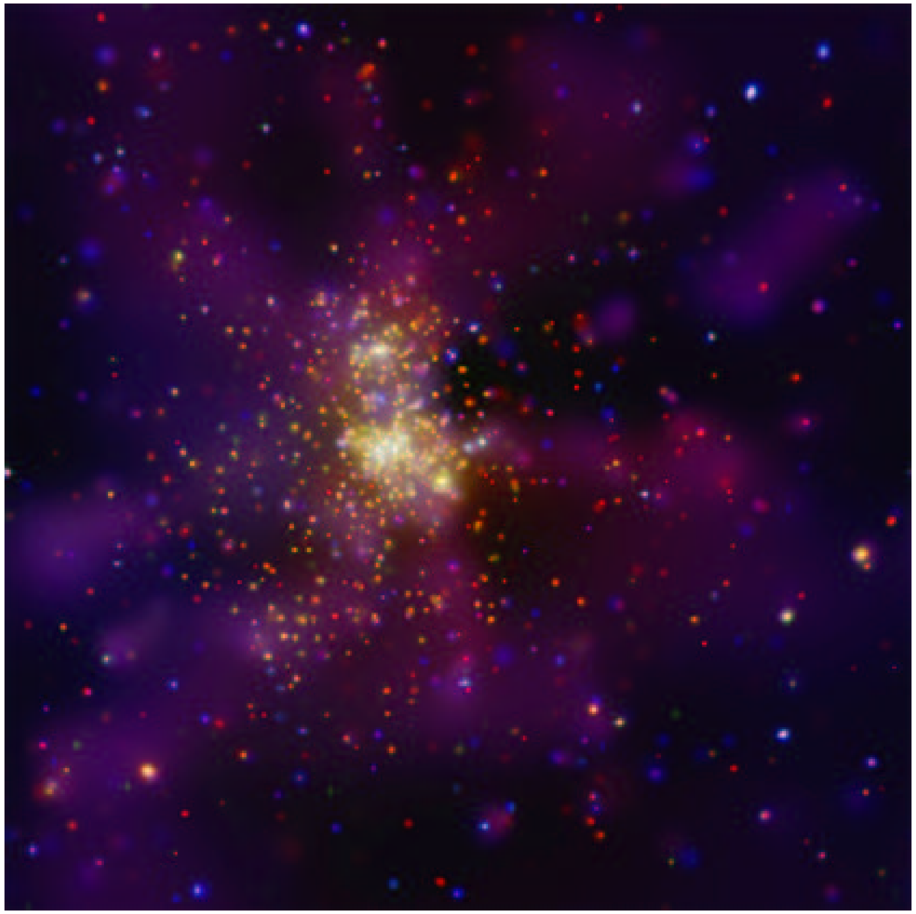
The X-Ray Universe

Potsdam University



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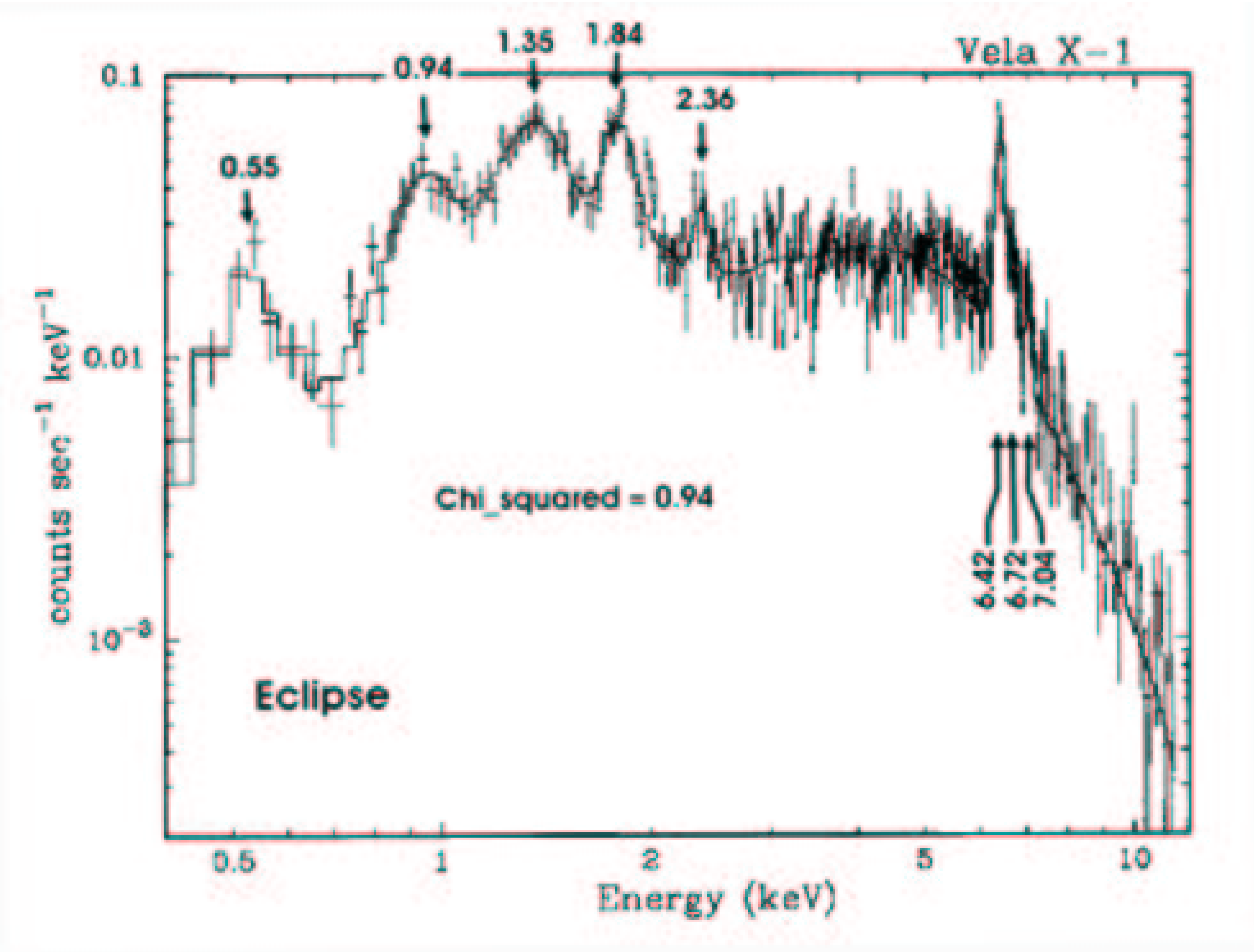
www.astro.physik.uni-potsdam.de/~lida/theormech.html

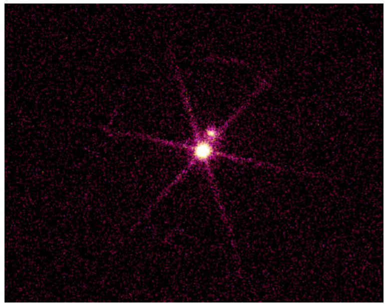
Chandra X-ray Observatory
Westerlund 2 - a young star cluster
d=2×10^4ly

IV. Radiation Processes

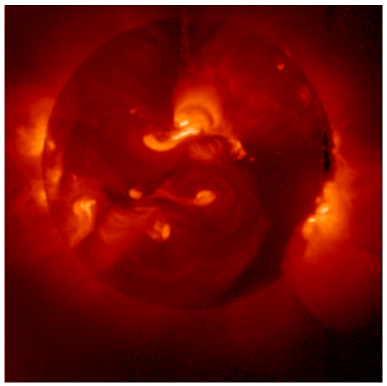


http://heasarc.gsfc.nasa.gov/docs/objects/binaries/v

IV. 23. Summary of Part I

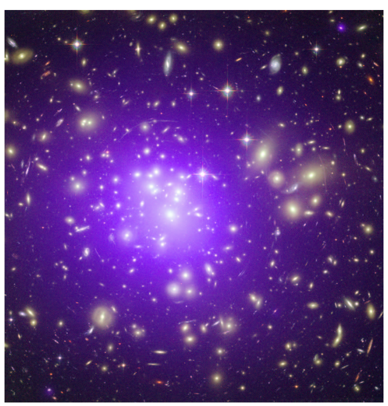


Blackbody: Neutron stars, WD

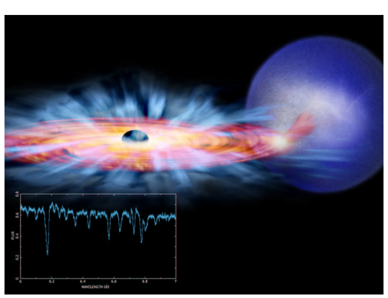


CIE plasma: stellar coronae

NEI: supernova remnants



Bremsstrahlung: galaxy clusters



Photoionized plasma: X-ray binaries

IV. 24. Principle Interactions

- Electron + nucleus: continuum Bremsstrahlung radiation
- Electron + ion: line recombination radiation
- **Electron + magnetic filed: cyclotron and synchrotron**

The emerged spectrum can be modified by:

* Interaction with ions: photoelectric absorption
* Interaction with electrons: comptonisation
* Interaction with energetic photons: photon-photon pair produc

If particle-particle collisions are importnat

then the energy distribution of electrons is **thermal: T**

If particle-particle collisions are **not** importnat

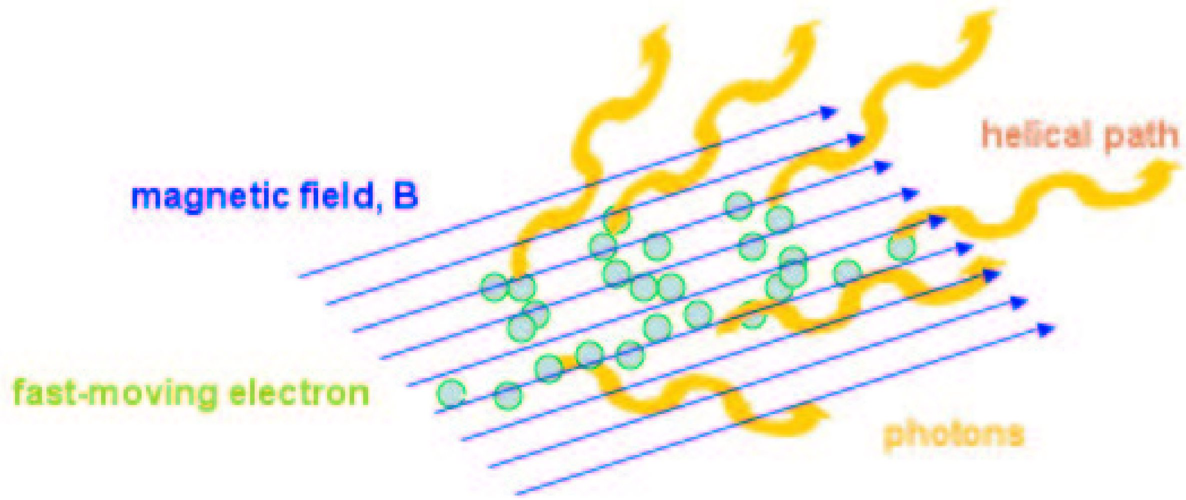
then the energy distribution of electrons is **non-thermal**

acceleration process, photoionized plasmas

IV. 25. Synchrotron emission

Synchrotron emission is non-thermal radiation generated by electrons spiralling around magnetic field lines at close to the speed of light.

The electrons are always changing direction: i.e accelerating and emitting photons with frequencies determined by the speed of the electron at that instant. **Magnetobremsstrahlung.**



http://astronomy.swin.edu.au/cosmos/

The radiation emitted is confined to a narrow cone pointing in the direction of the motion of the particle: beaming.

Radiation is polarised in the plane perpendicular to the magnetic field: the degree and orientation of the polarisation providing information about the magnetic field.

IV. 26. Synchrotron emission (cont.)

Single electorn in magnetic field

Total radiated power:

$$P = 1.6 \times 10^{-15} \gamma^2 B^2 \beta^2 \sin\alpha \quad \text{[erg/s]}$$

where β=v/c, $\gamma=(1-\beta^2)^{-1/2}=E/mc^2$, E-particle energy

B magnetic induction in Gauss, α pitch angle between B and v

Synchrotron lifetime:

$$t = \frac{3\times10^8}{\gamma B^2 \beta^2 \sin^2(\alpha)} \quad \text{[s]}$$

Book: Cosmic Magnetobremsstrahlung (synchrotron Radiation)

(Ginzburg, V. L., Syrovatskii, S. I., 1965)

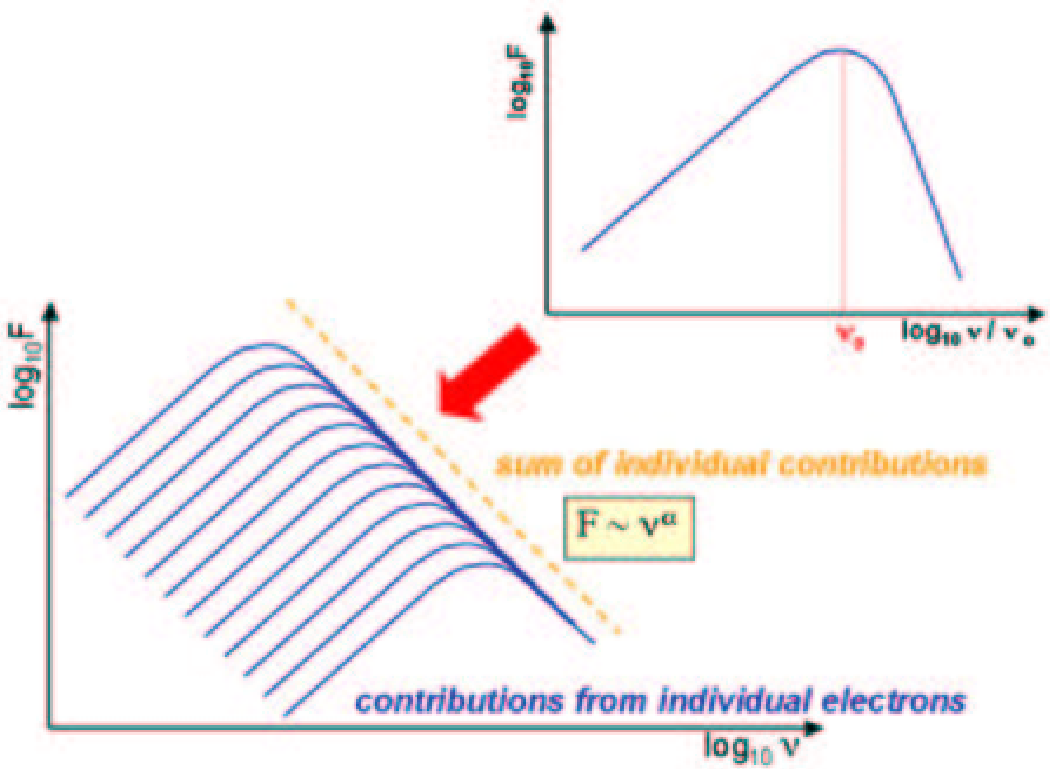
available at ADS

IV. 27. Spectrum of synchrotron emission

The spectrum of synchrotron emission: Σ the spectra of individual electrons.

As the electron spirals around the magnetic field,
it emits radiation over a range of frequencies peaking at ν_0 the critical frequency.

* The longer the electron travels around the magnetic field,
* the more energy it loses,
* the narrower the spiral it makes,
* and the longer the wavelength of the critical frequency.



$$\nu_0 = 4.3 \times 10^6 B\gamma^2 \sin\alpha \ \text{[Hz]}$$

Σ spectra of e →

→ $P = 2.3 \times 10^{-22} B \sin\alpha F(\nu/\nu_0)$ [erg/s/Hz]

F(u) an integral over modified Bessel function

Power low spectrum $F \propto \nu^a$

Radio Galaxy: a=-0.7

Pulsar: a=-2...-3

AGN: a=-1...+1

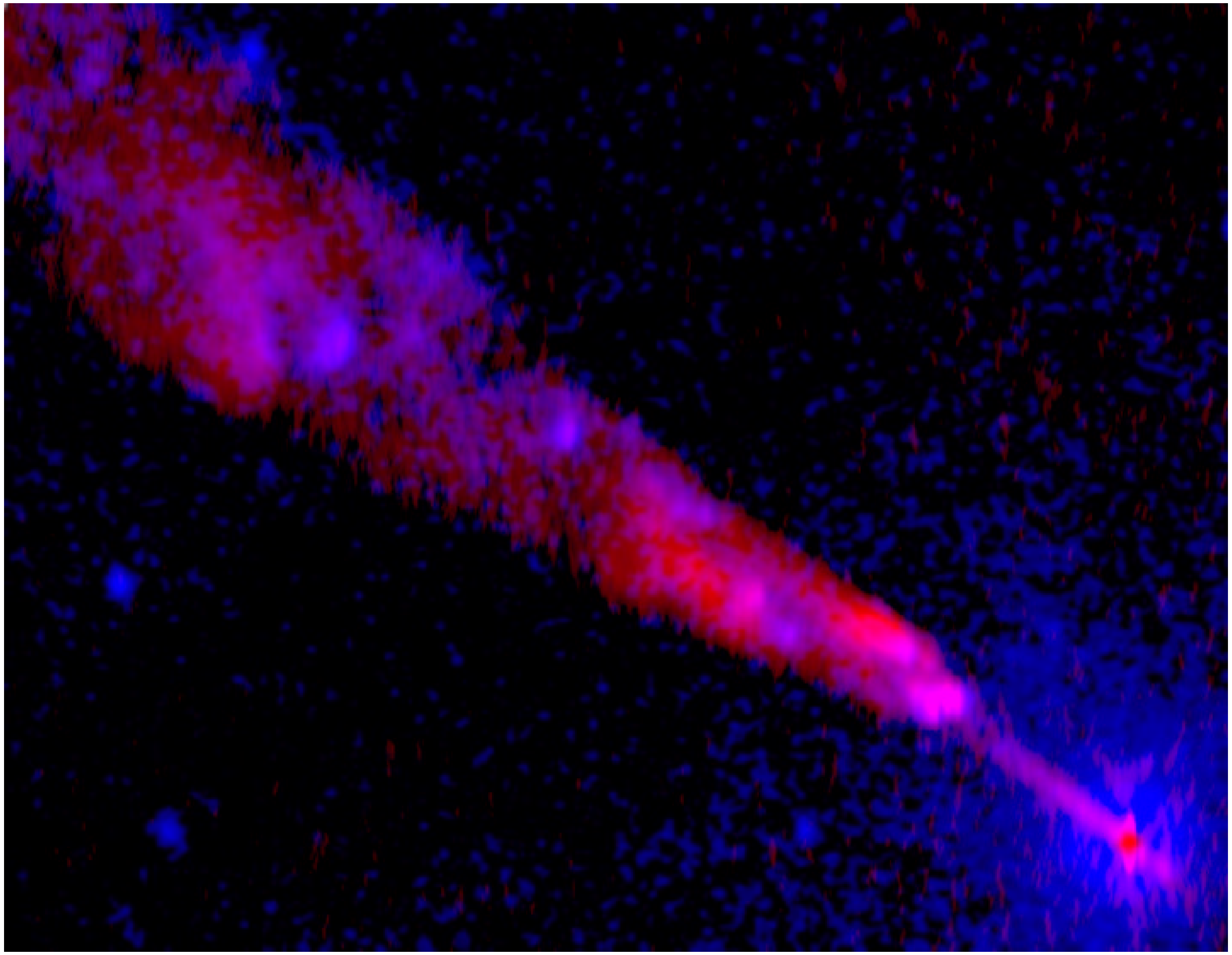
theoretical maximum a=+2.5

http://astronomy.swin.edu.au/cosmos/

IV. 28. Example: Jets from active galaxies

Magnetized jet in Centaurus A (NGC5128): an active elliptical galaxy. Chandra X-ray (blue) VLA radio (red)

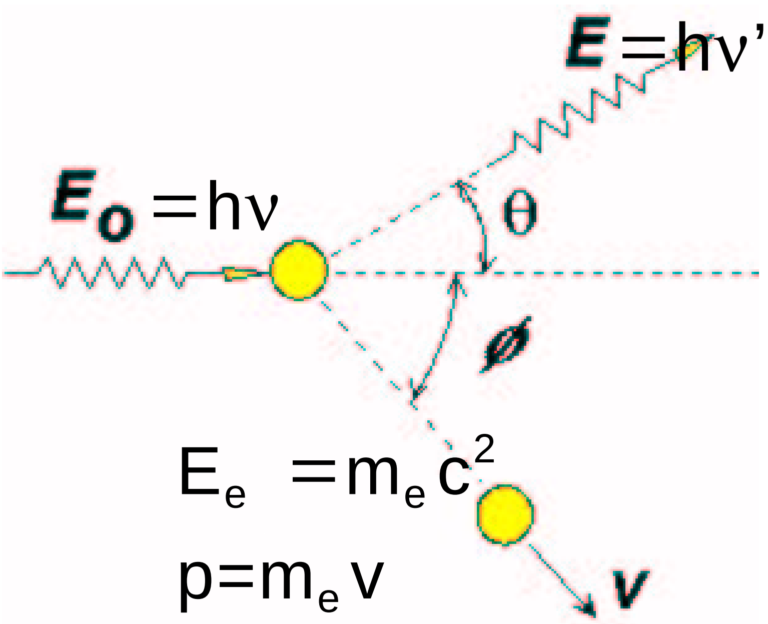
>0.5c - speed of electrons, 11 million light years



http://chandra.harvard.edu/photo/2003

IV. 29. Compton Effect

Compton scattering (Compton effect) is the decrease in energy of an X-ray photon, when it interacts with matter.



$$\lambda' - \lambda = \frac{h}{m_e c}(1 - \cos\theta)$$

E(photon) ~ eV

comparable to the binding energy of e in atom →

photoeffect i.e. ejection of an electron

E(photon)~ keV

comparable to the binding energy of e →

i.e. electron may be considered free

energy and momentum is conserved

Compton effect

E(photon)~ MeV

comparable to the binding energy of p →

Pair production (positron and e)

IV. 30. Compton effect (cont.)

1923 Arthur Compton → 1927 Nobel Prize in Physics.

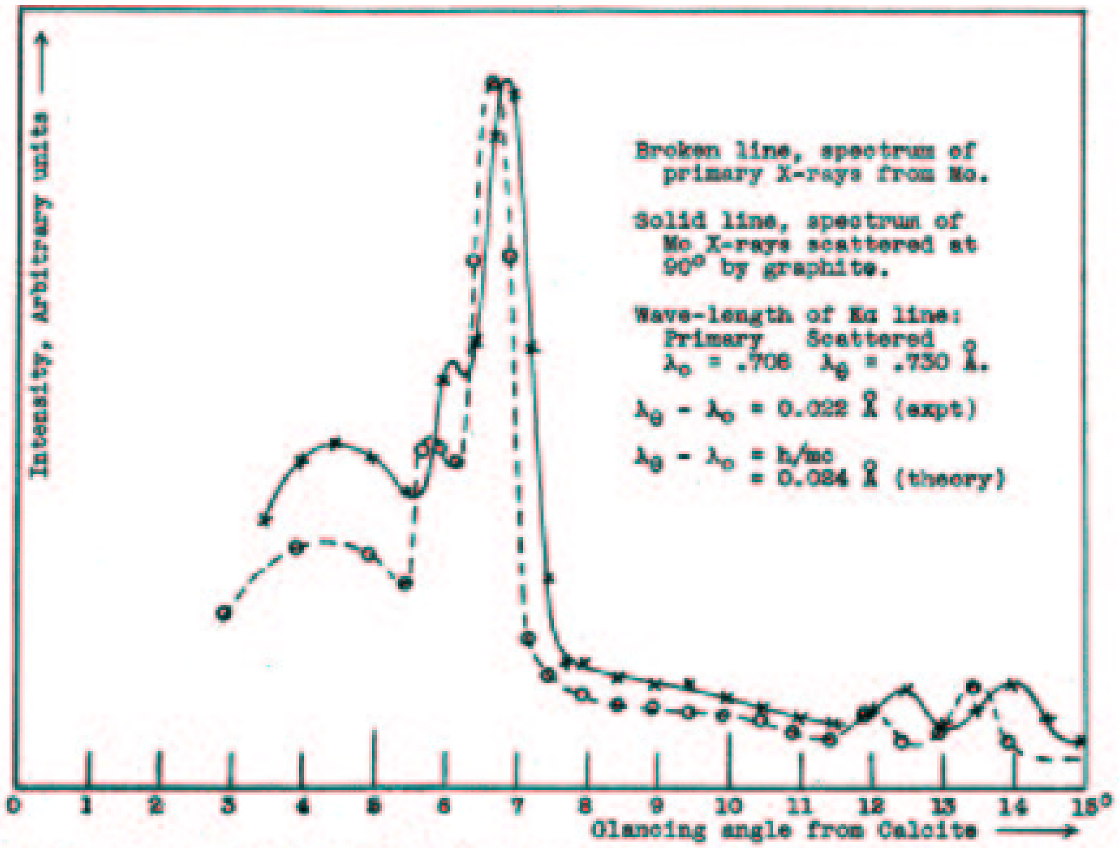


Fig. 4. Spectrum of molybdenum X-rays scattered by graphite, compared with the spectrum of the primary X-rays, showing an increase in wave-length on scattering.

Prove: light cannot be explained purely as a wave phenomenon.

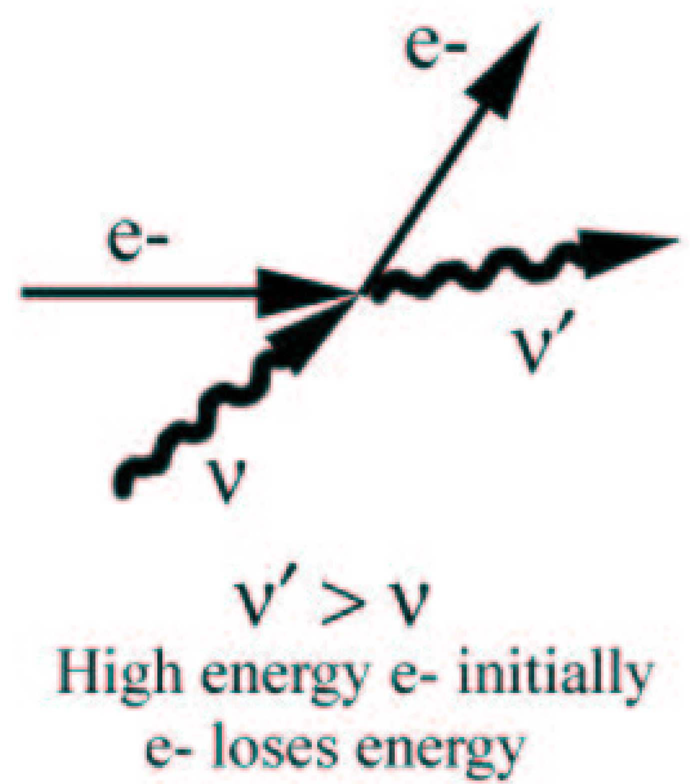
Classical cross-section of electron: Thomson

The Klein-Nishina formula incorporates radiation pressure, corrects for relativistic quantum mechanics, and takes into account the interaction of the spin and magnetic moment of the electron with electromagnetic radiation.

IV. 31. Inverse Compton effect

Occurs when electron cannot be considered at rest

Inverse Compton scattering is astrophysically more important



http://venables.asu.edu/quant/proj/compton.html

The energy is transferred from the e to the ph

Lets $h\nu << \gamma mc^2$, γ is Lorentz factor

i. the cross-section is independent of the ph energy and is approximately Thomson cross-section σ_T

ii. The mean frequency of the ph after the collision is found to increase by a factor γ^2

iii. high frequency radio photons in collisions with relativistic e ($\gamma = 10^3 - 10^4$) are **boosted** to X-rays.

$h\nu' = h\nu + \gamma mc^2$, maximum E=$\gamma mc^2$

The power emitted in the case of an isotropic distributi

$$P_{\mathrm{IC}} = 4/3\sigma_T \gamma^2 \beta^2 U_{\mathrm{rad}} \text{ [erg/s]}$$

Note how similiar this is the power due to synchrotron emission!

$P_{\mathrm{IC}}/P_{\mathrm{Syn}} = U_{\mathrm{rad}}^2/B^2$ the photon energy density / the magnetic energy density

Synchrotron Self Compton **synchrotron → ph → IC → X-ray**

IV. 32. Comptonisation

If the spectrum of a source is primarily determined by Compton processes it is termed Comptonised. In this case the plasma must be thin enough that other processes, such as bremsstrahlung, do not dominate the spectrum instead. The hotter the gas, the more chance of Comptonisation.

- hot gas near binary X-ray sources
- hot plasma near center of active galactic nuclei
- hot plasma in clusters of galaxies
- primordial gas cooling after the Big Bang

$h\nu << mc^2$ - the electrons loose energy: plasma cooling $\frac{dE}{E} = \frac{4kT_e}{m_e c^2}$

$h\nu >> mc^2$ - the electrons looses energy: plasma heatig $\frac{dE}{E} = \frac{h\nu}{{}_e c^2}$

Let's consider a thermal distribution of electrons T_e $\frac{3}{2}kT_e = \frac{1}{2}m_e v^2$

Combining $\Delta E = \frac{E}{m_e c^2}(4kT_e - h\nu)$

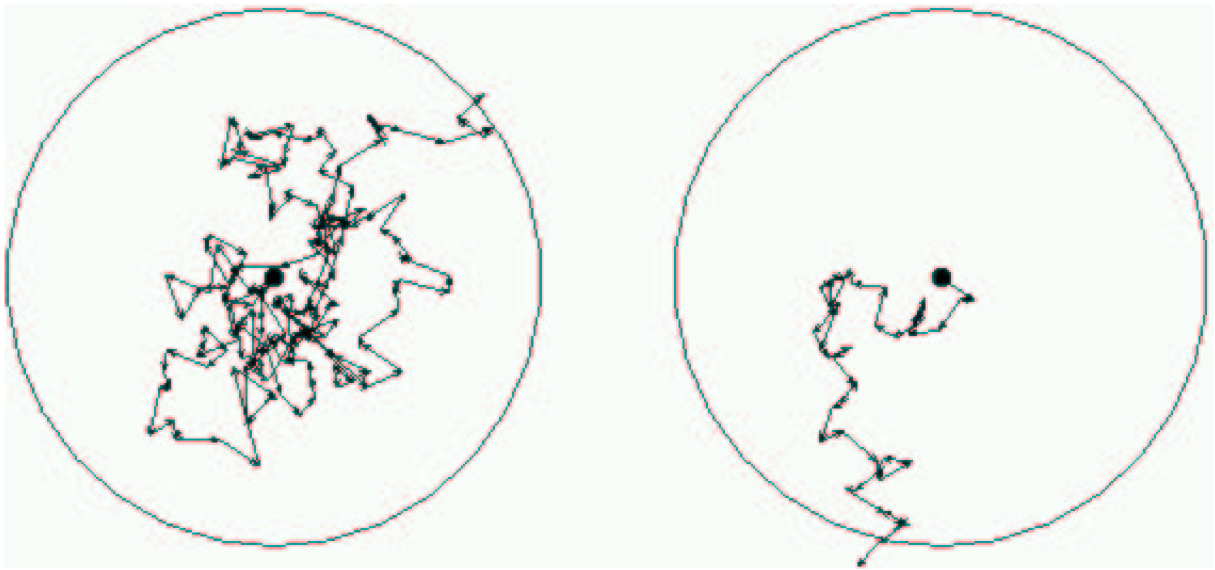
- $h\nu = 4kT_e$, there is no energy exchange
- $h\nu > 4kT_e$, electrons gain energy
- **h**$\nu < 4kT_e$, photons gain energy

IV. 33. Compton factor

Consider a plasma cloud of electron density n_e and characteristic size r.

The optical depth te to Compton scattering is $\tau = n_e \sigma_T r$.

If $\tau >> 1$, the cloud is optically thick, and a number of scatterings is τ^2



http://www.astro.utu.fi/~cflynn/astroII/l7.htmlρανωαλκ

After one scattering, energy E is increased by $\Delta E = E(1+4kT_e/m_e c^2)$

The Compton y-parameter, y = (Number of scatterings)x(Energy gain/scattering).

$y = (4kT_e/m_e c^2)\max(\tau, \tau^2)$, the ratio of final to inital ph energy $\epsilon_f/\epsilon_i \propto \exp y$

Spectrum from Kompaneets equation for the diffusion of photons in energy space

Power-law with $\alpha = \sqrt{2.25 + 4/y} - 1.5$

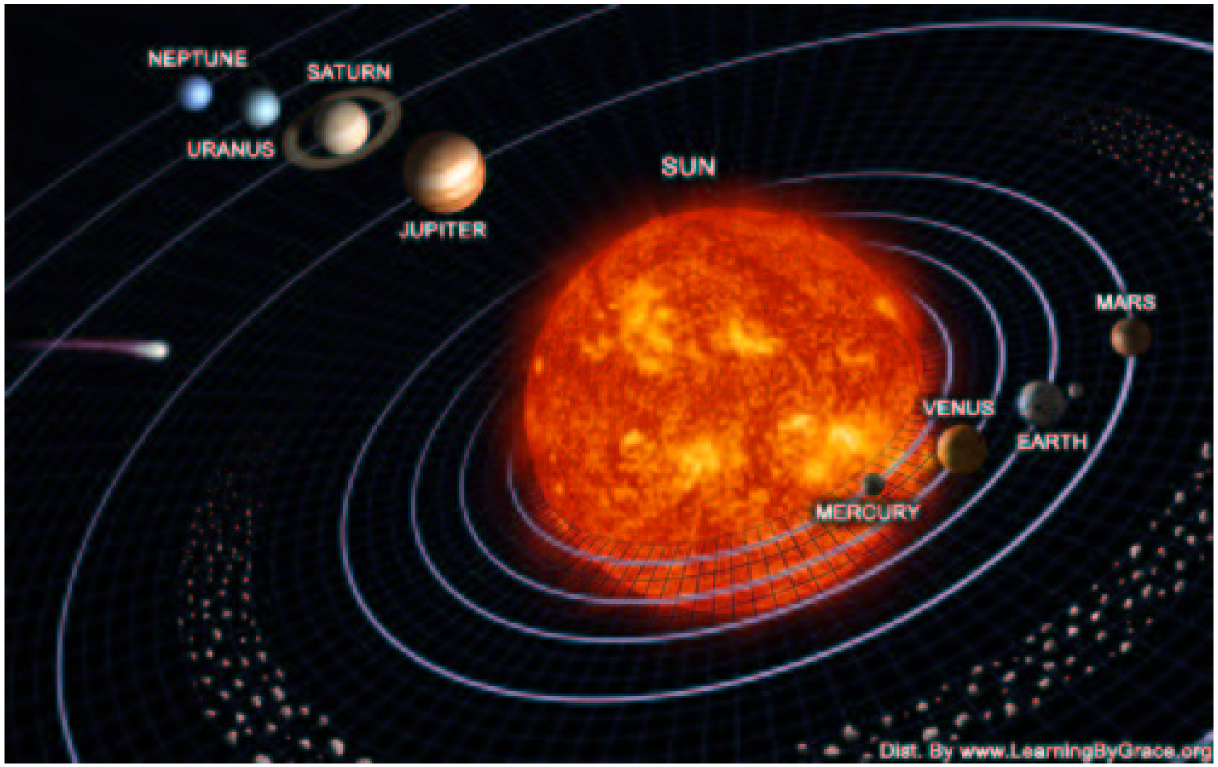
Case $\tau \sim 1$ and $kT_e/m_e c^2 \sim \Theta \sim 1$. After k scattering the photon energy $\epsilon_f \sim A^k$, where

$A = ln(1 + 4\Theta + 16\Theta^2)$ → powerlaw with $\alpha = \ln\tau/A$

IV. 34. Charge exchange

Important in environment where ions and neutrals can interact

Such as planetary systems, i.e. solar



http://www.thejubileeacademy.org/marketing/media/solar_system1.jpg

High ions are produced in corona and are carried by solar wind

Neutrals can be found in Comets, planetary atmospheres

During interaction electron is transferred

$$A^{q+} + N \to A^{(q-1)+,*} + N^{-} \to A^{(q-1)+} + N^{-} + h\nu_X$$

A^{q+} is high ion (i.e. O, C, Fe), N is neutral(i.e. H, H_2O, O)

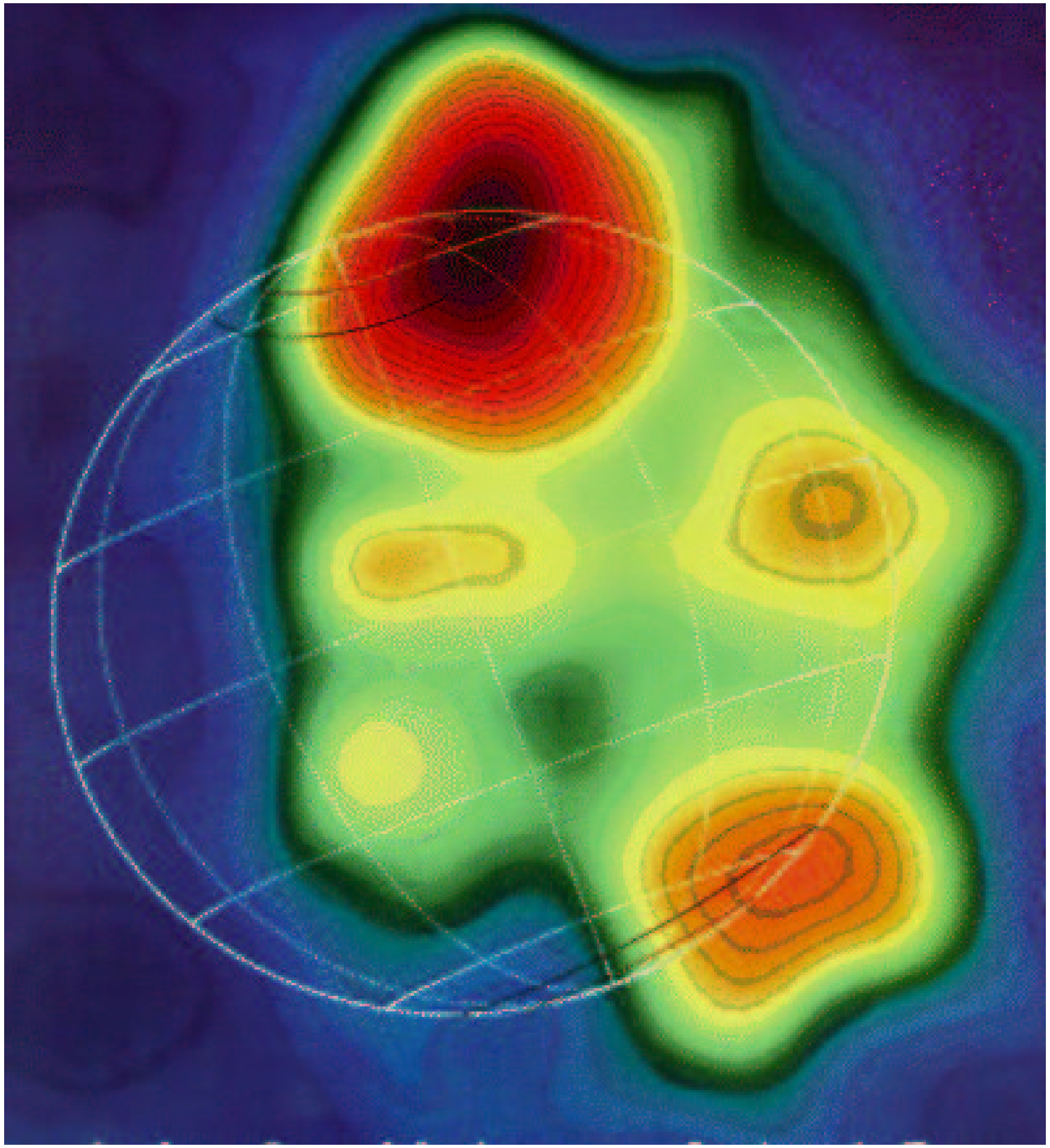
De-exitation cascade in $A^{(q-1)+,*}$ leads to emission of X-ray photon

if ion is singly ionized, it may become neural. If it was bound to a magnetic field line, it becomes un-bound

IV. 35 Summary of Radiative Processes

- Blackbody: Neutron stars, WD
- CIE plasma: stellar coronae
- NEI: supernova remnants
- Bremsstrahlung: galaxy clusters
- Photoionized plasma: X-ray binaries
- Synchrotron: AGN jets
- Componisation: AGN, BH, galaxy clusters
- Charge Exchange: planetary systems

V. X-rays in Solar System



http://heasarc.gsfc.nasa.gov

High Resolution Imager (HRI) on the ROSAT

Impact of comet Shoemaker-Levy 9 in July, 1994 on Jupiter

V. 1. Introduction

Solar system: Except of solar corona no thermal X-rays

- Coronal star the Sun, four Eathlike planets, four giant planets
- 10^{2} moons,$10^{?}$ asteroids and comets
- All are embedded in solar wind: paricles emanating from the Sun

During the last few years our knowledge about the X-ray emission from bodies within the solar system has significantly improved.

Apart from the Sun, the objects shining in X-rays at energies below 2 keV

* planets (Venus, Earth, Mars, Jupiter, and Saturn)
* satellites (Moon, Io, Europa, and Ganymede)
* all active comets

Recent review: Bhardwaj et al. 2007, Planetary and Space Science 55 1135

V. 2. Brief History

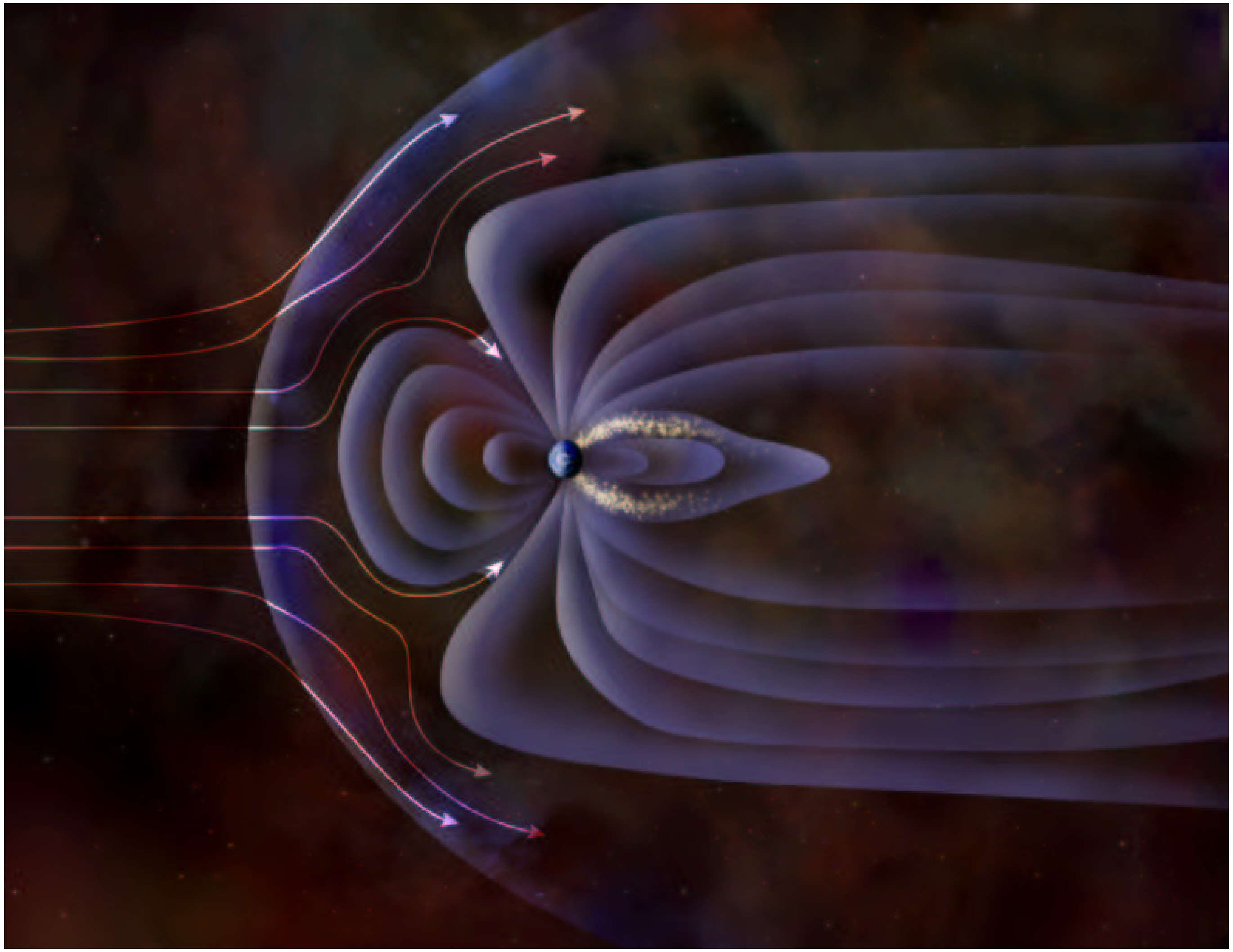
- 1950s: Earth’s Aurorae X-ray emission
- 1962: First X-ray rockets search X-rays from the Moon,

  but find accreting black holes
- 1970s: Appolo mission detects X-rays from lunar surface
- 1996: Rosat discovers X-rays from comets
- Today: X-rays from major and minor bodies
- search continues

all weak extended sources

high sensitivity and angular resolution is required

V. 3. Planetary magnetospheres



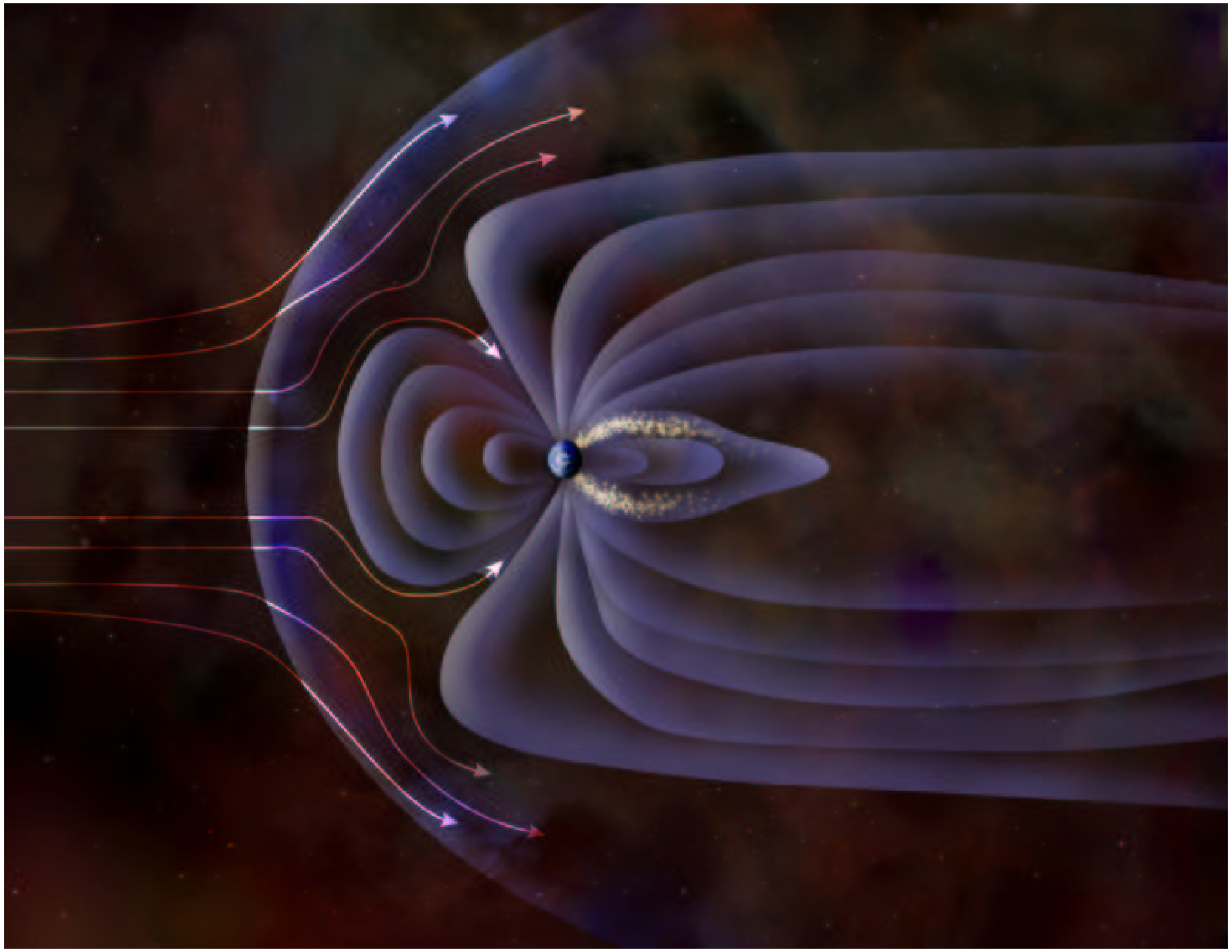
http://chandra.harvard.edu/photo/2005/earth/

Cavity surrounding a planet that contains and is controlled by magnetic field.

Balance between gas pressure of the solar wind (v_r~500km/s) and magentic pressure

The action of the solar wind on the magnetosphere: compresses the magnetic field on the dayside and drags it into a long comet-like magnetic tail, typically thousands of planetary radii in length, on the nightside.

V. 3. Planetary magnetospheres (cont.)

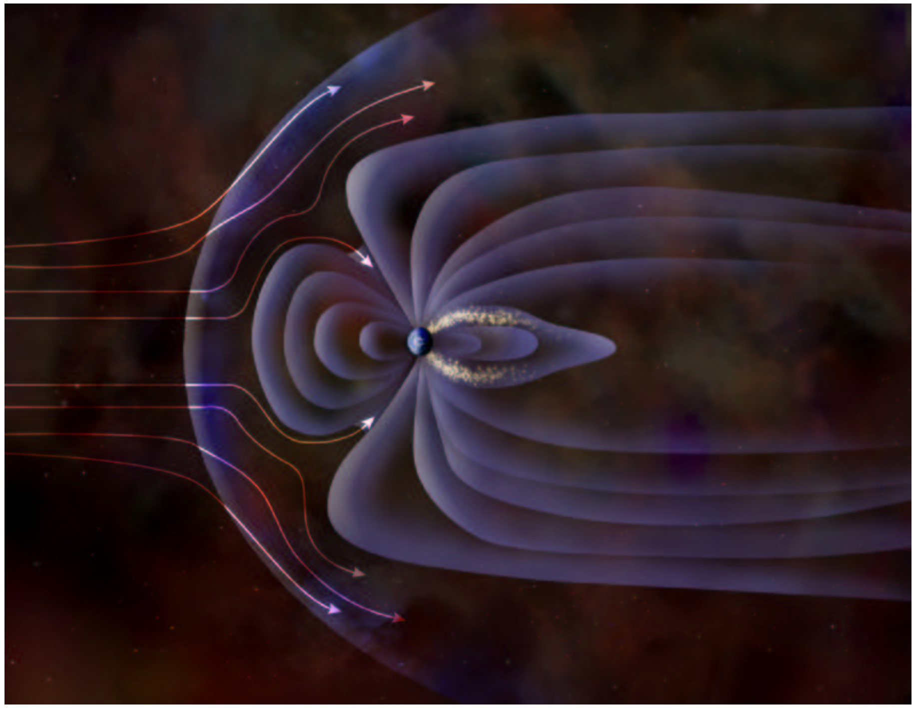


http://chandra.harvard.edu/photo/2005/earth/

Because the solar wind is highly supersonic with respect to the magnetosphere there exists a standing bow shock upstream of the magnetosphere, across which the solar wind is compressed, heated and slowed enough to flow around the magnetosphere in a region called the magnetosheath.

The magnetosphere effectively shields the planet from the the solar wind plasma

V. 3. Planetary magnetospheres (cont.)



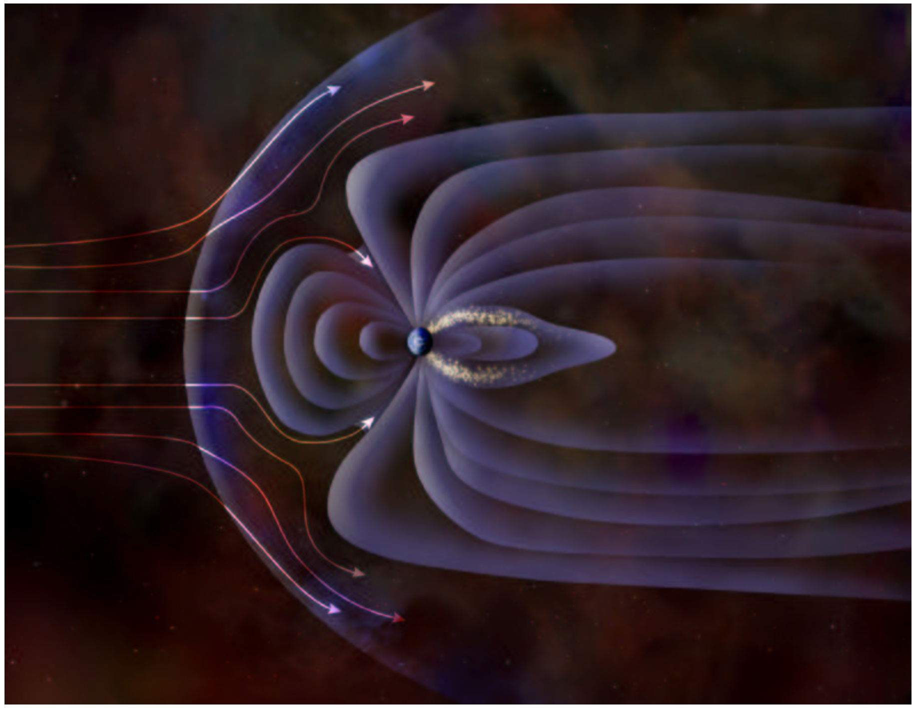
http://chandra.harvard.edu/photo/2005/earth/

Dungey cycle (1961): A fraction of solar wind particles, diffuse across the boundary. Magnetic reconnection occurs: magnetic field dragged by solar wind joins with the planetary magnetic field to form open field lines with one end fixed to the planet and the other open to the solar wind.

Open field lines are dragged anti-sunward by the flow of the solar wind, where they eventually reconnect again and the resulting newly-closed field lines travel back to the dayside where the cycle repeats.

It is one of the two primary mechanisms that drive convection in a magnetosphere, the other being the rotation of the planet. The dominance of either of these processes determines the overall dynamics of each of the solar system's various magnetospheres.

V. 4. Bremsstrahlung emission aurorae



http://chandra.harvard.edu/photo/2005/earth/

The dynamics of magnetosphere generate flows of electrons, that circulate around the magnetosphere. In the polar regions of the planet these currents flow into and out of the planet's upper atmosphere, and streams of electrons are caused to flow down the magnetic field lines, impacting on the molecules in the atmosphere.

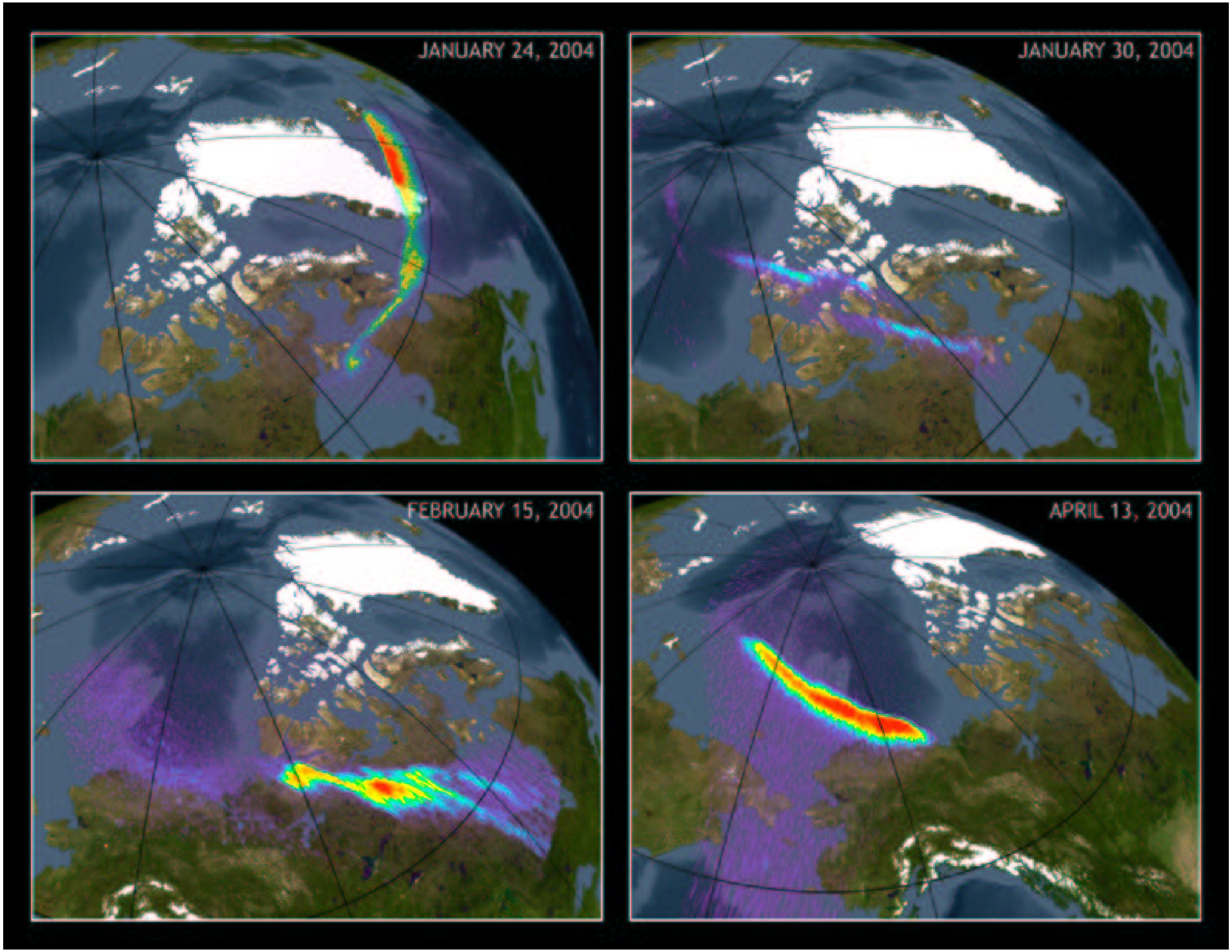
As a charged particle passes a nucleus it is accelerated. The total spectrum depends on the corss-section and the electron spectrum. Bremsstrahlung.

V. 5. Earth aurorare

Most aurora occur at latitudes between closed-dipole filed and the regions with open filed lines, apporx 65-70 degrees. Electrons have energies of few keV. X-raus are at altitude 2000-10000 km

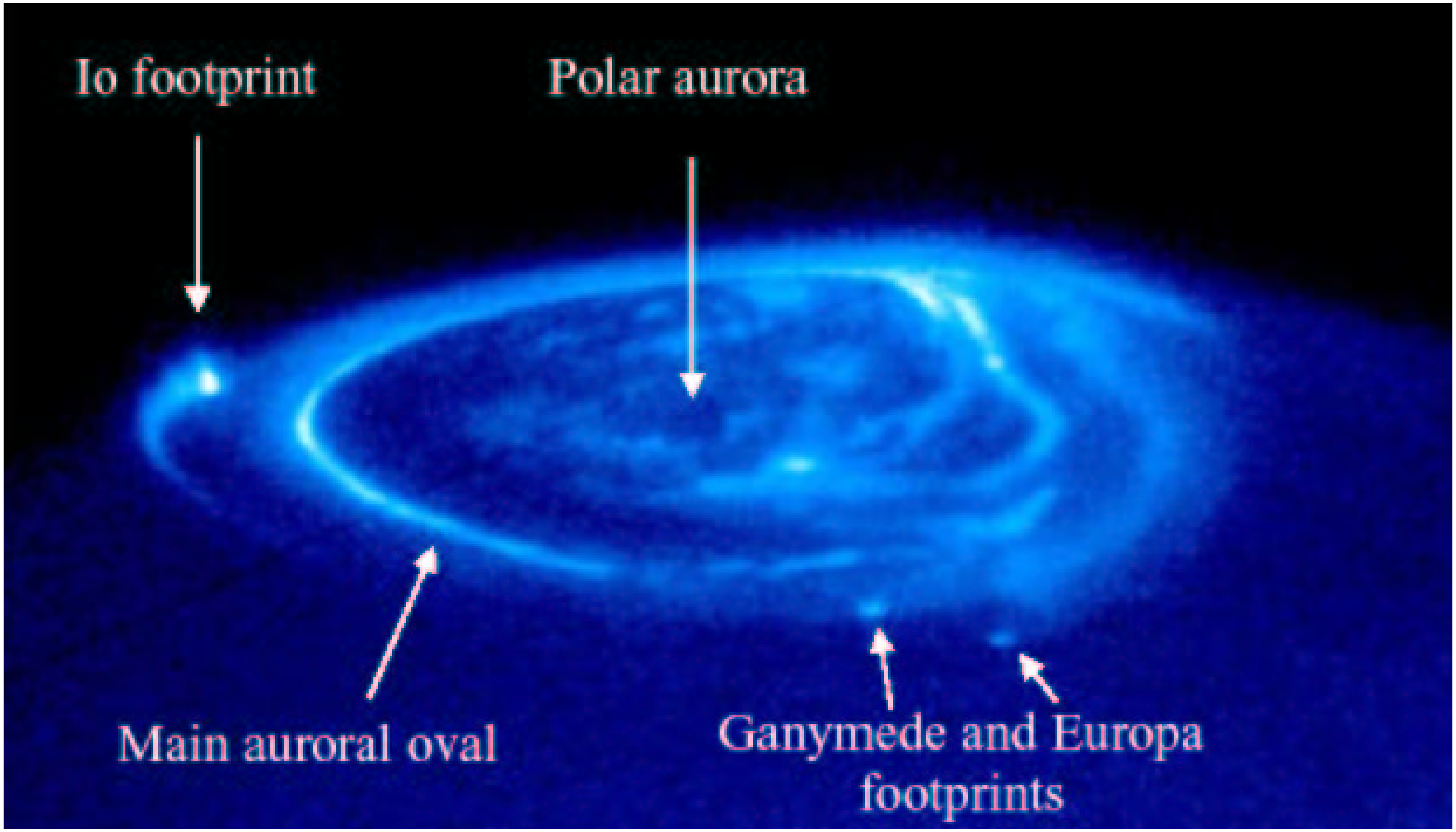
Electron exitation and ionization of atoms and molecules giving rise to visible aurorae. In X-rays Bremsstrahlung. At lower latitudes (< 65 degrees), electrons are trapped in dipol fields, and scatter. Diffuse aurorae are created.

V. 5. In X-rays from space or baloons



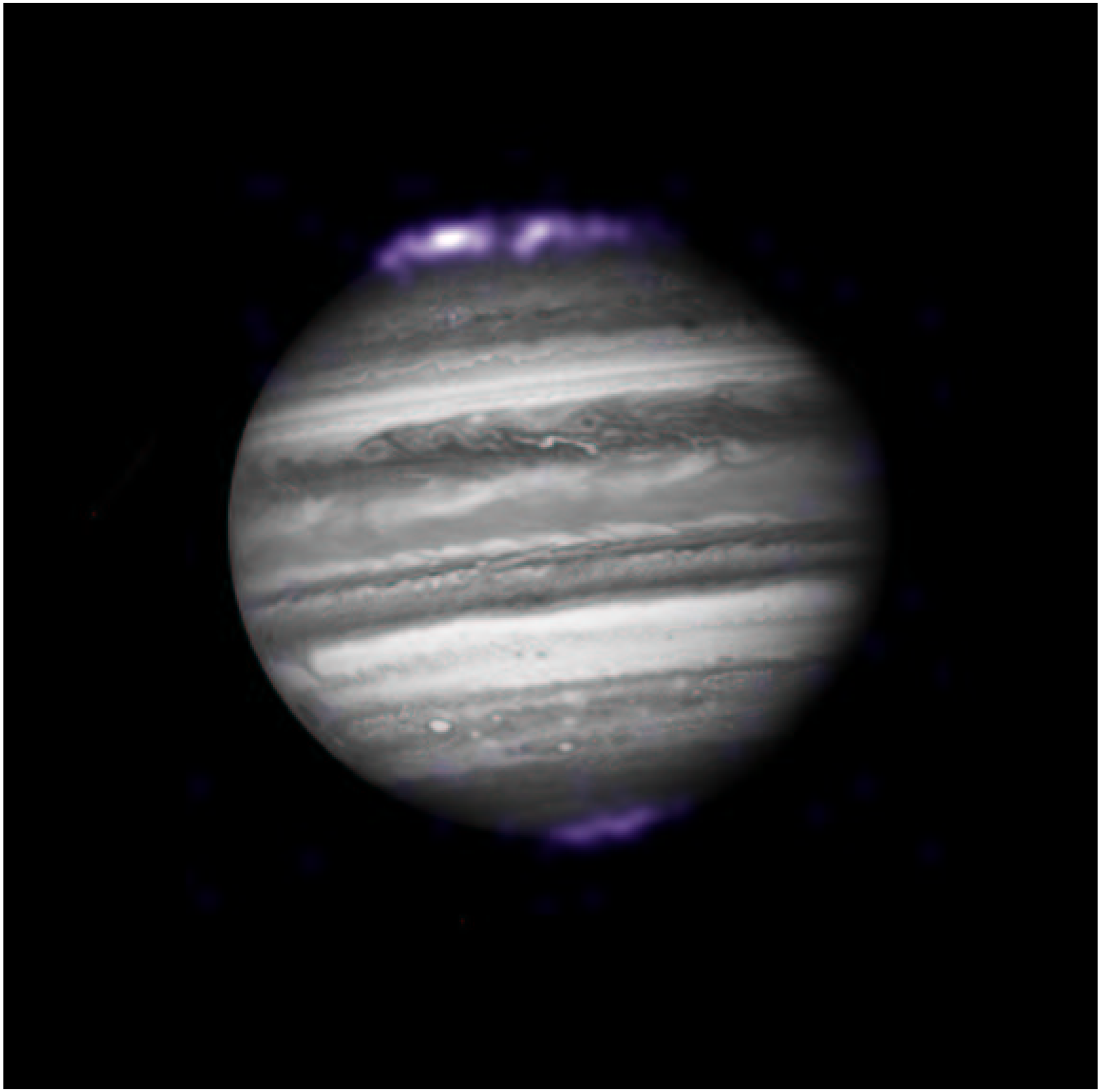
http://chandra.harvard.edu/photo/2005/earth/

V. 5. Saturn



http://www.bu.edu/csp/PASS/

V. 5. Jupiter



http://chandra.harvard.edu/