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
Or
http://www.ebooksdirectory.com/details.php?ebook=2399

- continuum
  - blackbody
  - synchrotron & bremsstrahlung
  - scattering
  - radiative recombination
- lines
  - charge exchange
  - fluorescence
  - thermal

Physical Processes Over View – More Equations Later

Melia ch 5 and Rosswog and Bruggen ch 3 Longair ch 6

- How are 'high energy' photons produced
  - Continuum

Thermal emission processes

Blackbody radiation
Bremsstrahlung

Non-thermal processes

Synchrotron radiation

Inverse Compton emission

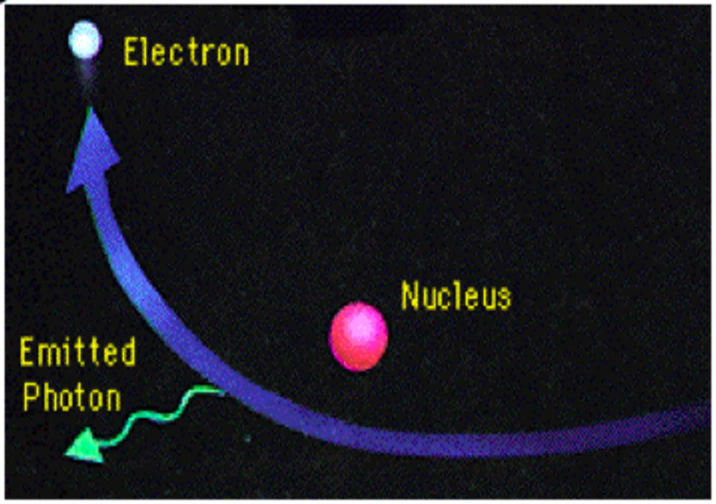
Non-thermal bremms

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

BREMSSTRAHLUNG

- "Braking radiation"



Examples: clusters of galaxies, supernova remnants, stellar coronae

Electromagnetic radiation is produced by the acceleration of charged particles (mostly electrons)

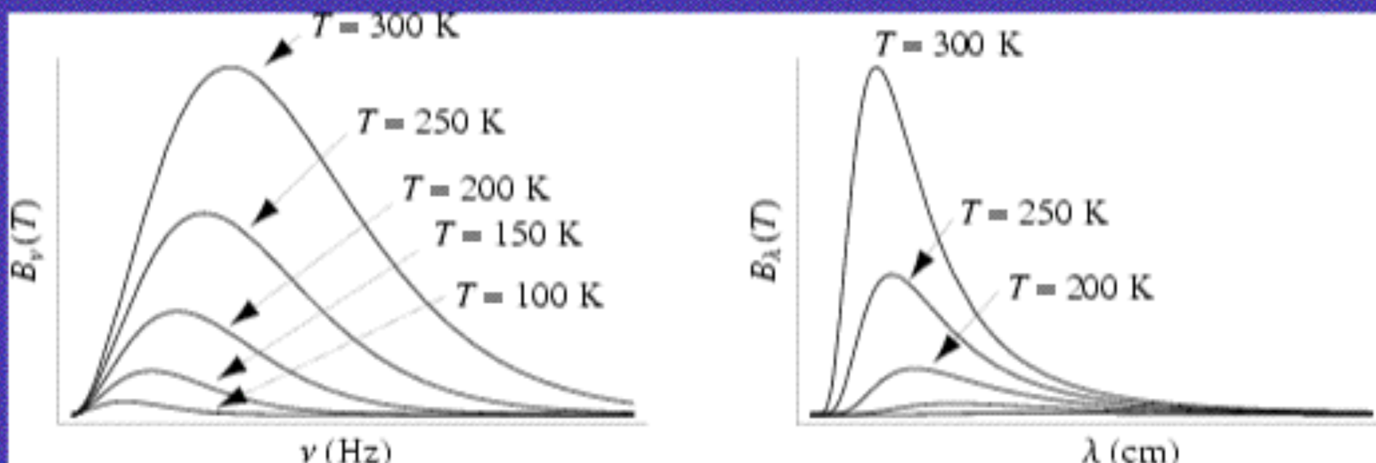
Black Body

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

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

ergs/s/cm^2/Hz/sr

$I(\nu,T)d\nu$ is the amount of energy per surface area, per unit time, per solid angle emitted in the frequency range between ν and $\delta\nu$ 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) $=2.9\times10^7(1/T)$Å

The energy of maximum intensity $E_m=0.245T_6$ keV

Total energy radiated $=A\sigma T^4$

Assumptions- photons and electrons are in equilibrium

System is 'perfect' emitter

Astrophysical example- some isolated neutron stars

$L= A\sigma T^4$;

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

A is the collecting area

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

Continuum Sources

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

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

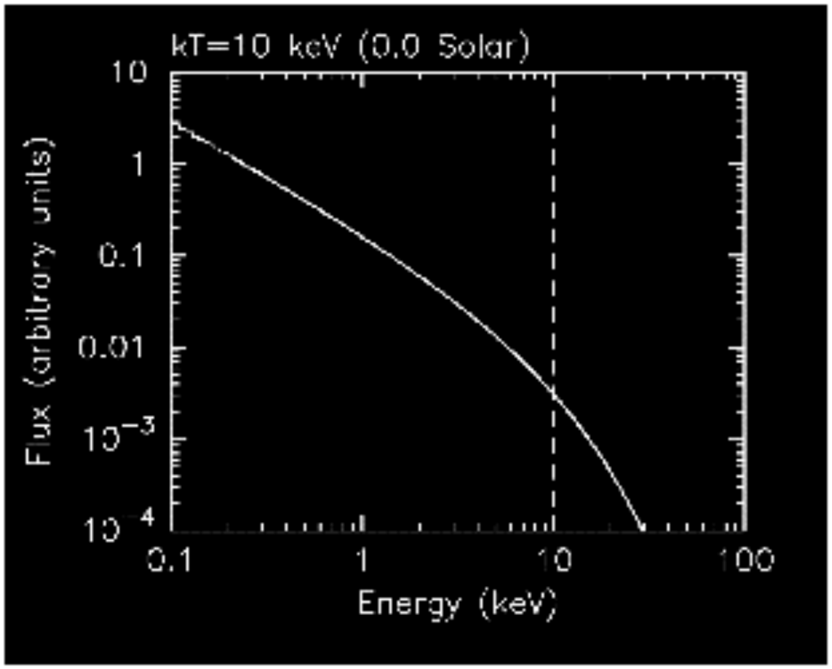
which causes the electron to spiral around the B field. The acceleration of the electron produces synchrotron radiation

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

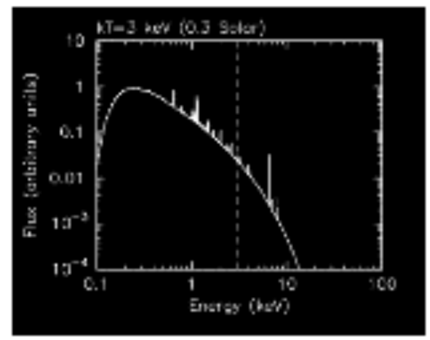
Black body emission and Bremsstrahlung are sometimes called thermal emission (because the statistical motion of the charged particles depends on temperature). Synchrotron emission is an example of non-thermal emission since the statistical motion of the charged particle depends on the magnetic field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

BREMSSTRAHLUNG SPECTRUM

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



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 $L = 2.4 \times 10^{-28} T^{1/2} n_e^{1/2} V$ (W) T = temperature, V = volume

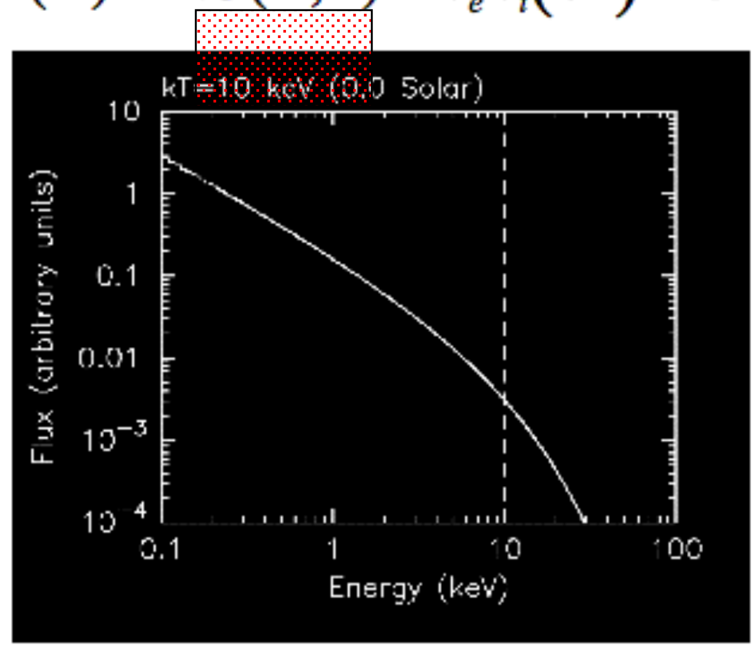
- Electron moves at a high velocity past a stationary proton (nucleus) Longair 6.3 for a detailed derivation for 1 interaction

Bremmstrahlung

- RB pg 97 (sec 3.8.1)Melia ch 5.3 point out that a proper derivation requires QED (quantum electrodynamics)- accelerated charged particles emit radiation
- Summary
  - Produced by charged particle collisions in ionized plasmas
  - Spectrum is flat at low energies (roughly a power law of I(E)~$E^{-0.4}$) with a *characteristic exponential turnoff at high energies related to the temperature of the electrons*
  - Total emission/unit volume ~ $n_e ni_{on} T^{1/2}$

BREMSSTRAHLUNG

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

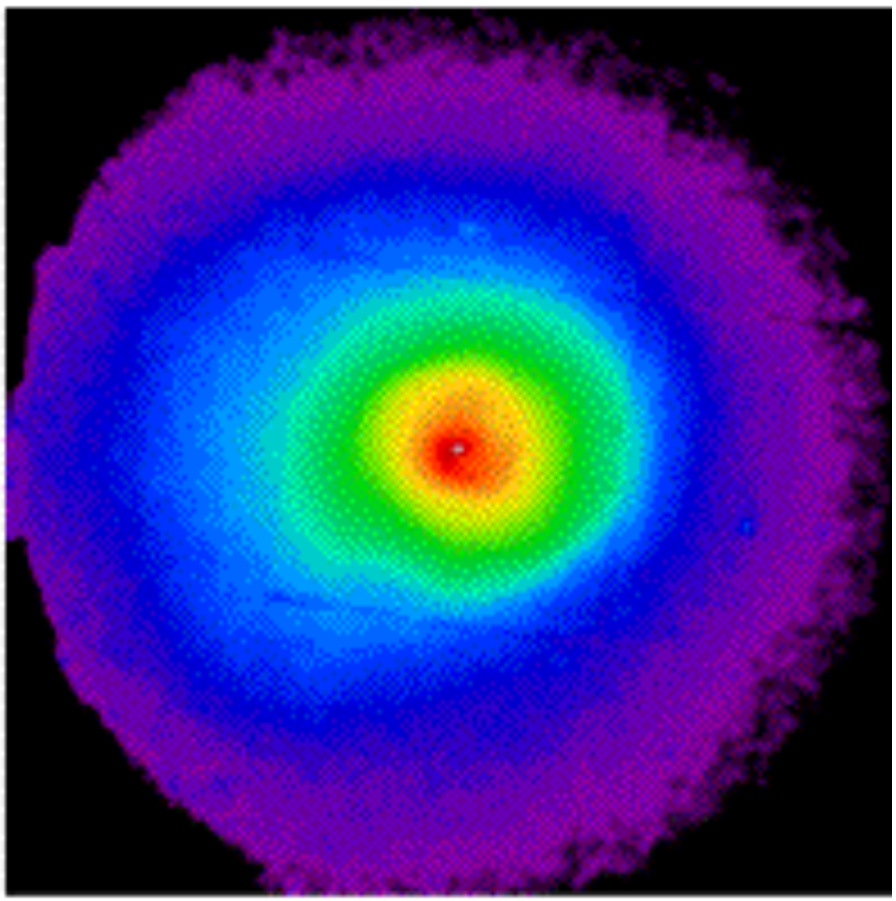


see Longair eqs 6.44-6.49
Inverse process 'free-free' absorption can be important in the radio

Bremsstrahlung Observed

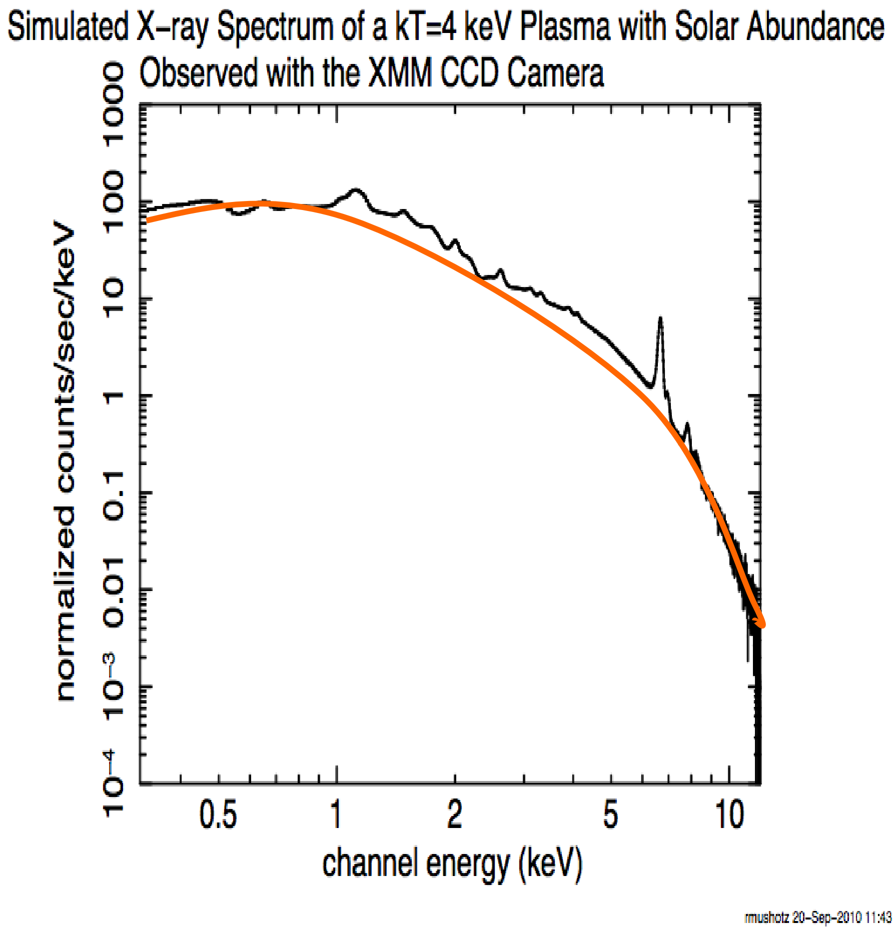
Coma cluster in X-ray and optical light

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



X-ray Spectrum of a Hot Plasma

- Continuum is due to thermal bremmstrahlung (see Longair figure 6.2)
- Emission lines are due to recombination of H and He-like ions (more later)
- Curvature of spectrum gives temperature- amplitude gives emission measure (n^2V)
- Detailed fit to shape confirms physical mechanism of radiation



SYNCHROTRON RADIATION

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

- Electrons spiralling in magnetic field

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

Rather complex derivation Ginzburg, V. L., Syrovatskii, S. I., ARAA, 1965
Longair Ch 8 , 5.4-5.6 in Melia

Synchrotron Radiation (Melia Ch 5.4 RB sec 3.8)

- For a single electron the characteristic frequency $\omega_{sync} = 3/2\gamma^2 B/m_e c$; B=magnetic field
- $dE/dt = P \sim\gamma^2 U \sim\gamma^2\beta^2 B^2/m^2_*$;γ is the Lorentz factor $1/\mathrm{sqrt}(1-v^2/c^2)$; is the mass of the radiating particles (electrons radiate much more efficiently than protons); for particles of interest $\beta^2\sim 1$

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

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

$t_{cool} \sim m_e c^2/4/3 u_B c\sigma_T\gamma \sim 16B^{-2}\gamma^{-1}$yrs; time for particles to loose 1/2 their energy

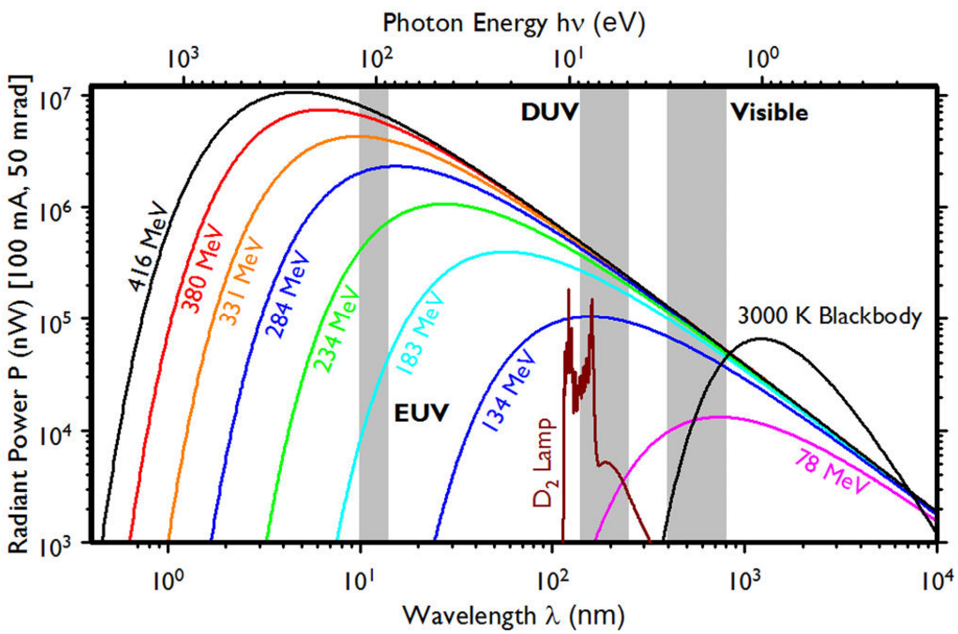
The most energetic particles have the shortest lifetimes

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

Synchrotron radiation is intrinsically polarized which allows measurements of the direction of the magnetic field- very important in radio astronomy

Synchrotron

- For a power law input spectrum of particles on gets out a power law photon spectrum out to some maximum frequency
- If particle spectrum is $dN/dE \sim N_0 E^{-p}$
- photon spectrum is $I_\nu \sim C_0 \nu^{-(p-1)/2}$
- Higher energy particles radiate at higher energies $\nu \sim \gamma^2 qB/mc$
- Where $C_0 \sim N_0 U_B \sigma_T$
  - depends on the energy density of the B field $U_B \sim B^2$
  - The Thompson cross section σ_T
  - and the number of particles N



NIST website
NIST SURF What is synchrotron radiation?

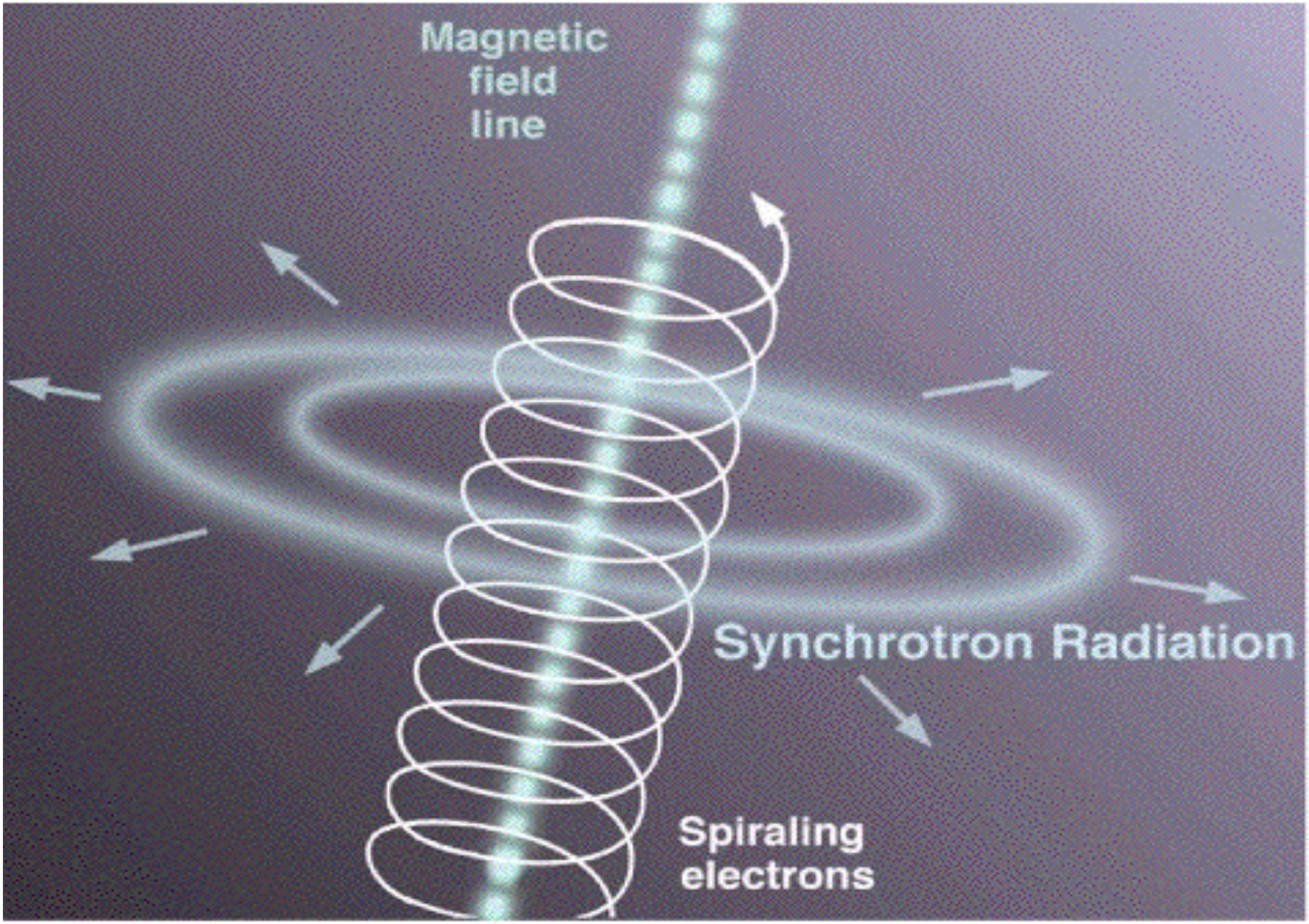
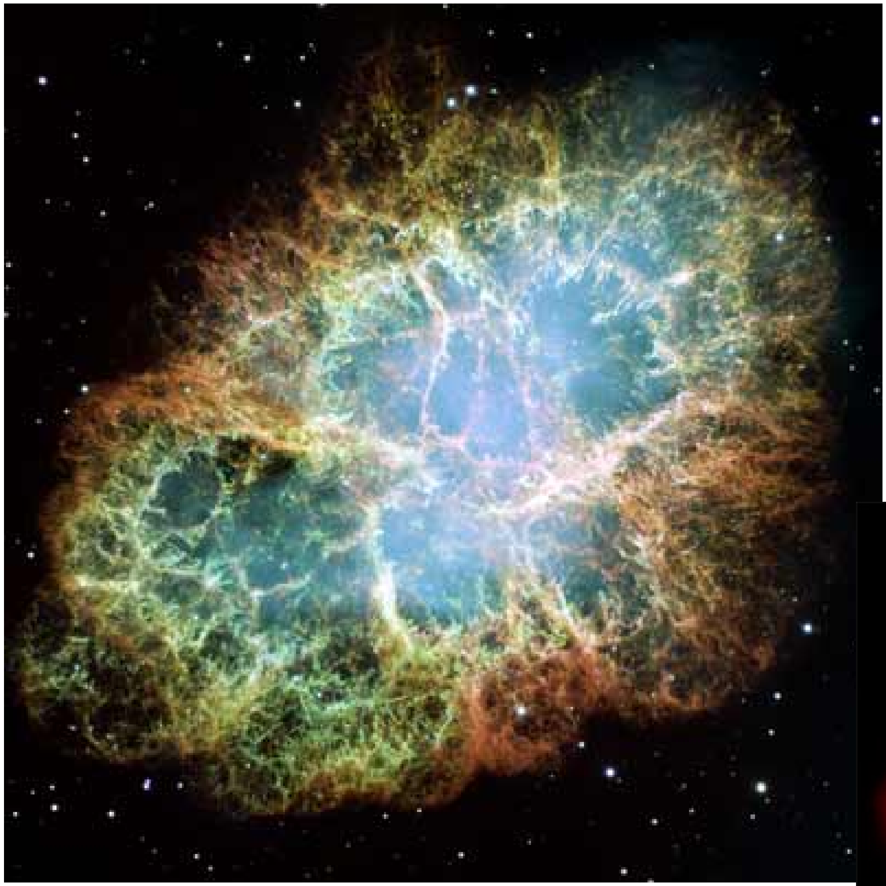


Fig. 1.— Artist's conception of synchrotron radiation. Cool figure from http://www.gemini.edu/gallery/science/m87/Synchrotron_Radiation_med.jpg

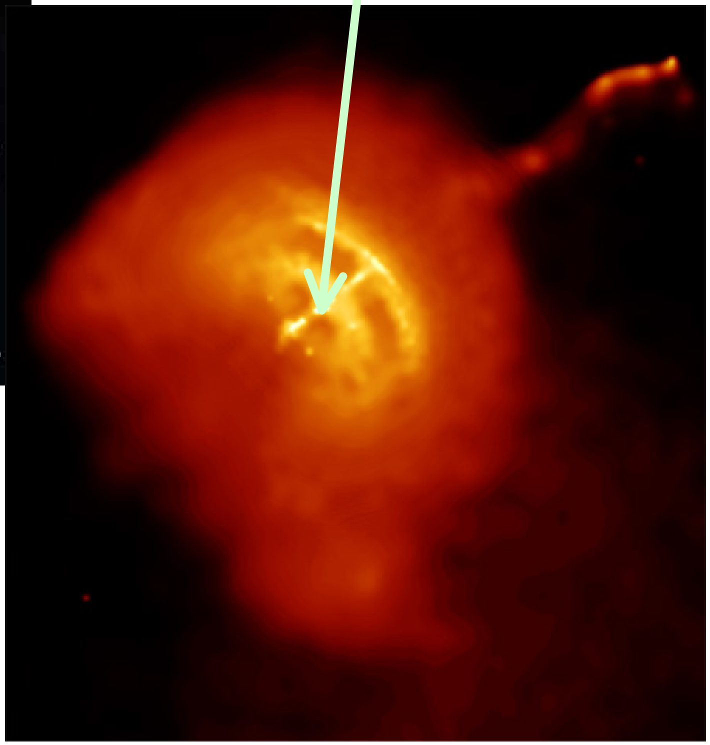
Synchrotron radiation- (some) SNR nebulae

Crab Nebula- optical IR and X-ray image

Supernova in 1054 AD

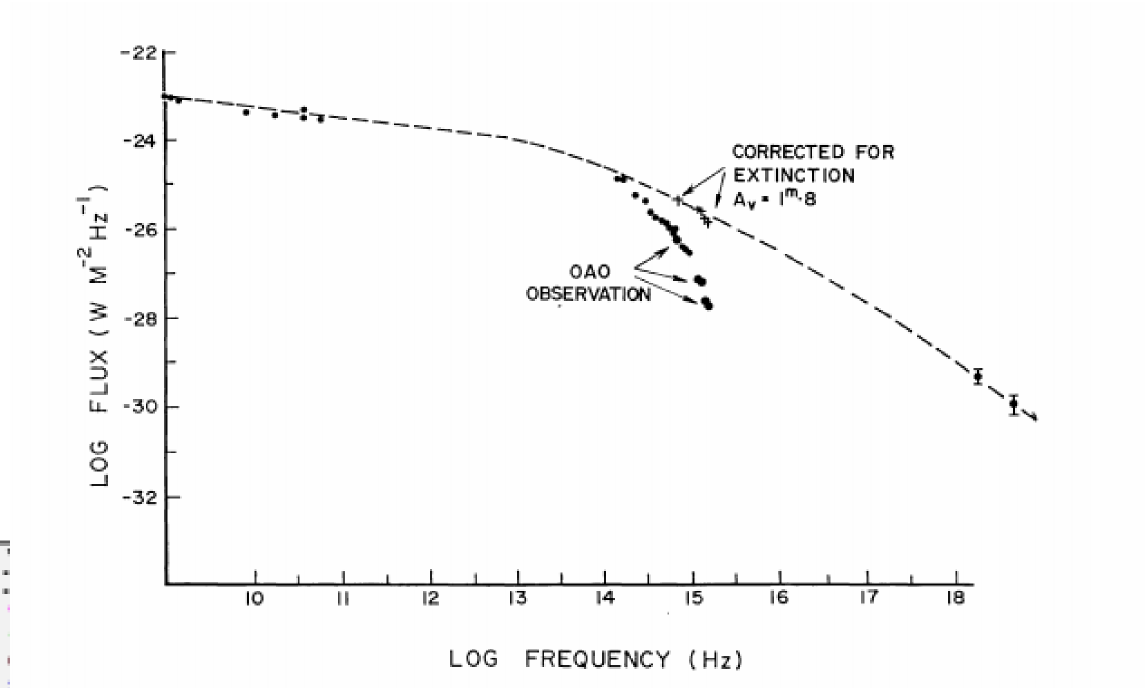


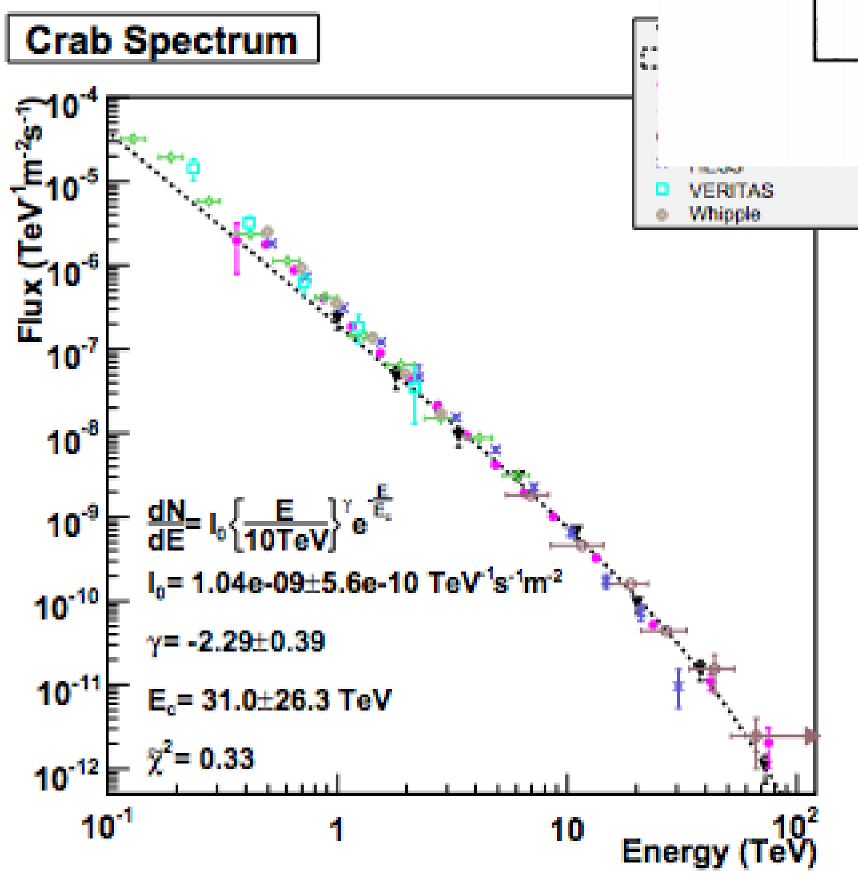
Pulsar-rotating, non-accreting Neutron star

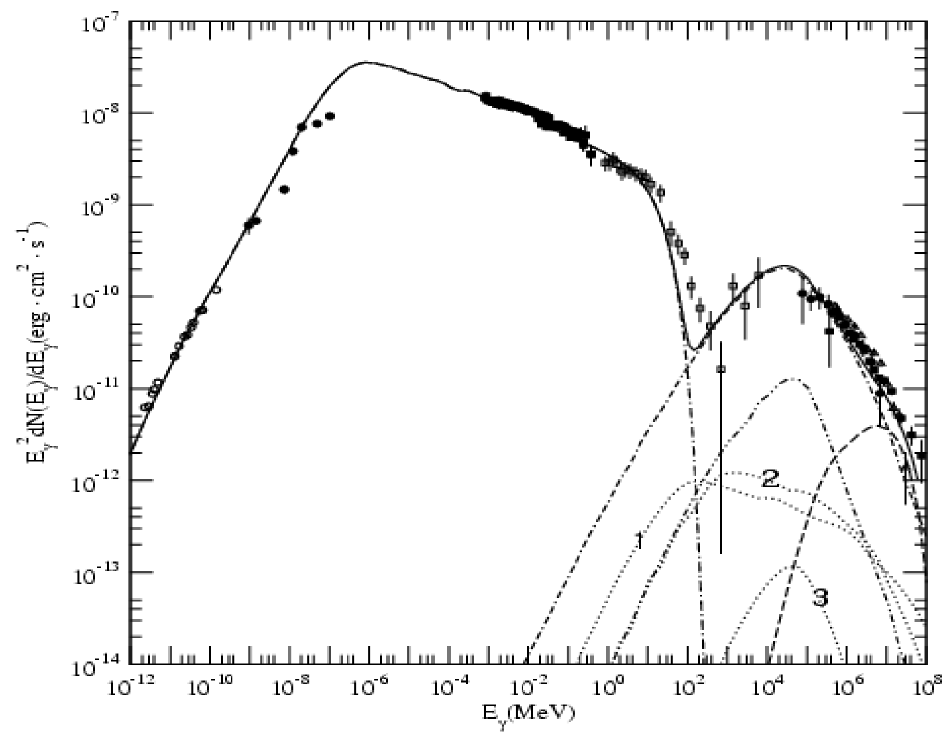


X-ray image of Vela pulsar

- Crab is the often used example of a 'pure' synchrotron emitter

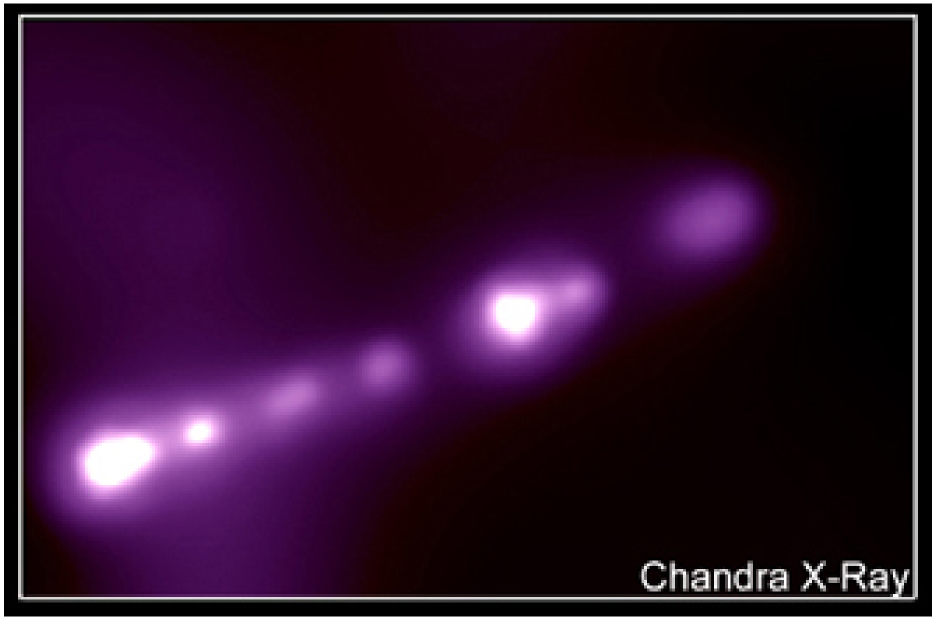




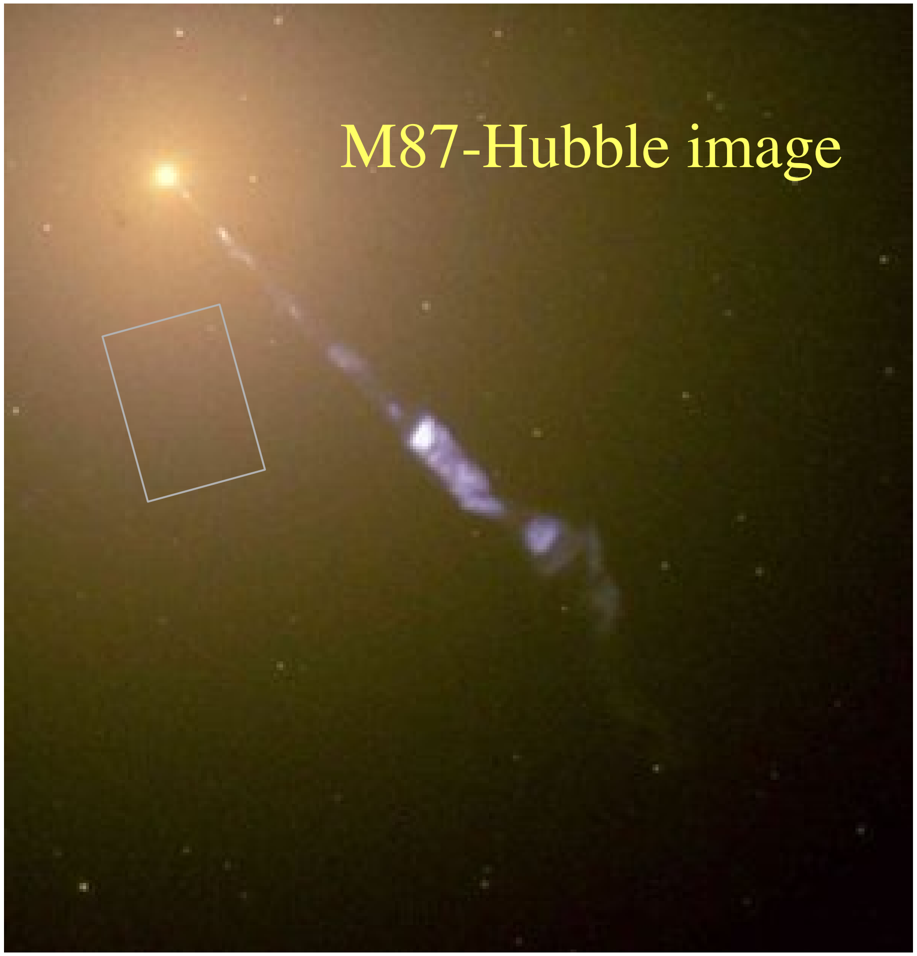


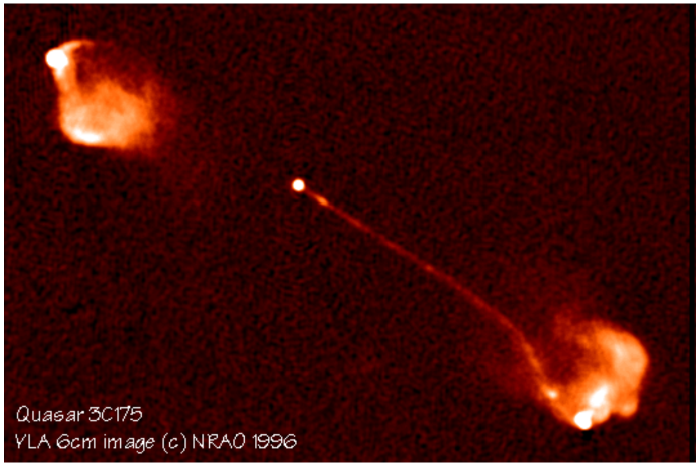
Synchrotron Radiation Examples

Image of M87 Synchrotron X-ray Radiation in jet



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

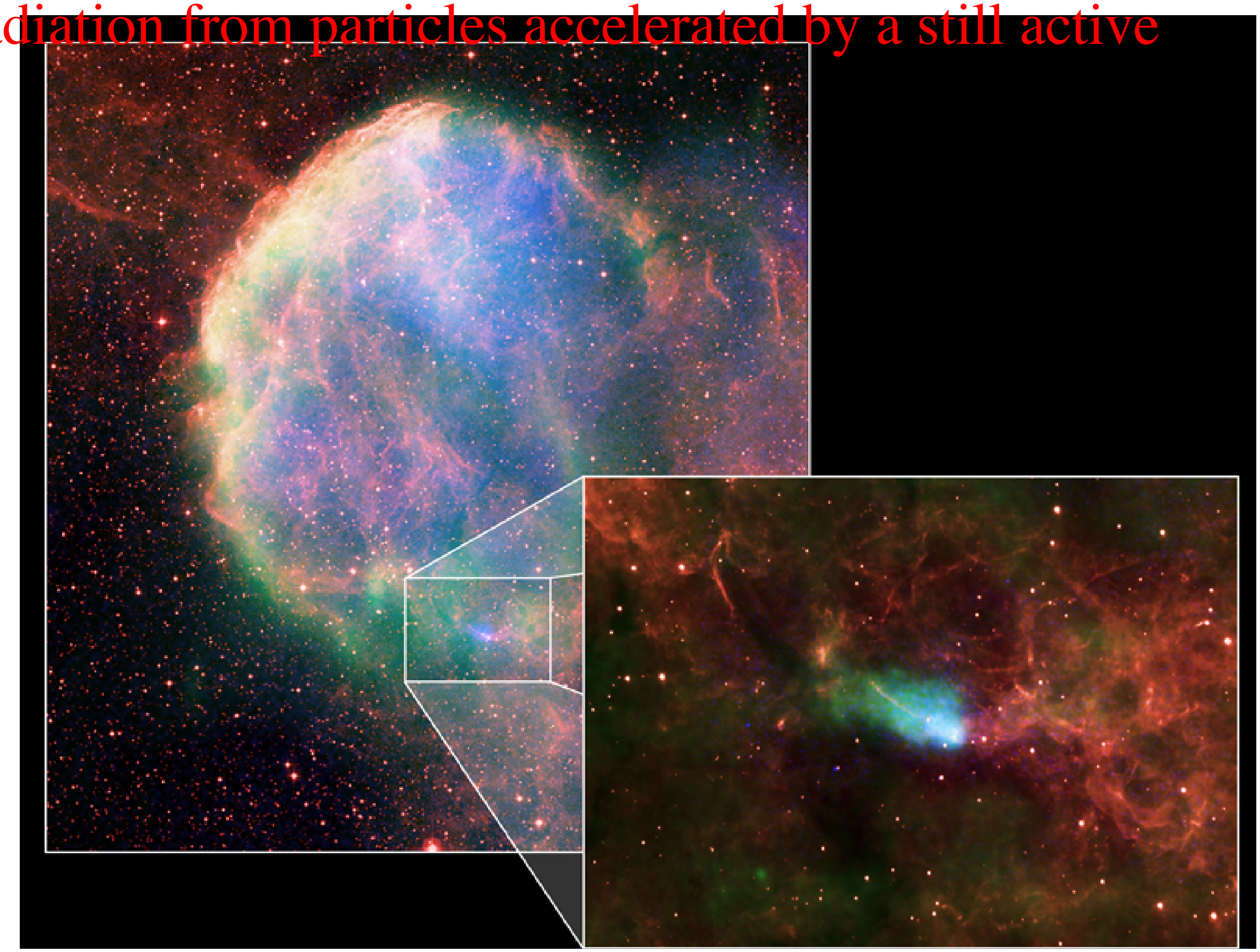




Radio image of a quasar

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

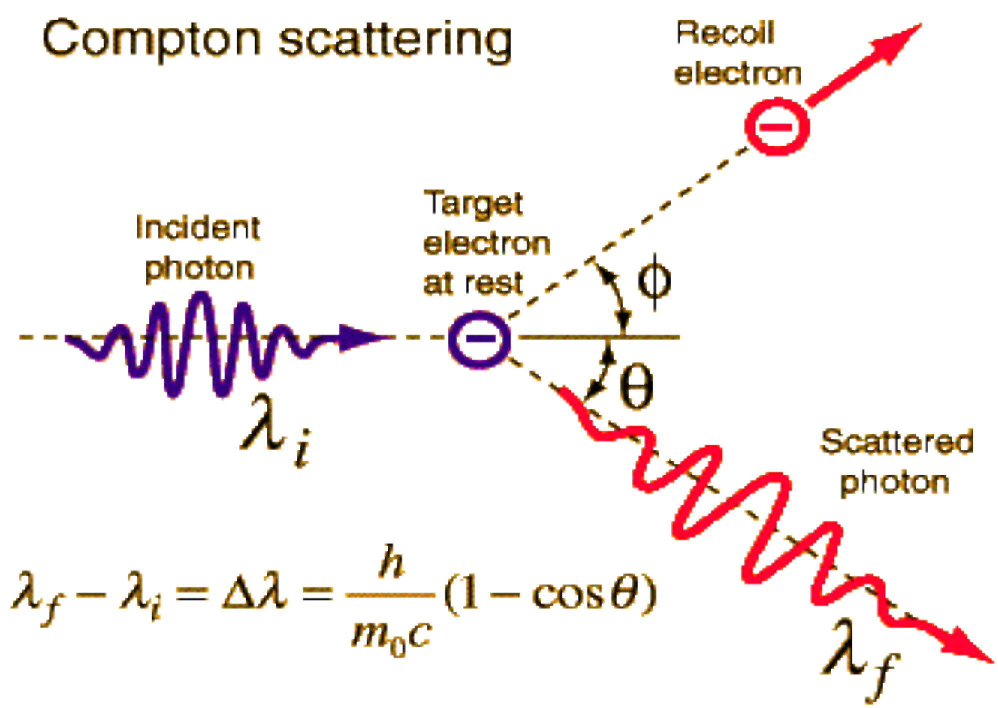


Thompson/Compton Scattering RB Ch 3.8

- Thomson scattering: elastic scattering of low-energy photons from low-energy electrons, with cross-section $\sigma_T = (8\pi/3)(e^2/mc^2) = 0.665 \times 10^{-24}$ cm^2
- Compton scattering: low-energy photon inelastically scatters off non-relativistic electron, photon ends up with lower energy
- Inverse Compton scattering: low-energy photon inelastically scatters off relativistic electron, photon gains energy in observer rest frame

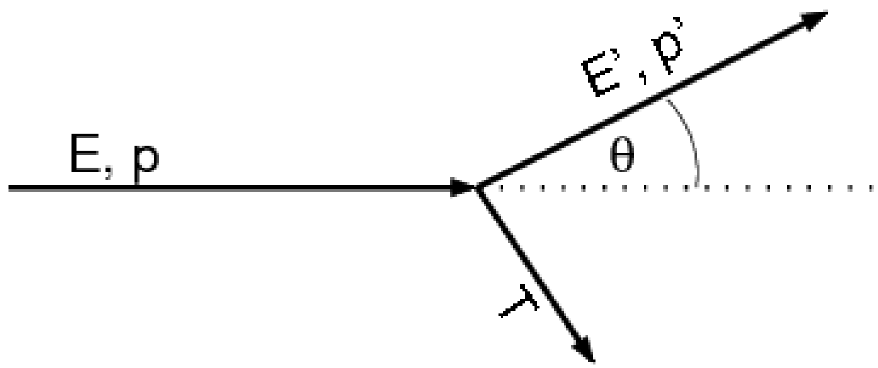
Whether the photon gives energy to the electron of vice versa

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



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 $E \ll m_e c^2$:

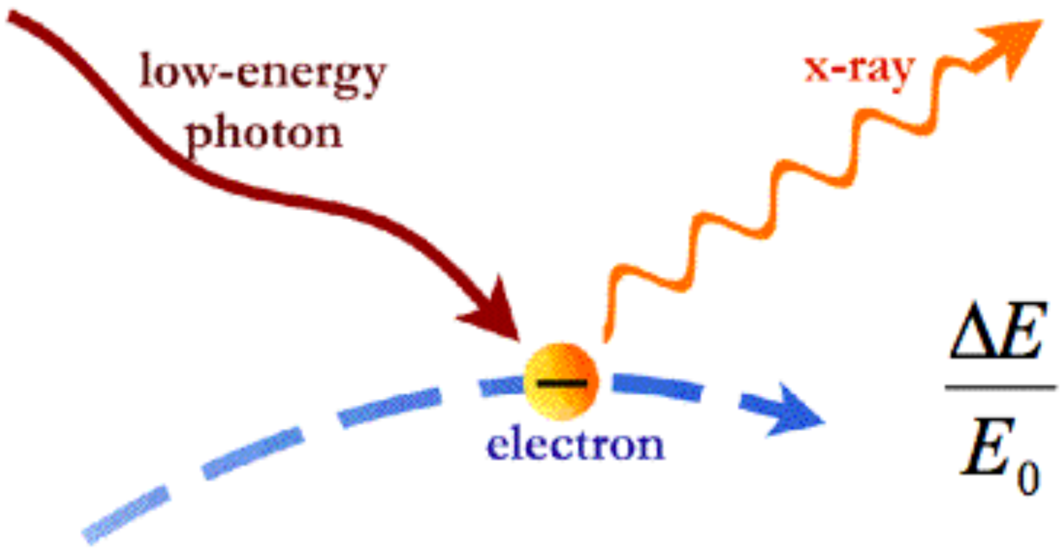
$$\frac{\Delta E}{E} \approx -\frac{E}{m_e c^2} \tag{7.16}$$

- 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

INVERSE COMPTON EMISSION

- Results depend on source geometry

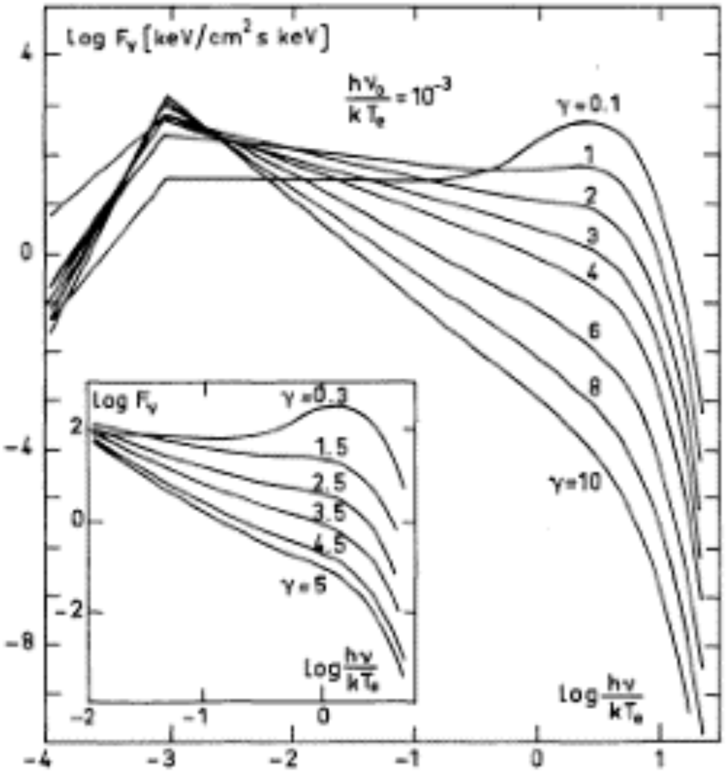


Fig. 5. The spectrum resulting from comptonization of low-frequency photons ($h\nu_0 = 10^{-3}$ kT$_e$) in a high temperature plasma clouds with different parameters γ (14)

Sunyaev & Titarchuk 1980

- ***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