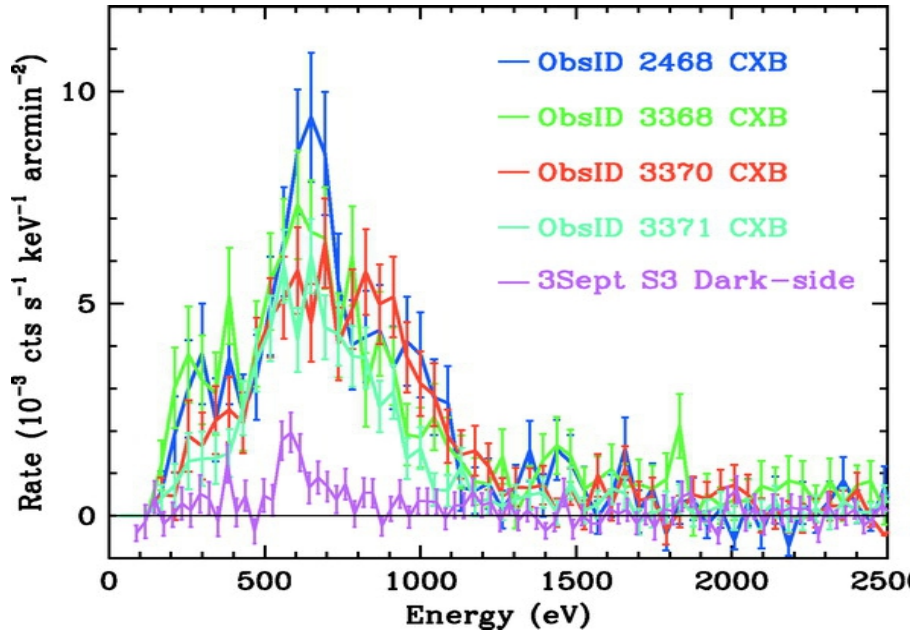
Three components:

1) scattering of solar X-rays (fluorescence),
2) shadowing of the diffuse cosmic bkgr. on the dark side,
3) excess X-rays at the dark side due to X-ray emission from the geocorona.

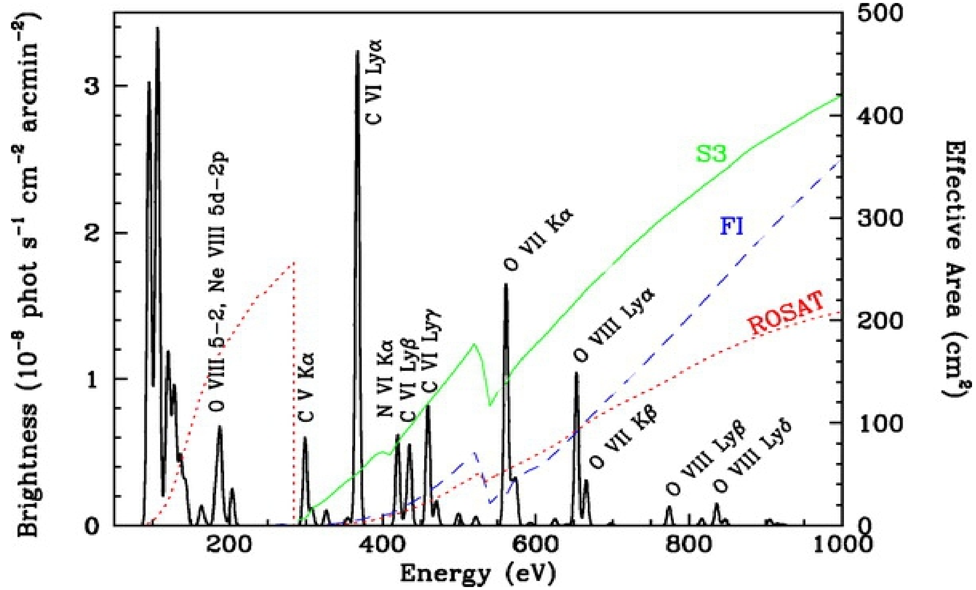
Chandra observations of the dark side of the moon



Wargelin+ 2004

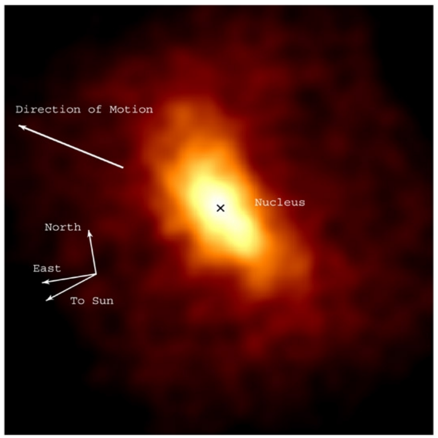


Modeled Charge Transfer lines:



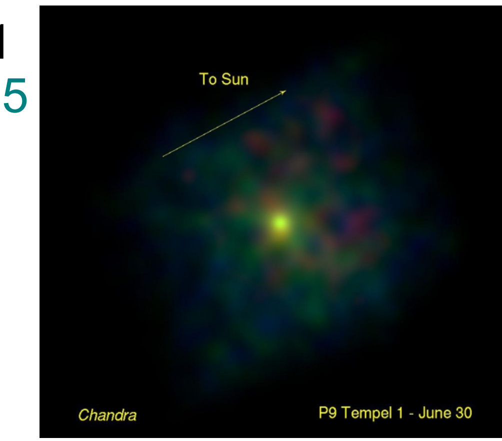
Comets are very efficient emitters of X-rays by CT process:

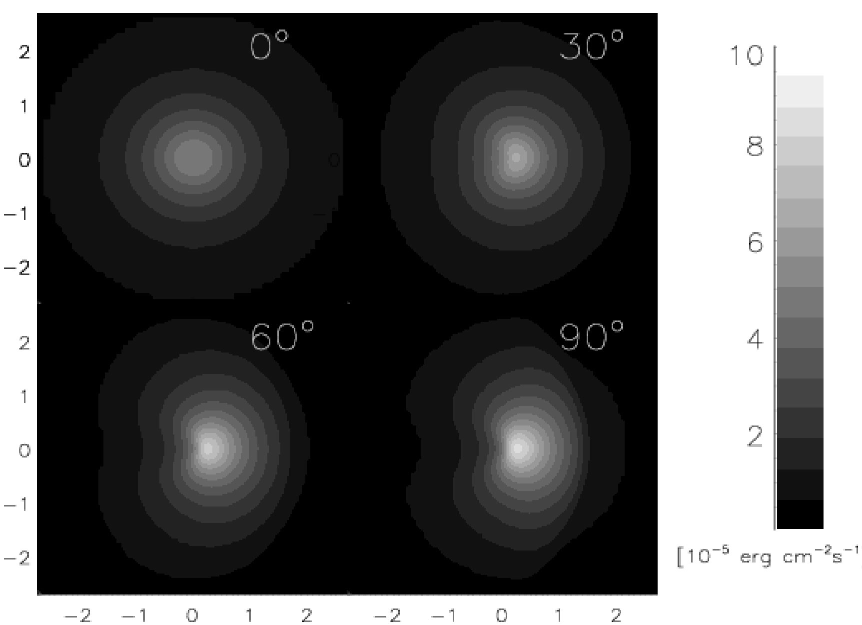
Tenuous cometary coma has free electrons producing large cross section, about 3 x 10^{-15} cm^2 for charge transfer process.



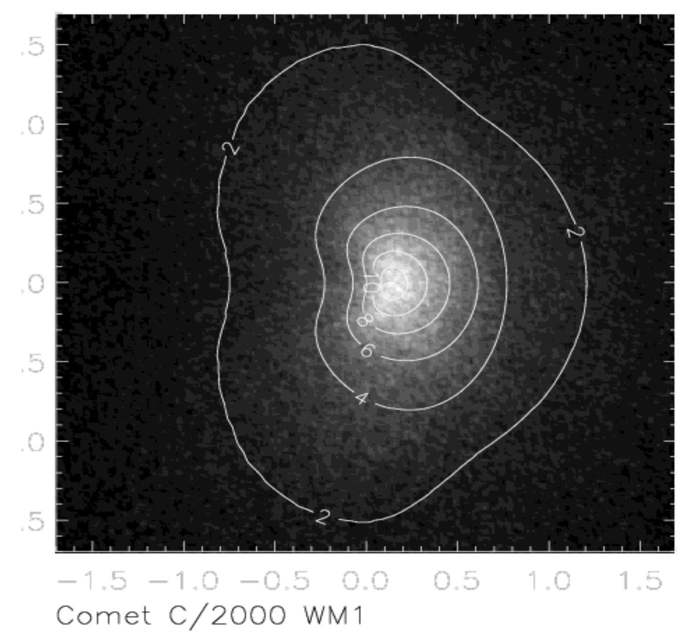
C/1999 S4 Linear
Chandra 2000

P9 Templet 1
Chandra 2005



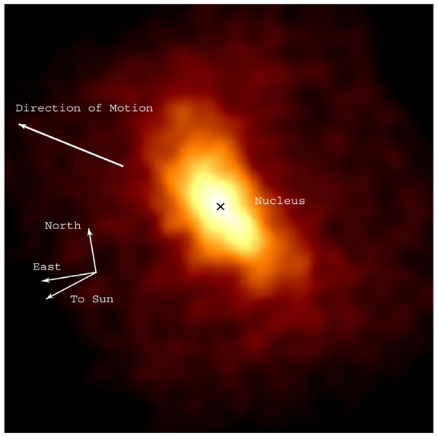


XMM-Newton
Wegmann+ 2004



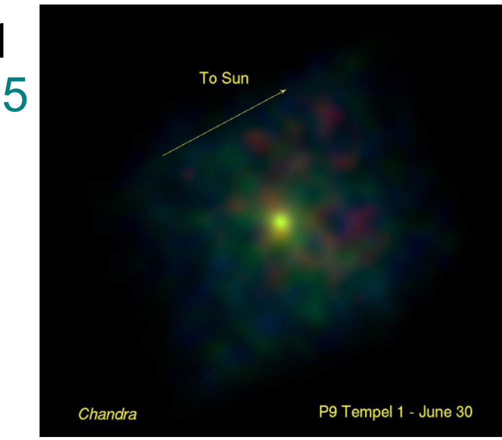
Comets are very efficient emitters of X-rays by CT process:

Tenuous cometary coma has free electrons producing large cross section, about 3 x 10^{-15} cm^2 for charge transfer process.

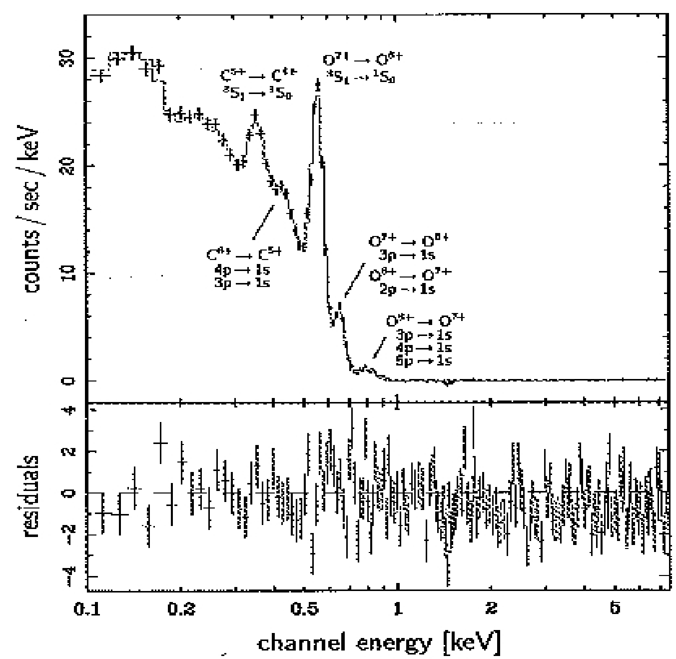


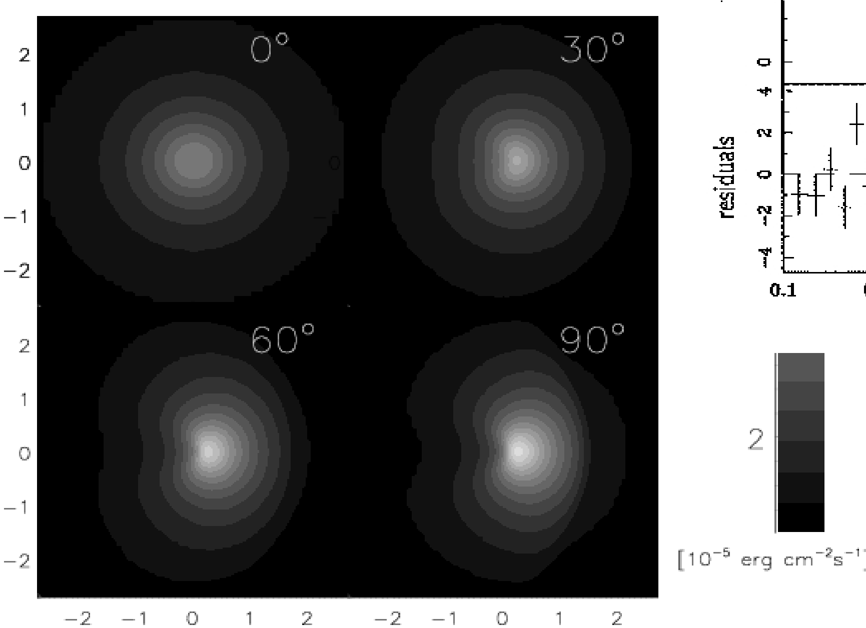
C/1999 S4 Linear
Chandra 2000

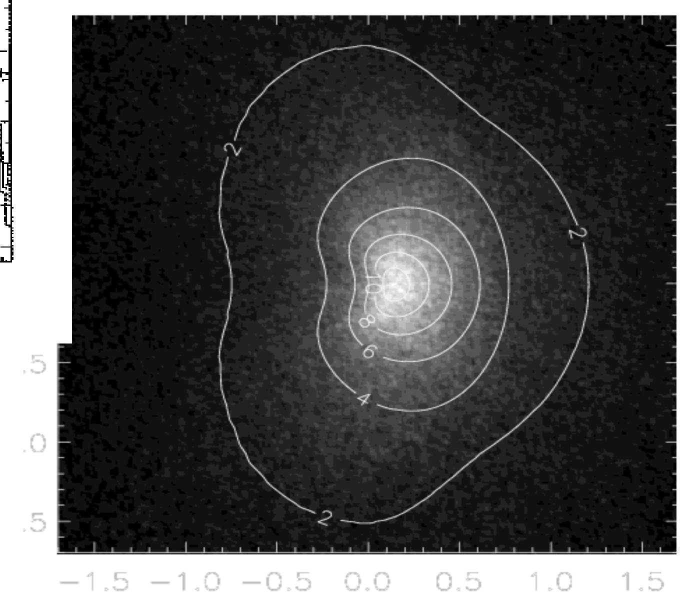
P9 Templet 1
Chandra 2005



C/2000 XMM-Newton

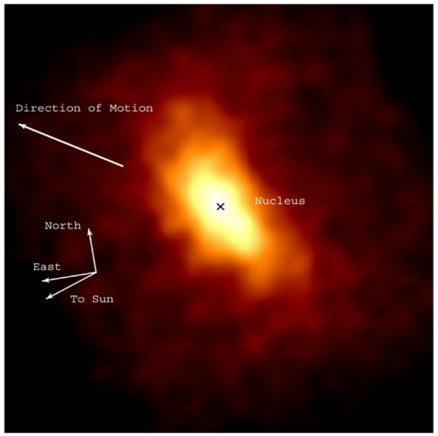






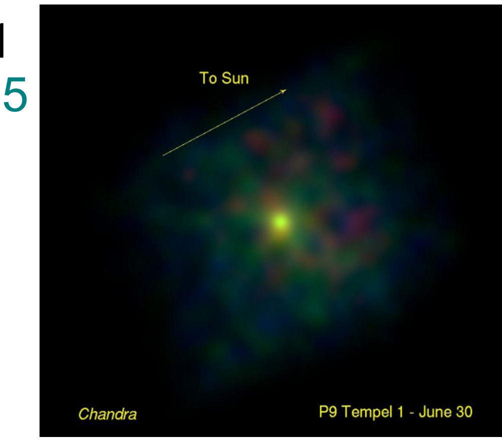
Comets are very efficient emitters of X-rays by CT process:

Tenuous cometary coma has free electrons producing large cross section, about 3×10^{-15} cm^2 for charge transfer process.

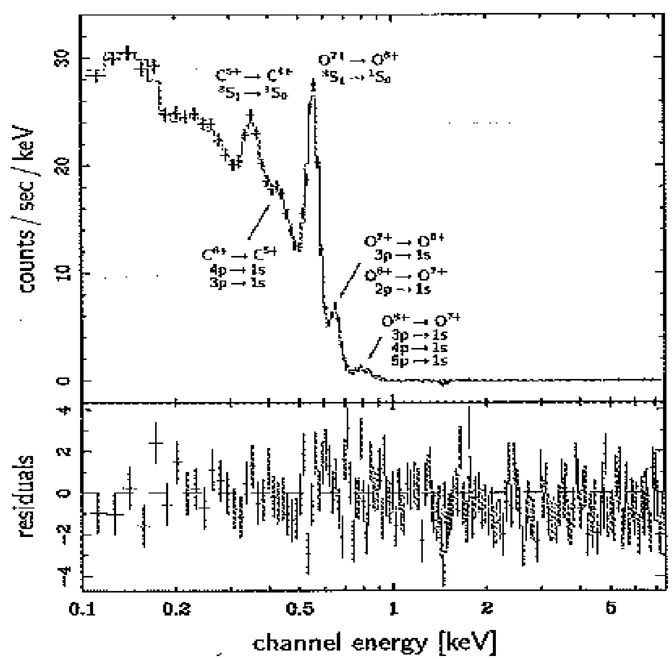


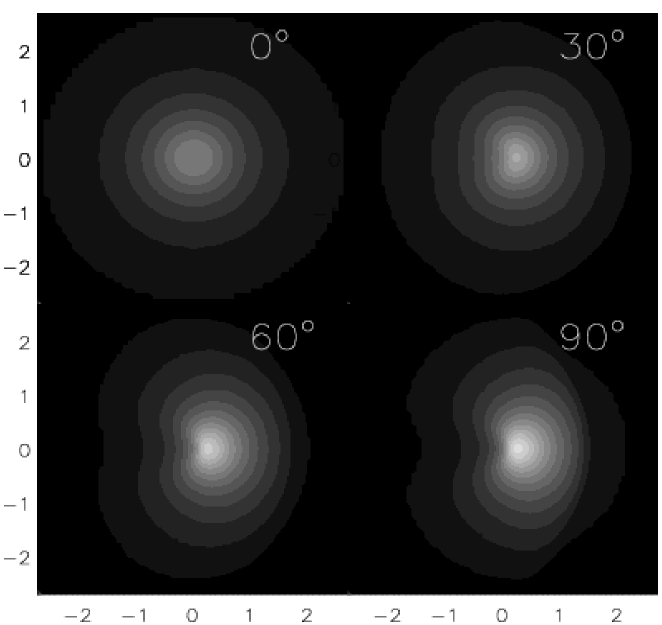
C/1999 S4 Linear
Chandra 2000

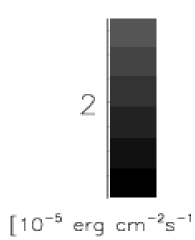
P9 Templet 1
Chandra 2005

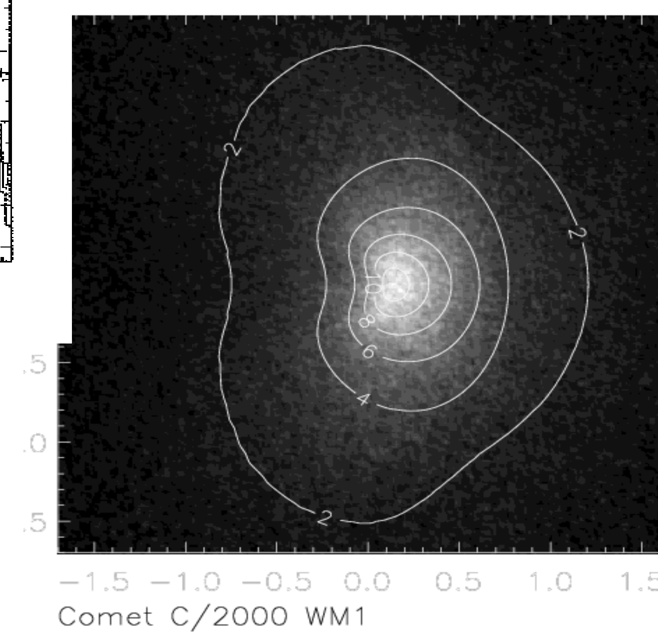


C/2000 XMM-Newton





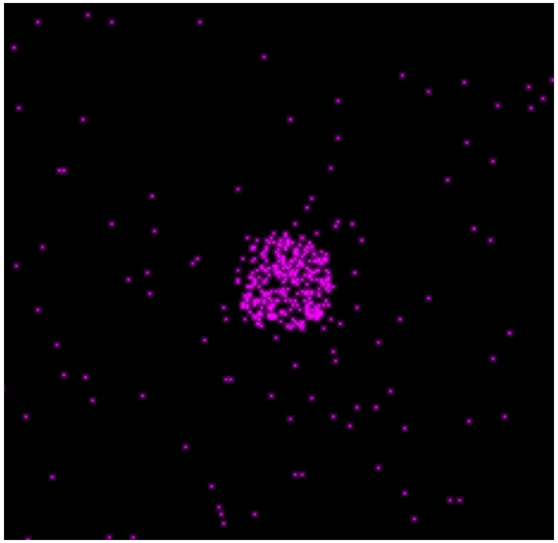


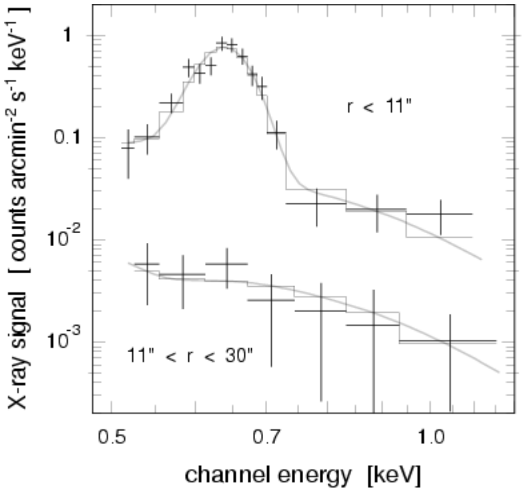


Planets:

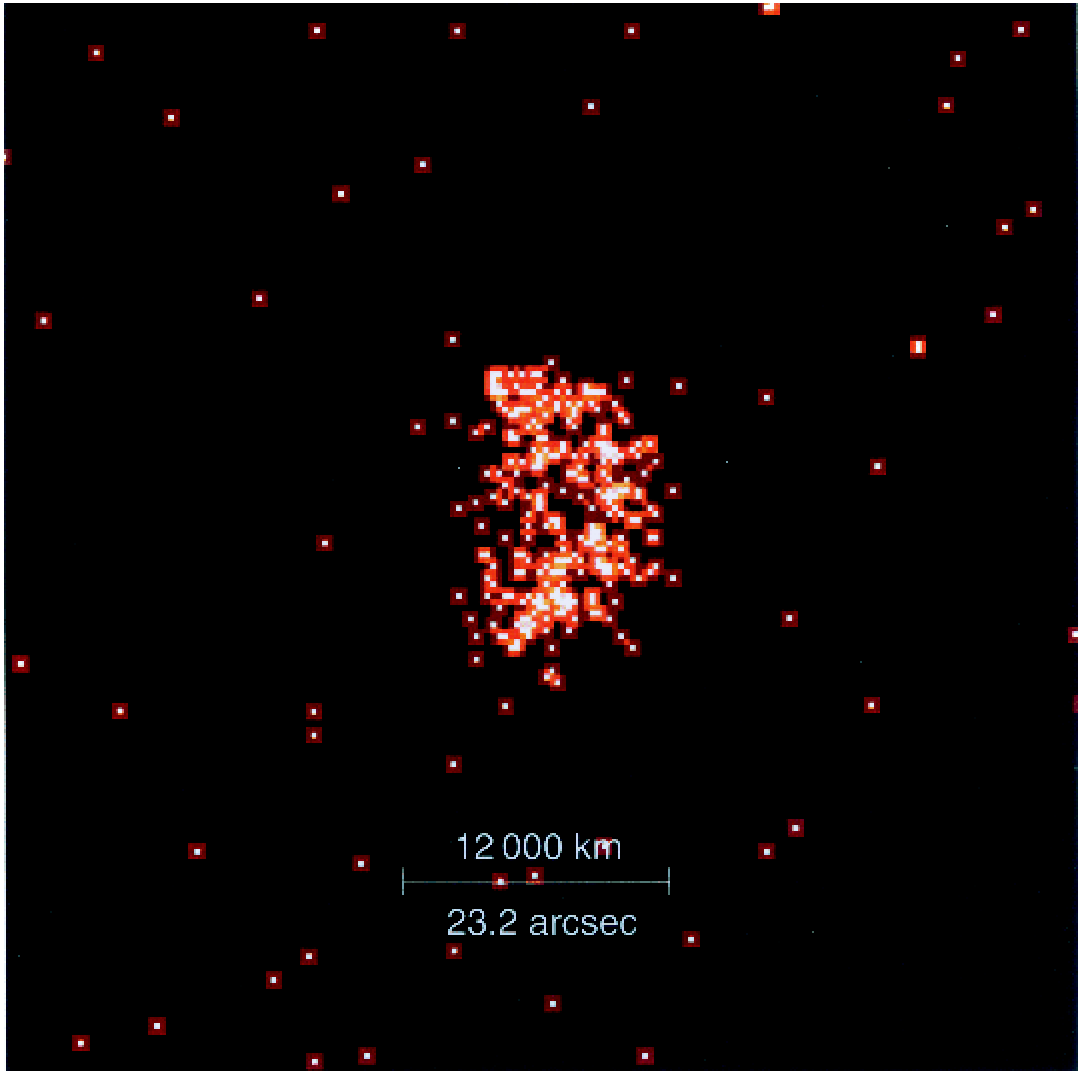
Fluorescence on Oxygen atoms:

Mars Chandra 2001



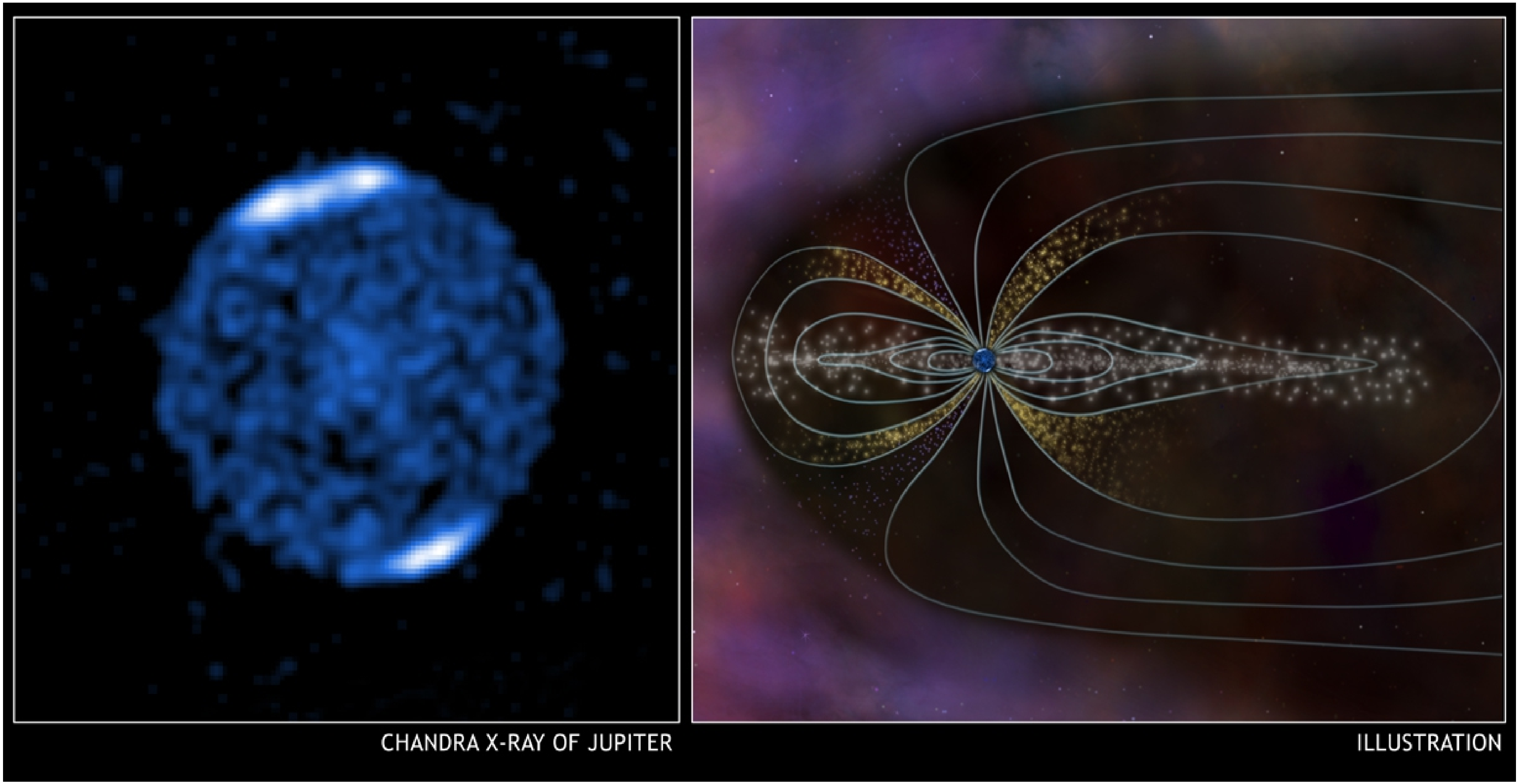


Venus Chandra 2001



Jupiter:

Chandra 2005

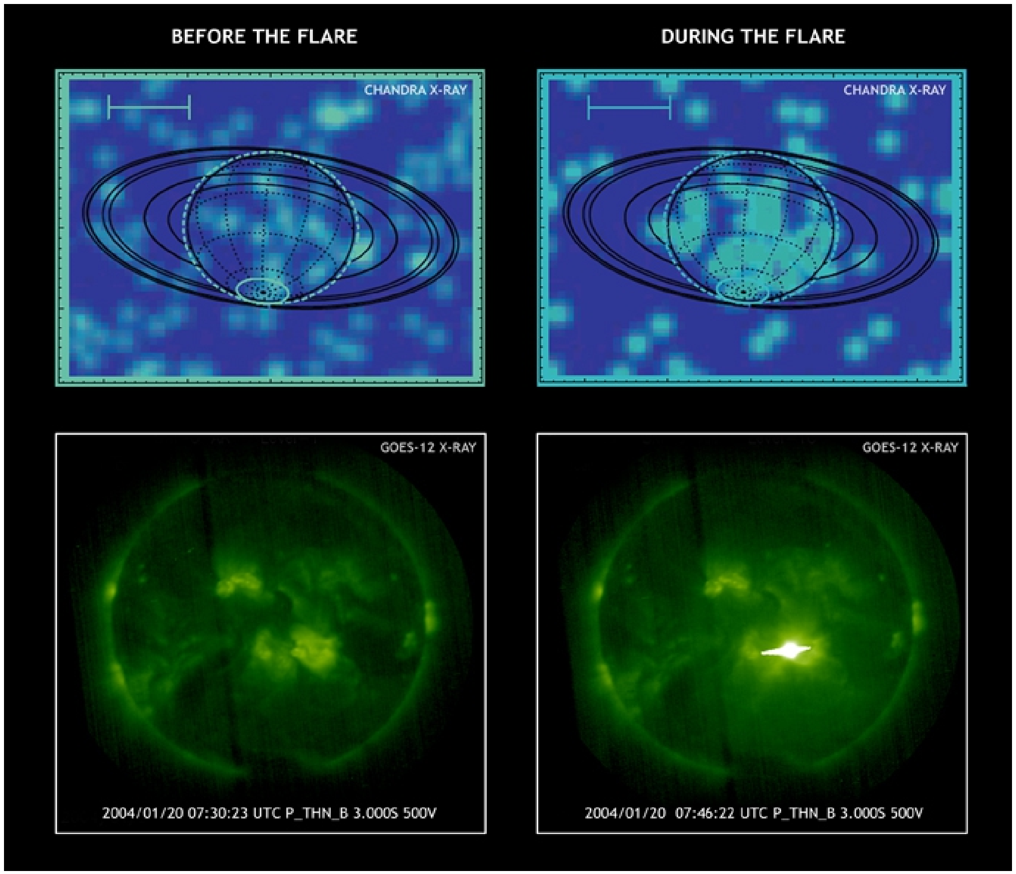


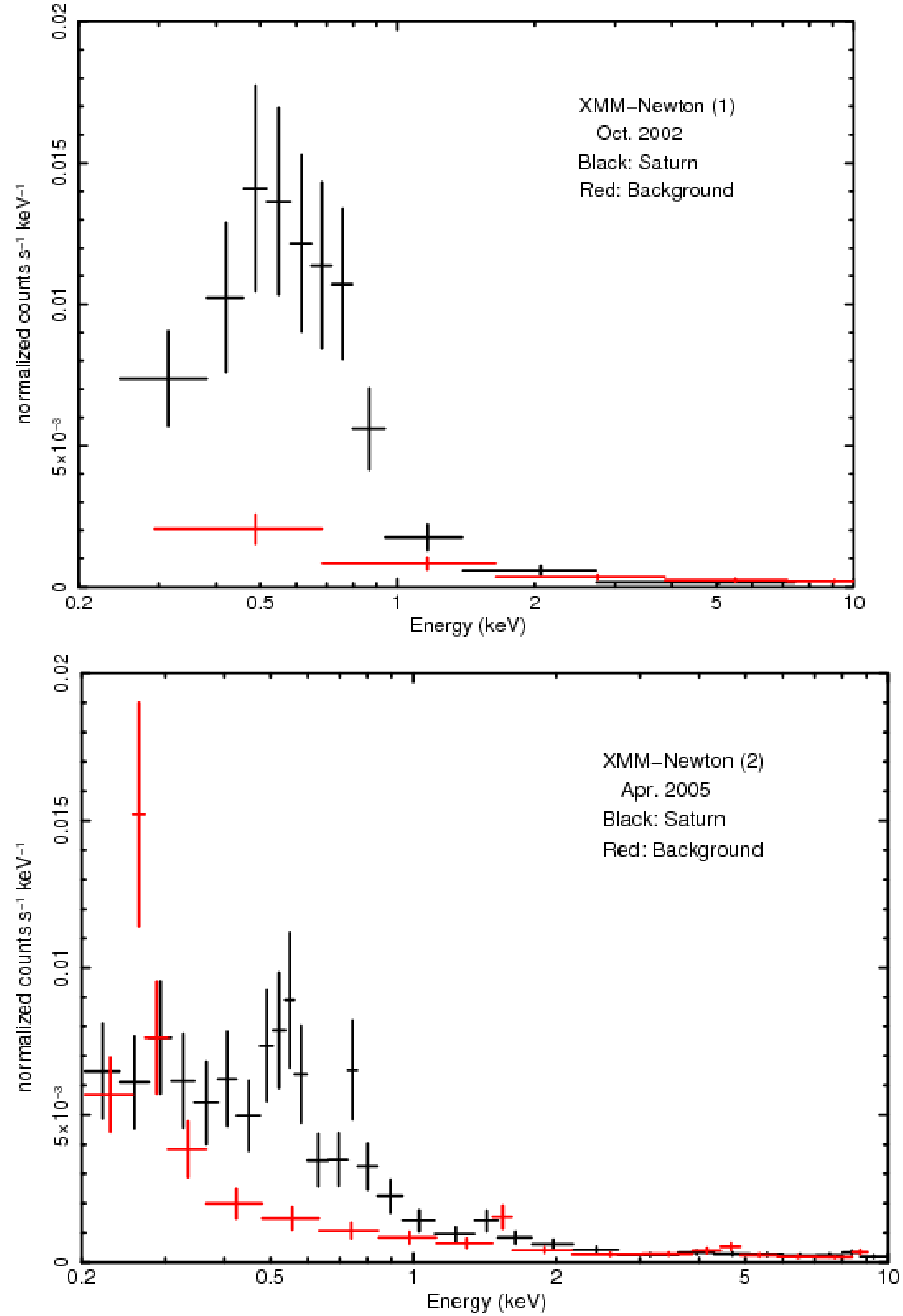
Auroral X-rays due to highly charged particles crashing into the atmosphere above Jupiter's poles

Saturn:

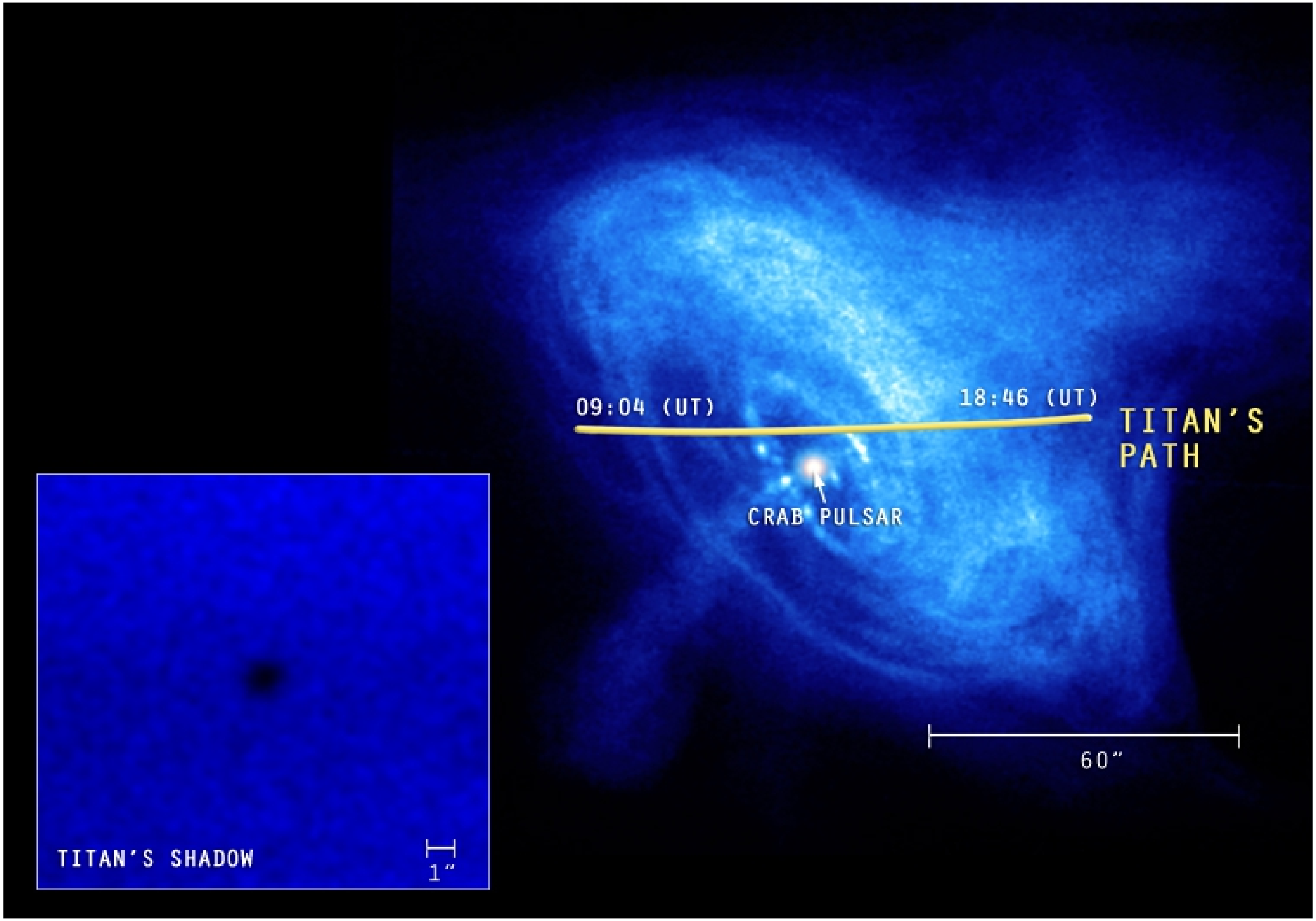
Branduardi-Raymont+ 2010

Chandra image of Saturn reflects Sun activity. Oxygen line is prominent. No auroral emission is present in south pole.





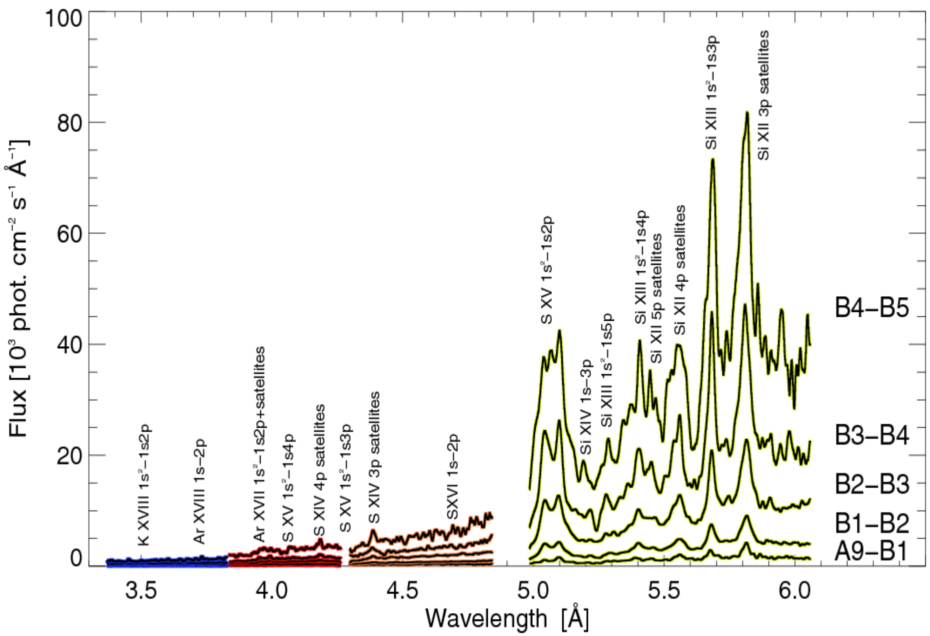
First X-ray image of Saturn's moon Titan, seen in absorption in front of the Crab nebula, taken with Chandra 2003.
This observation made it possible to measure Titan's atmospheric extent at X-ray wavelengths. 880 km for the height of the X-ray absorbing region above Titan's atmosphere.

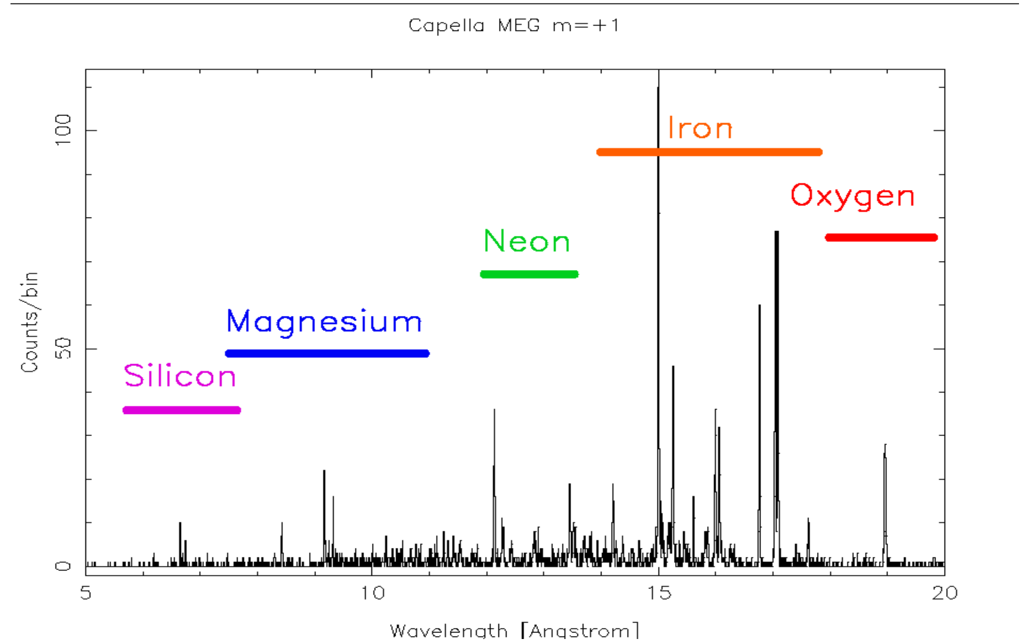


Nuclear burning stars:

Solar corona – production of forbidden transitions of highly ionized atoms, which requires temperatures in excess of 1 MK – coronal lines.

Sylwester+ 2010

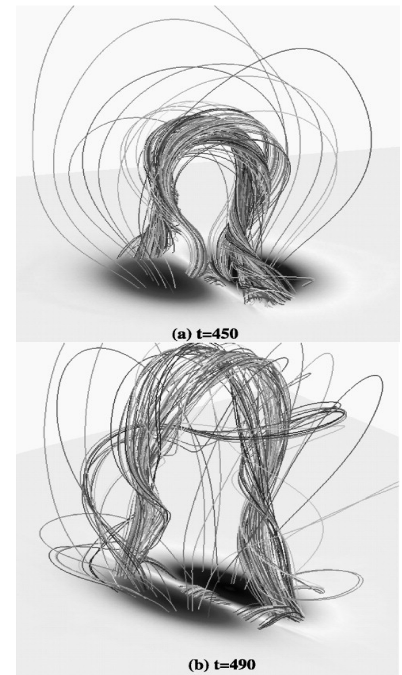


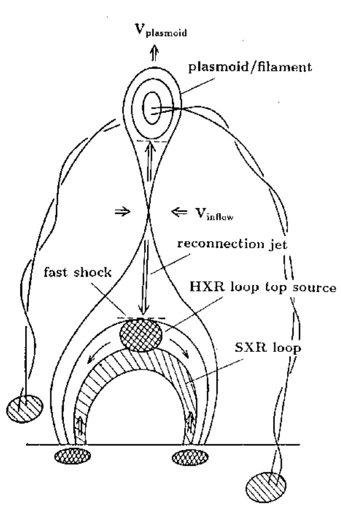


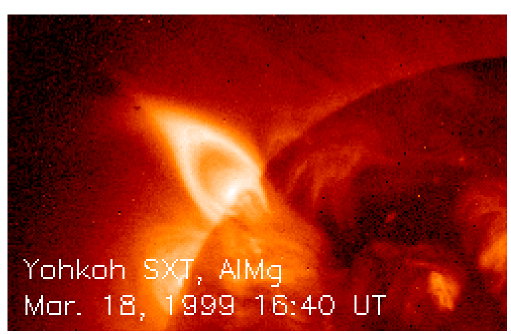
Outer layers of the Sun are much hotter, but the heating process is still the holy grail of solar coronal physics.

Magnetic heating of solar corona universally accepted:

Magnetic dynamo operating in or at the base of a convection zone.
αΩ – dynamo on the border of radiative and convective zone.







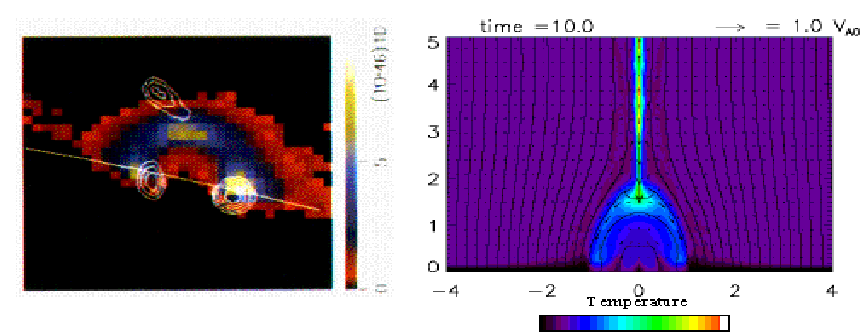


Fig. 1-Left panel: A flaring loop observed by *Yohkoh*. Colors mean the emission measure derived from soft X-ray data and contours mean the intensity of hard X-ray. From Masuda et al. (1994). Right panel: Simulation result. Colors, contours, and arrows mean the temperature, magnetic field lines, and fluid velocity field. From Magara et al. (1996).

X-ray observations can be a key diagnostic for magnetic activity:

Stellar coroane cannot be angularly resolved – only in eclipsing binaries, where size information can be inferred from light curve analysis:

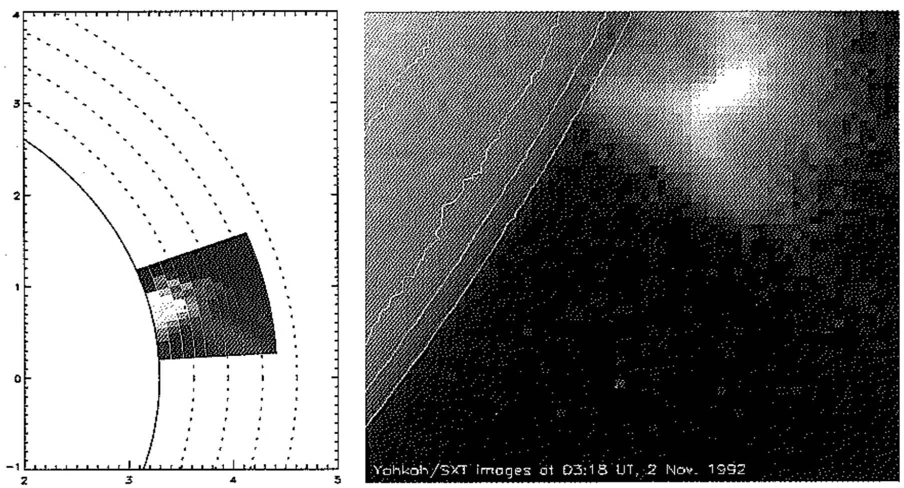
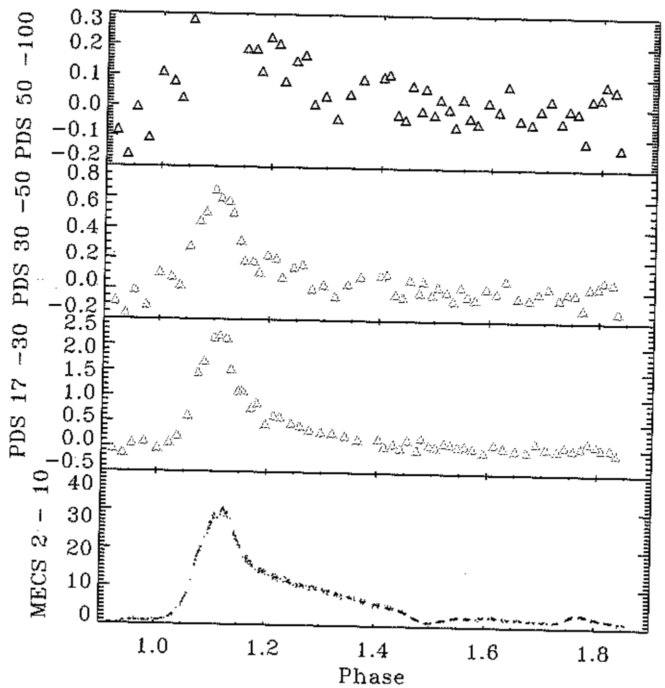


Fig. 10.2 *left*: Reconstructed spatial distribution of the flaring region on Algol B. All of the flaring plasma was assumed to be located at a fixed longitude of $\phi = 70°$. The *solid circle* represents the limb of the K star, units are in solar radius; *dashed circles* indicate heights in steps of 0.1 stellar radii. *Fig. 4 from [44]*; *right*: *Yohkoh* image of a solar limb flare on November 2, 1992 available under http://www.lmsal.com/SXT/. Limb flares on the Sun allow to study the geometry of the X-ray emitting plasma; the loop footpoints and the hot loop top are particularly well visible



Beppo Sax lightcurves of Agol in different energy bands.

Cool secondary observed in the front of B star. Around phase 1.5 X-ray dark primary is in front of the X-ray emitting secondary.

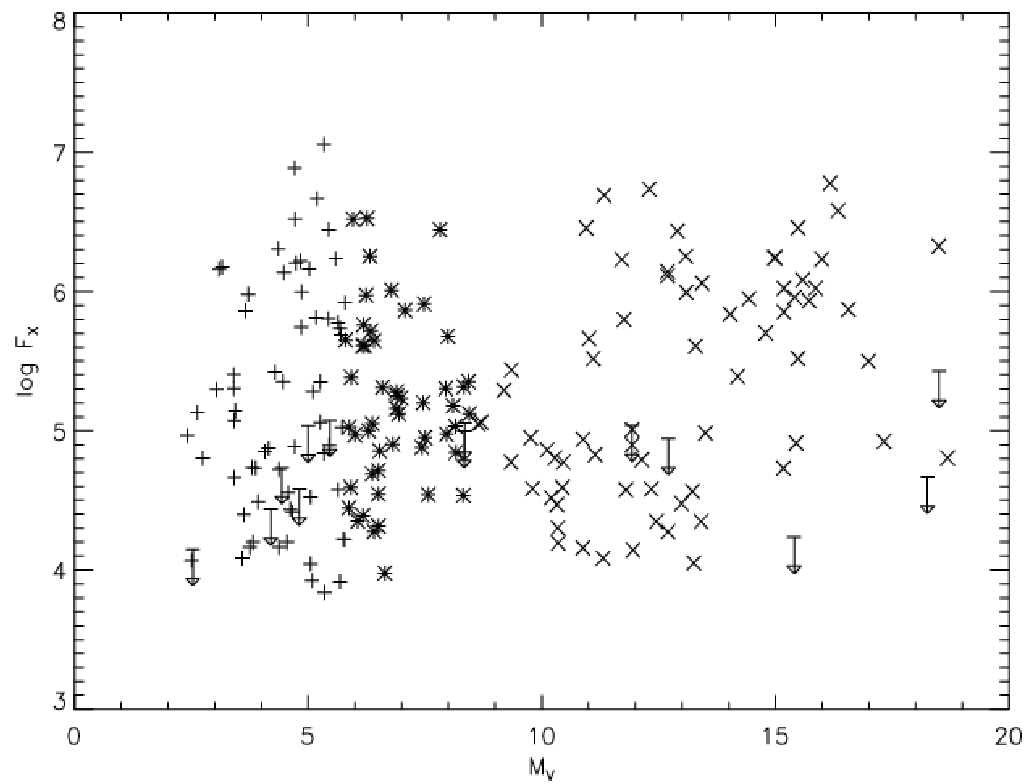
Solar-Stellar connection: cool field stars around Sun:

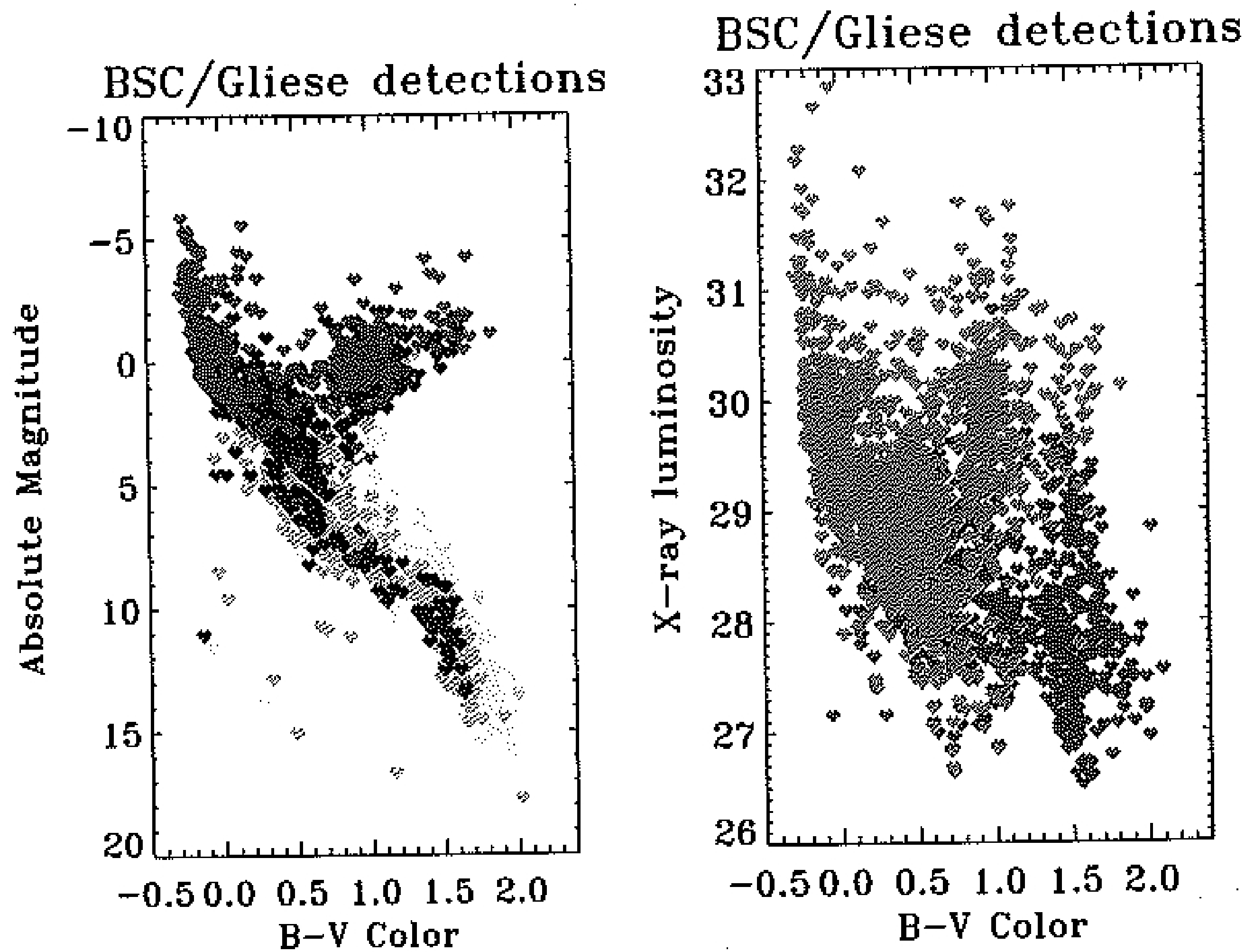
RASS – ROSAT All Sky Survey, spatially compete but flux limited all-sky survey (low luminosity objects Are not taken into account properly).

NEXXUS data base – volume limited samples were constructed For F, G, and M dwarfs. Together with RASS Gives complete survey up to M_V=20 mag.

Formation of X-ray emitting coronae appears to be universal for solar-like MS stars, X-ray dark solar-like stars do not exist.

$$F_{X,limit} \approx 10^4\, erg\, cm^{-2}\, s^{-1}$$

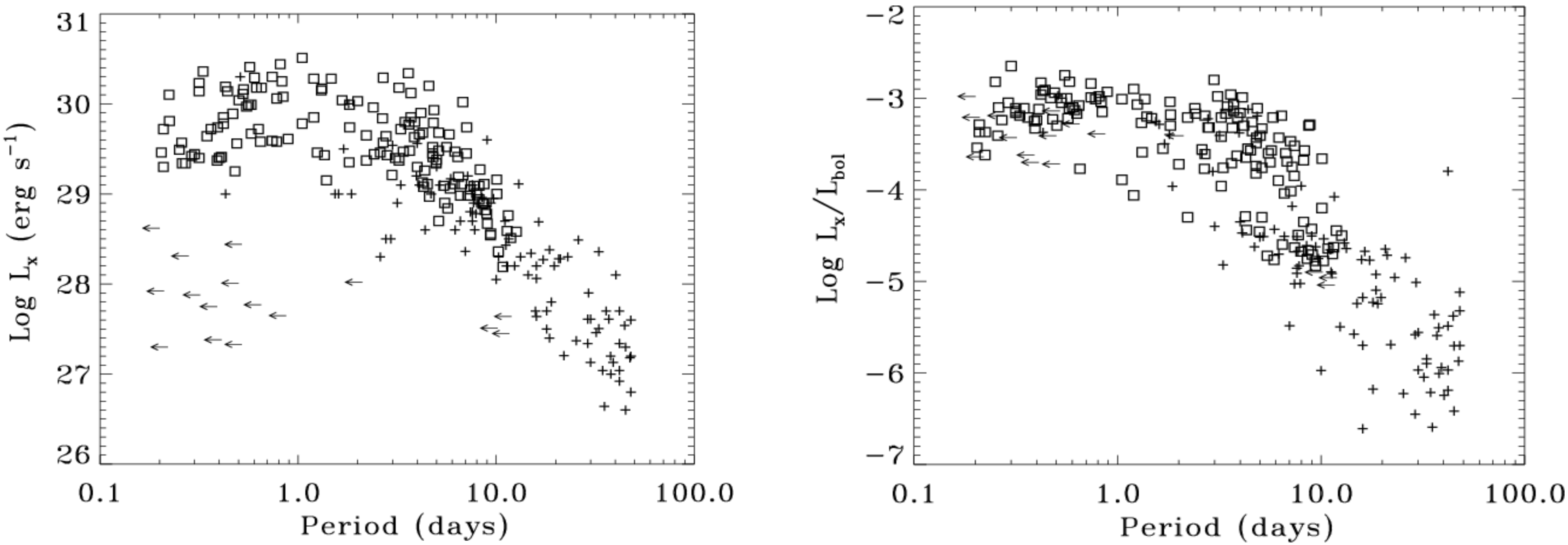




Color-magnitude diagram of RASS detected BSC and Gliese stars

Connection of X-ray emission with other stellar parameters:

Pizzolato+2003

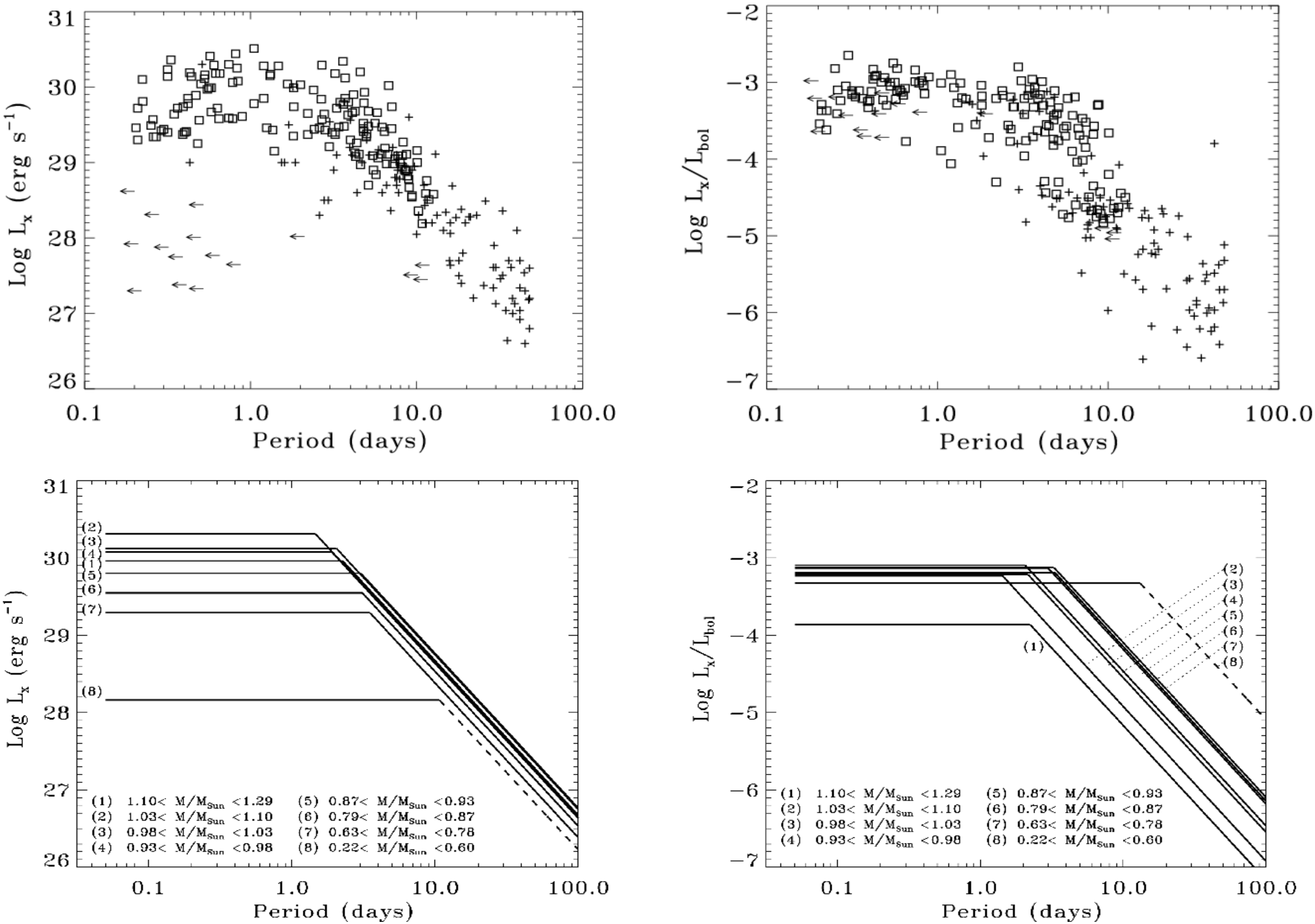


Saturation limit: $L_X / L_{bol} \sim 10^{-3}$

For slowly rotating stars with periods longer than ≈ 5 days, the observed X-ray luminosity scales inversely with period. Explanation in long term variability … cycles needed....

Connection of X-ray emission with other stellar parameters:

Pizzolato+2003



Intermediate-Mass Stars:

Spectral type A stars are devoid of outer convection zone, and should hence not display any coronal emission. A stars and late-B stars also have weak stellar winds, so no mechanism to emit X-rays.

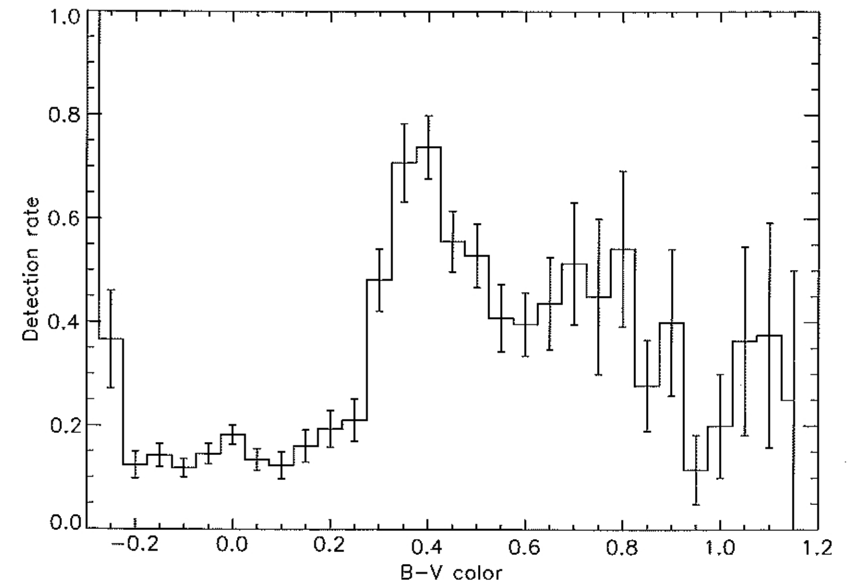


Fig. 10.8 Detection rate of BSC stars in the RASS shown as a function of $B-V$ color, a proxy for spectral type. The transition from A to F spectral types is located at $B-V \sim 0.3$ mag, and coincident with a sharp increase of the X-ray detection rate

Prototypical A star Vega is hard to detect in X-rays. Upper limit is

$$L_X \sim 5.5 \times 10^{25}\, erg\, s^{-1}$$

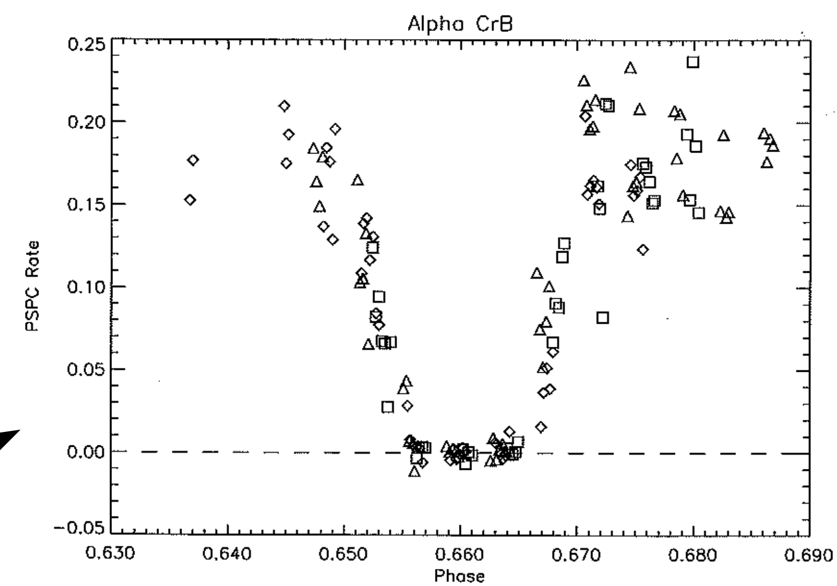


Fig. 10.9 ROSAT PSPC lightcurve of the eclipsing binary α CrB at optical secondary eclipse (A star in front of G star); note the totality of the eclipse

αCrB – late-type secondary
A0V – early-type primary

Coronal age-activity relation: Open Clusters:

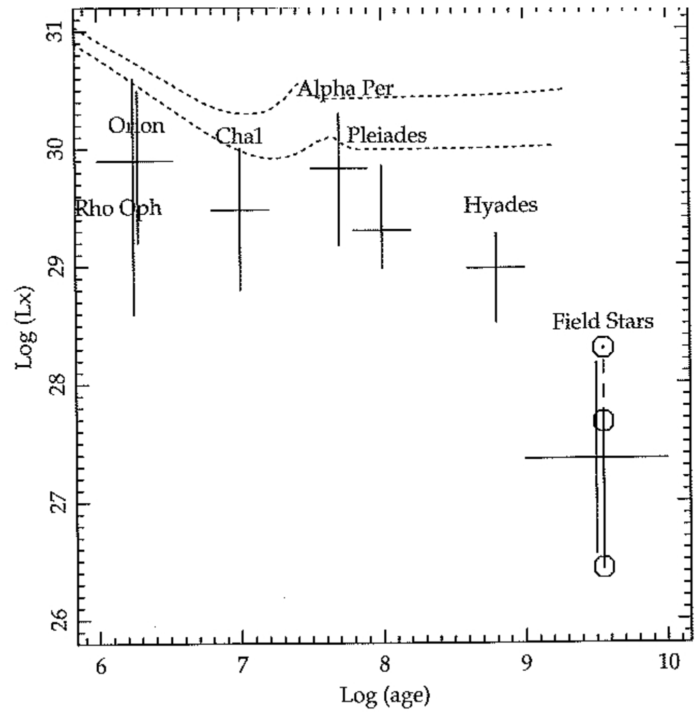
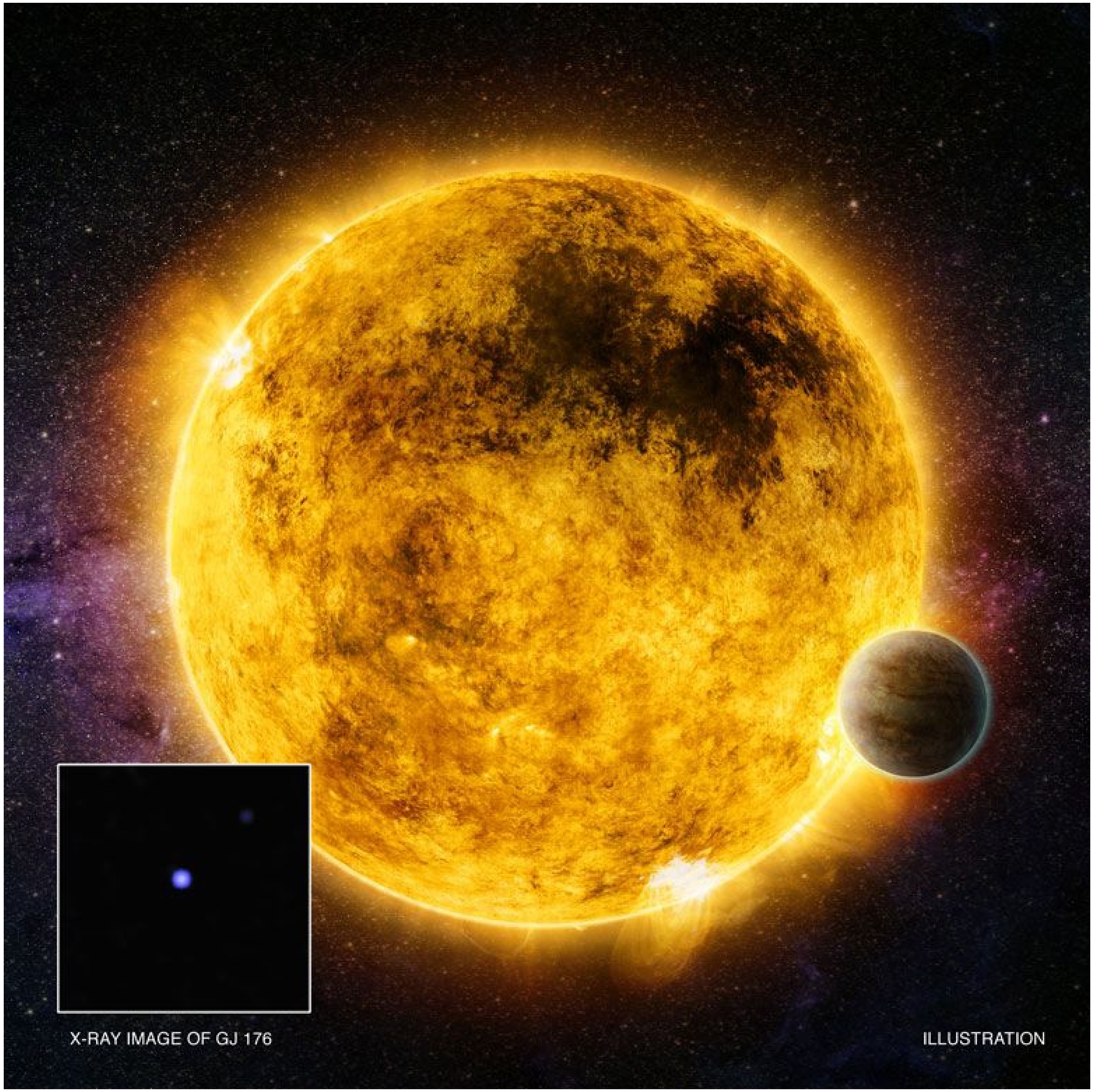


Fig. 10.11 X-ray luminosity of dG stars from the Orion, ρ Oph, and Cha I star forming regions, the α Per, Pleiades, and Hyades open clusters, the Sun and field stars together with the 1 σ equivalent data spread as a function of age; the *lines* show the X-ray luminosities corresponding to the saturation limit of a 0.8 $M_\odot$ and 1.0 $M_\odot$ star; *Fig. 21 from [7]*

The exploration of the consequences of the enhanced UV/X-ray and particles fluxes in the early solar system has become vital for an understanding of planet formation.

The new study uses X-ray data from Chandra and XMM-Newton show a decrease in X-ray brightness surprisingly quickly.



GJ 176: A Sun-like Star More than a Billion Years Old. Credit: X-ray: NASA/CXC/Queens Univ. of Belfast/R. Booth, et al.; Illustration: NASA/CXC/M. Weiss

Close Binaries:

Rapid rotation can usually produces significant activity and large X-ray fluxes; all cool stars follow this rule:

Young, single stars or noninteracting systems with old companions rapidly rotating.

RS Cvn-type binaries – two usually evolved, but detached late type stars, with P from few days up to 2 weeks. The rotation and orbital period are synchronized. X-ray activity four orders of magnitude higher than Sun.

Agol systems – early type primary, but late type rapidly rotating companion.

WUMa – two close late-type stars within a common envelope and typical periods of the order of days. Rapid rotation provides to large X-ray luminosities up to 10^{32} erg/s.

Very low-mass (VLM) stars and brown dwarfs: fully convective:

In such fully convective stars, a solar-like dynamo cannot operate since there is no radiative core (for stars below 0.35 M_{sun}).

Magnetic activity plus rotation may provide to X-ray emission.

Difficult to search because of the considerable distance.

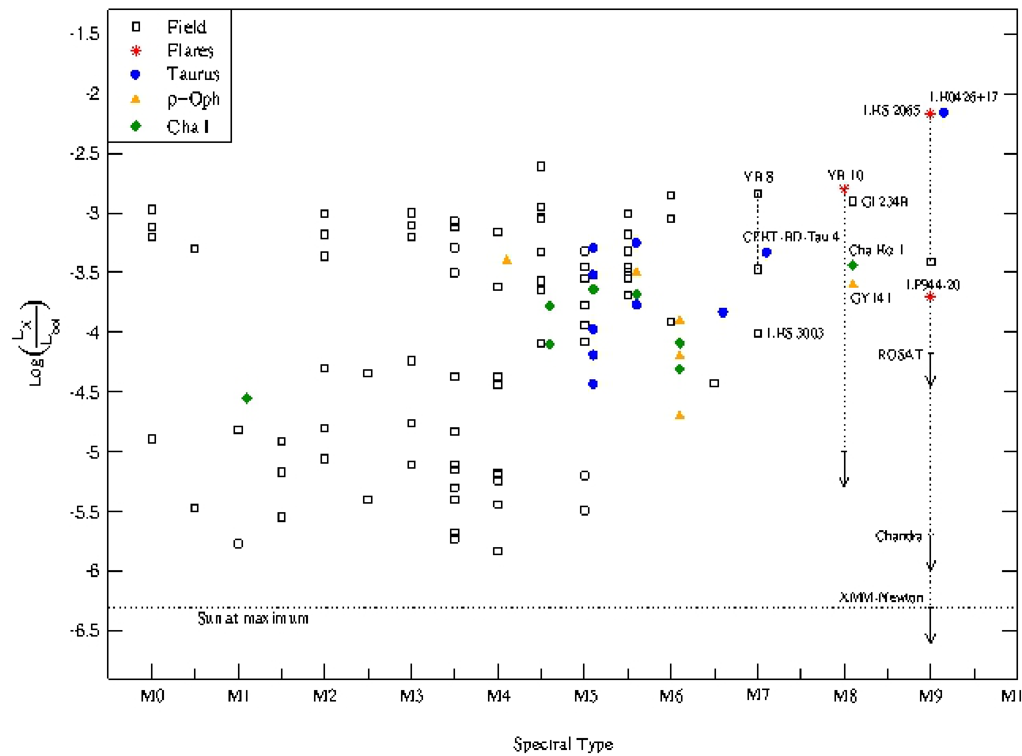
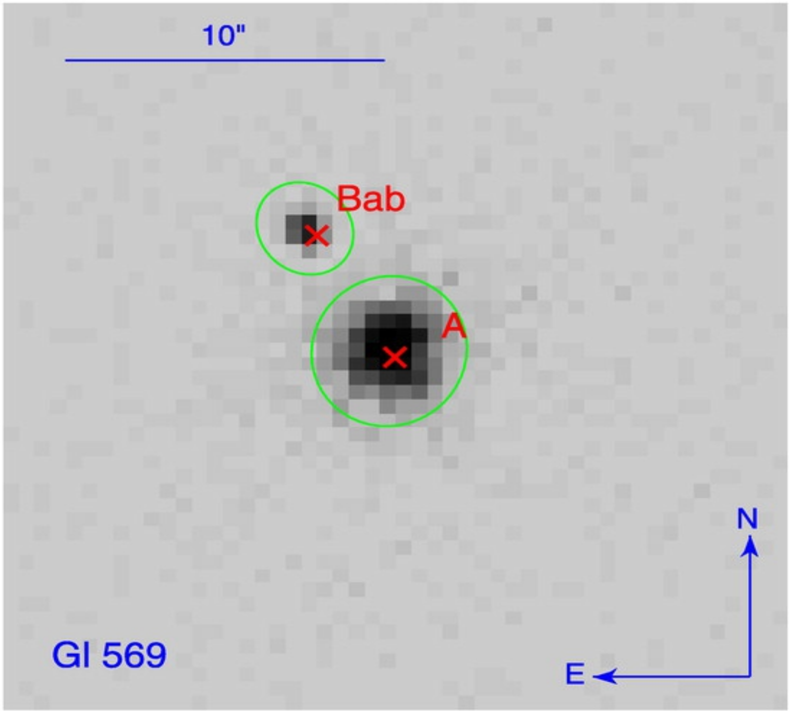
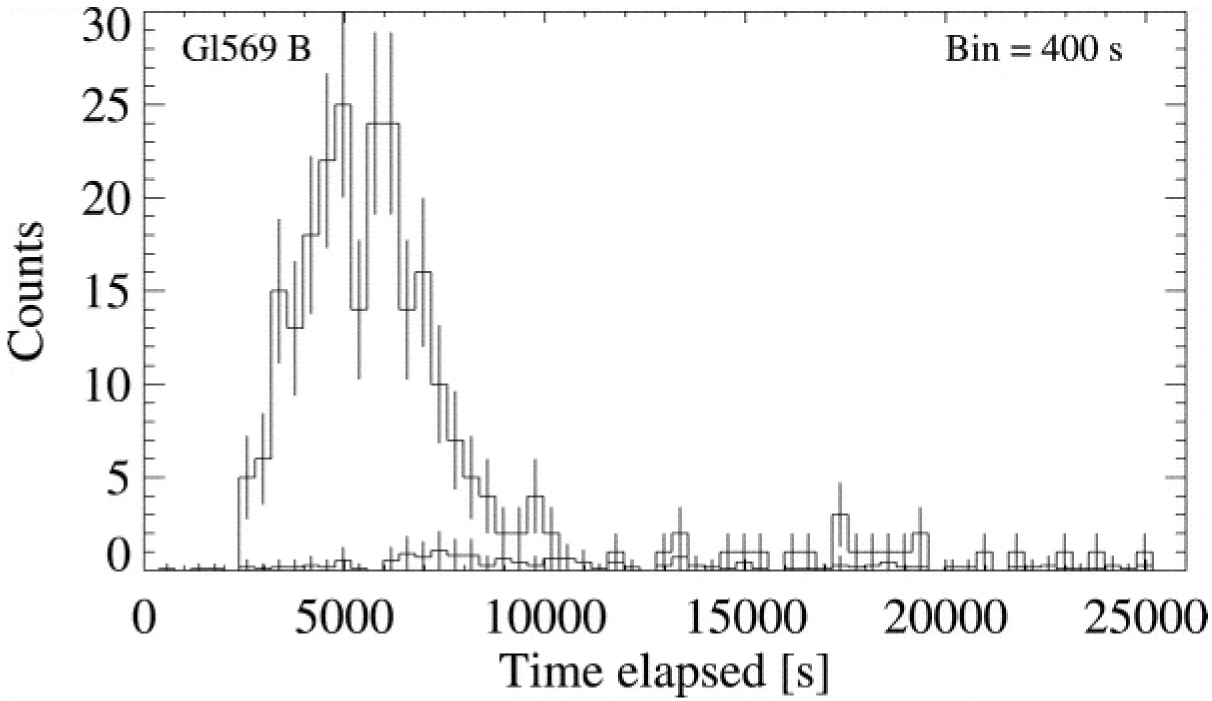


Fig. 4.— Distribution of X-ray luminosity of dM dwarfs as a function of spectral type. The squares represent values obtained for field dwarfs (Fleming et al. (1993); Fleming, Schmitt, & Giampapa (1995); Fleming et al. (2000); Giampapa et al. (1996); Rutledge et al. (2000)). The circles, diamonds and triangles denote young objects in star-forming regions. The stars represent the flaring objects at their maximum with the corresponding value or upper limit on the quiescent emission linked by a dotted line. To avoid confusion, the Taurus object's spectral types have been shifted by 0.1 subclass.

Very low-mass (VLM) stars and brown dwarfs: fully convective:

Almost all detections of evolved ultracool dwarfs are attributed to flares and it has remained unclear whether VLM stars and brown dwarfs are capable of producing quiescent, persistent X-ray emission. Gl569 Bab – two brown dwarfs around a main sequence star – triple system.





XMM-Newton, Stelzer 2004

Hands-on exercise #3:

Density of X-ray Sources

Basic Steps:

1. Find Chandra Observation of 3C295 cluster
   Obsid:
2. What detector configuration and mode were used in this observation?
3. Does data need to be reprocessed? Why or why not?
4. Where is the location of the aim point for this observation?
5. Does the PSF vary across the field of view?

Advanced Topics:

1. Does the data need to be time filtered due to the background flares? Was there any flare during the observation?
2. Create the images in soft (0.5-2keV) and hard (2-10keV) bands. Do you see the same sources in both?
3. Run `wavedetect` for this observation. How many sources were found? Is this an indication of overdensity?
4. Overlay the detected source region on the image.
5. How would you calculate the flux for each source?
6. What is the flux limit in this observation?

Suggested reading: "Chandra Study of an Overdensity of X-Ray Sources around Two Distant ($z \sim 0.5$) Clusters", Cappi et al 2001 Ap.J. 548, 624

The same lecture on Jan. 3rd 2023

NEXT NEW LECTURE on Jan. 5th 2023

- Overview of HW#5

- theory, but we still practice

wi-fi password: a w sercu maj
We have eduroam as well