Todays Lecture- How are Photons Generated/Absorbed

- Physical processes (Longair, Part II 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.
  - **Bremmstrahlung** (Longair 6.2-6.6)
  - **Synchrotron radiation**

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

Compton scattering
Electrons scattering of photons/ scattering off electrons and vv (Longair 9.2-9.5)

Line Emission and absorption
Atomic transitions in atoms- x-rays mostly from K, L shell transitions (not in Longair)

Photoelectric Absorption (Longair 9.1)
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

Goals of Lecture

- The physical origin of the continuum in many high energy sources
  - what can we learn about the physics of the sources
  - Material to be stressed is usually in 'boxes', colored or in **bold**.

- continuum
  - blackbody
  - synchrotron & bremsstrahlung
  - Compton scattering
- lines
  - charge exchange (will not discuss in class)
  - fluorescence
  - thermal
  - photoionization

What Do We Want to Learn From Continuum Spectra?

- Physical process responsible for emission, particle acceleration.
- Total power in system
- Breakdown of energy budget (how much in particles, fields)
- Particle distributions (e.g. temperatures, power law slopes etc)
- Magnetic field
- How does the system produce the energy needed for the radiation

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

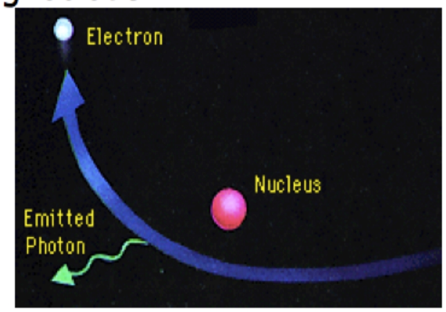
Non-thermal bremms

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)

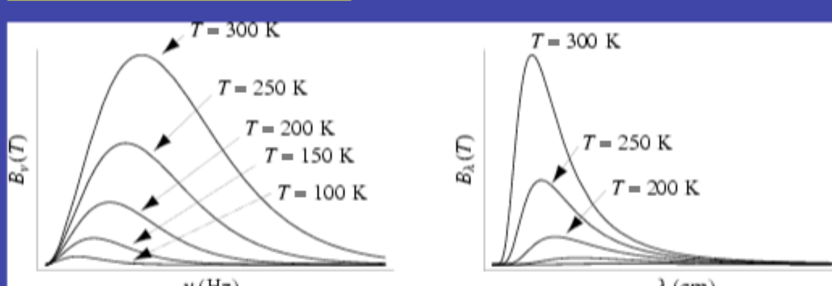
Black Body

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~AσT^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) =2.9x10^7(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

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

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

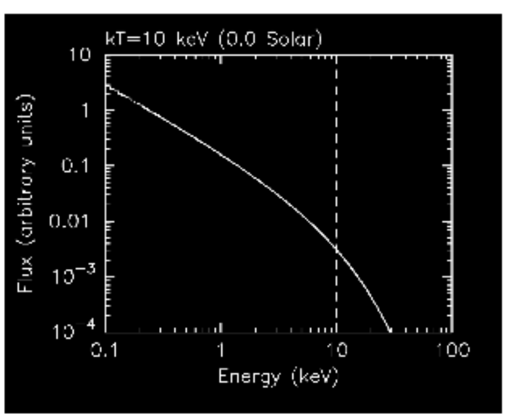
- Bremsstrahlung is caused by a "collision" between a free electron and an ion. The emissivity ε_{ff} (photons m^{-3} s^{-1} J^{-1}) can be written as:
- $\varepsilon_{ff} = [C n_e n_i Z^2 T^{1/2} g_{ff} \exp(-E/kT)]/E$,
- The factor g_{ff} is the so-called Gaunt factor and is a dimensionless quantity of order unity. Z is the charge of the ion,

- we see immediately that the Bremsstrahlung spectrum is flat for $E \ll kT$ (equivalent power law energy index $\alpha = 0$, photon index $\Gamma = 1$), and for $E > kT$ it drops exponentially.
- In order to measure the temperature of a hot plasma, one needs to measure near $E \simeq kT$.

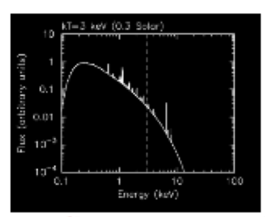
Read Longair Ch 6- (except 6.5.2,6.6) ; you will NOT be responsible for the derivations

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) $\quad T$ = temperature, V = volume

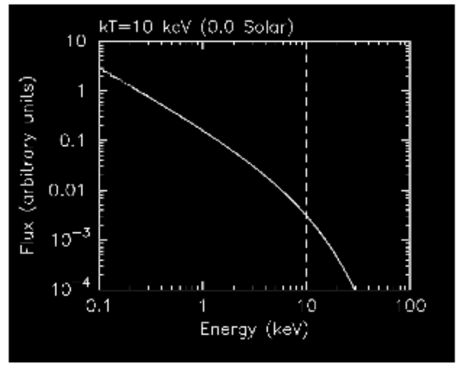
- Electron moves at a high velocity past a stationary proton (nucleus) where Coulomb interaction accelerate it Longair 6.3 for a detailed derivation for 1 interaction

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 $I(E) \sim E^{-0.4}$) with a *characteristic exponential turnoff at high energies related to the temperature of the electrons*
  - Total emission/unit volume ~ $n_e n_{ion} T^{1/2}$ (Longair 6.46)

BREMSSTRAHLUNG

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



G (E,T) is the Gaunt factor

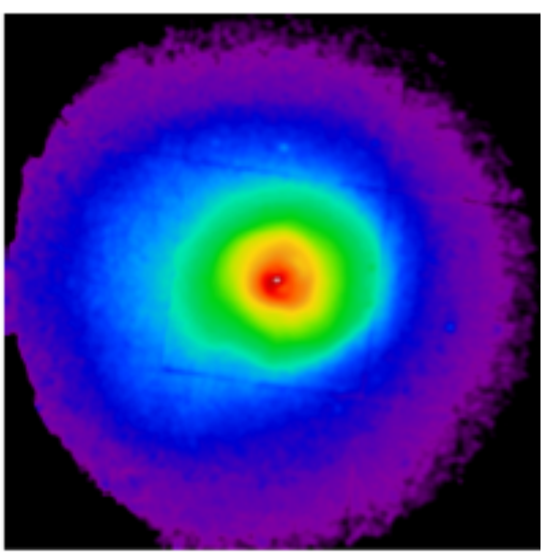
see Longair eqs 6.44-6.49

Inverse process 'free-free' absorption can be important in the radio

Bremsstrahlung Observed

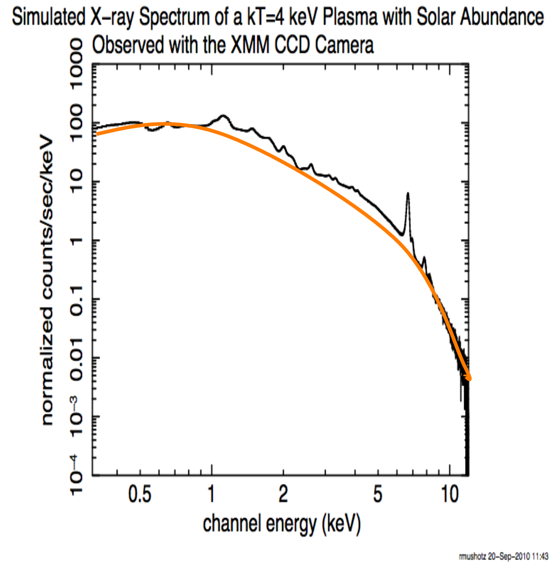
Coma cluster in X-ray and optical light

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 6.3)
- 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)- integrating this over the image gives the gas mass and total energy in the gas.
- Detailed fit to shape confirms physical mechanism of radiation



Synchrotron Emission

- Galactic radio emission (radiation from the halo and the disk),
- radio emission from the shell of supernova remnants
- X-ray synchrotron from PWN in SNRs
- Radio galaxies – lobes and jets
- Low Energy (radio-UV) Blazar continuum

Read Longair Ch 8- this is very detailed and you will NOT be responsible for the derivations

SYNCHROTRON RADIATION

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

- Electrons spiralling in magnetic field

Spectrum for power-law electron distribution:

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

Longair Ch 8

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

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

$\nu_c = (eB/2\pi m_e)\gamma^2 = (eB/2\pi m_e)(E/m_e c^2)^2 = 6.3\times10^{12}\mathrm{Hz}\ [B(E/m_e c^2)/10^3)]$

- to a good approximation, all the radiation of an electron of energy E is radiated at the critical frequency ν_c

Synchrotron Radiation (Melia Ch 5.4 RB sec 3.8)

To repeat

Electrons with energy *E* moving at pitch angle in a magnetic field of strength *B* emit most of their energy near the critical frequency ν_c,

in units of Ghz ν_c=~0.016(Bsinθ/μG)(E/Gev)^2

and the lifetime

τ=E/DE/dt~1.06x109(Bsinθ/μG) $^{-3/2}$ (ν_c/Ghz)$^{-1/2}$

https://ned.ipac.caltech.edu/level5/Condon/condon4_1.html

To get x-ray photons (x-rays) ν~10^{18} Hz need very high energies of electrons or very strong magnetic field

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

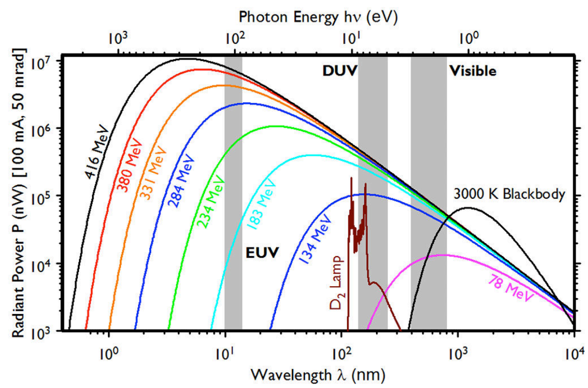
Synchrotron radiation is *intrinsically polarized* which allows measurements of the direction of the magnetic field- very important in radio astronomy

- see http:/asd.gsfc.nasa.gov/Volker.Beckman
- synchrotron radiation, the emission of very relativistic and ultrarelativistic electrons gyrating in a magnetic field, is an important process in much of high energy astrophysics.
- It was originally observed in early betatron experiments in which electrons were first accelerated to ultrarelativistic energies.
- This process is responsible for the radio emission from the Galaxy, from supernova remnants and extragalactic radio sources and optical and X-ray emission observed in the Crab Nebula and other 'plerions'

- One of the basic features of the radiation of relativistic particles in general is the fact that the radiation is beamed in the direction of motion of the particles
- Very high brightness temperature

Synchrotron

- For a power law input spectrum of particles ⟶ 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_0



NIST website
NIST SURF What is synchrotron radiation?

- The classical formula for the radiated power from an accelerated electron is

$$P = \frac{2Ke^2}{3c^3} a^2$$

- For a non-relativistic circular orbit, the acceleration is just the centripetal acceleration, v^2/r. The orbits of interest in accelerators are highly relativistic, so the relativistic acceleration can be gotten from $a=\gamma^2 v^2/r$ and thus the total power is $P=2Ke^2\gamma^4 v^4/3c^3 r^2$

- r is the gyral radius of the particle or in an accelerator the size

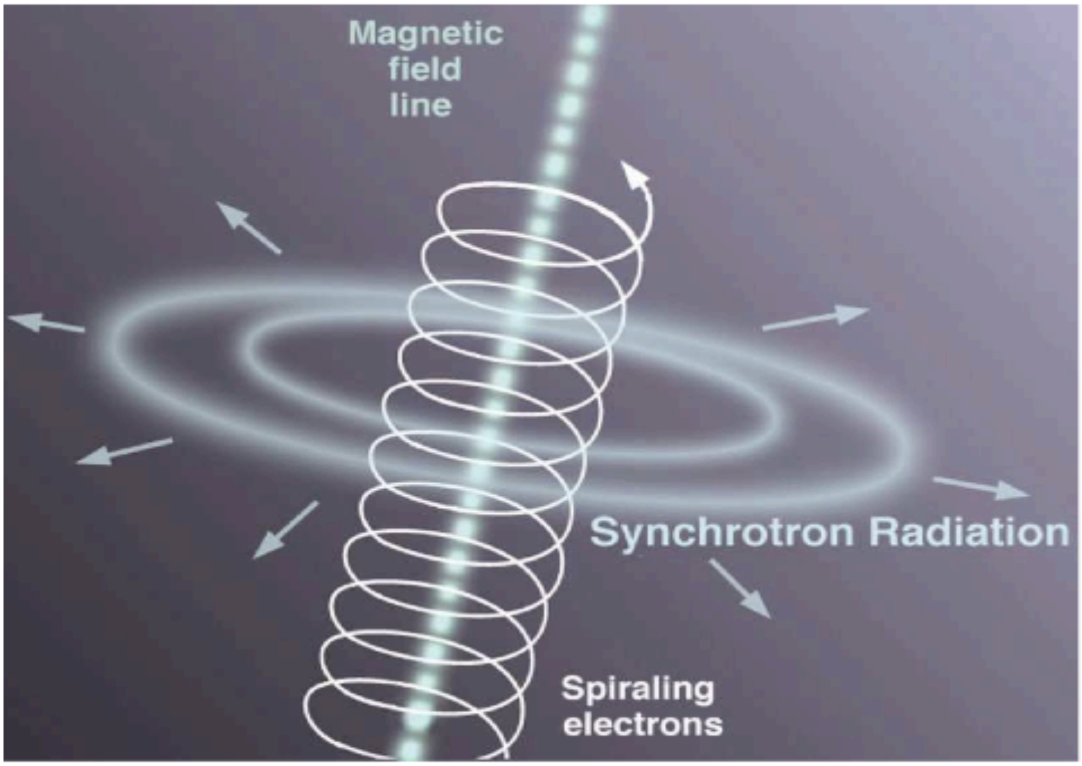
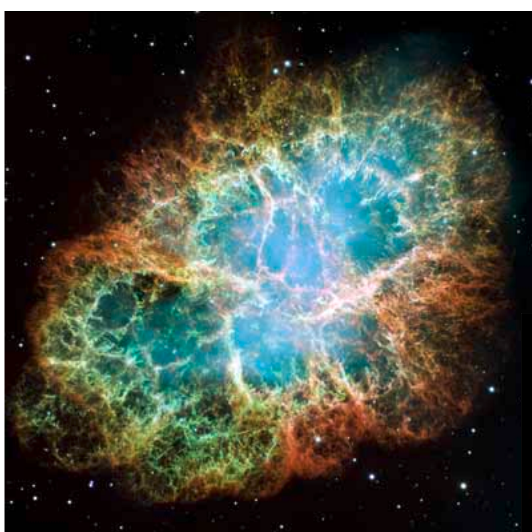


Fig. 1.— Artist's conception of synchrotron radiation. Cool figure from http://www.gemini.edu/gallery/science/m87/Synchrotron_Radiation_med.jpg

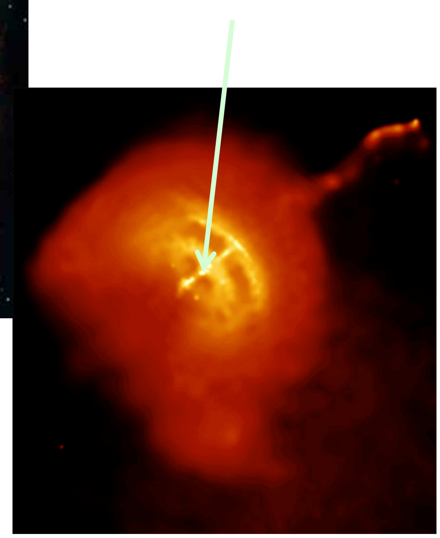
Synchrotron radiation- (some) SNR nebulae

Crab Nebula- optical IR and X-ray image

Supernova in 1054 AD



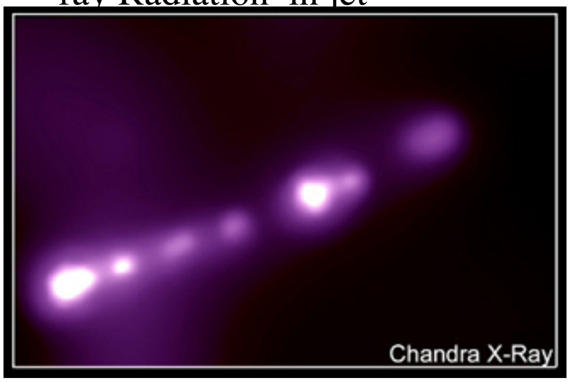
Pulsar-rotating, non-accreting Neutron star



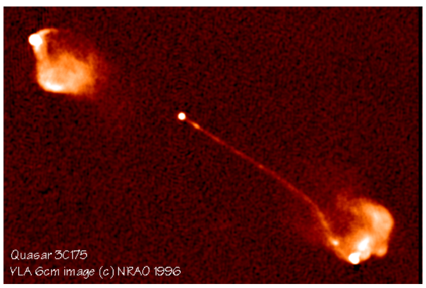
X-ray image of Vela pulsar

Synchrotron Radiation Examples

Image of M87 Synchrotron X-ray Radiation in jet

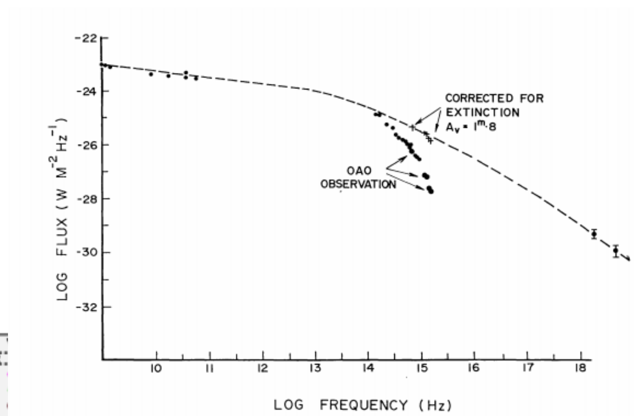


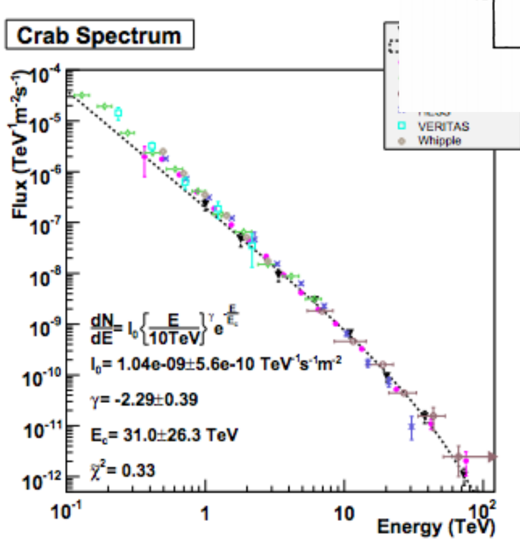
~1.5kpc=5x10^{21}cm long

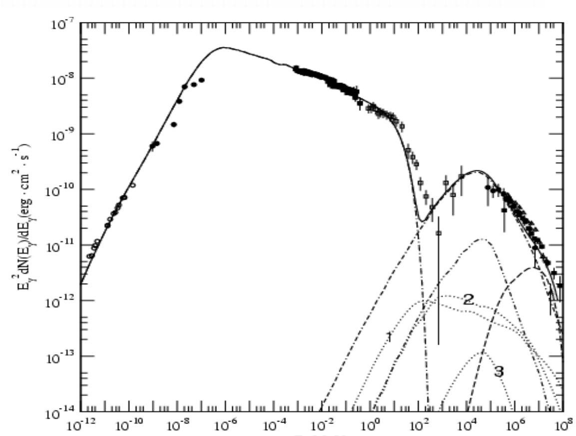


Radio image of a quasar

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







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

Read Longair Ch 9.2-9.6 (9.1in next lecture,9.4.3 not covered)RB Ch 3.8

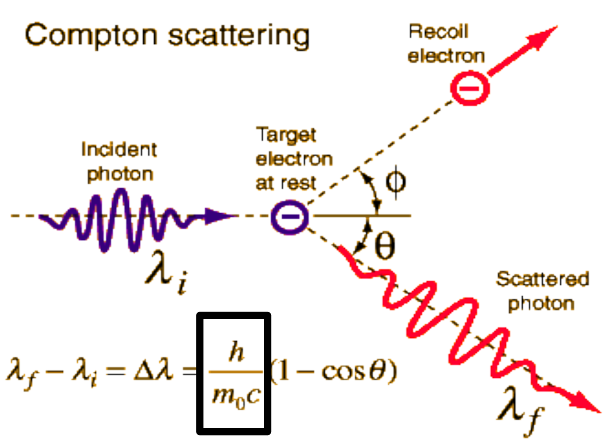
•Thomson scattering: elastic scattering of low-energy photons from low-energy electrons, with cross-section $\sigma_T = (8\pi/3)\,(e^2/m_e c^2) = 6.65\times10^{-25}\ \mathrm{cm}^2$

•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*

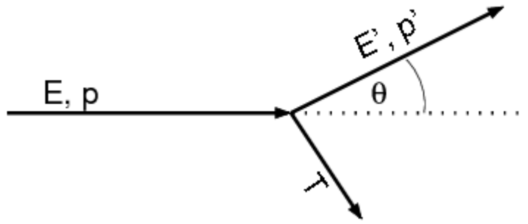
Whether the photon gives energy to the electron or vice versa

Compton Wavelength $=h/m_e c=0.00243$ 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 $E \ll m_e c^2$:

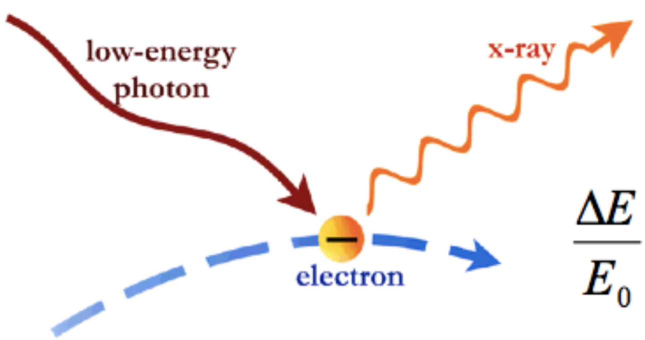
$$\frac{\Delta E}{E} \approx -\frac{E}{m_e c^2} \tag{7.16}$$

- 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

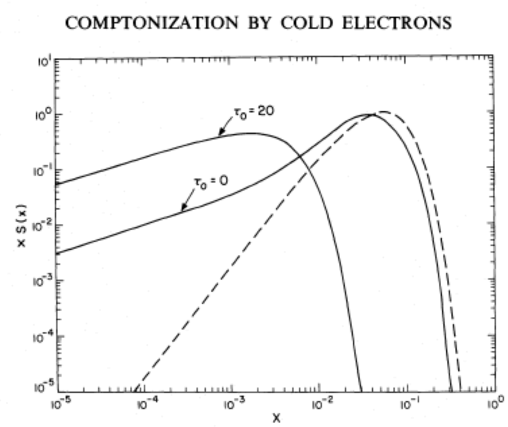


$$\frac{\Delta E}{E_0} = \frac{1}{m_e c^2}(4kT - E_0)$$

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

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
- Down scattering a 'black body-like' distribution

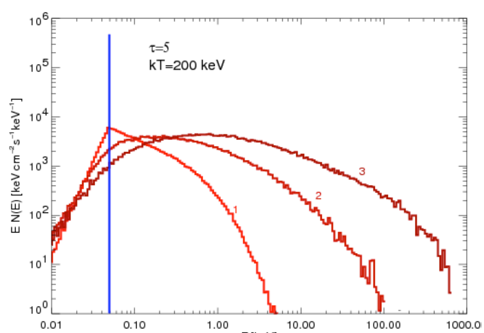


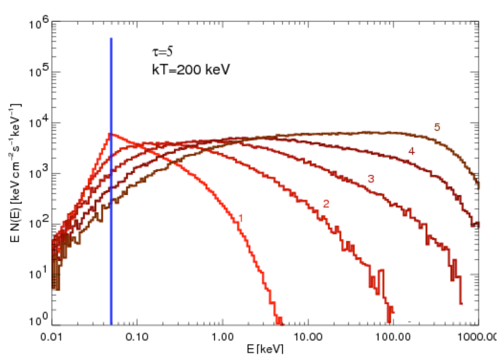
Compton scattering

- 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 comptonized spectra with kT_e~150 kev, y~1 ($y=4kT_e/m_ec^2(\max(\tau,\tau^2))$)

When averaging over angles the free parameters of Compton scattering are the probability of interacting (parameterized by τ - the optical depth) and the electron temperature (T_e) as long as the effective temperature of the photons is $<<T_e$

- 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.

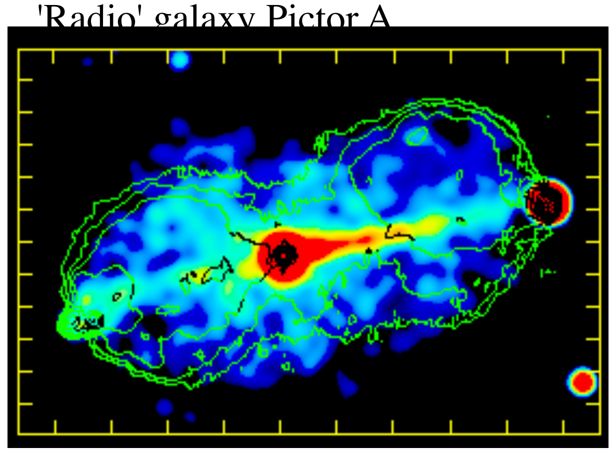
Synchrotron power
$P_{synch}=4/3\sigma_T c^2 U_B\beta^2\gamma^2$

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

INVERSE COMPTON EMISSION

- Results depend on source geometry

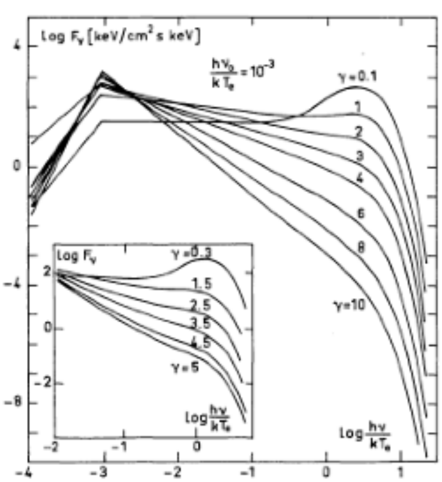


Fig. 5. The spectrum resulting from comptonization of low-frequency photons ($h\nu_0=10^{-3}\,kT_e$) in a high temperature plasma clouds with different parameters γ (14)

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