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**.

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, Melia 5.3) –'breaking radiation'acceleration of the electron in the electrostatic field of the nucleus
  - **Synchrotron radiation**

    High energy (relativistic) particles 'spiraling' in a magnetic field (accelerated electrons) Melia 5.6

Compton scattering
Electrons scattering of photons/ scattering off electrons and vv (Longair 9.2-9.5, Melia 5.7)

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 –

https://julianoliver.com/share/free-science-books/elements.pdf

- continuum- this lecture
  - blackbody
  - synchrotron & bremsstrahlung
  - Compton scattering
- lines- *next lecture*
  - fluorescence
  - thermal
  - photoionization

See for a nice web resource on continuum processes https://asd.gsfc.nasa.gov/Volker.Beckmann/school/download/Longair_Radiation1.pdf

Todays Lecture- How are Photons Generated/Absorbed

- Physical processes (Melia ch 5,RB ch 3 Longair Part II of book) −see Ghisellini_course_notes
  - **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

Bremmstrahlung- electrons whose path is changed by interaction with nuceli- the electron moves at a high velocity past the stationary nucleus .

UC Berkeley, Astro 201, Radiative Processes in Astrophysics
- Physics oriented
E. Chiang −
see https://casper.ssl.berkeley.edu/astrobaki/index.php/Radiative_Processes_in_Astrophysics

What Do We Want to Learn From Continuum Spectra?

- Physical process responsible for photon emission
- Total power in system
- Breakdown of energy budget (how much in particles, fields, thermal energy, kinetic energy)
- Particle distributions (e.g. temperatures, power law slopes etc)
- Magnetic field

How does the system produce the energy needed for the radiation that is measured

Physical Processes Over View – More Equations Later

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

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

The two main 'thermal' processes are

- thermal bremmstrahlung
- black body radiation

Non-thermal processes

- synchrotron radiation
- '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

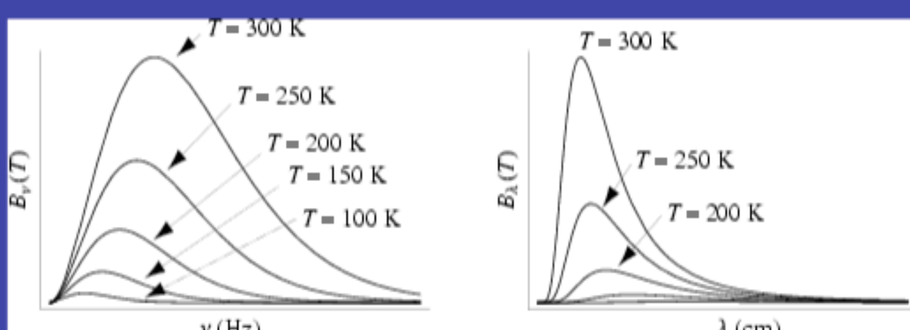
An accelerated charge can produce EM radiation over a continuous range of frequencies (energies).

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

$L \sim A\sigma T^4$



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

<u>Total energy radiated =$L=A\sigma T^4$;</u>

A= area

Assumptions- photons and electrons are in equilibrium
System is 'perfect' emitter

Astrophysical example- some isolated neutron stars

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

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

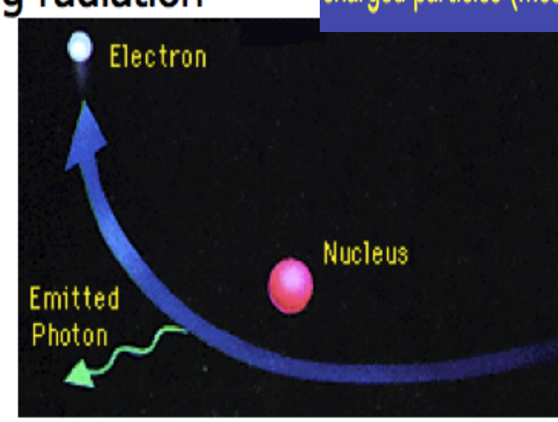
Physical Processes Over View – More Equations Later

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

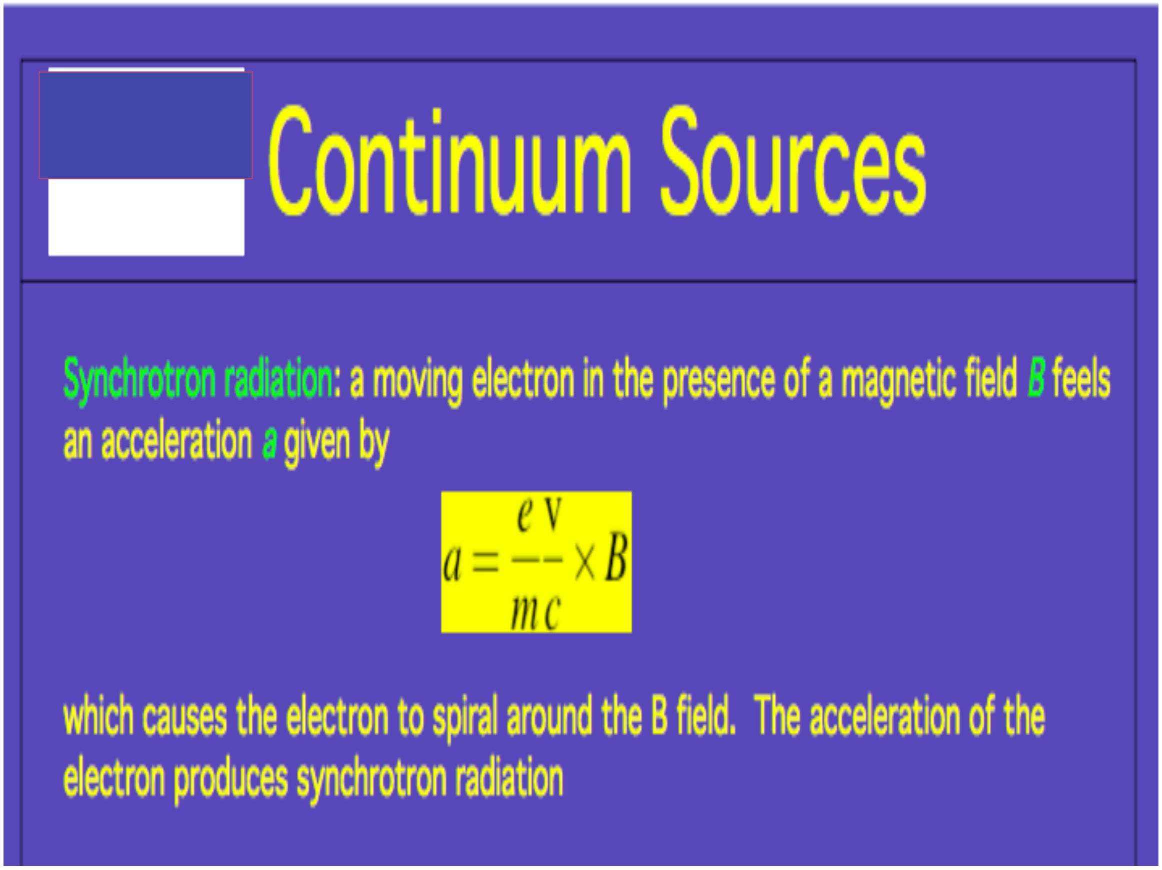
BREMSSTRAHLUNG

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

- "Braking radiation"



Examples: clusters of galaxies, supernova remnants, stellar coronae



Bremsstrahlung

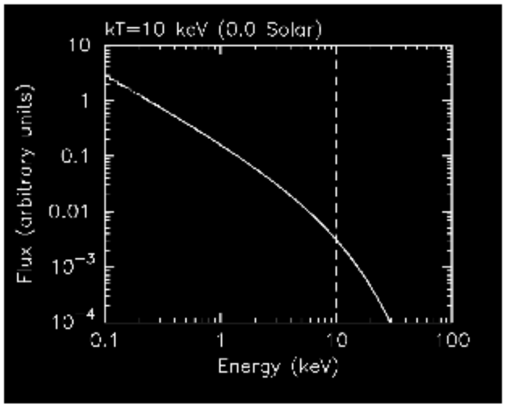
- Bremsstrahlung is caused by a "collision" between a free electron and an ion. The emissivity ε_{ff} (photons $m^{-3}\ s^{-1}\ J^{-1}$) can be written as:
- $\varepsilon_{ff} = [C n_e n_i Z^2 T^{1/2} g_{ff} \exp(-E/kT)]/E$,
- The factor g_{ff} is the so-called Gaunt factor and is a dimensionless quantity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

- The Bremsstrahlung spectrum is flat for $E \ll kT$ (power law slope ~-1 when include gaunt factor ~-0.4) and for $E > kT$ it drops exponentially.
- In order to measure the temperature of a hot plasma, one needs to measure near $E \simeq kT$.

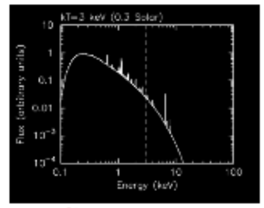
Longair Ch 6- (except 6.5.2,6.6) ; you will NOT be responsible for the derivations

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 $E \ll kT$ the spectrum is approximately a power law
for $h\nu \gg kT$ 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

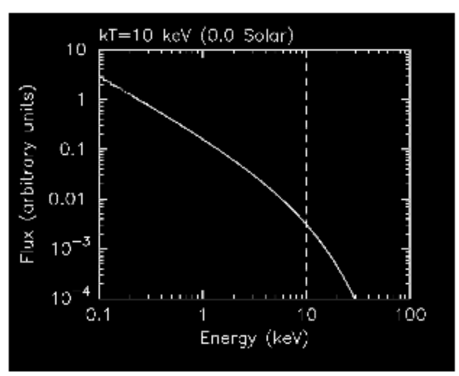
- Electron moves at a high velocity past a stationary proton (nucleus) where Coulomb interaction accelerate it Longair 6.3 for a detailed derivation for 1 interaction

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

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



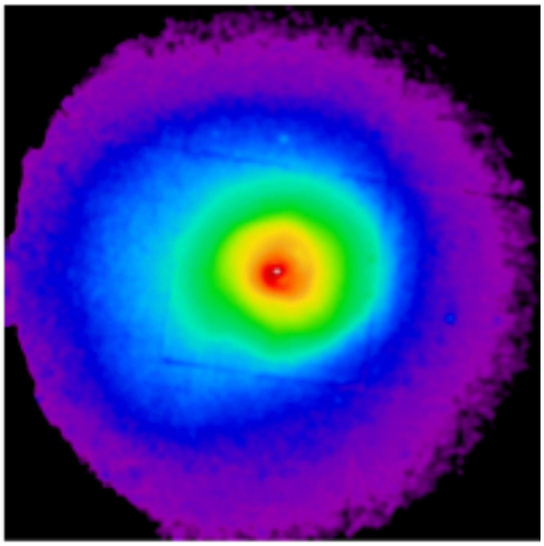
G (E,T) is the Gaunt factor

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

Bremsstrahlung Observed

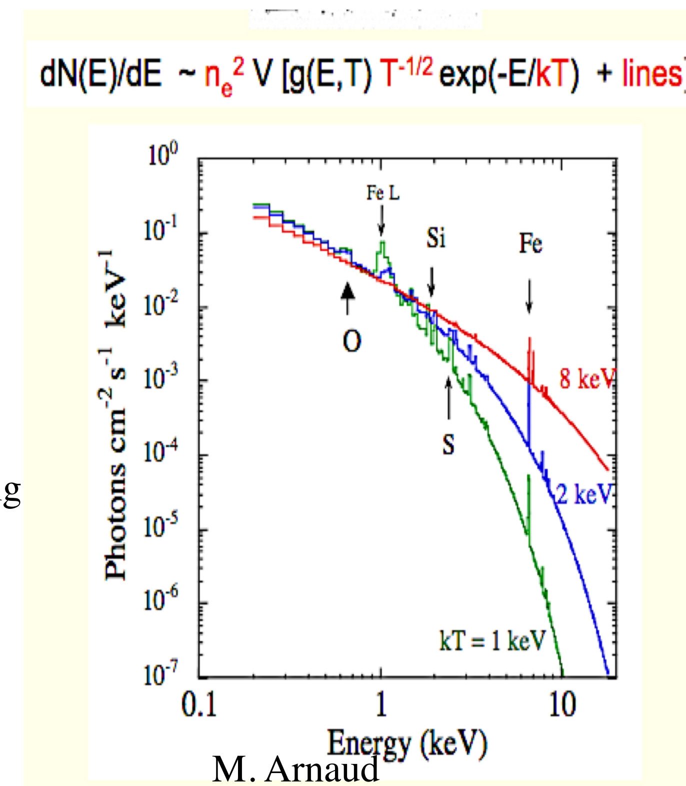
Coma cluster in X-ray and optical light

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



X-ray Spectrum of a Hot Plasma

- Continuum is due to thermal bremmstrahlung (see figure)
- 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



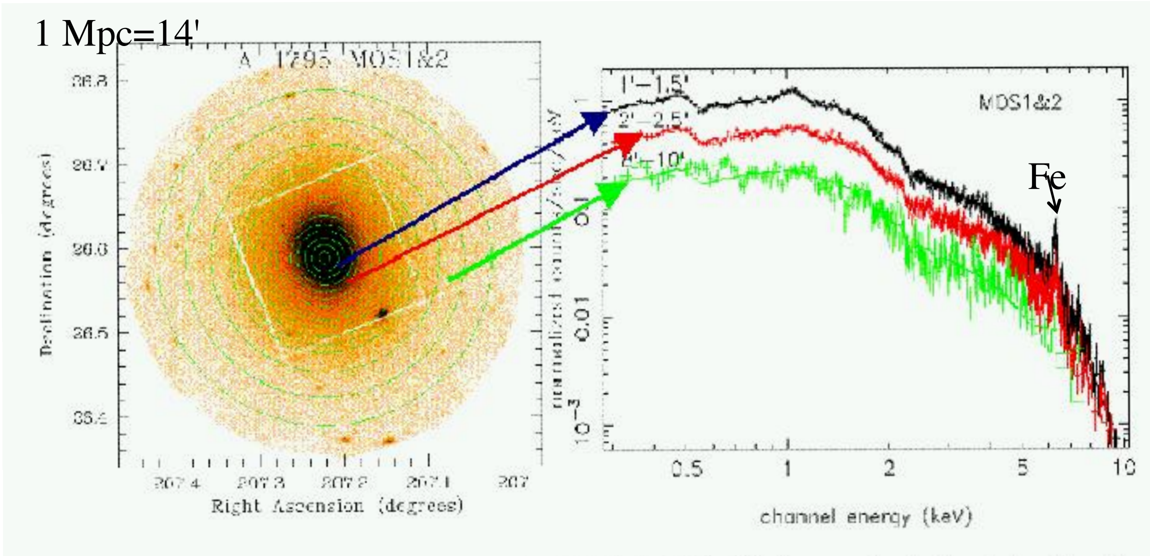
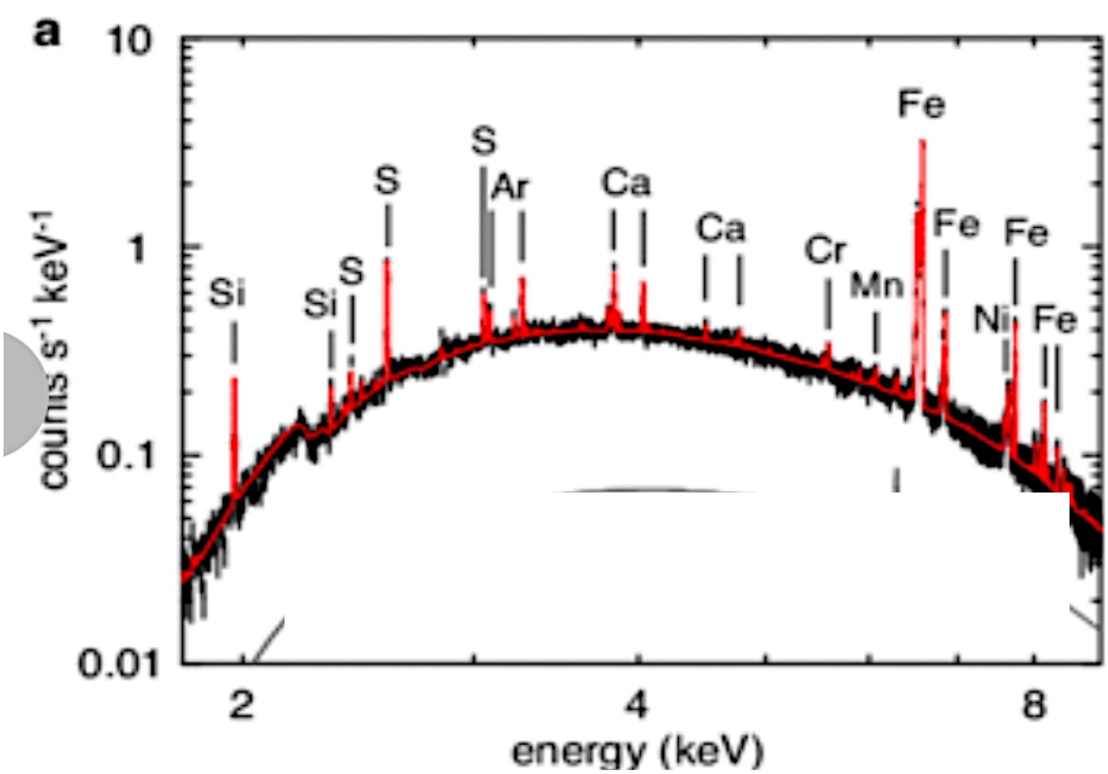


Figure 6: **Left:**Combined EPIC/MOS1&2 image of A 1795 in the [0.3 − 10]keV energy band. The circles define the

X-ray spectra of a Cluster

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

Hitomi Spectrum of Perseus Cluster



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 **of electrons**

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 $\beta^2 \sim 1$

$$\nu_c = (eB/2\pi m_e)\gamma^2$$

- to a good approximation, all the radiation of an electron of energy E is radiated at the critical frequency ν_c
  - get broad band emission due to wide range of energy of particles in a power law distribution function

Synchrotron Radiation (Melia Ch 5.4 RB sec 3.8)

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

$$\nu_c = \sim 0.016(B\sin\theta/\mu G)(E/Gev)^2 \text{ Ghz}$$

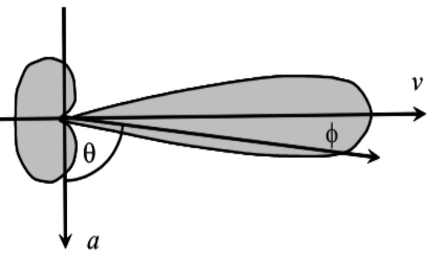
and the lifetime

$\tau = E/DE/dt \sim 1.06\times10^9 (B\sin\theta/\mu G)^{-3/2} (\nu_c/\text{Ghz})^{-1/2}$

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

The radiation is beamed in the forward direction

An 1 keV x-ray has a frequency of 2.4x10^8 Ghz and so either the B field is very strong and/or the particle energy is high to emit x-rays



Synchrotron Radiation (Melia Ch 5.4 RB sec 3.8)

To get x-ray photons (x-rays) $\nu \sim 10^{18}$ 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** (B is in gauss)

So x-ray emitting particles have short lifetimes

The most energetic particles have the shortest lifetimes

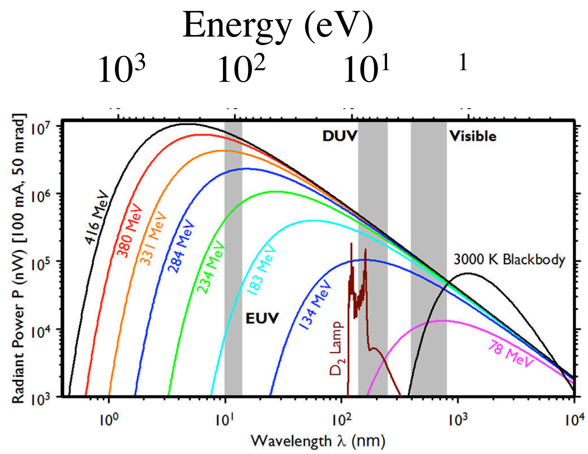
Field strengths vary enormously from 10^{-6} G in radio galaxies to 10^{13}G in pulsars

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 ⟶ 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 $\nu \sim \gamma^2 qB/mc$**



NIST website

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

Synchrotron Radiation

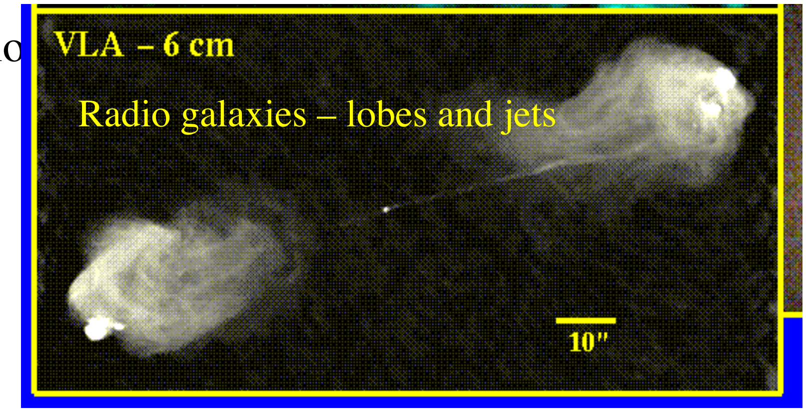
- synchrotron radiation, the emission of very relativistic and ultrarelativistic electrons gyrating in a magnetic field, is an important process in much of high energy astrophysics.

- It is responsible for
  - the radio emission from the Galaxy,
  - extragalactic radio sources
  - optical and X-ray emission observed in the Crab Nebula and other 'plerions' and 'rims' of most SNR
  - Blazar radio thru x-ray emission

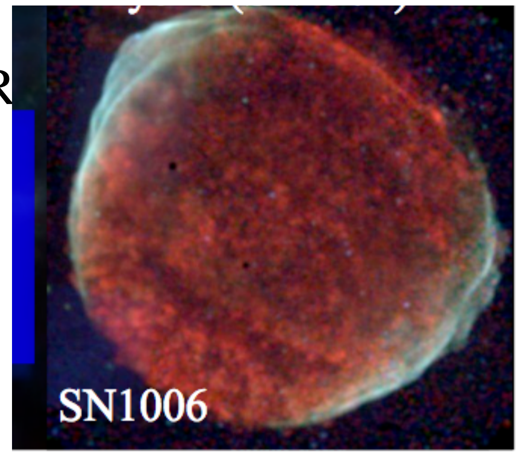
- see https://asd.gsfc.nasa.gov/Volker.Beckmann/school/download/Longair_Radiation2.pdf

Synchrotron Emissio

- 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
- Low Energy (radio-UV) Blazar continuum



'rims' of SNR



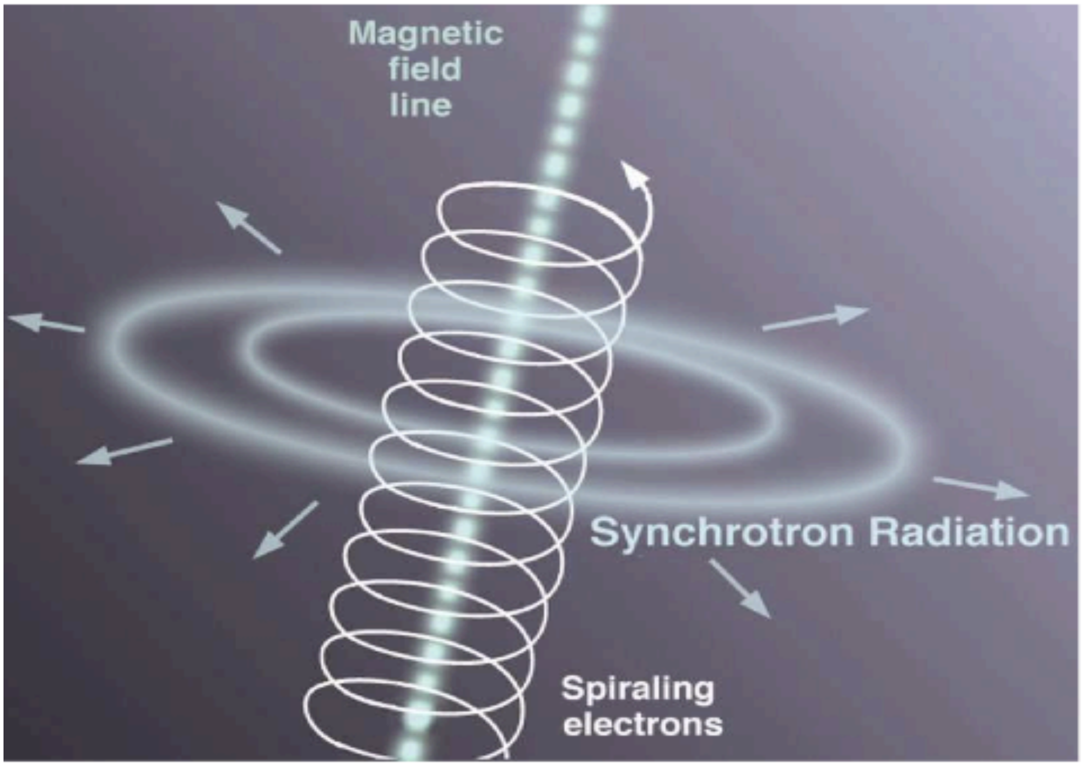
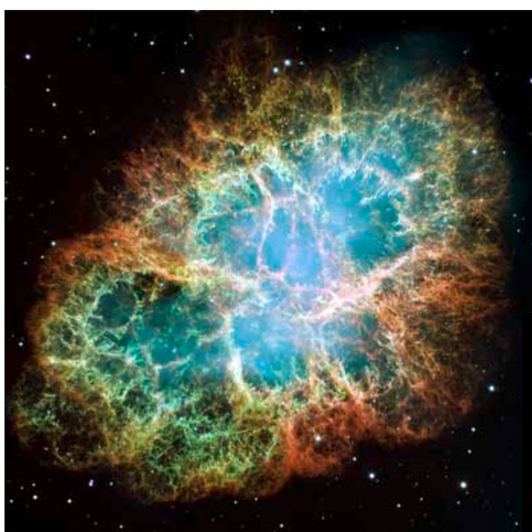


Fig. 1.— Artist's conception of synchrotron radiation. Cool figure from http://www.gemini.edu/gallery/science/m87/Synchrotron_Radiation_med.jpg

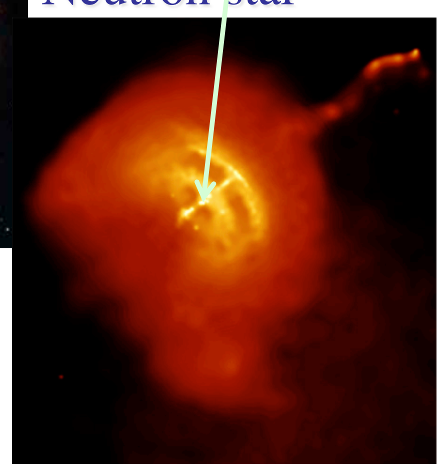
Synchrotron radiation- (some) SNR nebulae

Crab Nebula- optical IR and X-ray image

Supernova in 1054 AD



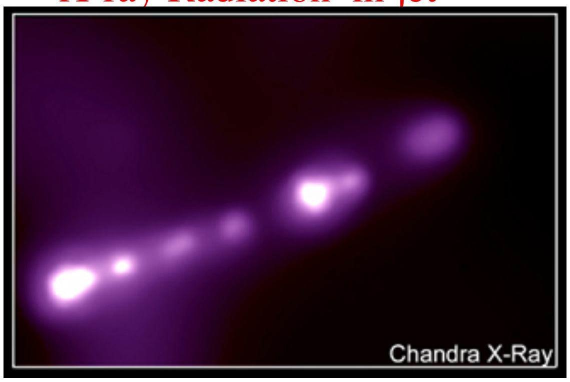
Pulsar-rotating, non-accreting Neutron star



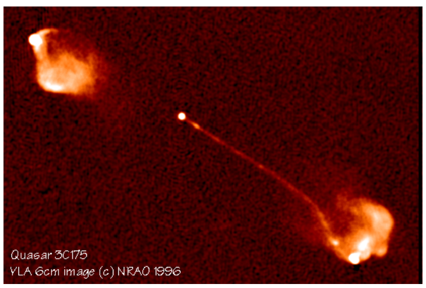
X-ray image of Vela pulsar

Synchrotron Radiation Examples

Image of M87 Synchrotron X-ray Radiation in jet

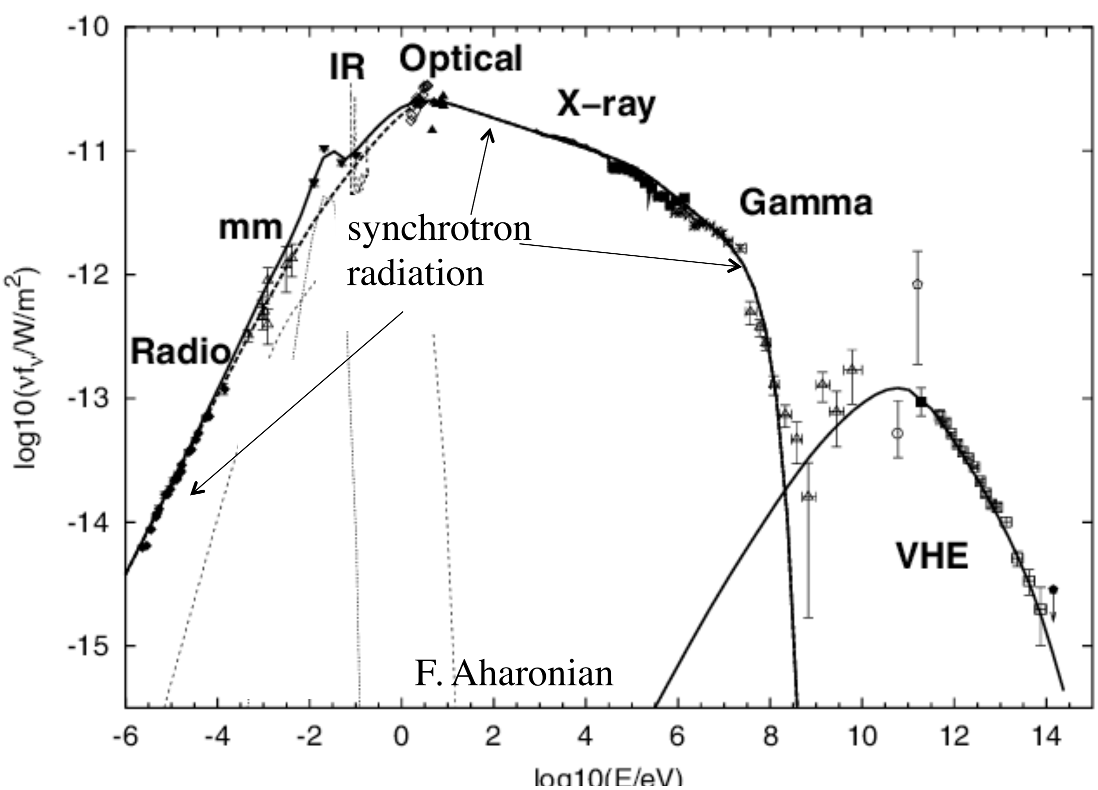


~1.5kpc=5×10^{21}cm long

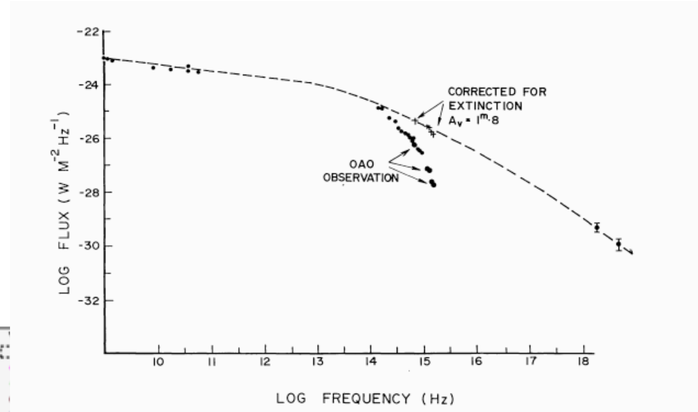


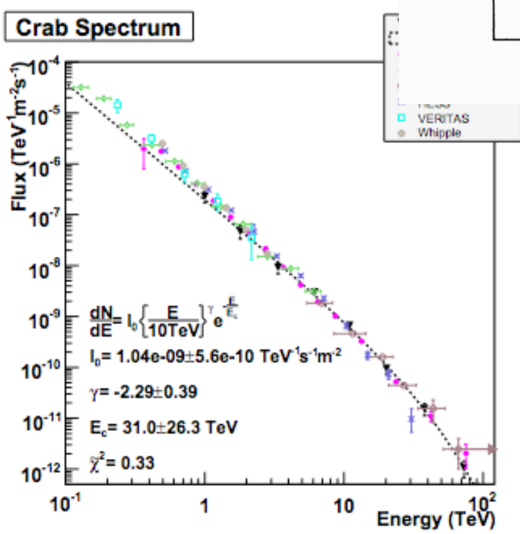
Radio image of a quasar

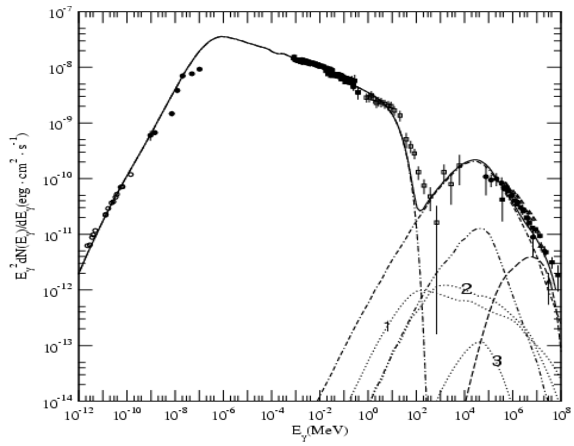
Broad Band Spectrum of Crab Nebula – 13 orders of magnitude in energy



- Crab nebulae: 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

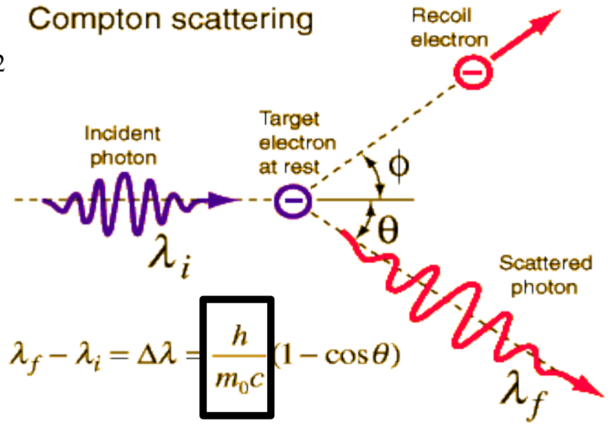
Longair Ch 9.2-9.6 (9.1in next lecture,9.4.3 not covered)RB Ch 3.8

Compton Wavelength
$=h/m_e c=0.00243$ nm for an electron

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

•Compton scattering: low-energy photon inelastically scatters off non-relativistic electron, ***photon loses energy***

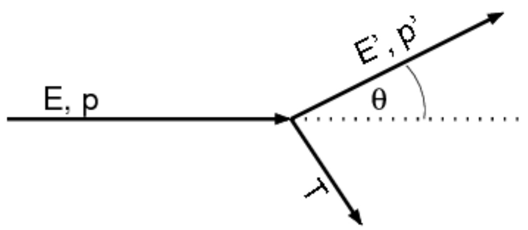
•<u>Inverse</u> Compton scattering: low-energy photon inelastically scatters off relativistic electron, ***photon gains energy in observer rest frame***



Whether the photon gives energy to the electron or vice versa

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:

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

and

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

where $h/m_e c = 2.426\times10^{-10}$ cm (Compton wavelength).

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

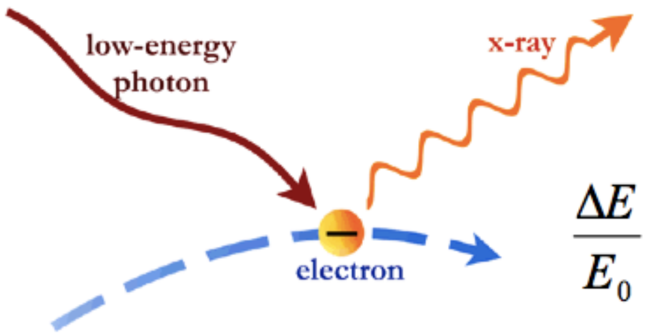
$$\frac{\Delta E}{E} \approx -\frac{E}{m_e c^2} \qquad (7.16)$$

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

INVERSE COMPTON EMISSION

https://asd.gsfc.nasa.gov/Volker.Beckmann/school/download/Longair_Radiation3.pdf

- 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

- $-(dE/dt) = \sigma_T c U_{rad}$,
- for relativistic particles
- $-(dEdt) = 4/3_T c U_{rad}(\gamma^2 - 1)$.
- The life time of the electron is
- $\tau = E|dE/dt| = E/(4/3)\,\sigma_T c\,\gamma^2 U_{rad}$

$\sim 2.3\times10^{12}\gamma\ (U_{rad}/2.6\times10^{-1}\text{eV cm}^{-3})^{-1}$ years

  - where $U_{rad}$is the energy density of radiation in the rest frame of the electron
  - the maximum energy which the photon can acquire corresponds to a head-on collision in which the photon is sent back along its original path.
  - The general result that the frequency of the scattered photons is $E \approx \gamma^2 E_0$

Compton Scattering

- Consider the scattering of radio, infrared and optical photons scattered by electrons with γ=1000.(V. Beckmann

Waveband	*Frequency (Hz)* ν_0	*Scattered Frequency (Hz) and Waveband*
Radio	10^9	10^{15} = UV
Far-infrared	3×10^{12}	3×10^{18} = X-rays
Optical	4×10^{14}	$4 \times 10^{21} \equiv 1.6$MeV = γ-rays

- The spectrum of the inverse Compton scattering of photons of energy E by a power-law distribution of electron energies $dN \propto E^{-p}dE$ gives a intensity spectrum of the scattered radiation of the form $I(E) \propto E^{-(p-1)/2}$

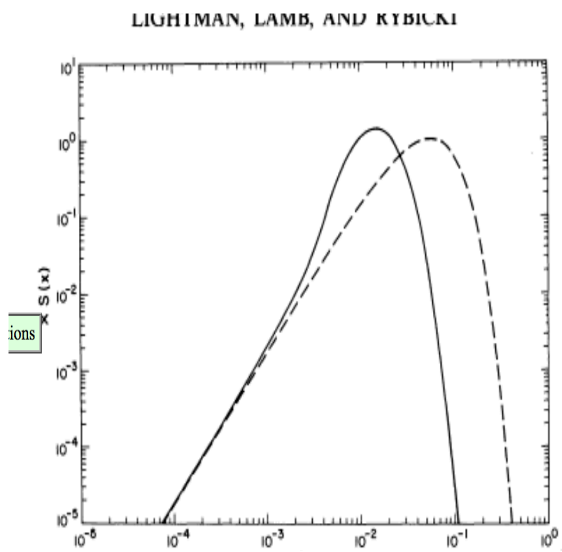
Inverse Compton Scattering

- In many x-ray sources the x-ray photons are due to the 'upscattering' of low energy photons by 'energetic' electrons and what we observe is due to many photons being scattered
- Inverse Compton scattering involves the scattering of low energy photons to high energies by energetic electrons so that the photons gain and the electrons lose energy.
  - The process is called inverse because the electrons lose energy rather than the photons, the opposite of the standard Compton effect.

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

Input spectrum is a BB----



Energy (arb units)

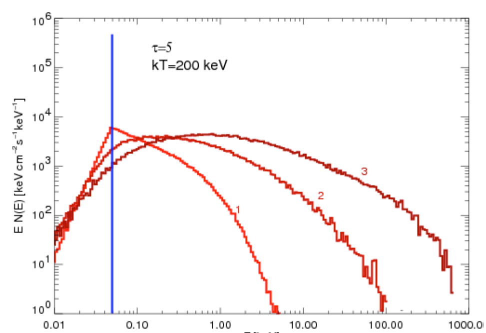
Sphere τ=10- cold electrons ApJ 248,738 1981

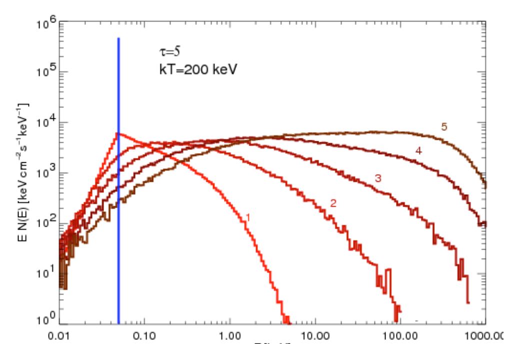
Inverse Compton scattering

- 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)

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





Relative Power in Compton and Synchrotron Radiation

$dE/dT = P_{IC} = 4/3\sigma_T c^2 U_{rad} \beta^2\gamma^2$

net inverse-Compton power gained by the radiation field and lost by the electron. $(\beta^2 = (v^2/c^2))$

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

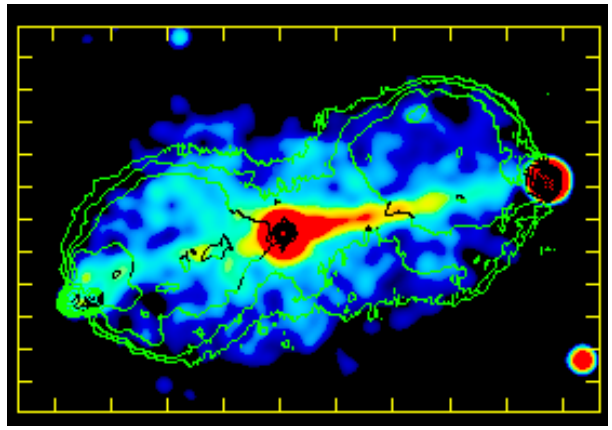
And U_{rad} is the energy density of the photon field

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

Ratio of Synchrotron to Compton

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- *board*

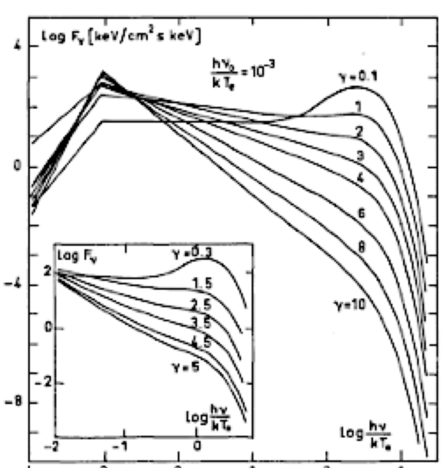


Fig. 5. The spectrum resulting from comptonization of low-frequency photons ($h\nu_0 = 10^{-3}$ kT$_e$) in a high temperature plasma clouds with different parameters γ (14)

- ***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 ($\alpha = \Gamma - 1$)

$E_c = kT$ = cutoff energy

Sunyaev & Titarchuk 1980