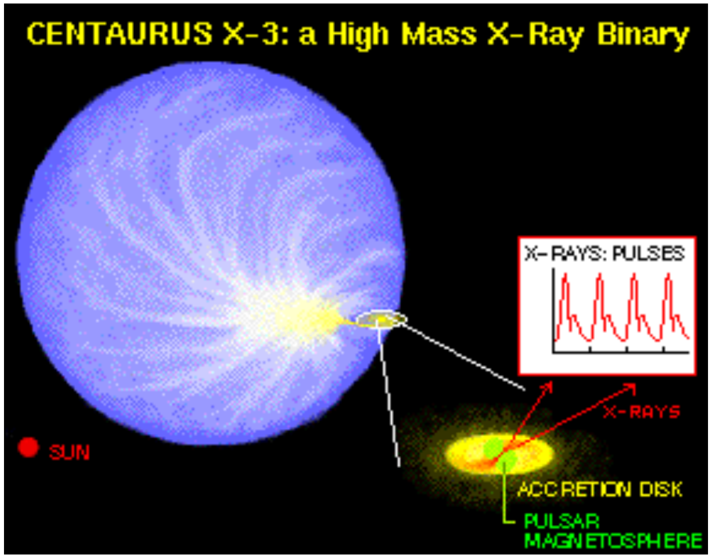
The Objects of High Energy Astrophysics-Neutron Stars

R+B pg 161 sec 5.1



- 1934, Baade and Zwicky proposed the existence of the neutron star a year after Chadwick's* discovery of the neutron - they proposed that the neutron star is formed in a supernova
- 1967, Shklovsky explained the X-ray and optical observations of Scorpius X-1 (the first non-solar) x-ray source as radiation coming from a neutron star via accretion.
- 1967, Jocelyn Bell and Antony Hewish** discovered regular radio pulses from the Crab-radiation from an isolated, rotating neutron star. The energy source of the pulsar is the rotational energy of the neutron star.
- 1971, Giacconi*** et al discovered 4.8 sec pulsations in an X-ray source in the constellation Centaurus, Cen X-3: Emission from a rotating hot neutron star. The energy source is the same as in Sco X-1

*Nobel laureate in physics awarded for his discovery of the neutron.

** Nobel laureate in physics 1974

***Nobel laureate in physics 2002

History: Baade and Zwicky

Walter Baade

"With all reserve, we advance the view that a *supernova* represents the transition of an ordinary star into a *neutron star* consisting mainly of neutrons…

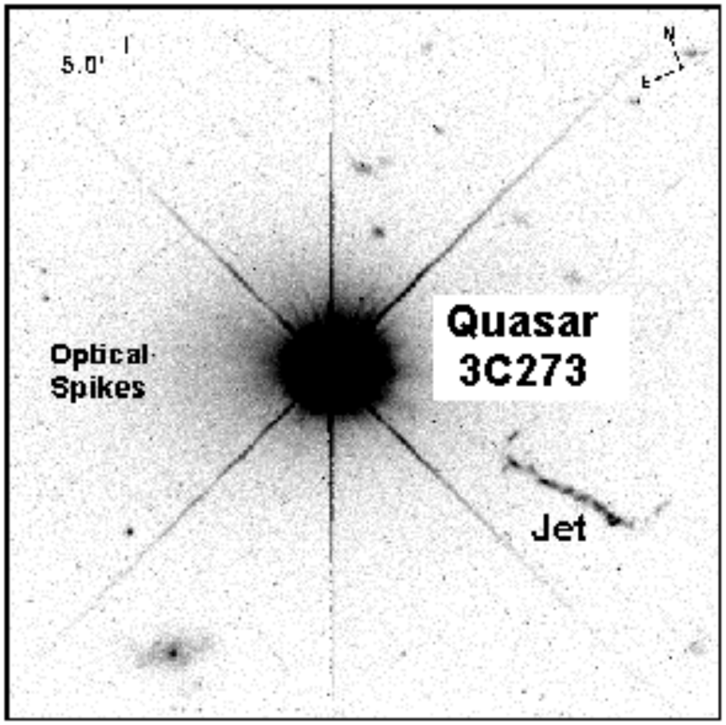
Baade & Zwicky (1934)

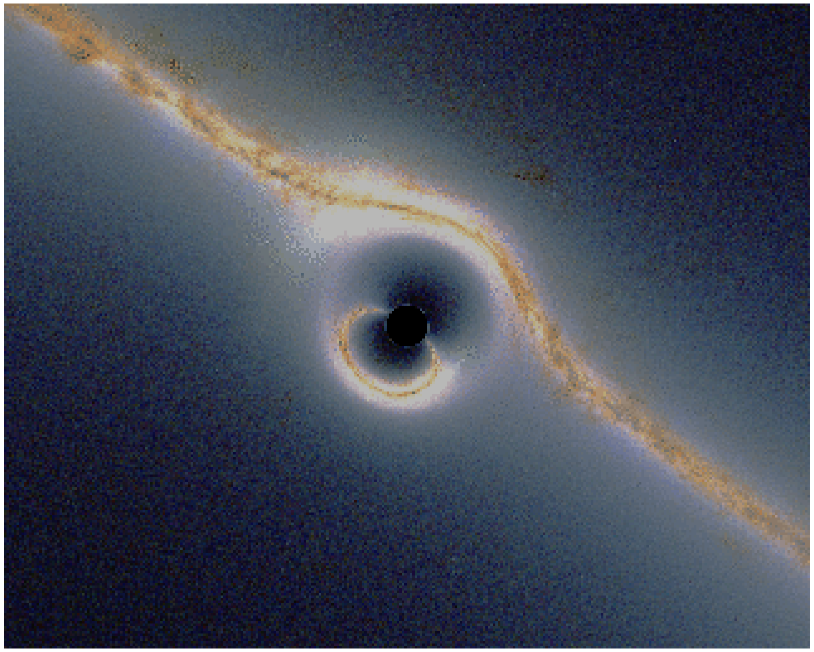
Just 2 yrs after the discovery of the neutron!

Fritz Zwicky

Black Holes Melia ch 10.1

- 1963 Schmidt identified the first quasar, showing that these starlike objects exhibit ordinary hydrogen lines, but at redshifts far greater than those observed in stars.
- Quasars were shown to be powerful x-ray sources in the mid-1970s
- Quasars are accreting supermassive ($M>10^6 M_{sun}$ black holes (*)- how do we know this??
- The first accreting 'stellar mass' black hole Cyg X-1 was identified in 1972 as an x-ray source
- About 20 BHs in the Milky Way are known
- $\sim 10^8$ AGN



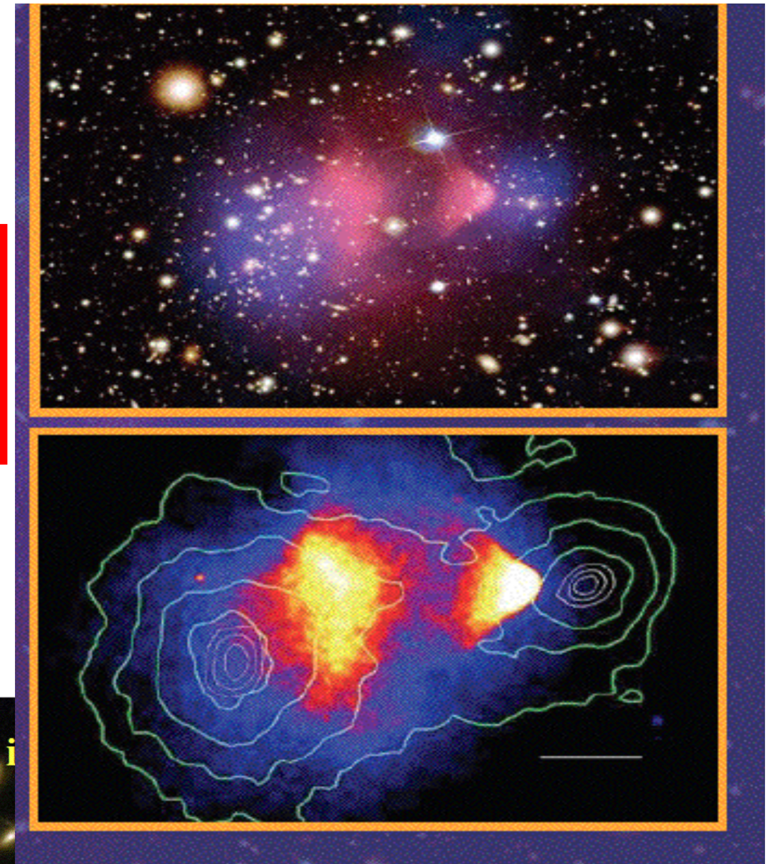


* $M_{sun=} 2x10^{33}$ gm

Clusters of Galaxies

Most massive and largest objects in the universe- $M>10^{14}M_{sun}$; $R\sim3\times10^{24}$ cm= 1 Mpc

**the bending of light by strong gravity can act as a lens



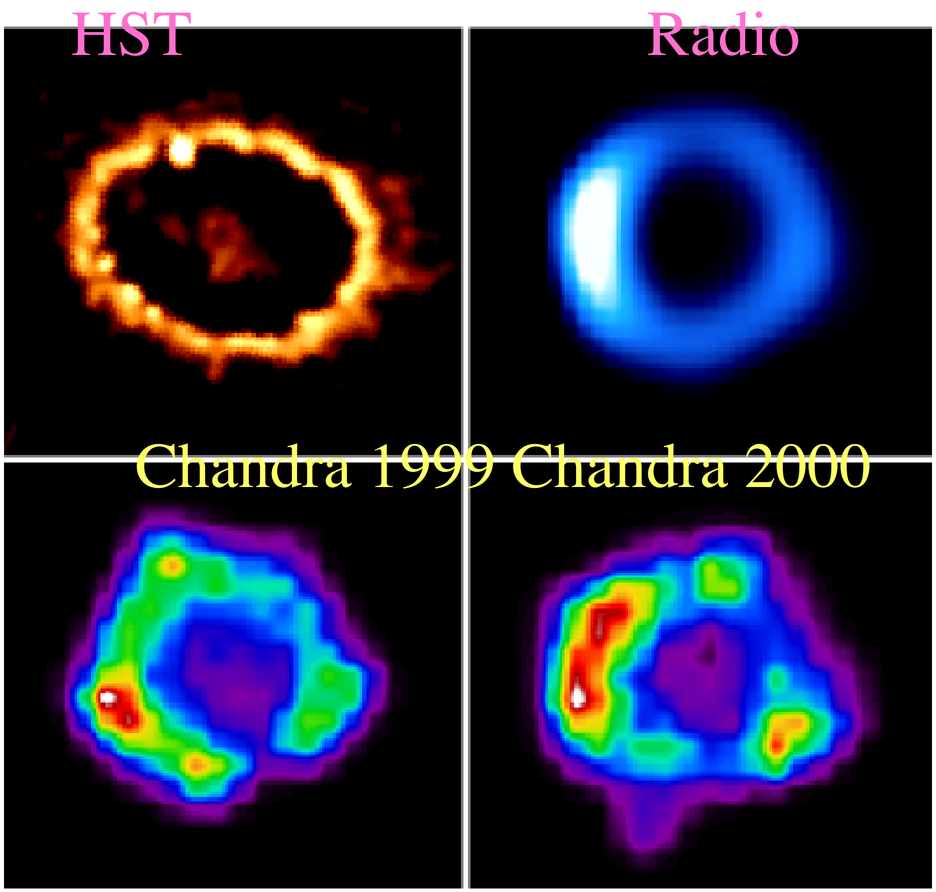
Most of the baryons* are in the hot x-ray emitting gas- most of the mass is dark matter

Can act as a gravitational lens**- revealing the amount of and distribution of **dark matter*****.

*Baryon- neutrons protons, nuclei of atoms

SuperNova Remnants

- Supernova Occur in two types
  - I- primarily the explosion of a low mass (accreting white dwarf) star
  - II- Explosion of a massive $M>8M_{\odot}$ star
- We will distinguish between
  - SN explosions (the actual events and the next few years) and
  - Remnants - what happens over the next few thousand years.



SN 1987A observed in 1999, 2000

SNRs enrich the ISM by dispersing material produced both during the star's life and at the moment of the SN event.

About 2 per century for Milky Way (all types)

Absences, academic dishonesty

- I strictly follow the University policy
- Absences – all must be documented
  - If scheduled (e.g. sports), bring paperwork *as soon as possible*.
  - Illness: contact me *before* missed class or assignment; arrange for make-up (if necessary) within one week
  - Let me know if you have a religious observance that will effect your attendance
- Academic dishonesty
  - Zero-tolerance policy
  - Absolutely no copying of homeworks or exams!
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Course structure

- Lectures
  - Attendance is crucial: a major part of this course will be in-class discussions!

- Other components
  - Homeworks (roughly 1 every two weeks) 1/4
  - Midterm exam 1/4
  - Final exam 1/3
  - Group project and presentation (more later in the semester) 1/5
  - Class participation

Todays Lecture- How are Photons Generated/Absorbed

- Physical processes (Melia ch 5,RB ch 3)
  - **Black body radiation-** system is in equilibrium and all electromagnetic radiation falling on it is absorbed. At a particular temperature a black body emits the maximum amount of energy possible for that temperature.
  - **Synchrotron radiation**

    High energy (relativistic) particles 'spiraling' in a magnetic field (accelerated electrons)

Compton scattering
Electrons scattering of photons/photons scattering off electrons

Line Emission and absorption
Atomic transitions in atoms- x-rays mostly from K, L shell transitions

Photoelectric Absorption
Photons are absorbed by atomic transitions

There is a good 'on-line' text book Elements of Astrophysics; N. Kaiser http://www.ifa.hawaii.edu/~kaiser/lectures/content.html

also

UC Berkeley, Astro 201, Radiative Processes in Astrophysics
E. Chiang - see link in web page

Physical Processes Over View – More Equations Later

Melia ch 5 and Rosswog and Bruggen ch 3- Kaiser Chapter II

- How are 'high energy' photons produced
  - Continuum

Thermal emission processes

Blackbody radiation

Bremsstrahlung

Non-thermal processes

Synchrotron radiation

Inverse Compton emission

Non-thermal bremms

In “thermal” processes the electrons are in a Maxwell-Boltzman distribution- the system has a ‘temperature’

In non-thermal the electron distribution is often a power law-no temperature

Continuum Sources

Synchrotron radiation: a moving electron in the presence of a magnetic field B feels an acceleration a given by

$$a = \frac{e\,\mathbf{v}}{m\,c} \times B$$

which causes the electron to spiral around the B field. The acceleration of the electron produces synchrotron radiation

And its Feynman diagram companion Compton scattering

Bremsstrahlung radiation: "braking" radiation, occurs in ionized gases (plasmas) when thermal electrons are accelerated by passing near another electron or an ion.

Black body emission and Bremsstrahlung are sometimes called thermal emission (because the statistical motion of the charged particles depends on temperature). Synchrotron emission is an example of non-thermal emission since the statistical motion of the charged particle depends on the magnetic field strength.

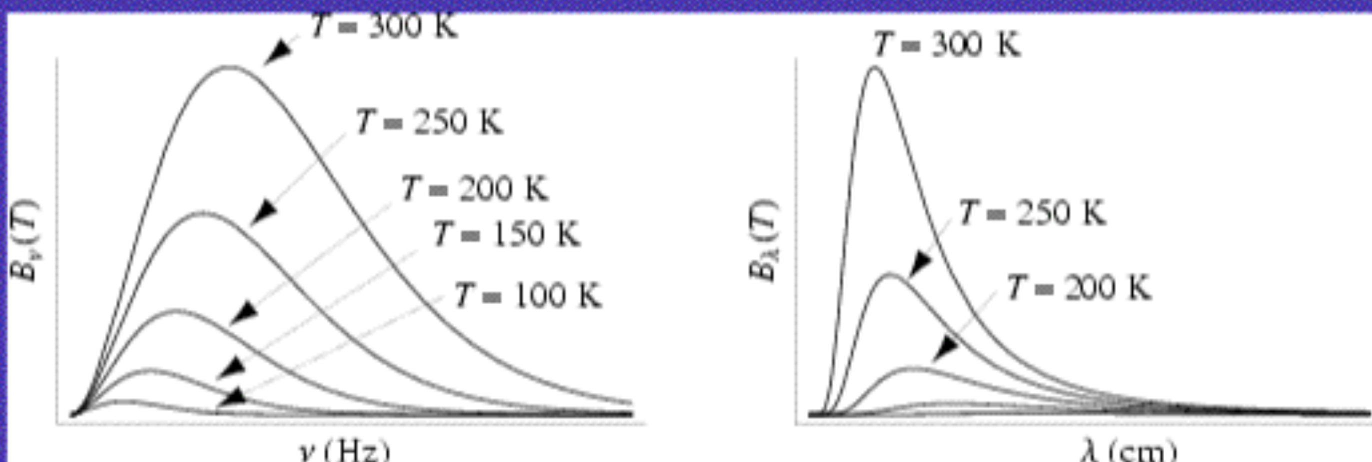
Black Body

An accelerated charge can produce EM radiation over a continuous range of frequencies (energies).

Black Body: An ensemble of charges which absorbs all radiation incident. The absorbed energy raises the temperature of the body, which radiates some of this energy. The radiation has a characteristic brightness distribution ($B_\nu(T)$), called the Planck curve:

$$B_\nu(T) = \frac{2h}{c^2}\frac{\nu^3}{e^{h\nu/kT}-1}$$ ergs s^{-1} cm^{-2} Hz^{-1} $steradian^{-1}$

$L \sim A\sigma T^4$



Black Body- RB Ch 3.5; Kaiser Ch 5, Bradt Ch 6

$$I(\nu,T)d\nu=(2h\nu^3/c^2)(1/(e^{h\nu/kT}-1))$$

$I(\nu,T)d\nu$ is the amount of energy per surface area per unit time per solid angle emitted in the frequency range between ν and $d\nu$ by a black body at temperature T

h is Planck's constant, c is the speed of light , k is Boltzman's constant

The wavelength of maximum intensity λ_m is b/T (b is Wiens constant)

The energy of maximum intensity $\nu_m=0.245T_6$ keV

$L= A\sigma T^4$;

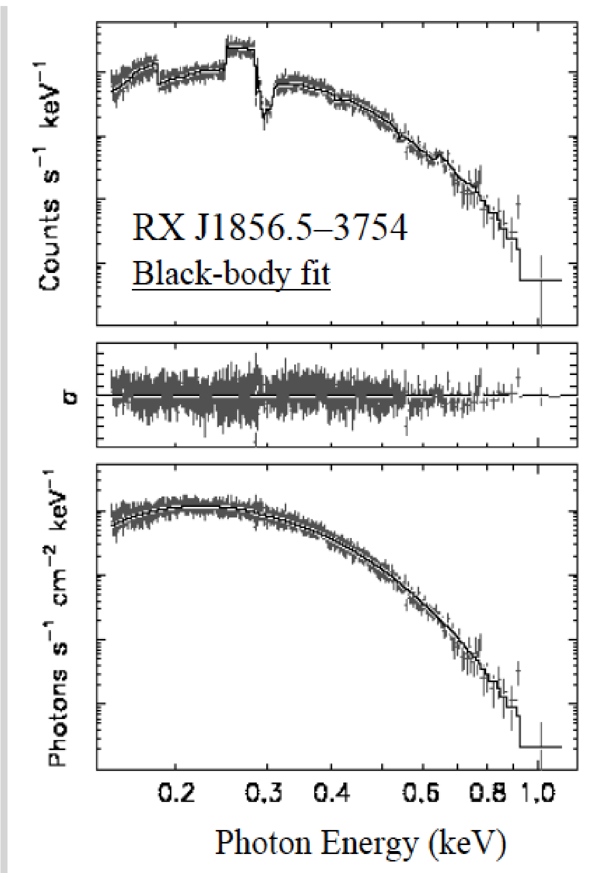
σ is Stefan-Boltman's constant 5.67×10^{-8} $W/m^{-2}K^{-4}$

A is the collecting area

$\sigma=2\pi^5k^4/15c^2h^3$

Black Body Observed

- Several isolated Neutron Stars x-ray spectra can be almost perfectly fit by a black body with kT=86eV, 63 eV



Haberl et al 2008, Burwitz 2003

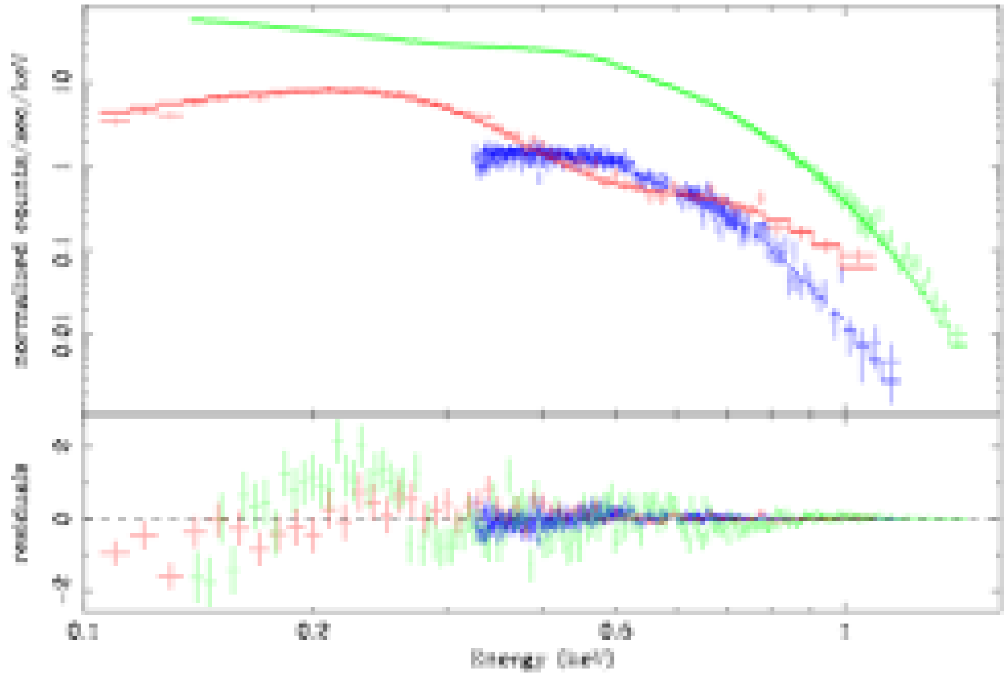


Fig. 2. Combined blackbody fit to the EPIC-PN (green), RGS (blue) and ROSAT PSPC (red) spectra of RXJ0720.4−3125.

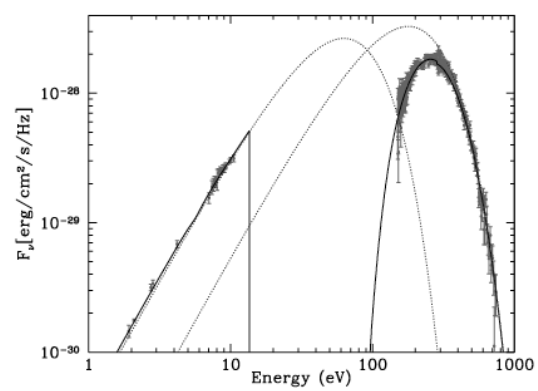


Fig. 3.| Broad band spectral t to RX J1856 3754. Optical/UV data points are drawn from van Kerkwijk & Kulkarni (2001a) and Pons et al. (2002). The dotted lines show the unabsorbed hot and cold blackbody components.

Bremmstrahlung- Kaiser Ch 12

- RB pg 97 (sec 3.8.1)Melia ch 5.3 point out that a proper derivation requires QED (quantum electrodynamics)
- Summary
  - Produced by charged particle collisions in ionized plasmas- e.g collisions between electrons and ions
  - Spectrum is flat at low energies (roughly a power law of $I(E) \sim E^{-0.4}$) with a characteristic exponential turnoff at high energies related to the temperature of the electrons
  - Total emission/unit volume ~ $n_e n_{ion} T^{1/2-}$ e.g scales as square of density

Thermal Bremms -
electrons have a Maxwell-Boltz Dist of velocities - then spectrum is

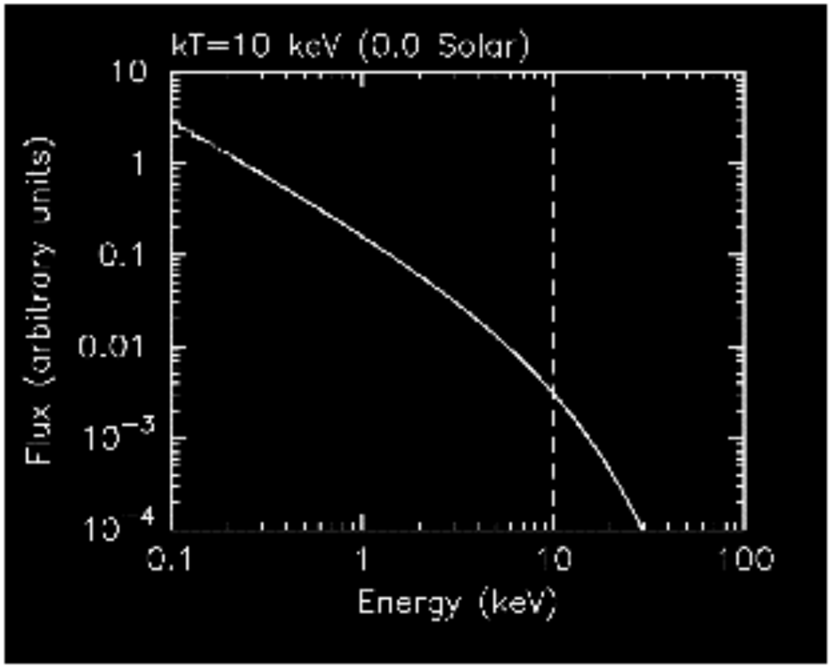
$$I(E) = AG(E,T)Z^2 n_e n_i (kT)^{-1/2} e^{-E/kT}$$

G(E,T) is the 'Gaunt' factor which contains much of the the quantum effects

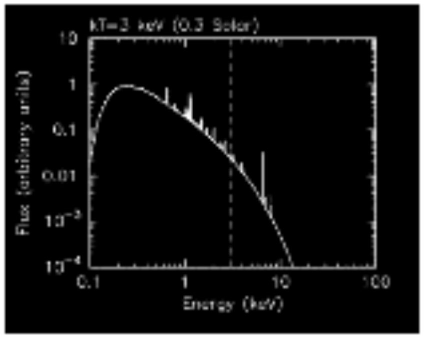
Kaiser Ch 12- Ch 5 of Bradt

BREMSSTRAHLUNG SPECTRUM

$$I(E) = AG(E,T)Z^2 n_e n_i (kT)^{-1/2} e^{-E/kT}$$ exponential fall off at high E



A = normalization, G = Gaunt factor,
Z = charge of positive ions
n_e and n_i electron and ion densities
for $E << kT$ the spectrum is approximately a power law
for $h\nu >> kT$ there is an exponential cutoff



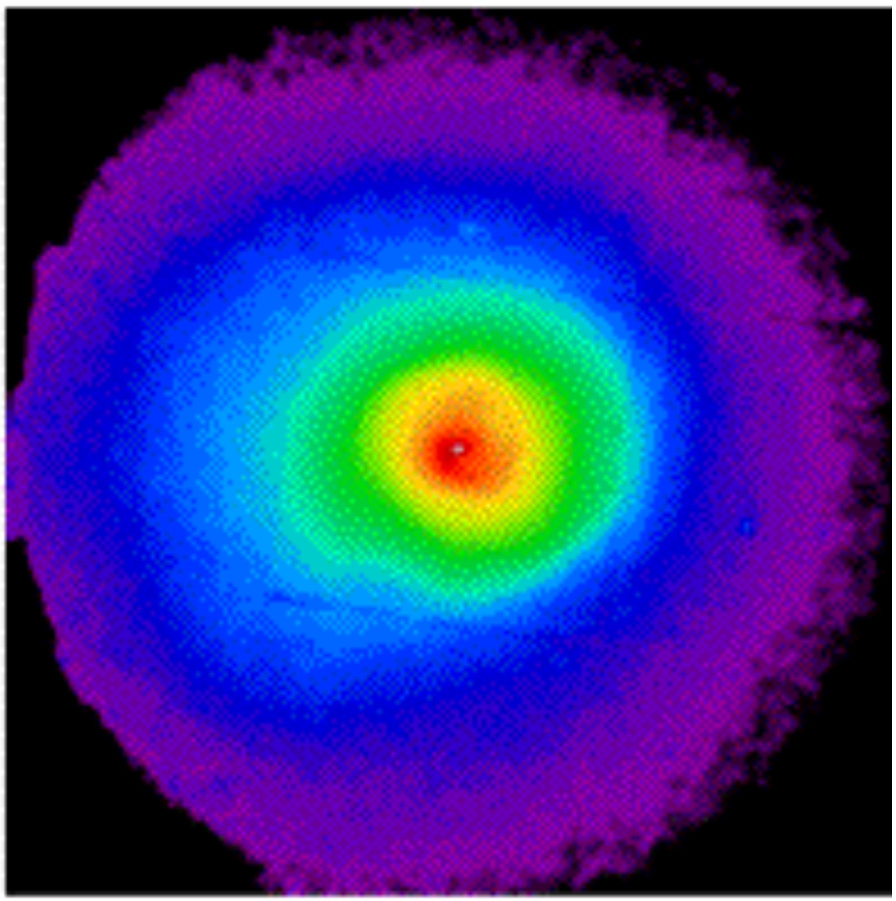
[In reality accompanied by recombination line emission]

Luminosity $L = 1.44\text{x}10^{-27}\ T^{1/2} Z^2 n_e n_{ion} G\ V$ T = temperature, V = volume

Bremsstrahlung Observed

Coma cluster in X-ray and optical light

x-ray emission is due to thermal bremsstrahlung +line emission



Cluster in X-rays and optical

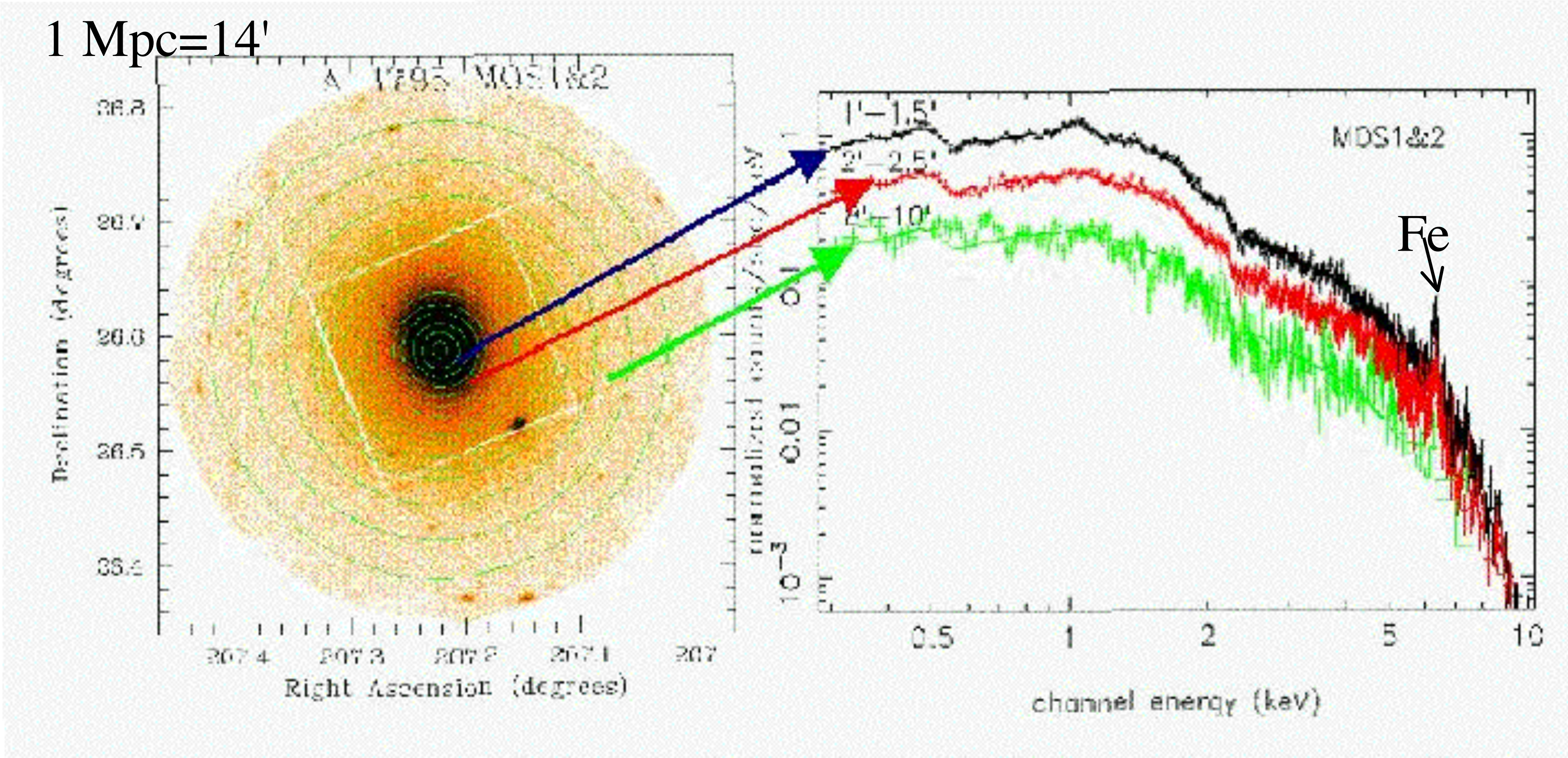


Figure 6: **Left:**Combined EPIC/MOS1&2 image of A 1795 in the [0.3−10]keV energy band. The circles define the

X-ray spectra of a Cluster

continuum due to bremmstrahlung - spectrum +geometry measure particle density and total mass of gas

SYNCHROTRON RADIATION

Nice summary at http://www.cv.nrao.edu/course/astr534

- Electrons spiralling in magnetic field

Kaiser Ch 13
Bradt Ch 8

Spectrum for power-law electron distribution:

$$I(\nu) = A(KB^{1+\alpha})\nu^{-\alpha}$$

A = constant, K = total energy of electrons,
B = magnetic field, α = spectral index

Examples: pulsar synchrotron nebulae, jets, most extragalactic radio sources

Radiation is polarized (up to 70%)

Rather complex derivation Ginzburg, V. L., Syrovatskii, S. I., ARAA, 1965

Synchrotron Radiation (Melia Ch 5.4 RB sec 3.8)

- For a single electron the characteristic frequency $\omega_{sync}=3/2\gamma^2 B/m_e c$
- $dE/dt = P \sim \gamma^2 B/m^2{}_*$

$\nu_c=6.3\times10^{12}\text{Hz}\ (B(E/m_ec^2)/10^3))$

To get x-ray photons $\nu\sim10^{18}$ Hz need very high energies or very strong magnetic field

$t_{cool} \sim m_ec^2/4/3u_Bc\sigma_T\gamma \sim 16\text{yr}B^{-2}\gamma^{-1}$

The most energetic particles have the shortest lifetimes

Field strengths vary enormously from 10^{-6} G in radio galaxies to 10^{13}G in pulsars

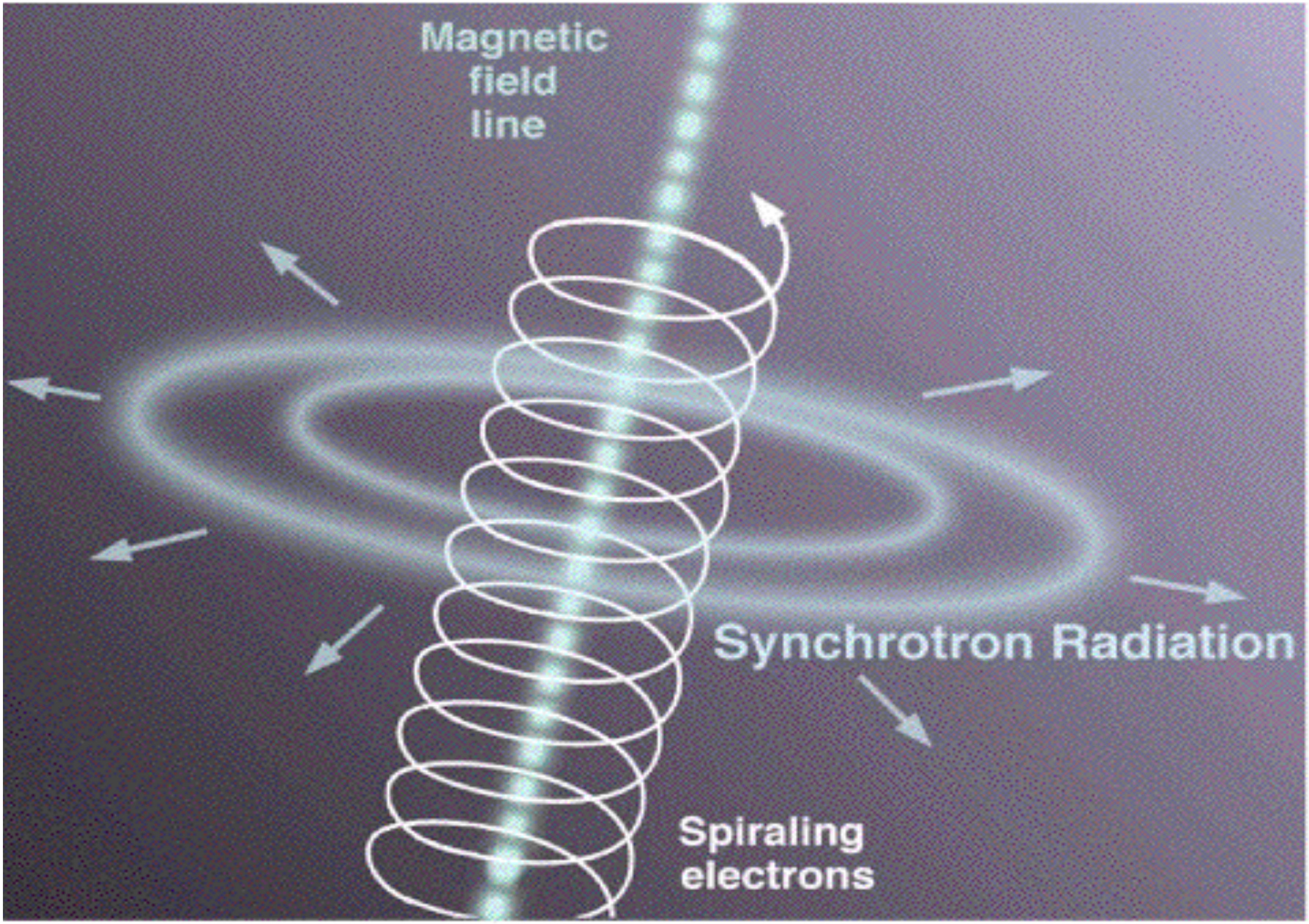
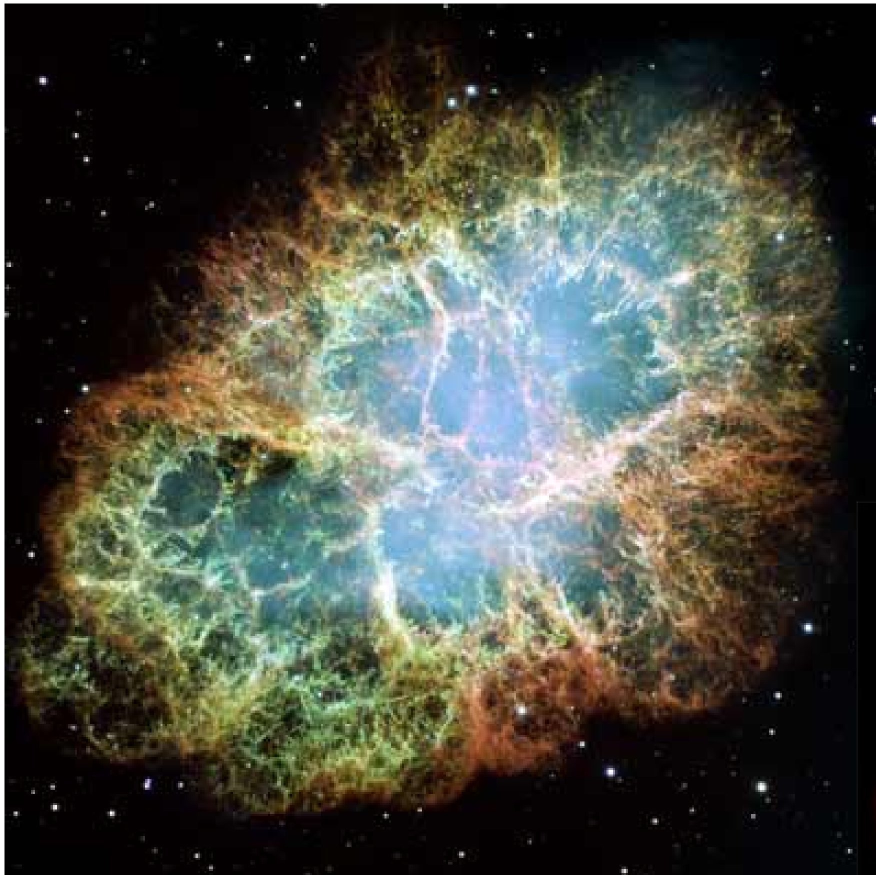


Fig. 1.— Artist's conception of synchrotron radiation. Cool figure from http://www.gemini.edu/gallery/science/m87/Synchrotron_Radiation_med.jpg

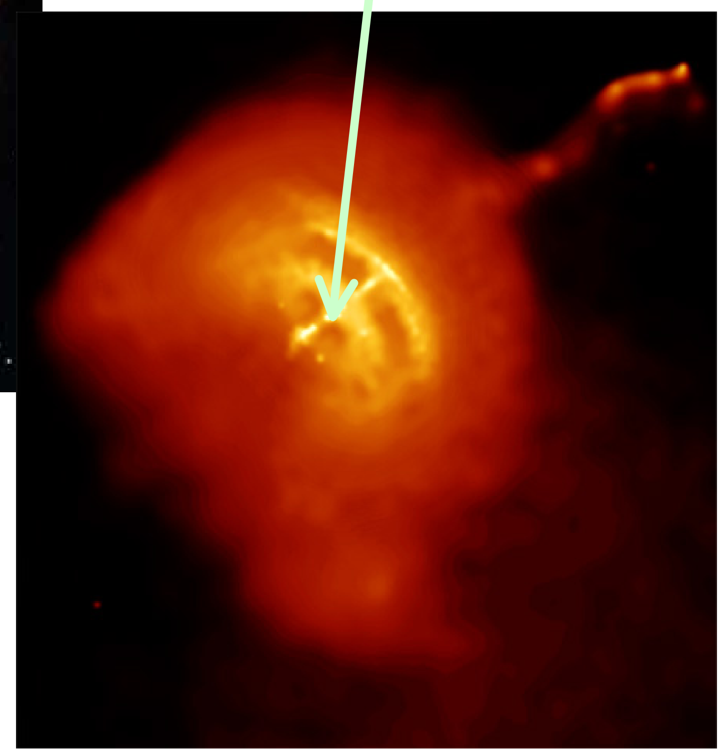
Synchrotron radiation-lit nebulae

Crab Nebula- optical IR and X-ray image

Supernova in 1054 AD



Pulsar-rotating, non-accreting Neutron star

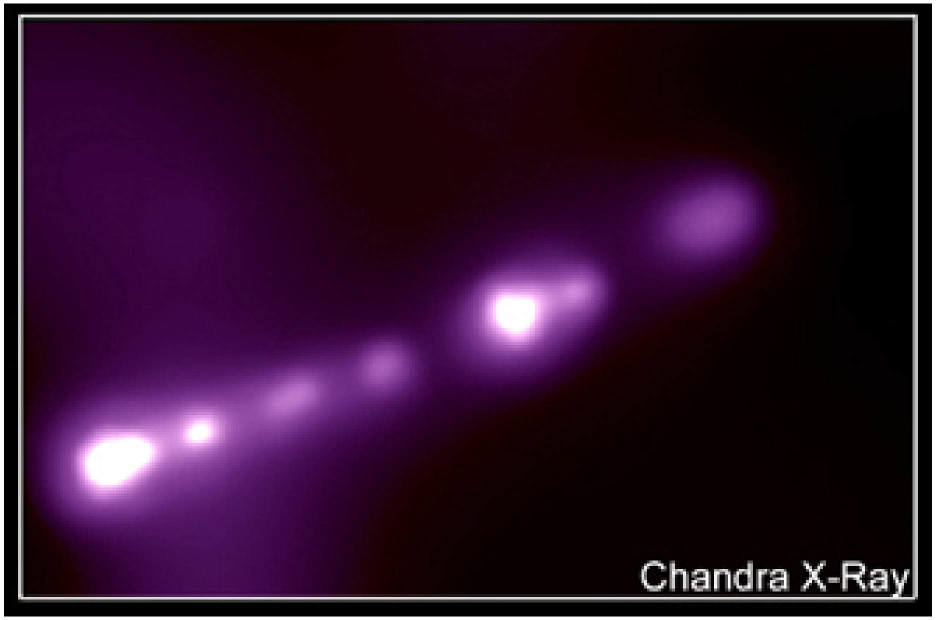


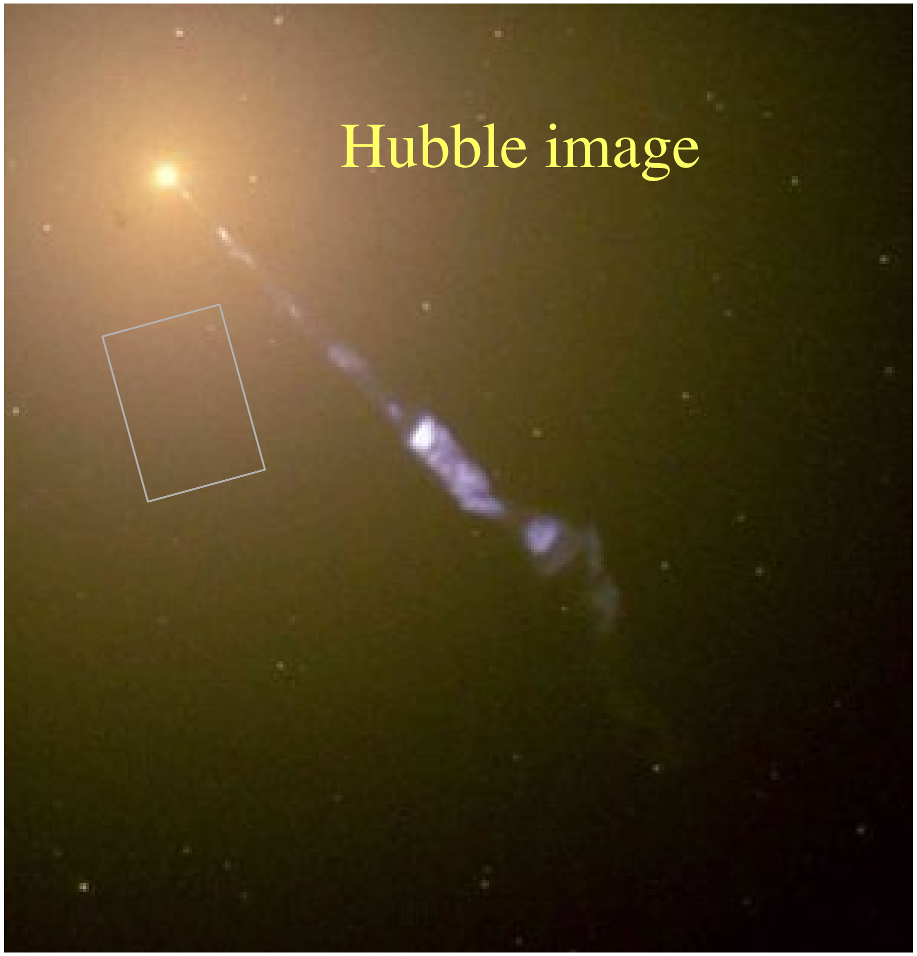
X-ray image of Vela pulsar

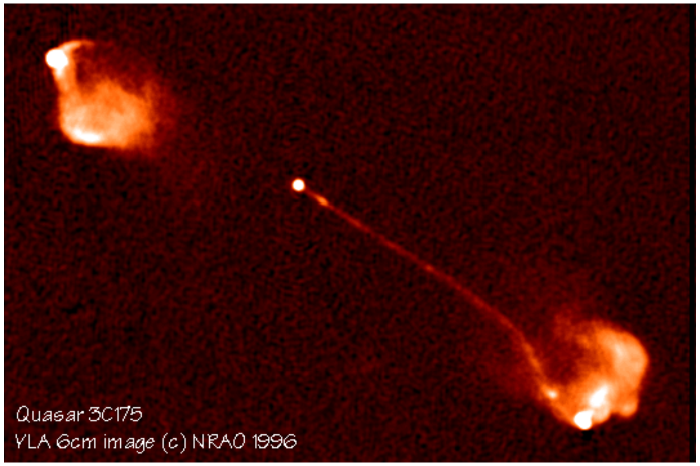
Synchrotron Radiation Examples

Image of M87 Synchrotron X-ray Radiation in jet

~1.5kpc=$5x10^{21}$cm long



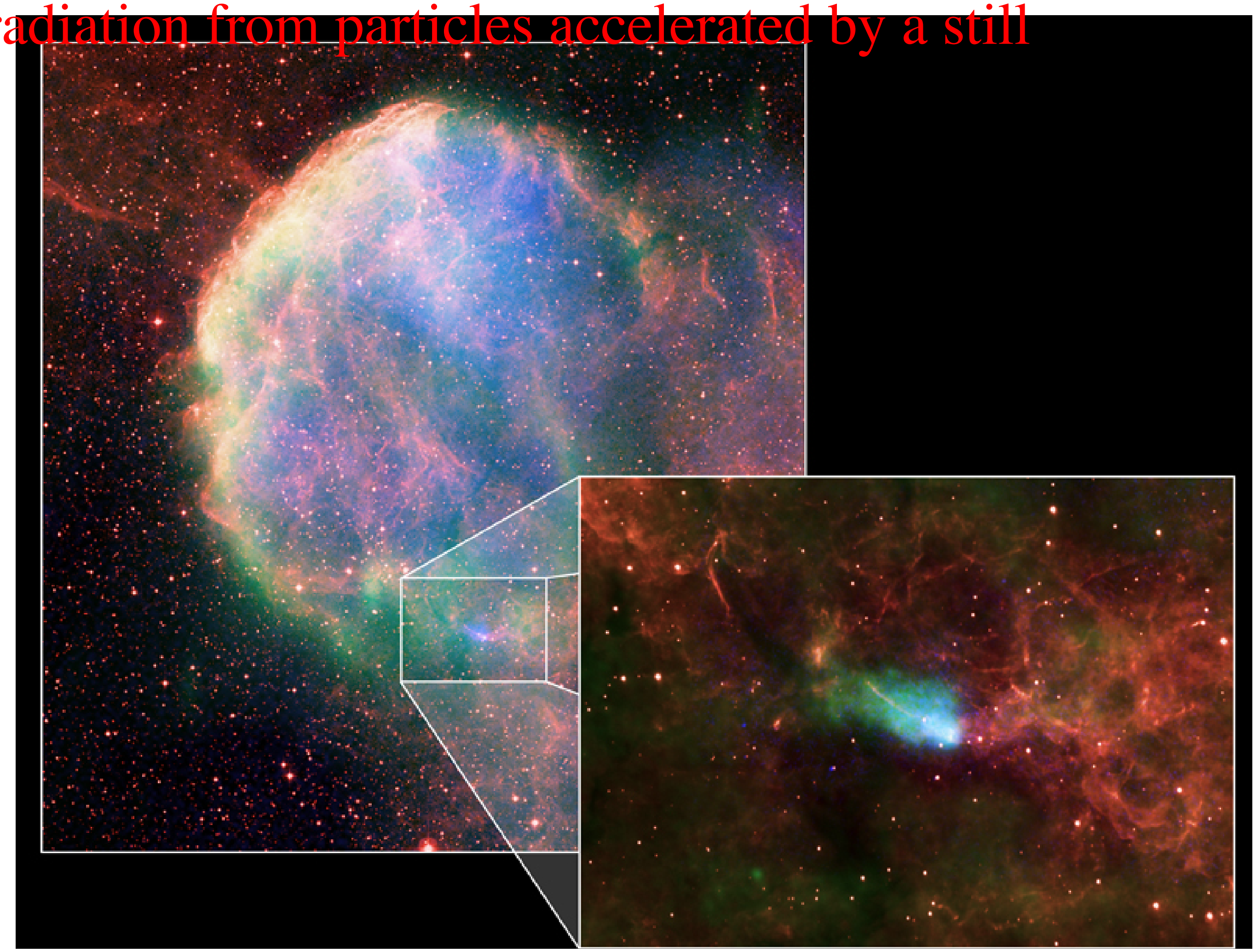




Radio image of a quasar

Combining Bremmstrahlung and Synchrotron Radiation

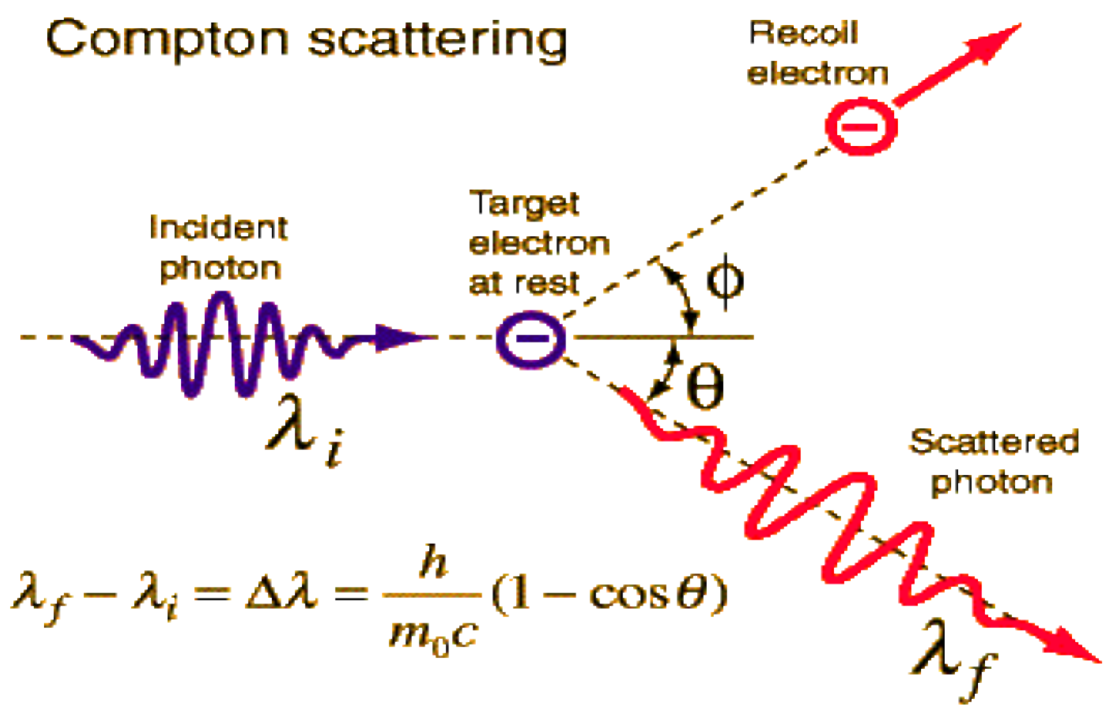
- In some supernova remnants one sees both processes at work
  - Bremmstrahlung from electrons that are shock heated by the SN blast wave
  - Synchrotron radiation from particles accelerated by a still active pulsar



Compton Effect(s) RB Ch 3.8, Kaiser Ch 14, Bradt (Astrophysical Processes Ch 9

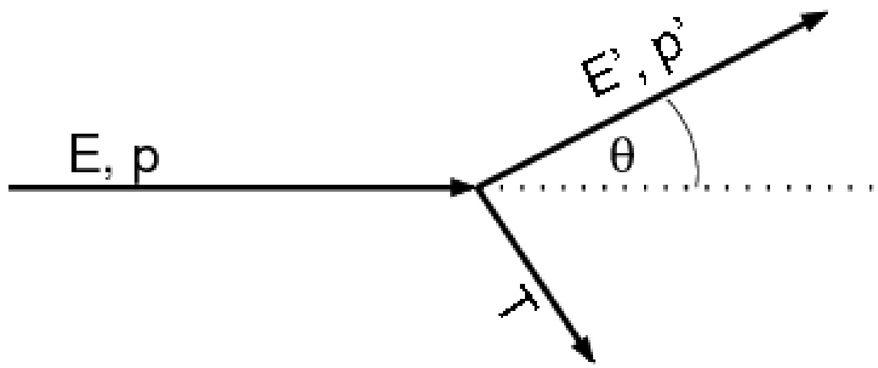
Compton Wavelength=h/mc=0.00243 nm for an electron

Whether the photon gives energy to the electron or vice versa



http://hyperphysics.phy-astr.gsu.edu/hbase/quantum/compton.html

Compton Scattering



Thomson scattering: initial and final wavelength are identical.

But: in reality: light consists of photons

$\Longrightarrow$ Scattering: photon changes direction

$\Longrightarrow$ Momentum change

$\Longrightarrow$ Energy change!

This is a quantum picture

$\Longrightarrow$ Compton scattering.

Dynamics of scattering gives energy/wavelength change:

$$E' = \frac{E}{1 + \frac{E}{m_e c^2}(1 - \cos\theta)} \sim E\left(1 - \frac{E}{m_e c^2}(1 - \cos\theta)\right) \tag{7.14}$$

and

$$\lambda' - \lambda = \frac{h}{m_e c}(1 - \cos\theta) \tag{7.15}$$

where $h/m_e c = 2.426 \times 10^{-10}$ cm (Compton wavelength).

Averaging over θ, for $E \ll m_e c^2$:

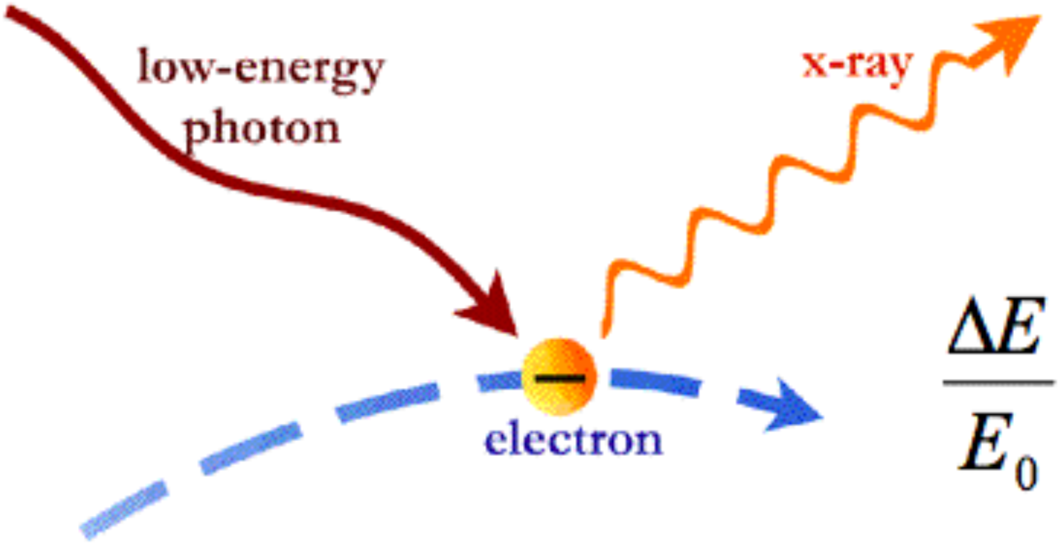
$$\frac{\Delta E}{E} \approx -\frac{E}{m_e c^2} \tag{7.16}$$

- http://pulsar.sternwarte.uni-erlangen.de/wilms/teach/radproc/radproc0177.html

INVERSE COMPTON EMISSION

Compton scattering

- Photon $E_0=h\nu$ boosted in energy by hot e$^-$ at kT to e.g. X-rays

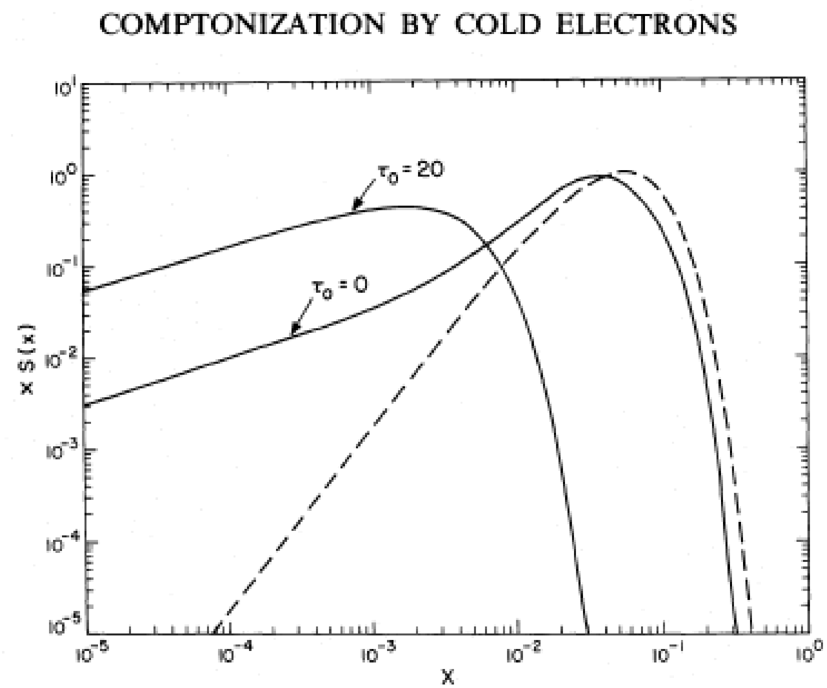


$$\frac{\Delta E}{E_0}=\frac{1}{m_e c^2}(4kT-E_0)$$

Examples in X-ray astronomy: active galactic nuclei (AGN), X-ray binaries

Comptonization

- The output spectrum depends on the distribution function of both the electrons and photons
- If the electrons are 'cooler' than the photons the spectrum is 'down scattered' if the electrons are hotter it is up scattered.
- If $E_{photon} < 4kT_e$ photons gain energy gas cools
- If $E_{photon} > 4kT_e$ electrons gain energy gas heats
- Up scattering tends to produce a power law distribution- downscattering asymptotes to a black body



INVERSE COMPTON EMISSION

- Results depend on source geometry

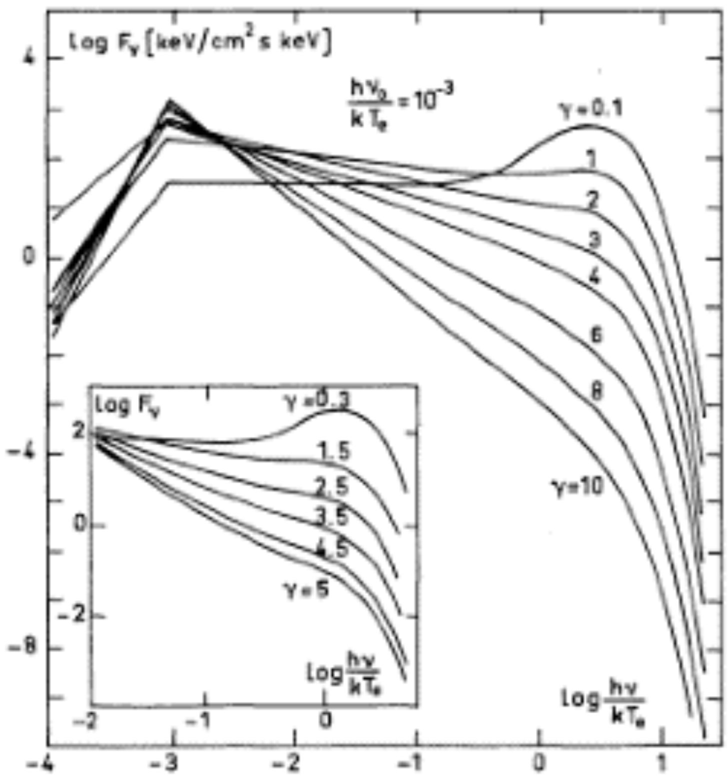


Fig. 5. The spectrum resulting from comptonization of low-frequency photons ($h\nu_0 = 10^{-3}$ kT$_e$) in a high temperature plasma clouds with different parameters γ (14)

- ***Power law***

$$F(E) = AE^{-\Gamma}e^{-E/E_c}$$

$$I(E) = BE^{-\alpha}e^{-E/E_c}$$

A,*B* normalizations

F,Γ ***photon*** flux photon index

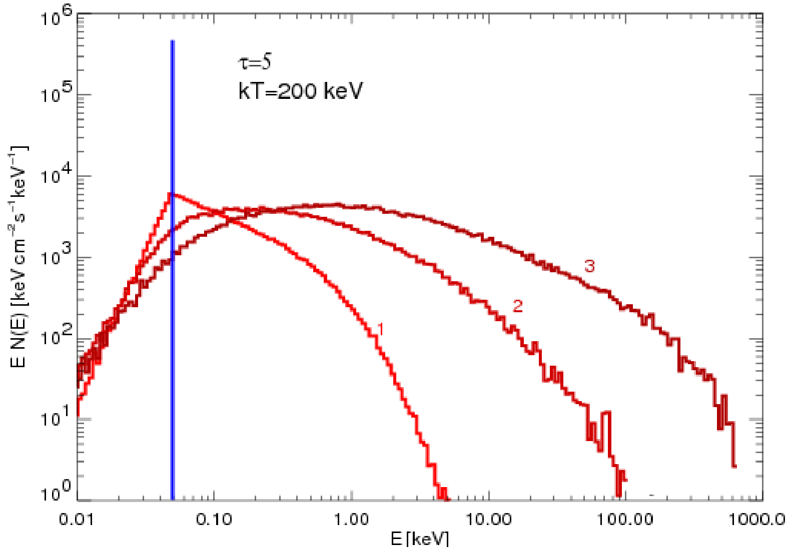
I,α ***energy*** flux, index (α=Γ-1)

E_c=*kT*=cutoff energy

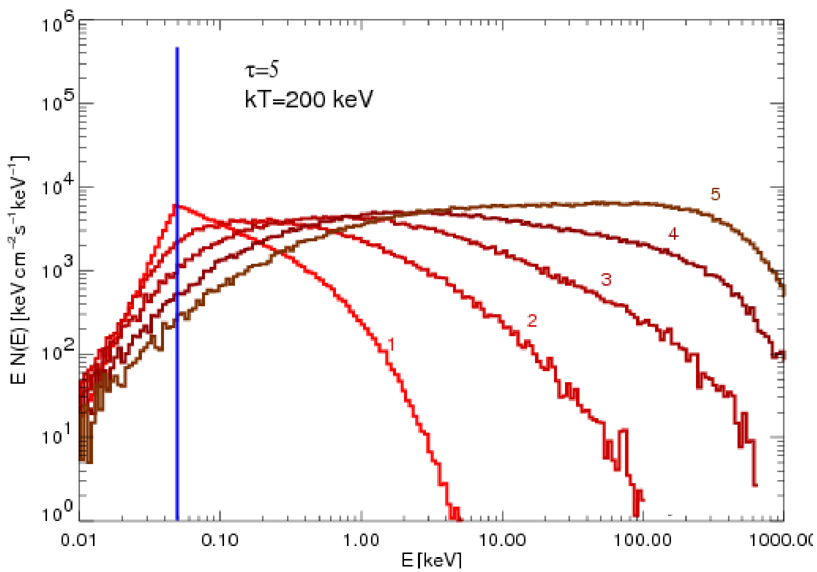
Sunyaev & Titarchuk 1980

Compton scattering

- Each scattering tends to produce a broad distribution of photons and the sum tends to a power law shape
- X-ray spectra of galactic and extragalactic black holes can be well explained by a comtptonized spectrum with kT_e~150 kev, y~1 $(y=4kT_e/m_ec^2(\max(\tau,\tau^2))$



- http://pulsar.sternwarte.uni-erlangen.de/wilms/teach/radproc/radproc0201.html



Relative Power in Compton and Synchrotron Radiation

$P_{IC} = 4/3 \sigma_T c^2 U_{rad} \beta^2 \gamma^2$
net inverse-Compton power gained by the radiation field and lost by the electron.

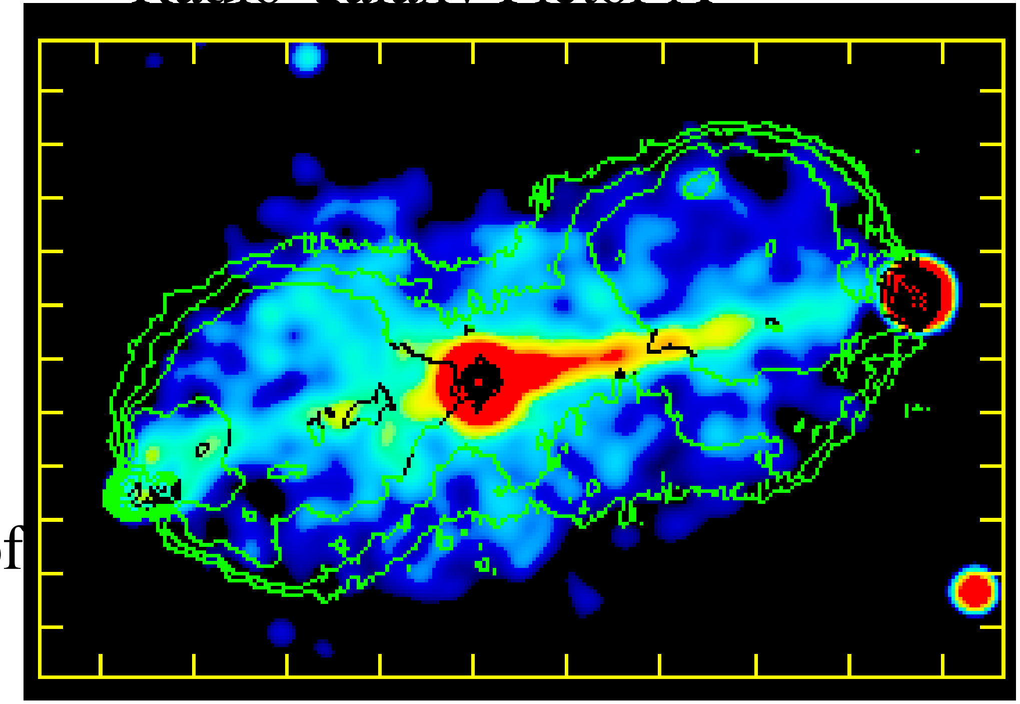
Synchrotron power
$P_{synch} = 4/3 \sigma_T c^2 U_B \beta^2 \gamma^2$

Where $U_B = B^2/8\pi$ is the energy density of the magnetic field
And U_{rad} is the energy density of the photon field

$\beta = v/c$; $\gamma = (1-\beta^2)^{-1/2}$

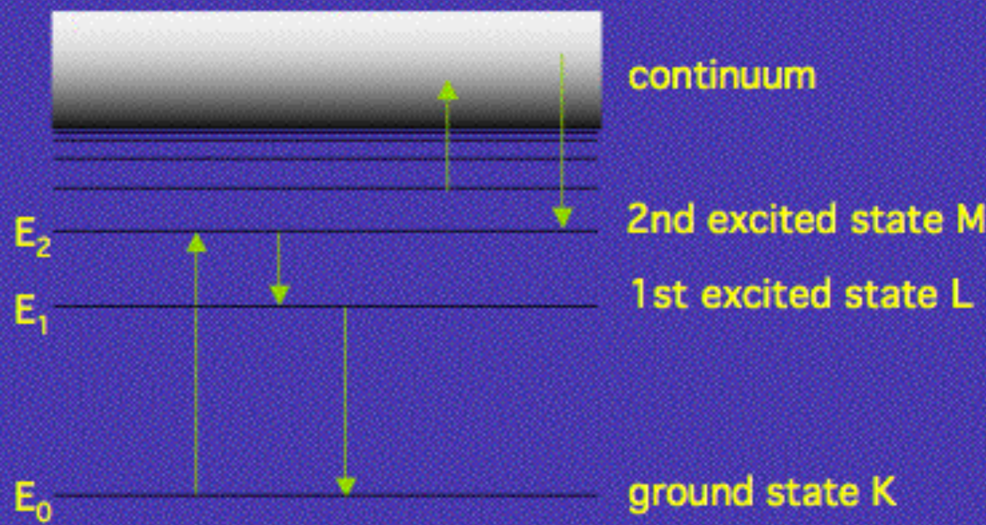
Ratio of Synchrotron to Compton is U_B/U_{rad}

'Radio' galaxy Pictor A



Radio image (synchrotron) green contours
IC image (x-rays, color) Hardcastle and Birkinshaw 2004

Electronic Processes



$E_0<E_1<E_2$ (it takes energy to move the electron away from the positively charged nucleus)

Atomic Energy Level Diagram (Schematic)

Excitation: an electron absorbs radiation of energy $E=E_N-E_M$ and jumps from energy level M to level N (M<N)

De-excitation: an electron jumps from level N to level M (M<N) and emits a quantum of radiation (a photon) of energy $E=E_N-E_M$

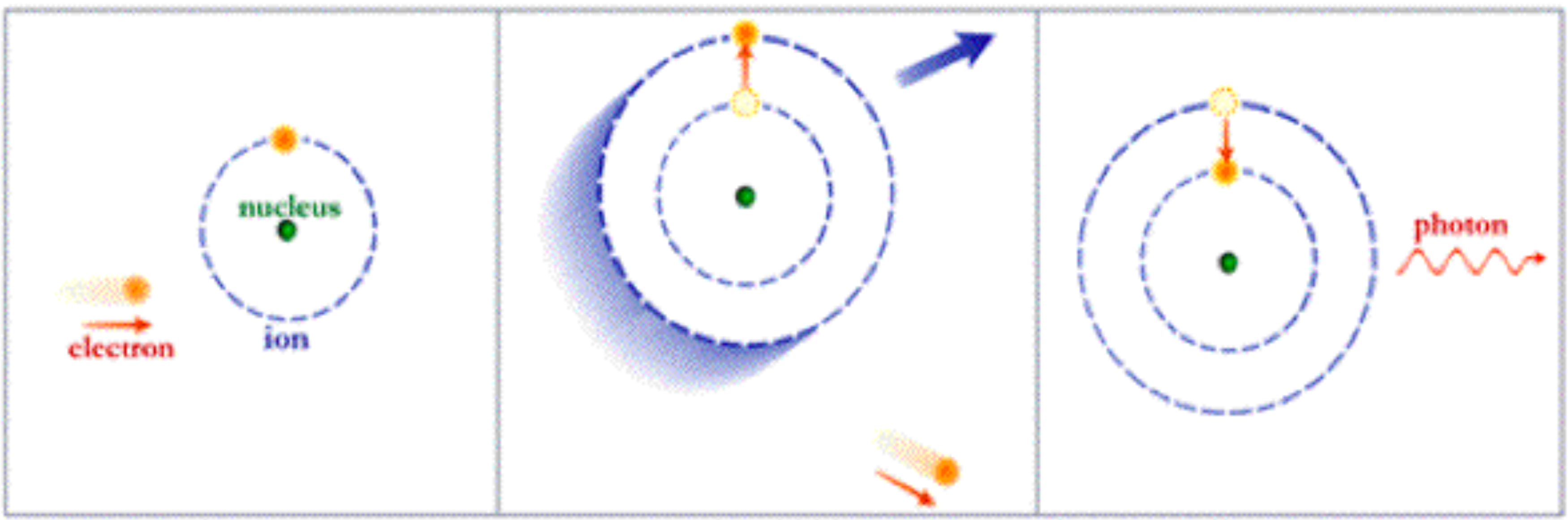
Ionization: an electron jumps from level N to the continuum (E_∞) after absorbing a photon of energy $E > E_N$. The energy required to ionize an atom from its ground state is called the **Ionization Potential**.

Recombination: A free electron is captured by an atom into some energy level N.

LINE EMISSION

- Excitation of atoms by:
  - Thermal collisions
  - Radiative excitation
- Then radiative de-excitation

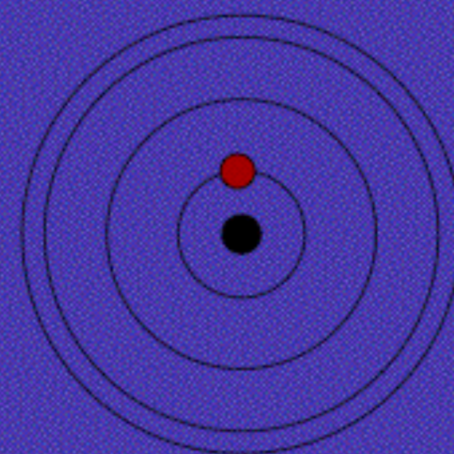
Duric Ch 12 - also see presentations by Behar, Paerels, Smith in web page



Specific Emission

Electron in bound orbitals around an atomic nucleus of nuclear charge Z can produce radiation at specific frequencies or energies, since electrons can only orbit the atomic nucleus in a well-defined set of allowed orbits.

Each orbit is associated with an electron energy, so are sometimes called energy levels. An electron has to gain energy to move from an inner to an outer energy level. An electron loses energy when moving from an outer to an inner energy level.



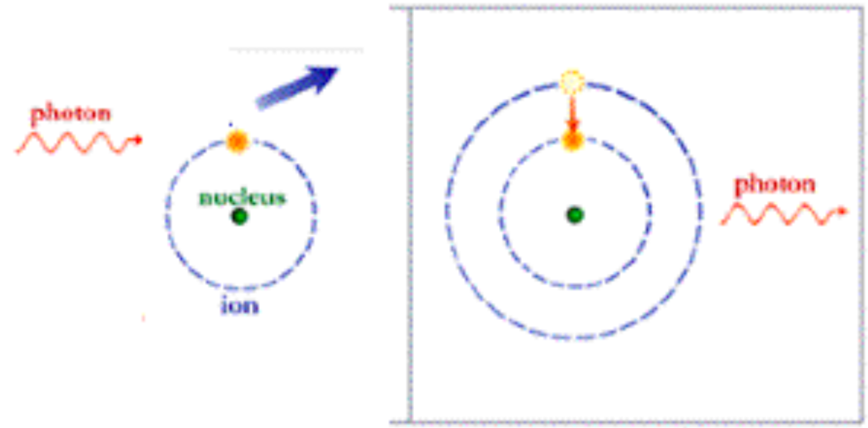
Each element has its own unique set of energy levels:

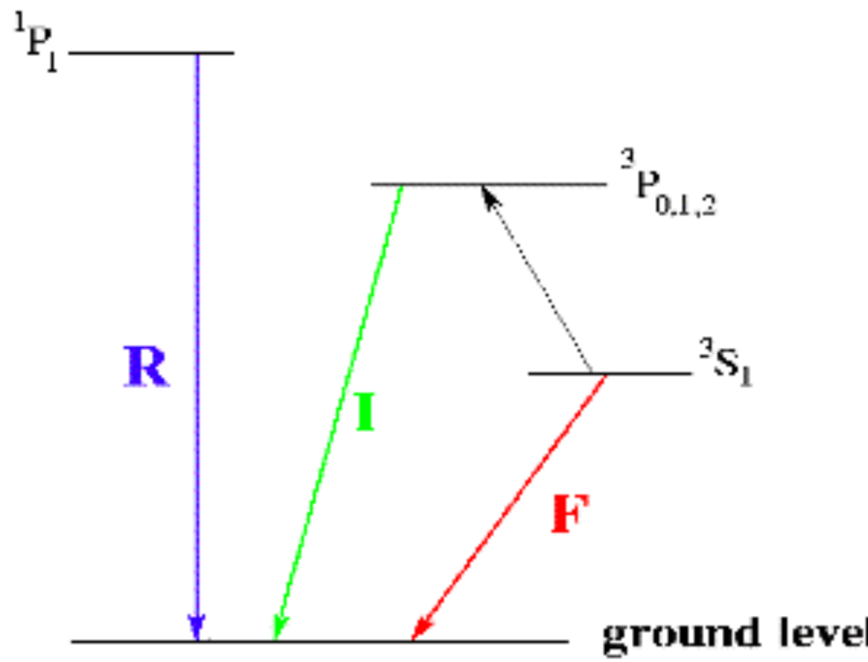
$$E_N = -\frac{13.58Z^2}{N^2}\text{electron volts (eV)}$$

TYPES OF LINE EMISSION

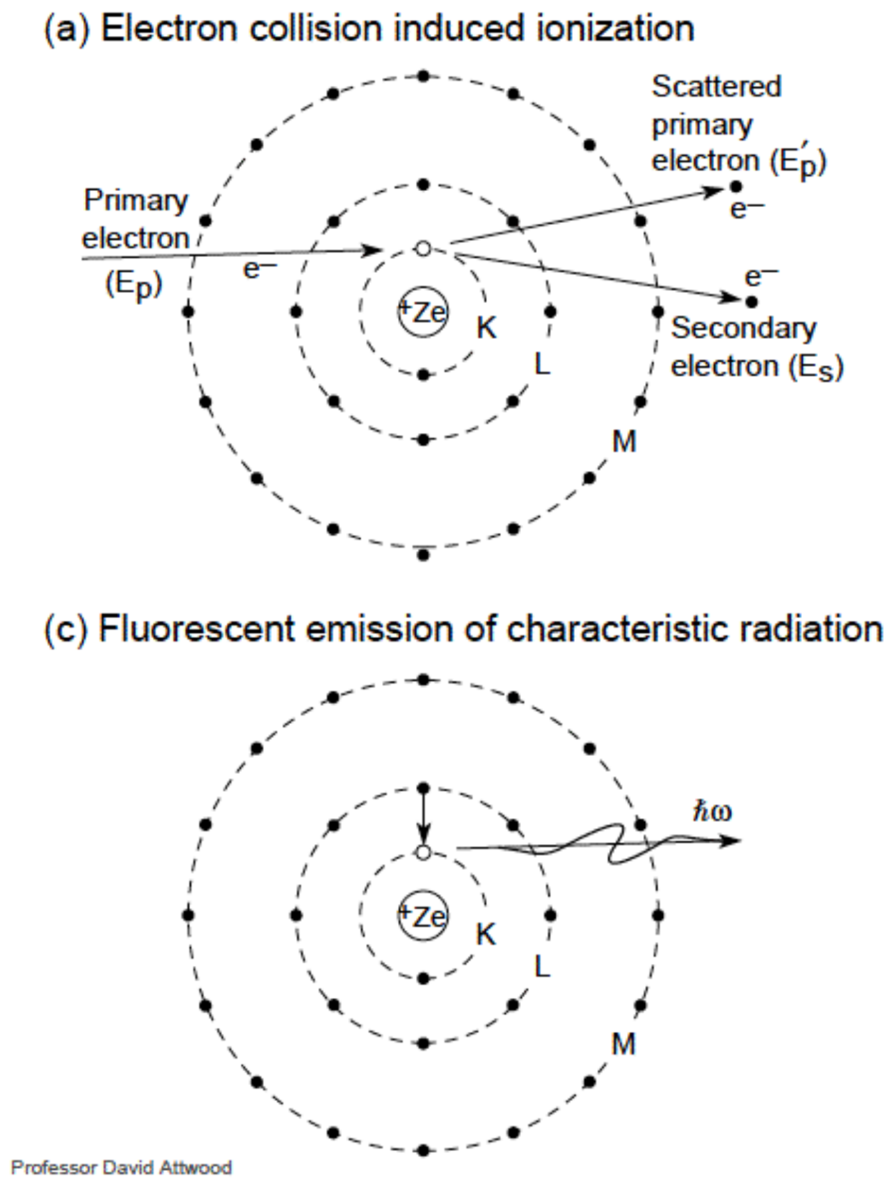
- Fluorescence:
  - Needs L-shell electrons
  - Photoionization, then either:
  - 2p->1s radiative transition
  - *or* Auger ionization
  - **Fluorescence yield** measures ratio

- Recombination (ionized)
  - He and H-like are most important
  - Triplet: forbidden, resonance, intercombination



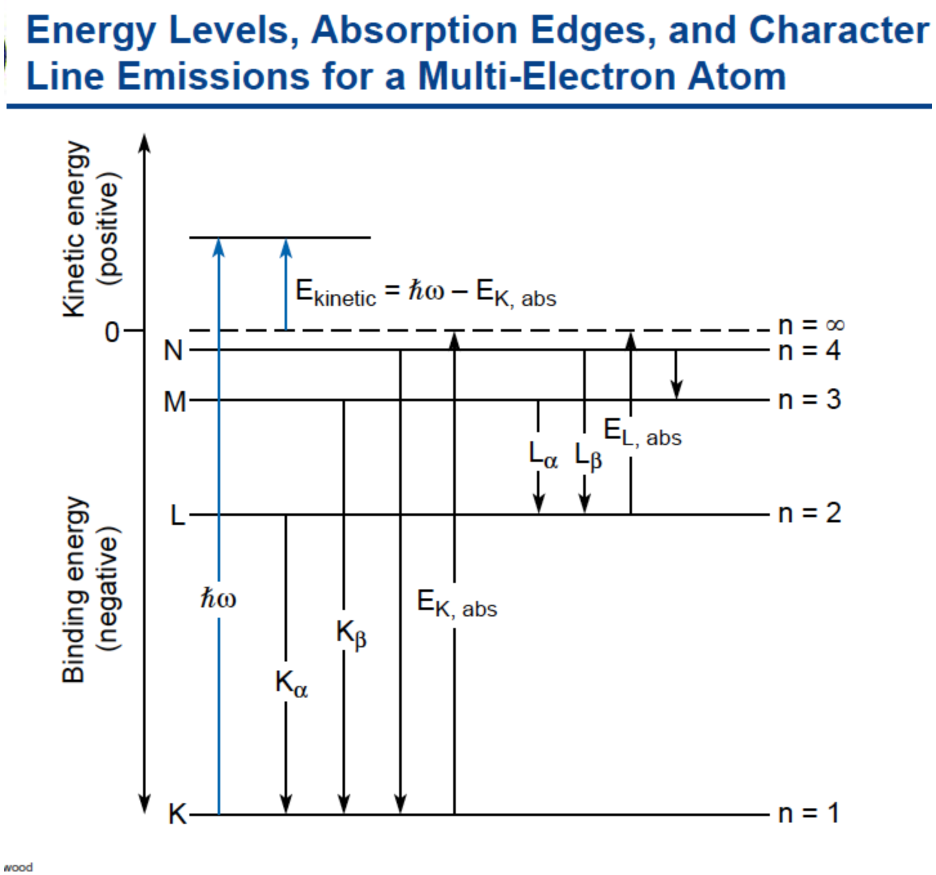


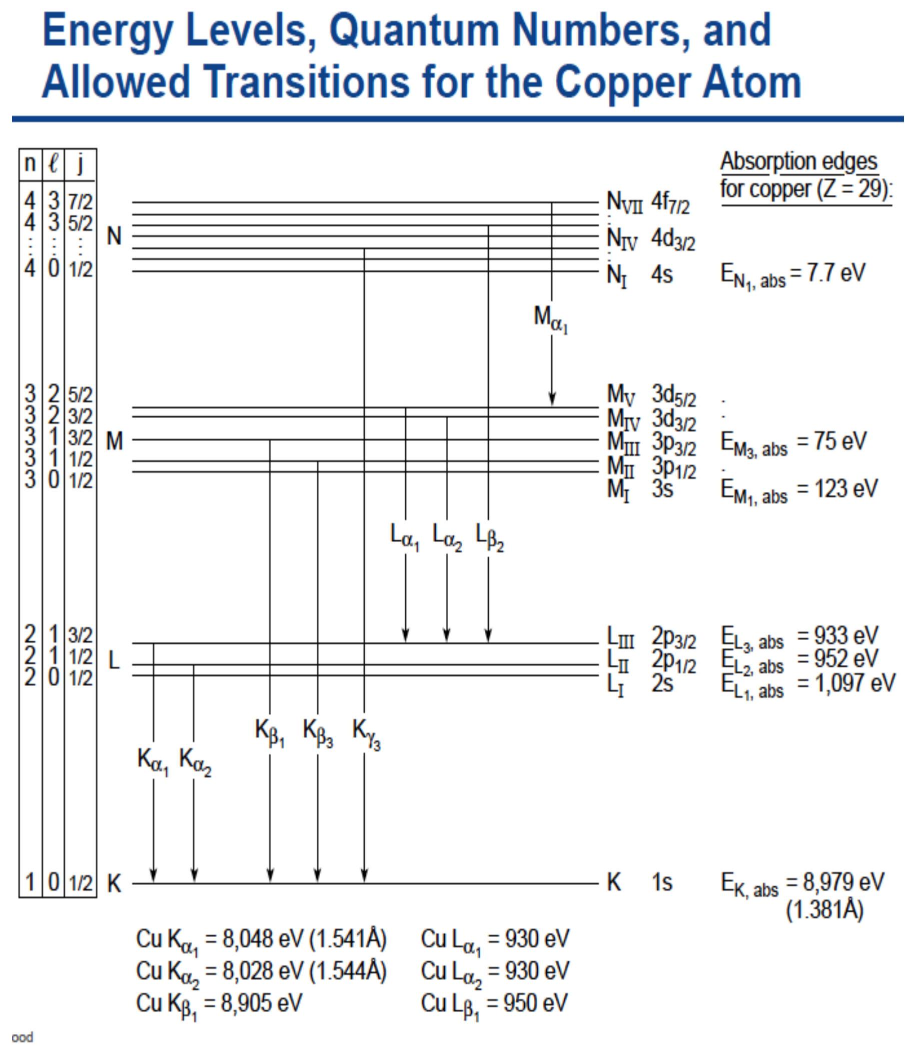
From R. Smith



3 ways to produce a Photon via 'atomic' process (an incomplete set)

- **Generic Atom**



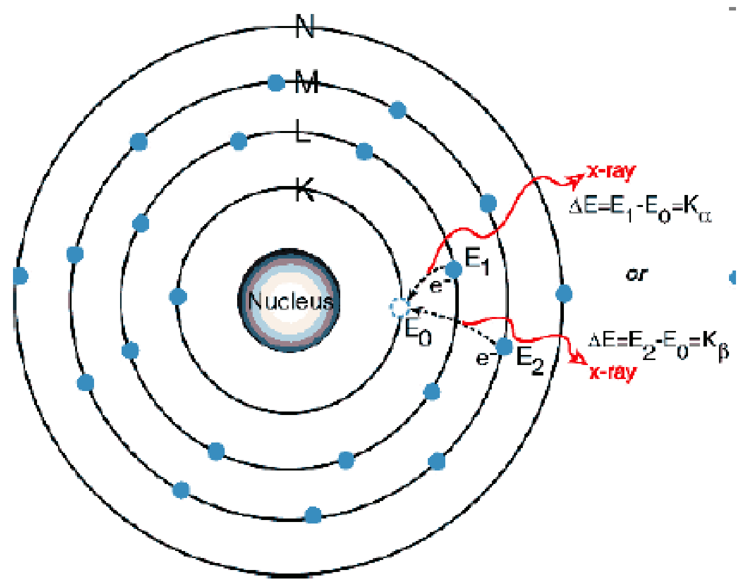


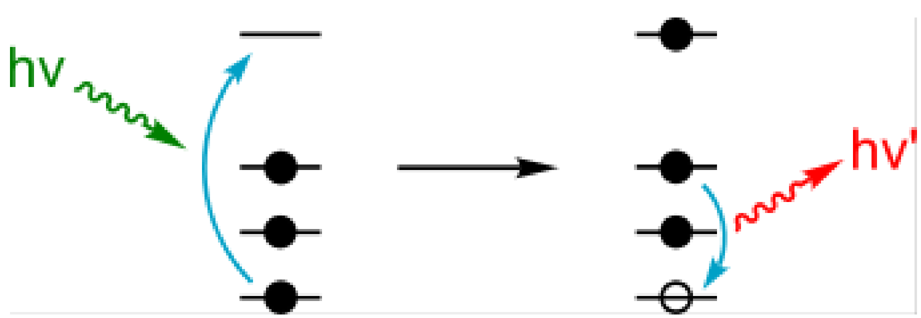
- **Copper Atom**

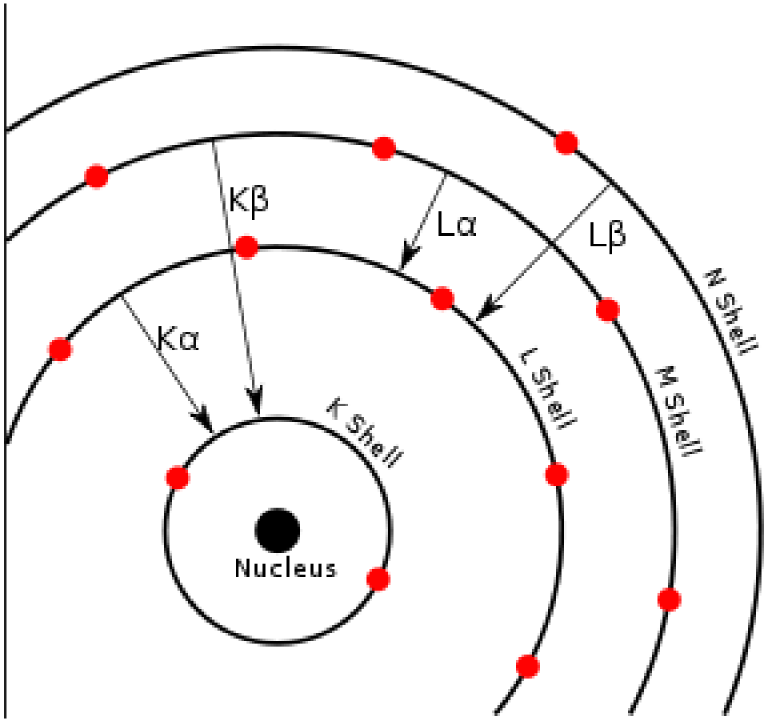
Fluorescence

- Following removal of an inner electron by an energetic photon by radiation source, an electron from an outer shell drops into its place. -
- This process can produce x-ray line radiation even from totally unionized (cold) atoms
- L→K transition Kα,
- M→K Kβ, M→Lα etc

- X-ray fluorescence

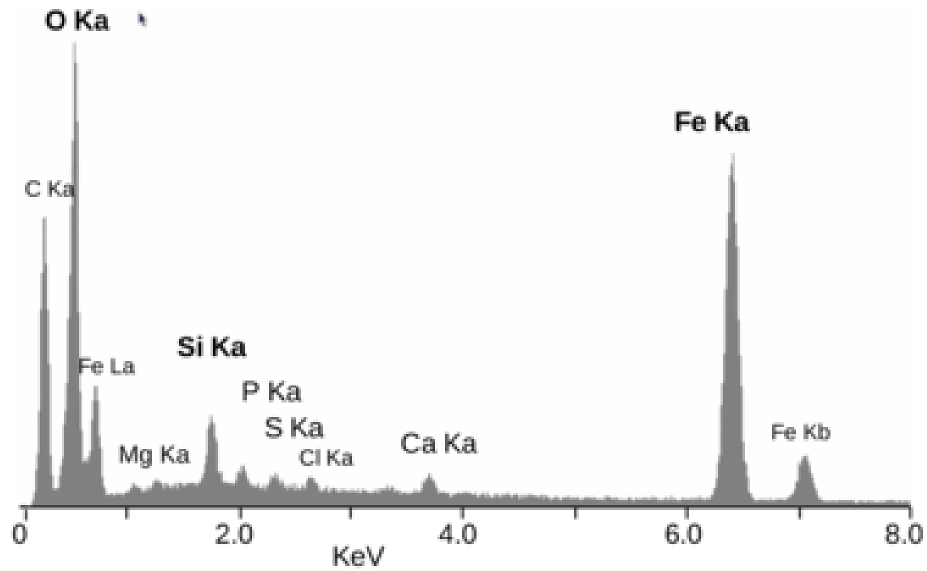


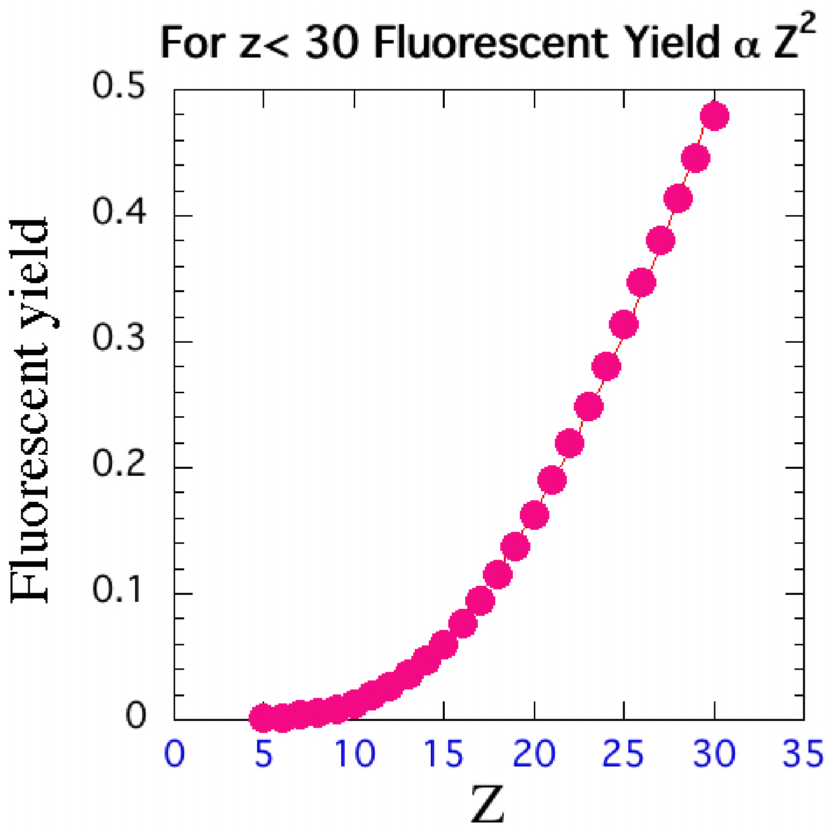




Fluorescence Spectroscopy

- Strength of lines is α to fluorescence yield x abundance
- fluorescence yield α to Z^2





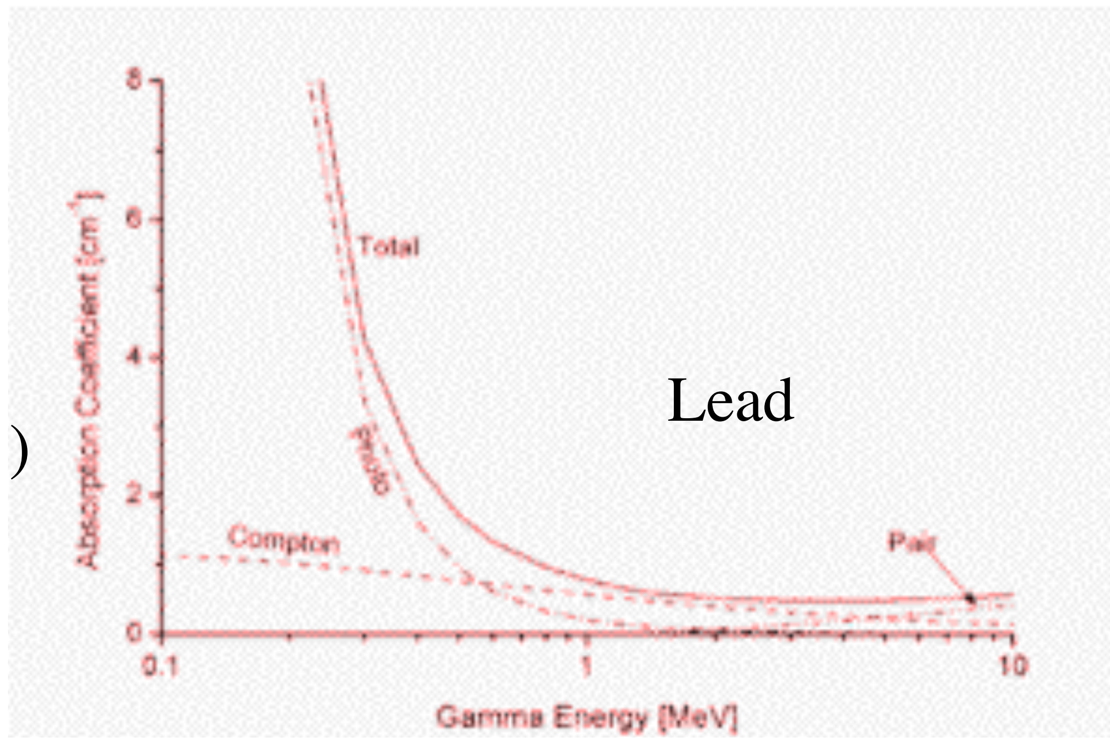
For most x-ray spectra Fe is the dominant fluorescent line

Absorption of X and γ-ray Photons

- Absorption processes
  - Photoelectric absorption
  - Ionized gas: warm absorbers
  - Absorption lines

absorption of γ-rays via pair creation, photoelectric effect, Compton scattering (photons reduced in energy, not absorbed).

X-ray and γ-rays are very penetrating radiation -but a 1 keV x-ray is totally absorbed by ~0.01gm of material (~10^{22} atms/cm^2)



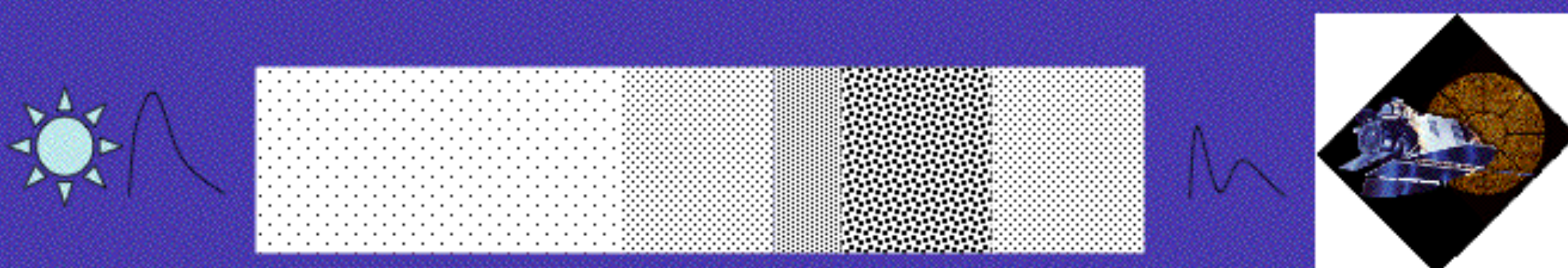
Absorption

As radiation passes through a medium, in general the medium will absorb some of the radiation, and emit some radiation. Thus the radiation received at a detector will be different from that emitted by the source. For a source of intensity I_0 whose light passes through an absorbing medium, the observed intensity I is

$$I = I_0 \exp^{-\tau}$$

where τ is the optical depth of the medium. τ is sometimes expressed in terms of an absorption cross-section σ and a column density N (the number of particles in a cylindrical column of unit area in the medium)

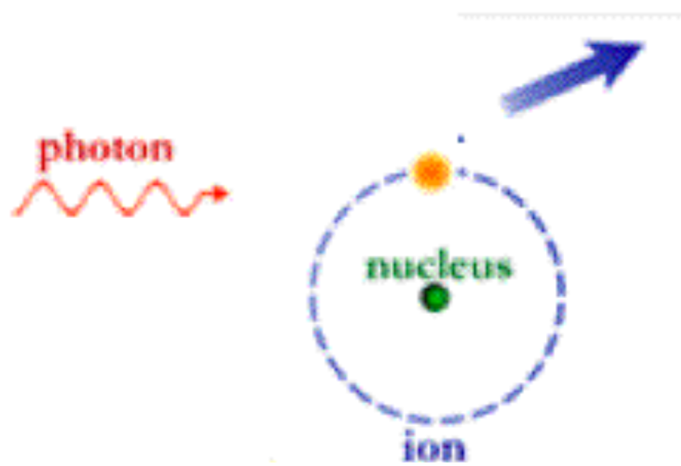
$$\tau = N\sigma$$



PHOTOELECTRIC ABSORPTION

- Bound-free ionization of e^- by photon
- Threshold energy $E_{th}=h\nu$ depending on ionziation potential of atom (i.e. on Z)
- Abundant elements (C,N,O) are light: absorption dominant at soft (<1 keV) X-rays

Continuum ⇒



⇐ Observer

PHOTOELECTRIC ABSORPTION

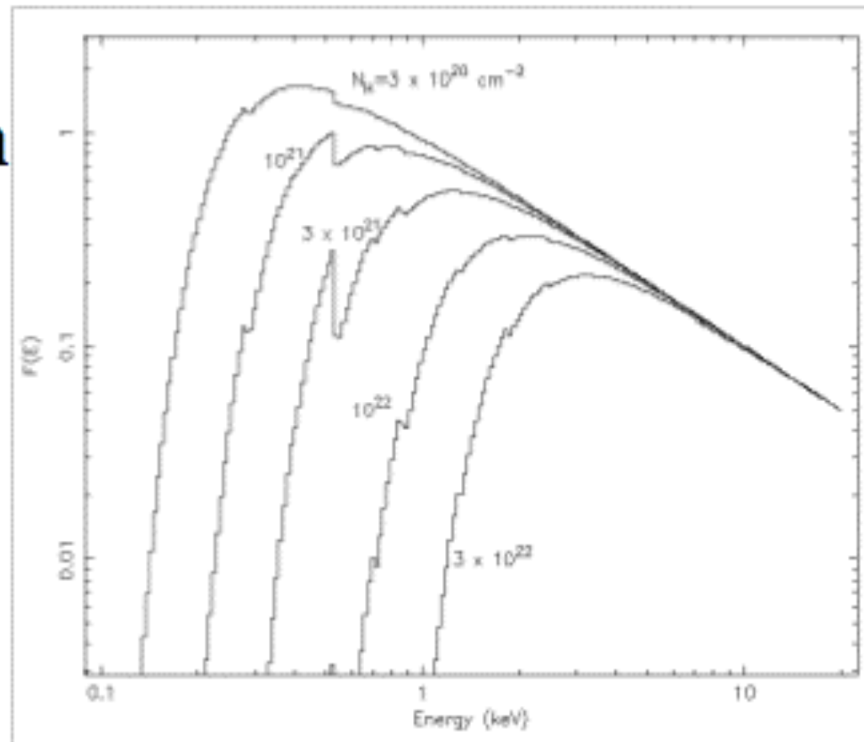
$N_H =$ Equivalent hydrogen column density (cm^{-2})

$\sigma(E) =$ cross section (cm^2)

$\tau = \sigma(E) N_H =$ optical depth

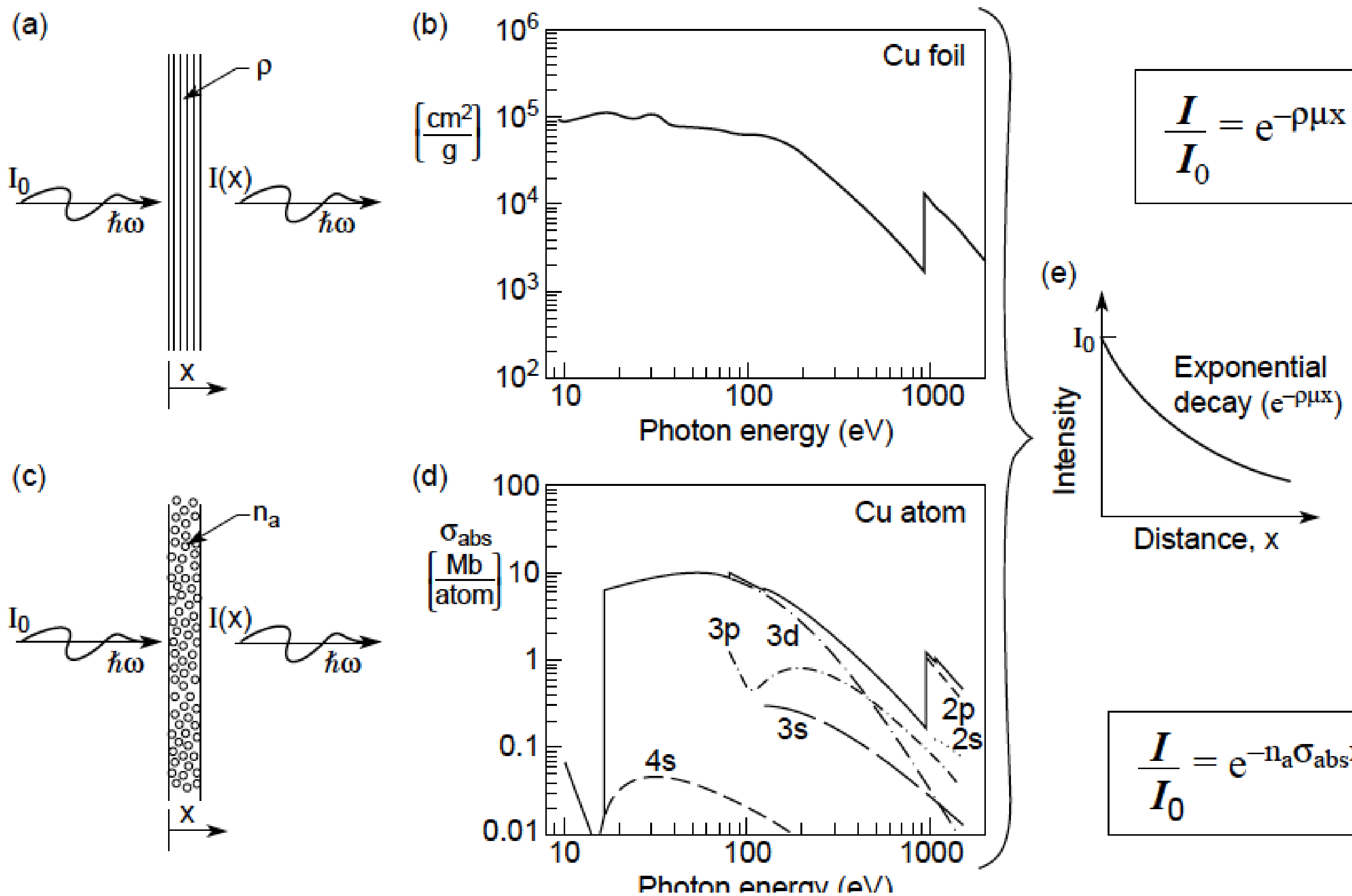
$$F(E) = AE^{-\Gamma} e^{-\sigma(E) N_H}$$

$$\sigma(E) \approx E^{-3}$$



Profile dominated by bound-free edges of abundant elements

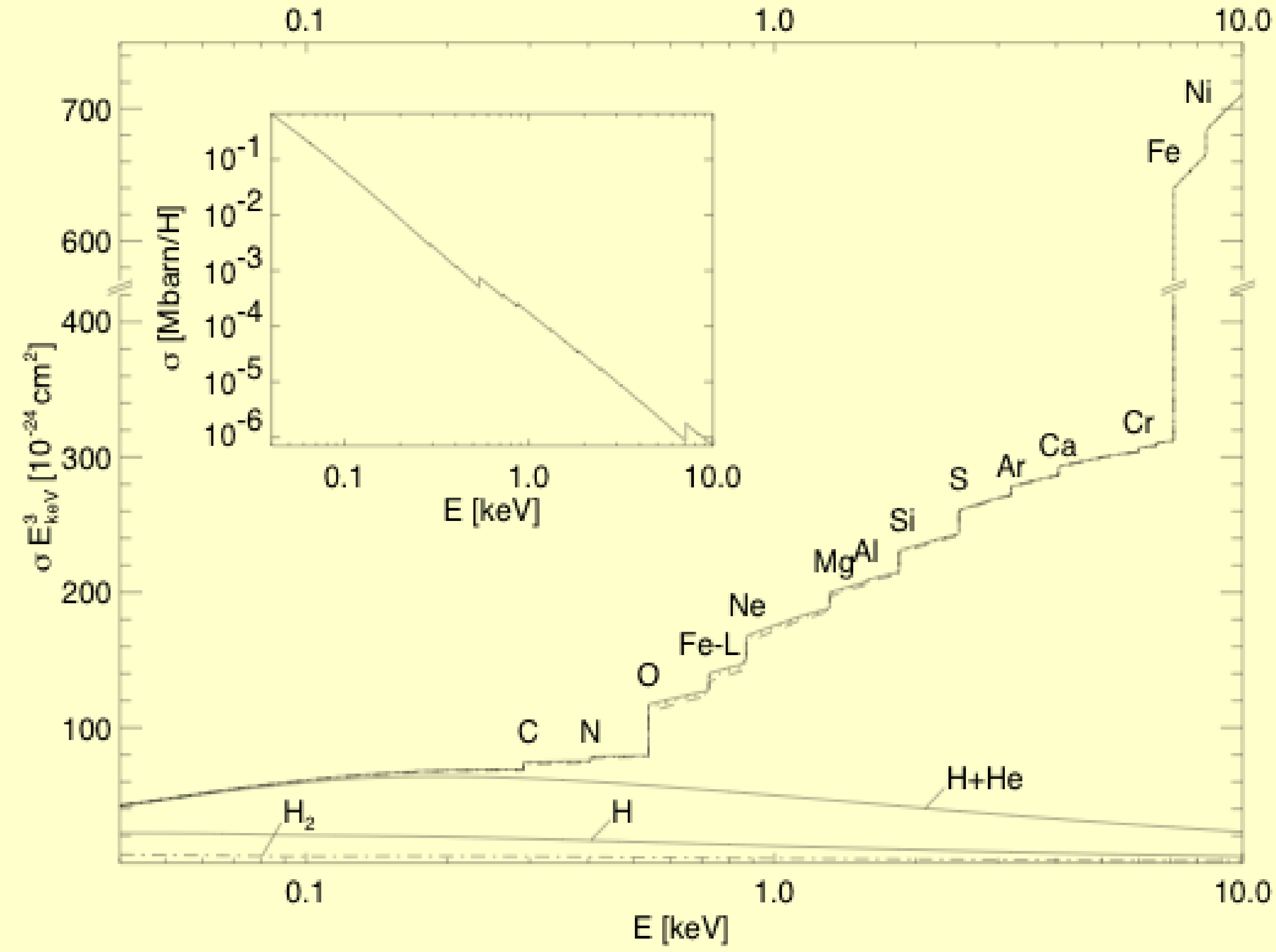
Photoabsorption by Thin Foils and Isolated Atoms



$$\frac{I}{I_0} = e^{-\rho\mu x}$$

$$\frac{I}{I_0} = e^{-n_a \sigma_{abs} x}$$

Photoelectric Absorption of ISM



Absorption cross section for material of cosmic abundances (Wilms, Allen & McCray, 2000),

IONIZED ABSORBERS

- In practice gas may be hot (collisionally ionized) or, more importantly, photoionized
- Ionization parameter (flux/density):

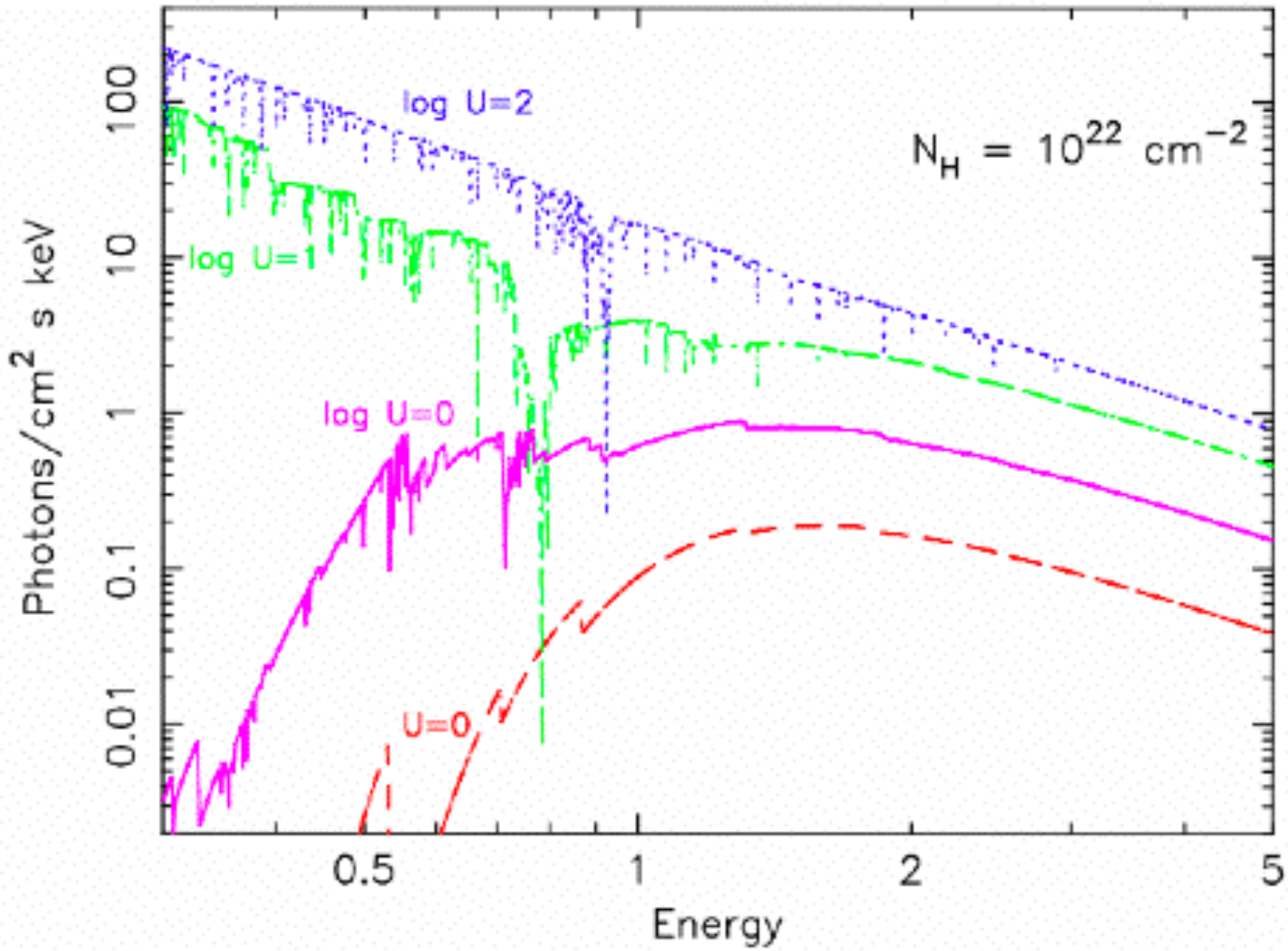
$$\xi \equiv \frac{L_X}{n_e R^2} \quad \text{Tarter, Tucker \& Salpeter (1969)}$$

$$U_X \equiv \frac{N_X}{4\pi R^2 n_e c} \quad \text{Davidson (1974)}$$

$$L_X \equiv \int_{E_{\min}}^{\infty} L(E)dE \qquad N_X \equiv \int_{E_{\min}}^{\infty} \frac{L(E)}{E}dE$$

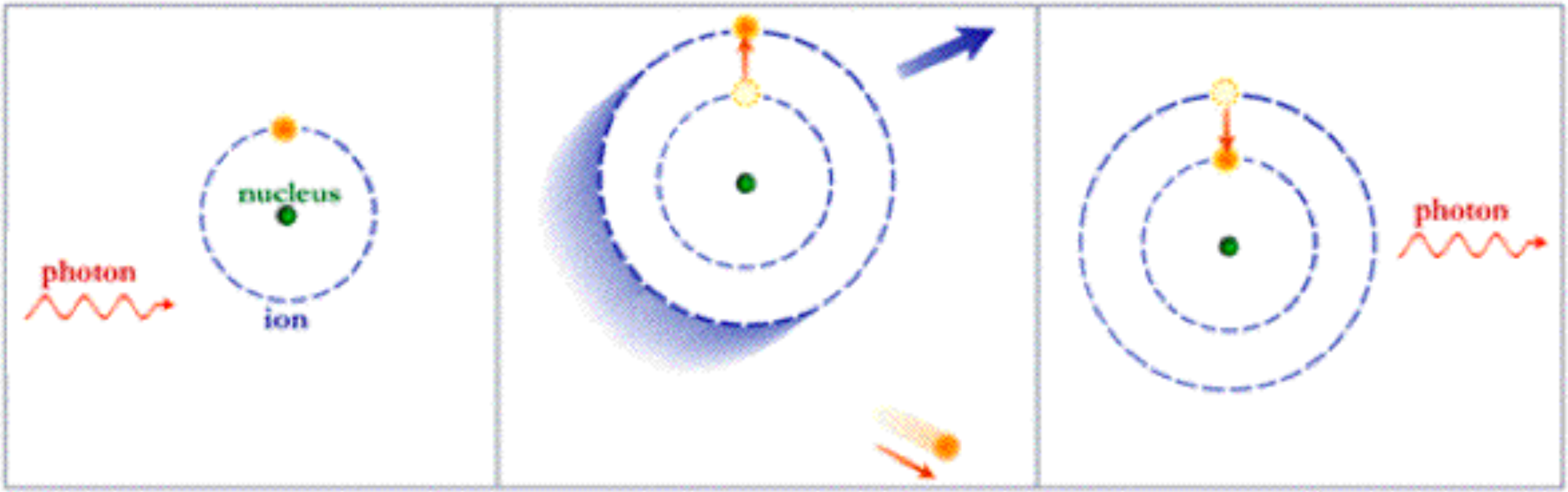
$E_{\min} = 13.6\text{eV}$, 0.1 keV, 0.7 keV (Davidson, Netzer, George)

IONIZED ABSORPTION



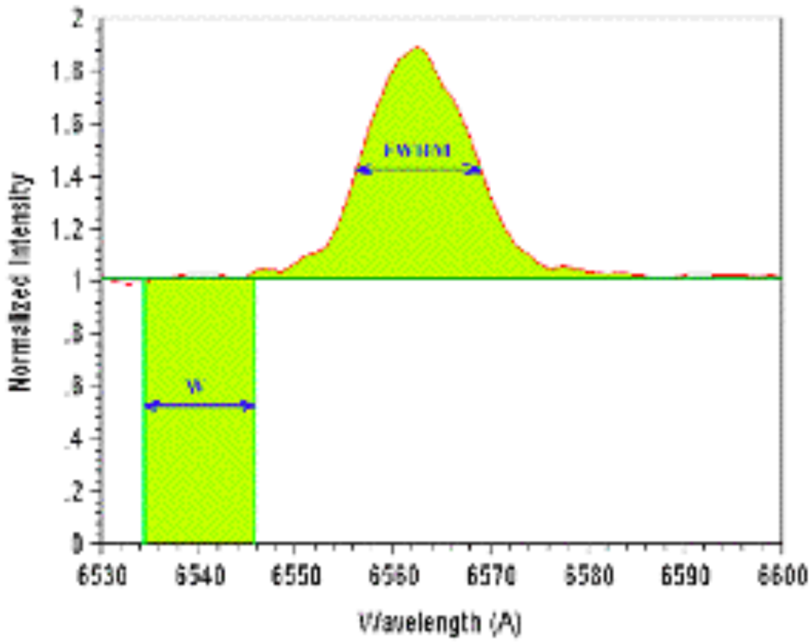
Continuum absorption profile still can be dominated by bound-free edges of abundant elements but….

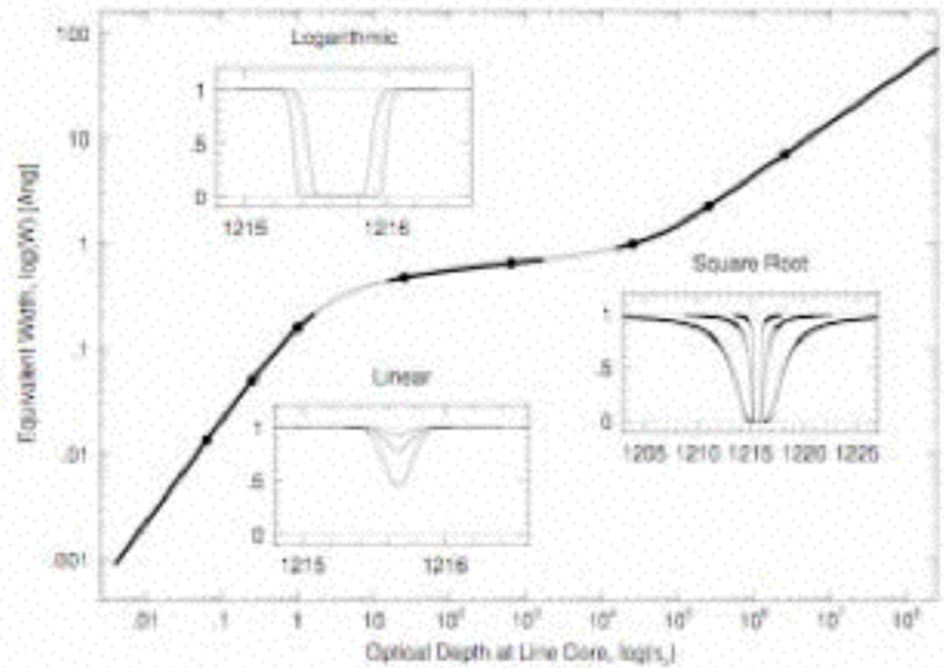
ABSORPTION LINES



- Absorption by a specific transition in atom
- Cross-sections larger than photoelectric
- But only over a small wavelength range
- Strength depends on Doppler parameter b
- Can measure N_H, U, velocity etc.

ABSORPTION LINES





Equivalent width:

$$EW = \frac{\int_{-\infty}^{\infty} F_l(E)\,dE}{F_c(E_l)}$$

$F_l =$ line flux, $F_c =$ continuum flux,

$E_l =$ line energy

Curve of growth:

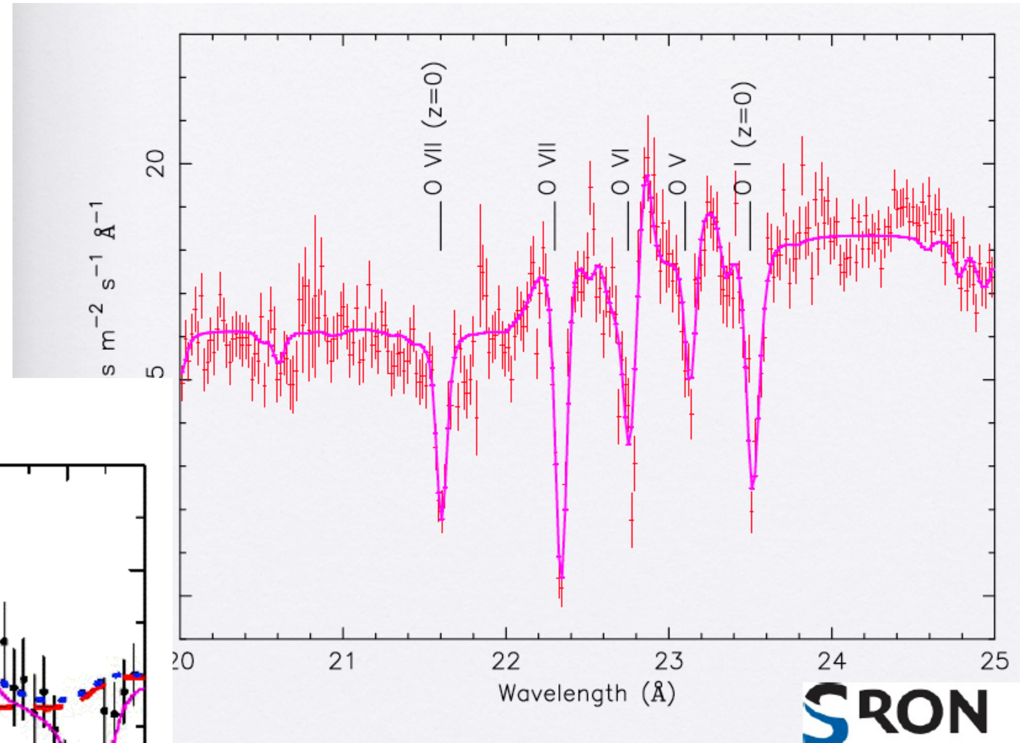
$\tau < 1 \quad EW \propto N$ (linear)

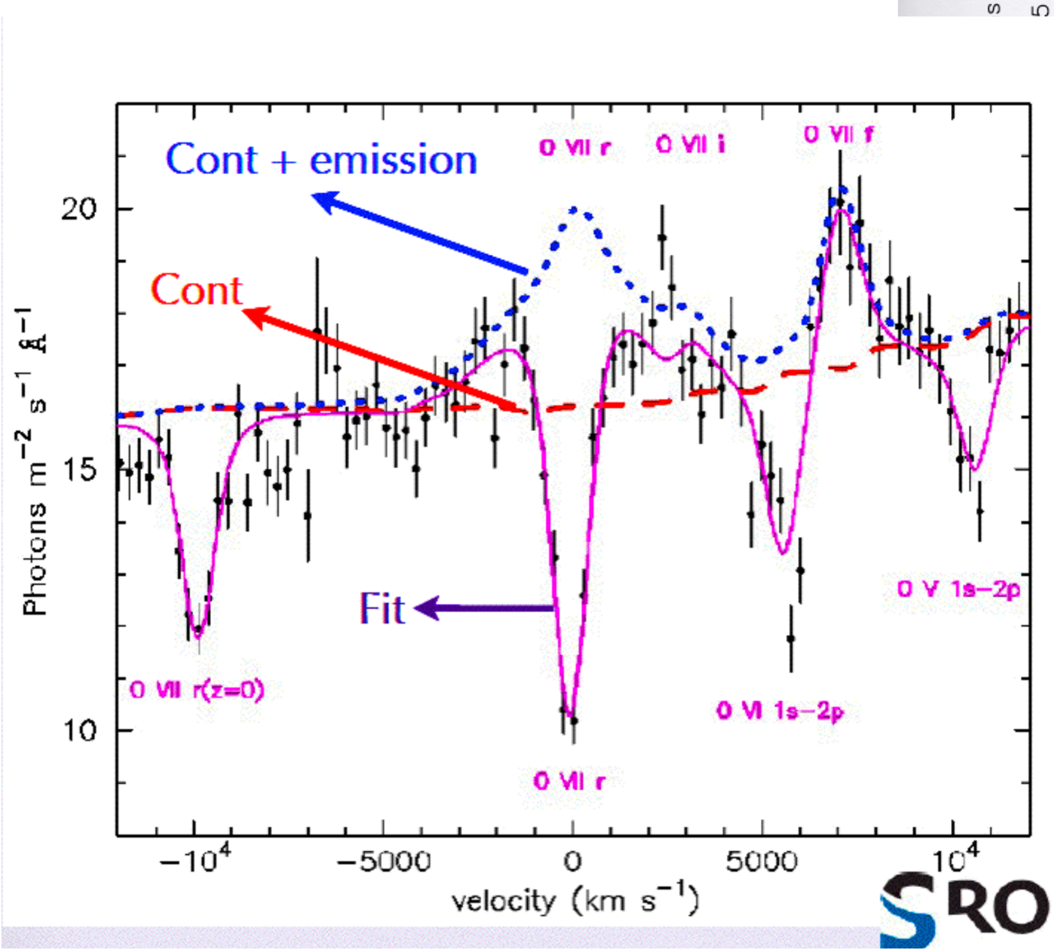
$10 < \tau < 10^3 \quad EW \approx const$ (saturated)

$\tau >> 10^4 \quad EW \propto \sqrt{N}$ (damping wings)

Examples of Emission and Absorption Lines

- Mkn509 - section of the x-ray spectrum
- Notice the wide range of ionization





Thursdays Lecture

- How are high energy photons detected?
  - X-ray imaging and spectroscopic detectors
  - □ γ-ray detectors
- X-ray telescopes