The Next 2-3 Lectures

- Today we are continuing the intro to the field and will discuss
- atmospheric transmission (Longair fig 1.3, Melia sec 1.3) ,
- the objects of high energy astrophysics (e.g. neutron stars, black holes, clusters of galaxies) from a very broad perspective (Rosswog and Bruggen ch 5.1 and Melia sec 10.1)
- a bit of the history of the field, (see heasarc.gsfc.nasa.gov/docs/heasarc/headates/heahistory.html
- A bit about instrumentation

Physical Processes-Longair parts of sec II Melia ch 5 and Rosswog and Bruggen ch 3

Black body radiation
Synchrotron Radiation
Compton Scattering
Line emission and absorption
Absorption (not in the recommended texts- see

In Response to Alex's Question

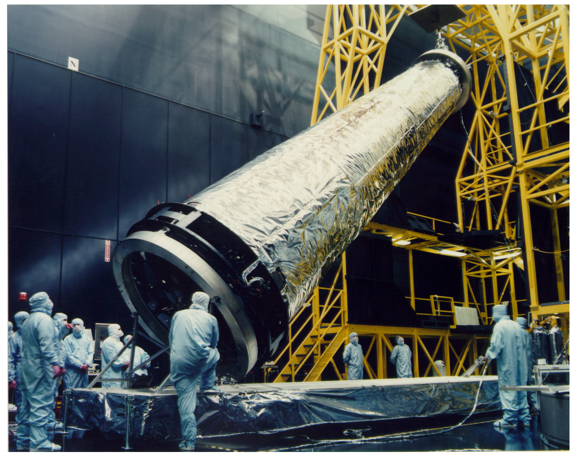
- Schmidt (1970) wrote: "We use the term —quasar for the class of objects of starlike appearance (or those containing a dominant starlike component) that exhibit redshifts much larger than those of ordinary stars in the Galaxy.
- QSOs are quasars selected on the basis of purely optical criteria, while QSSs are quasars selected on both the optical and radio criteria. "
- Chandrasekhar , the Editor of the Astrophysical Journal , responded with a footnote saying: "The Astrophysical Journal has until now not recognized the term —quasar; and it regrets that it must now concede: Dr. Schmidt feels that, with his precise definition, the term can no longer be ignored ."
- The term quasar ‘ has caught on' and is now commonly used in both the popular and professional literature.
- https://arxiv.org/ftp/arxiv/papers/1304/1304.3627.pdf in he Caltech conference —Fifty Years of Quasars

(http://www.astro.caltech.edu/q50/Home.html)

- The atmosphere is opaque (at ground level) to all wavelengths from γ-rays (GeVs) to ultra-violet(10^{11}-10 eV;1eV=1.6×10^{-12} ergs/cm^2/sec)**
- Thus to detect 'high energy' photons need to go to space*
- Space missions are expensive and take a lot of time

*its possible to detect TeV photons from the ground

** I will use CGS rather than MKS- it is traditional in astrophysics- I will also often use eV, keV etc for energy and flux in photons/cm^2/sec/energy

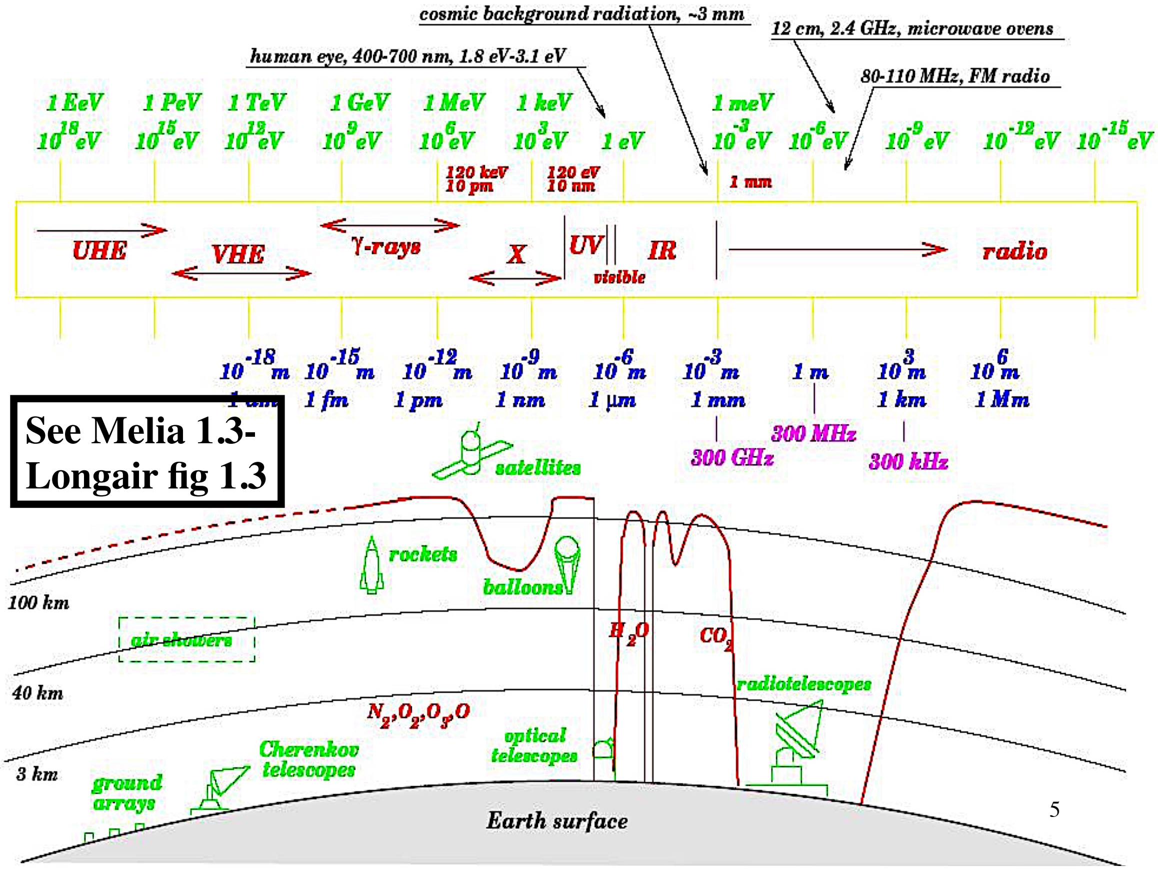


Chandra Optical Bench

Why All this Emphasis on Space Observatories ?

The history of the field is thus tied to the opening up of the space age

The sociology is thus very different,
space observatories have a finite lifetime
strong mass limits into how big something
can be and still be affordable. (Chandra is 5,860 kg,
HST 10,863 kg
Fermi 4,303 kg
JWST 6200 kg)



See Melia 1.3- Longair fig 1.3

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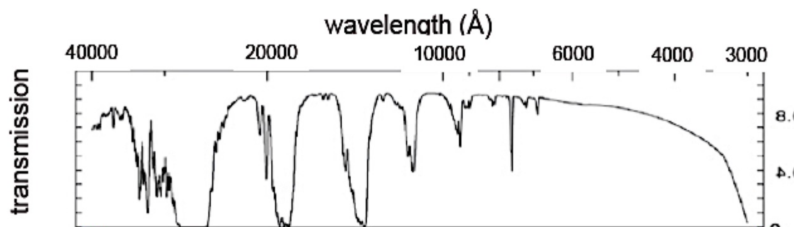
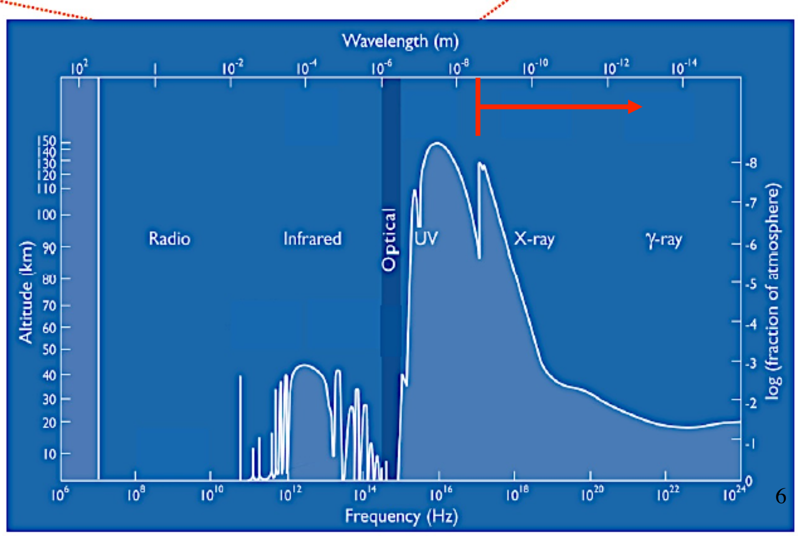
Atmospheric transmission



optical-near IR

Why go into space?
High Energy Photons get absorbed in earths atmosphere- graph shows atmospheric height at which 1/2 of photons absorbed



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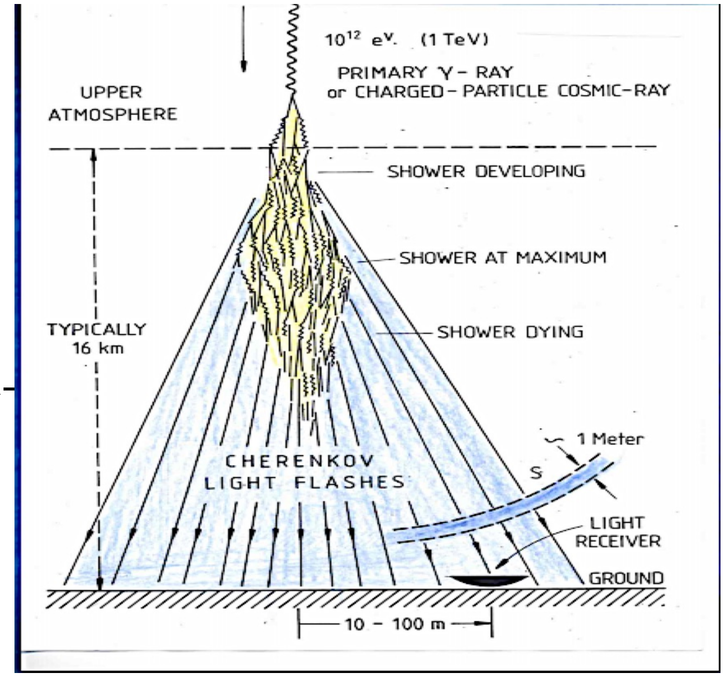
Very High Energy Cosmic Rays and TeV Astronomy

- Very high energy photons and cosmic rays interact in the atmosphere but produce observable effects from the ground (e.g. HAWC-https://www.hawc-observatory.org/science) and HESS-https://www.mpi-hd.mpg.de/hfm/HESS/)



Weekes 2007

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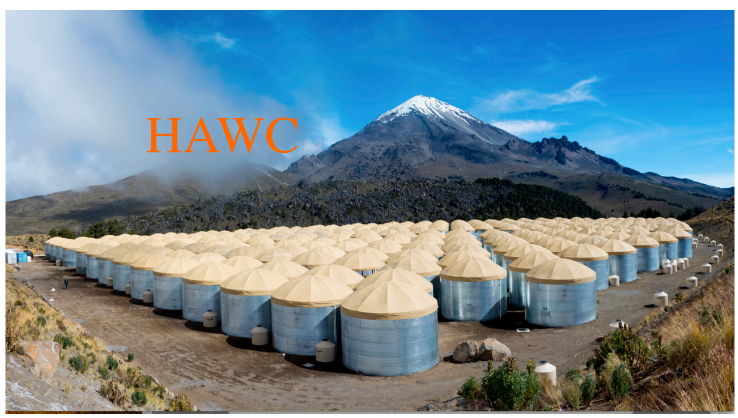
- While HAWC and HESS both are ground based very high energy γ-ray detectors they use VERY different technologies



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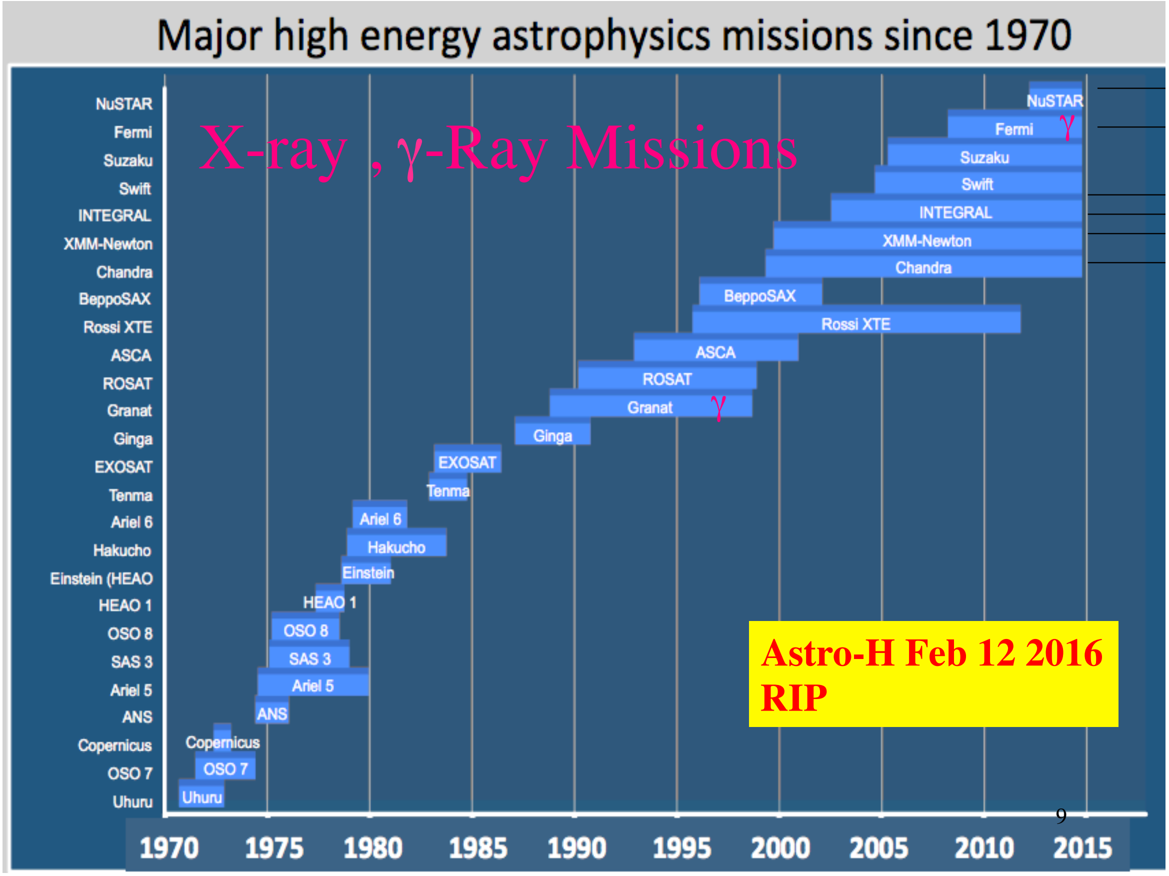


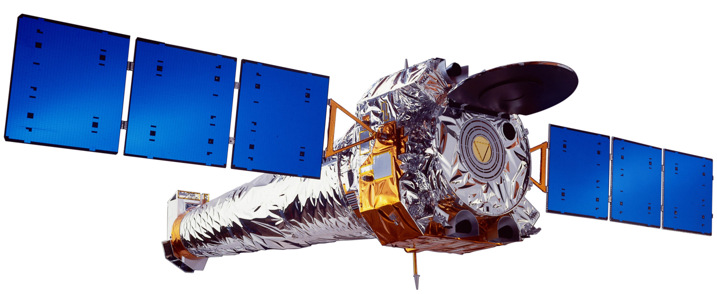
Operating Satellites

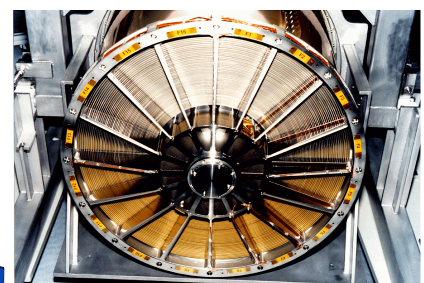
- Chandra 1999
- XMM-Newton (ESA) 1999
- INTEGRAL 2002
- Swift 2004
- Agile (γ) 2007
- Fermi (γ) 2008
- Nustar 2012
- AstroSat (Indian) 2015
- NICER (ISS) 2017
- HMXT China 2017

eRosita (Russia/Germany) 2019 (?)

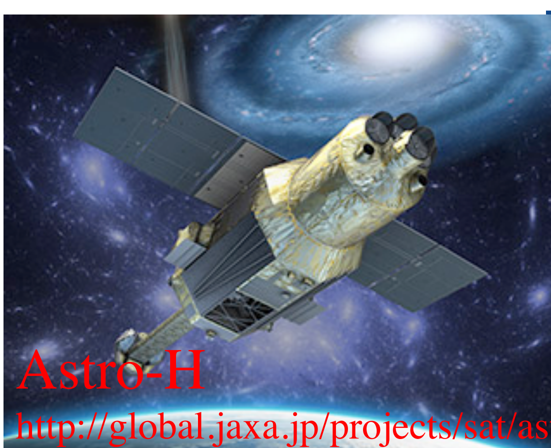
Each has a different set of instruments and capabilities https://heasarc.gsfc.nasa.gov/docs/heasarc/missions/comparison.html

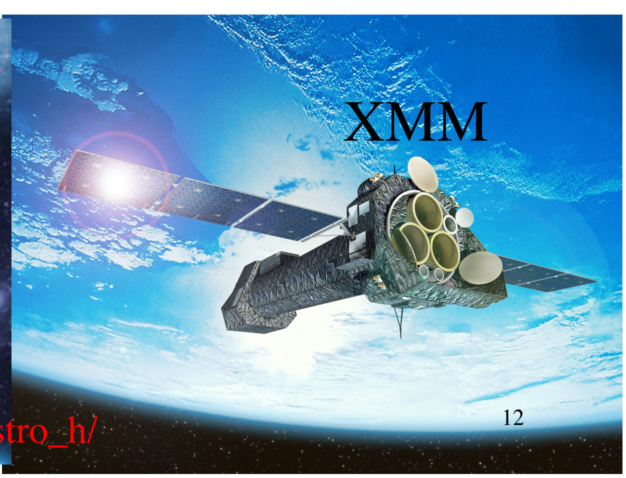
Chandra X-ray Observatory



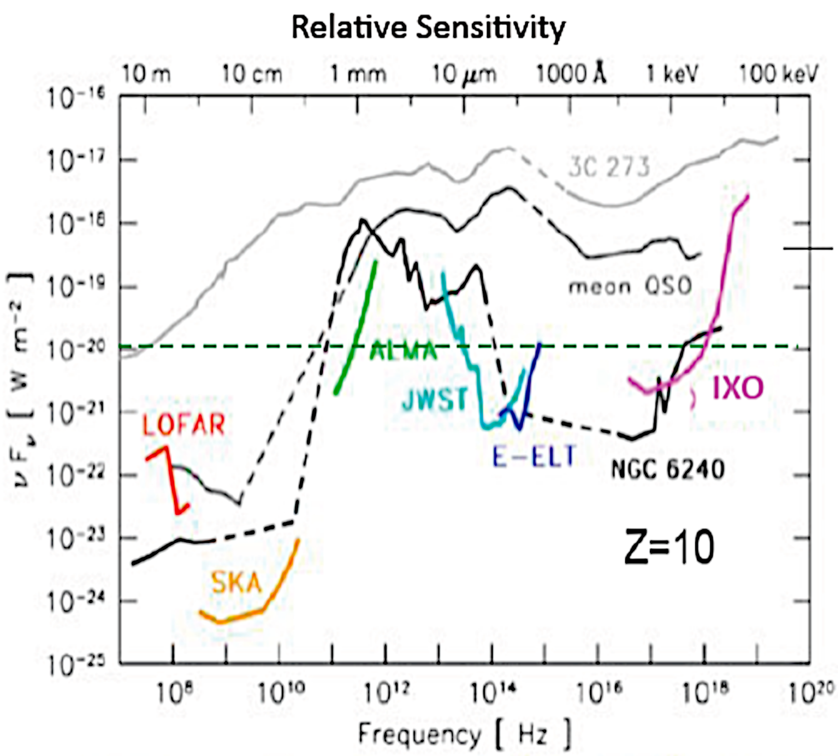


XMM mirror





Relative Sensitivity of Astronomical Observatories

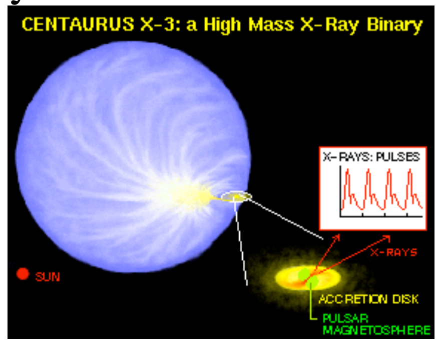


- For study of the faintest known x-ray sources one needs the largest optical and IR telescopes

The Objects of High Energy Astrophysics-Neutron Stars

Longair 13.4 ; R+B pg 161 sec 5.1

- 1934, Baade and Zwicky proposed the existence of neutron stars a year after Chadwick's* discovery of the neutron −and it 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 **accretion,** 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)

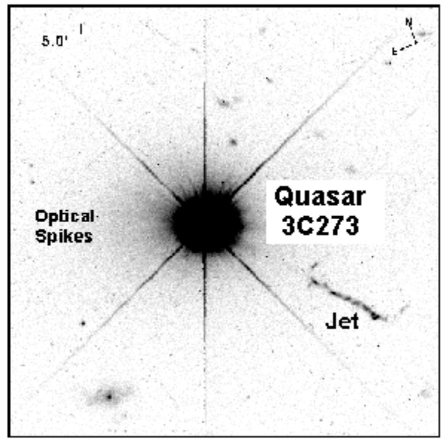
Just 2 yrs after the discovery of the neutron!

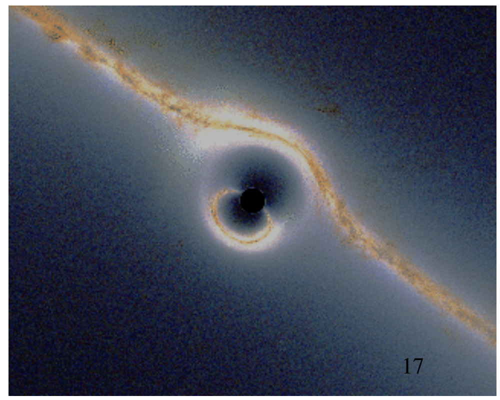
Fritz Zwicky

Black Holes Longair 19 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??) (https://arxiv.org/1304.3627.pdf)
- 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 (those with accurate masses) and a few in nearby galaxies
- ~10^8 AGN are 'known'

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





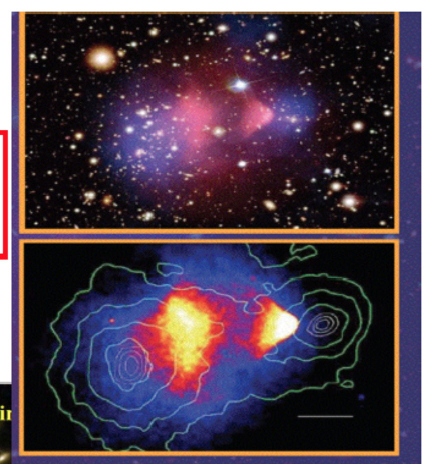
Clusters of Galaxies

Most massive and largest objects in the universe- $M>10^{14}M_\odot$ $R\sim3.08x10^{24}$ cm= 1 Mpc

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

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

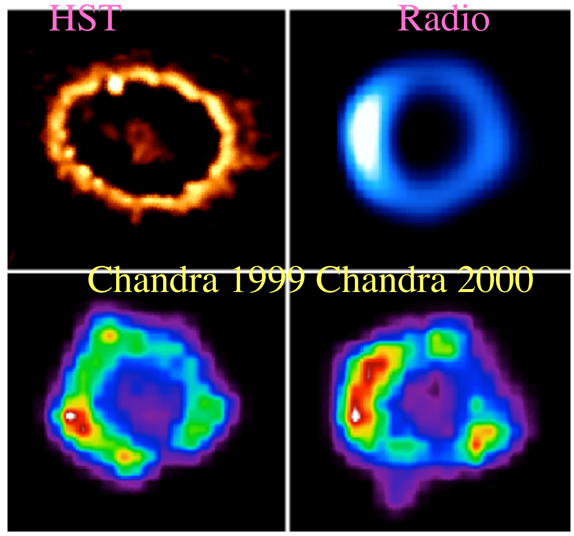
Can act as a gravitational lens**- revealing the amount of and distribution of **dark matter*****.



*Baryon- neutrons protons, nuclei of atoms

SuperNova and Remnants- Various Places in Longair

- 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)

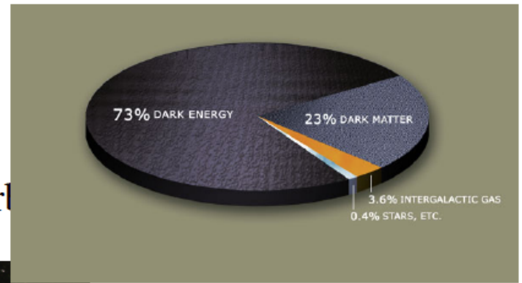
SuperNova Remnants

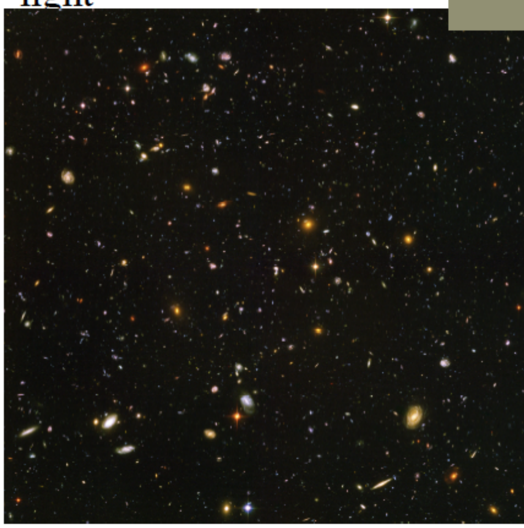
- X-ray and γ-ray emitters
  - x-rays from hot shock gas
  - γ-rays from cosmic ray interactions with material

Cas-A Chandra Image
-color coded by elements (blue is shock)

Dark Matter

- 'Dark' matter is material that interacts via gravity but does not emit or absorb light





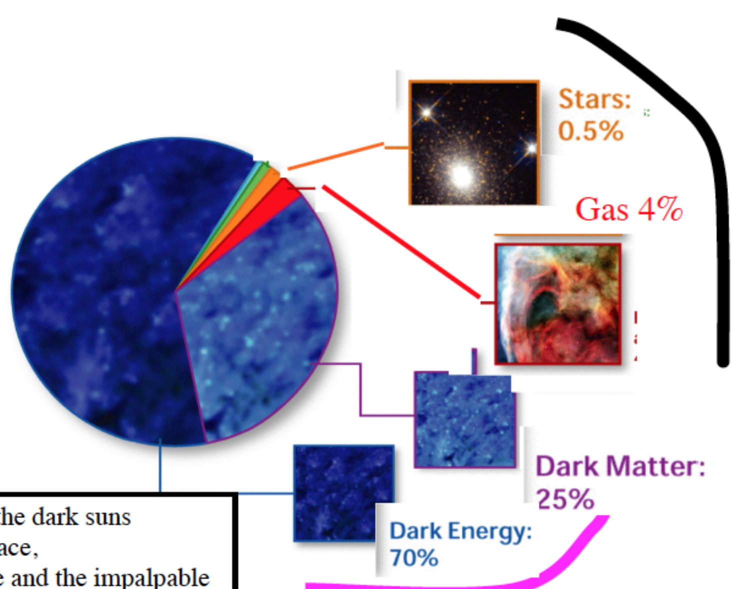
Dark matter has 6x mass of baryons averaged over the entire universe.

Hubble deep field

Dark Matter

- The biggest indication that we do not understand the universe very well
- **95% of the universe consists of stuff that is not understood and can't be 'seen'**
- **The name 'Dark Matter' conveys what we don't know**

Stuff we understand



Stuff we **don't** understand

> The bright suns I see and the dark suns
> I cannot see are in their place,
> The palpable is in its place and the impalpable
> is in its place
> **Walt Whitman Leaves of Grass**

Physical Processes Over View – More Equations Later

Melia ch 5 and Rosswog and Bruggen ch 3

- How are 'high energy' photons produced
  - Continuum

Thermal emission processes

Blackbody radiation

Bremsstrahlung

Non-thermal processes

Synchrotron radiation

Inverse Compton emission

Non-thermal bremms

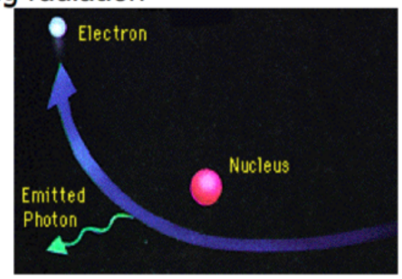
In “thermal” processes the electrons are in a Maxwell-Boltzman distribution- the system has a ‘temperature’

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

Longair 6,8,9

BREMSSTRAHLUNG

- “Braking radiation”



Examples: clusters of galaxies, supernova remnants, stellar coronae

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

Physical Processes Over View – **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

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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

The term nonthermal emission is frequently used in high energy astrophysics for the continuum radiation from a distribution of particles with a non-Maxwellian energy spectrum.

Continuum emission is often referred to as ‘non-thermal’ if its spectrum cannot be accounted for by the spectrum of thermal bremsstrahlung or black-body radiation.

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

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
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

Continuum Generation Processes

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

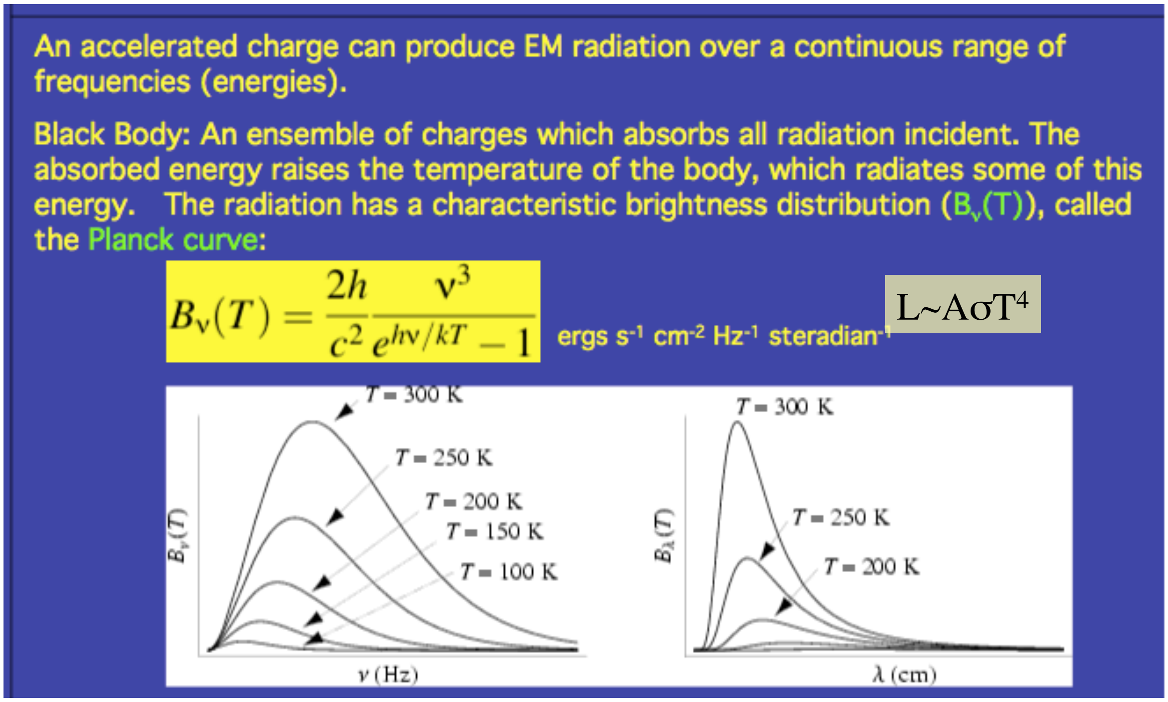
$$a = \frac{e\,\mathrm{v}}{m\,c} \times B$$

which causes the electron to spiral around the B field. The acceleration of the electron produces synchrotron radiation Longair pg 193

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



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

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

eq 8.97 Longair

- in long λ limit $\approx 2kT_b/\lambda^2$

$I(\nu,T)d\nu$ 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

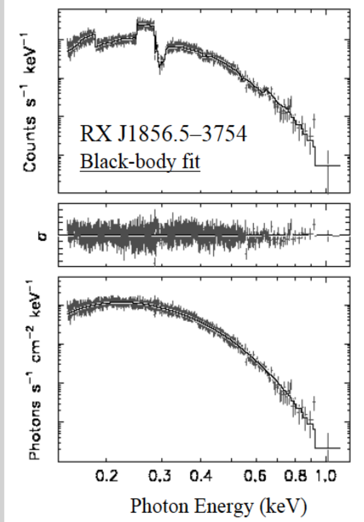
The wavelength of maximum intensity λ_m is b/T (b is Wien's constant)

The energy of maximum intensity $h\nu_m=0.245T_6$ 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
$\sigma=2\pi^5k^4/15c^2h^3$
b=0.2898 centimeter-kelvin)

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

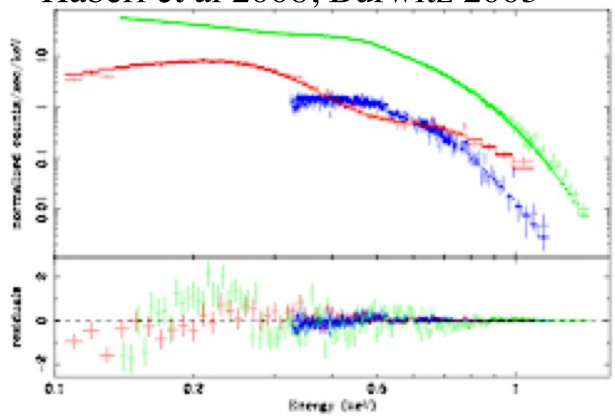


Fig. 2. Combined blackbody fit to the EPIC-PN (green), RGS (blue) and ROSAT PSPC (red) spectra of RX J0720.4−3125.

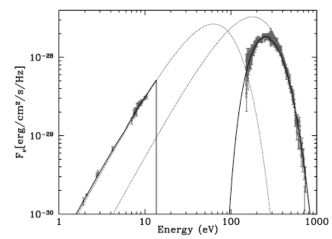


Fig. 3.| Broad band spectral fit to RX J1856 3754. Optical/UV data points are drawn from van Kerkwijk & Kulkarni (2001a) and Pons et al. (2002). The dotted lines show the unabsorbed hot and cold blackbody components.

Bremmstrahlung- Longair 6.5.1 Spectral emissivity of thermal bremsstrahlung Kaiser Ch 12

- RB pg 97 (sec 3.8.1)Melia ch 5.3 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

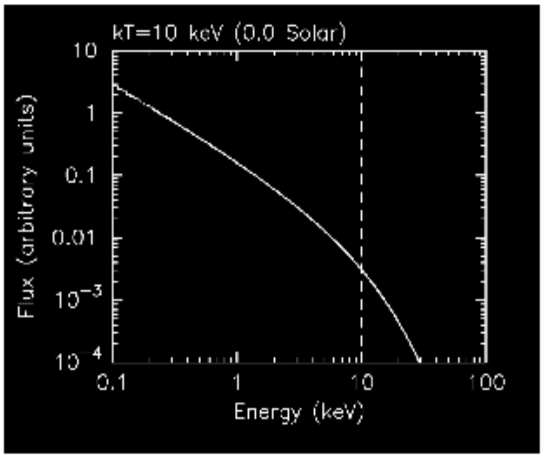
$$I(E) = A\,G(E,T)\,Z^2 n_e n_i (kT)^{-1/2} e^{-E/kT}$$

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

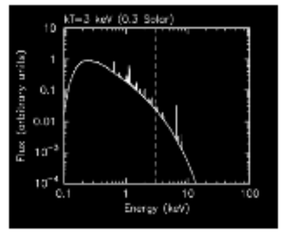
Kaiser Ch 12- Ch 5 of Bradt Ch 6.3, 6.5 of Longair

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



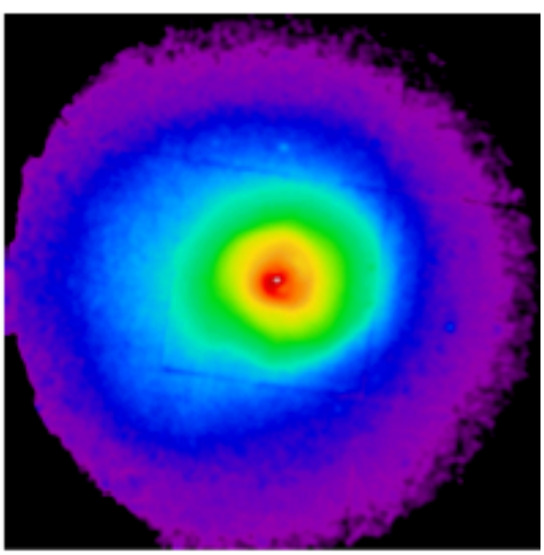
[In reality accompanied by recombination line emission]

Luminosity $L = 1.44\times10^{-27}\, T^{1/2} Z^2 n_e n_{ion} G\, V$ 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

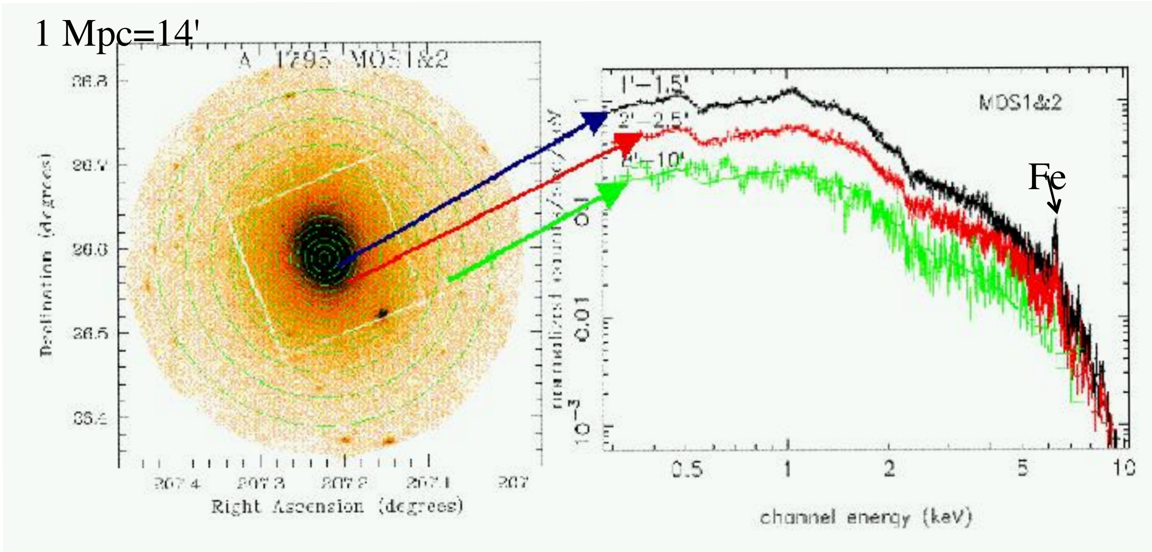
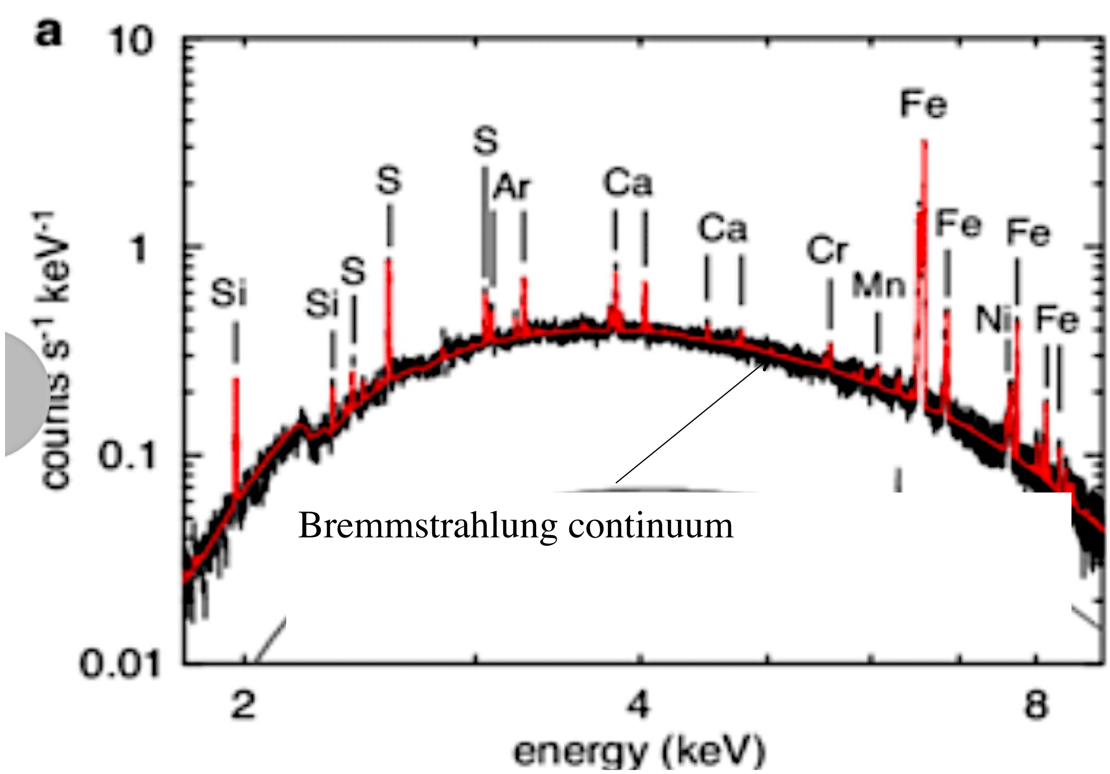


Figure 6: **Left:**Combined EPIC/MOS1&2 image of A 1795 in the [0.3 − 10]keV energy band. The circles define the

X-ray spectra of a Cluster

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

Hitomi Spectrum



SYNCHROTRON RADIATION

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

- Electrons spiralling in magnetic field

Kaiser Ch 13
Bradt Ch 8
Longair 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- Longair has a VERY long and involved discussion)

- For a single electron the characteristic frequency $\omega_{sync} = 3/2\gamma^2 B/m_e c$
- $dE/dt = P \sim B^2/m^2_e\, (v^2/c^2)\, \gamma^2$
- in Ultra-relativisitic limit $-dE/dt = 2\sigma_T c U_{mag}\gamma^2$ where U is the energy density of the magnetic field (Longair 8.8)

$\nu_c = 6.3\times10^{12}$Hz $(B(E/m_e c^2)/10^3))$; E is the energy of the electron

To get x-ray photons $\nu \sim 10^{18}$ Hz need very high energy electrons or very strong magnetic field

- To radiate at 20 keV in a magnetic field $B \sim 10^{-4}$ Gauss the Lorentz factor is γ » 4×10^7 the electron energy is $E = \gamma m_e c^2$ » 30 erg

$t_{cool} \sim m_e c^2/4/3 u_B c \sigma_T \gamma$ ~26yr $(B^{-2}\gamma^{-1})$ or ~50 years for the above example (Ghisilleni eq 4.11)

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 Continued

- For a power law electron distribution
  $N(\gamma)=K\gamma^{-p}=N(E)dE/d\gamma$

synchrotron emissivity produced by these particles is

- $\varrho_s(\nu,\theta)=(1/4\pi)\int_{\gamma min}^{\gamma max} N(\gamma)P(\gamma,\nu,\theta)d\gamma$
- $\propto KB^{(p+1)/2}\nu^{-(p-1)/2}=KB^{\alpha+1}\nu^{-\alpha}$,Longair 8.8.1

to simplify a power law photon spectrum $\varrho_s \propto \nu^{-\alpha}$. of energy slope $\alpha=(p-1)/2$ with upper and lower frequency cutoffs related to the upper and lower values of γ - at high energies there is a ~exponential cutoff

- To first order the spectrum emitted by a single electron can be approximated by $\nu s = \gamma^2\nu_L$; $\nu_L \equiv eB/2\pi m_e c$
- Synchrotron radiation can be highly polarized depending on the geometry of the magnetic field

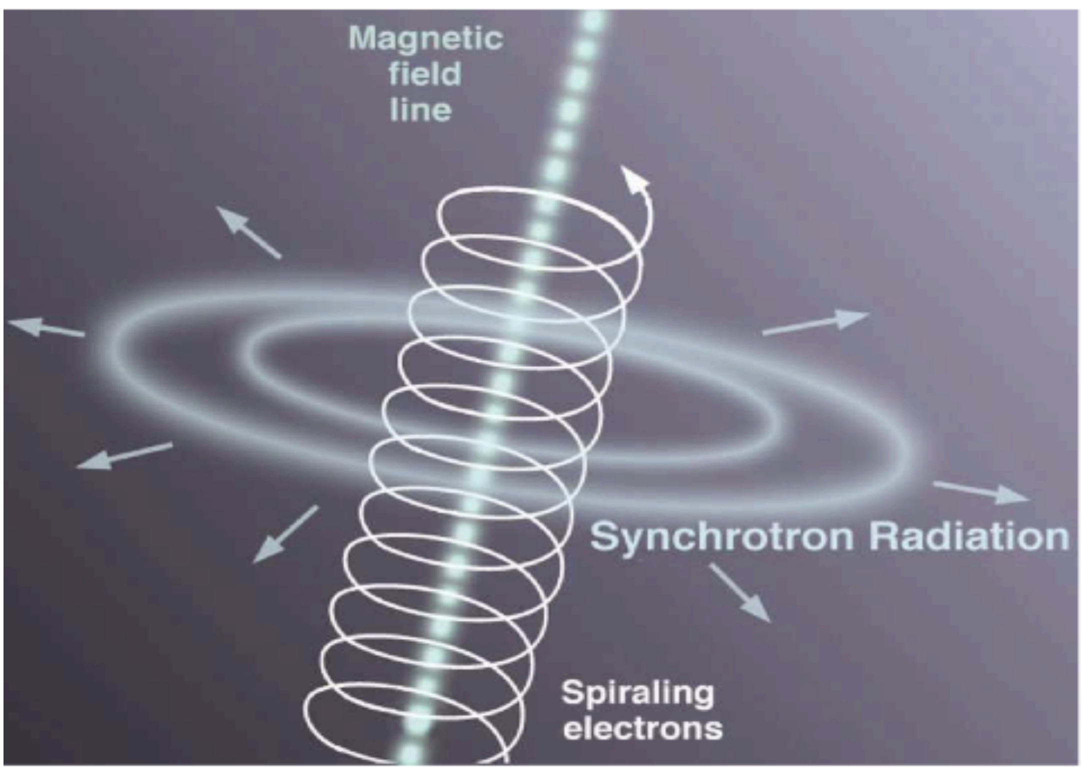
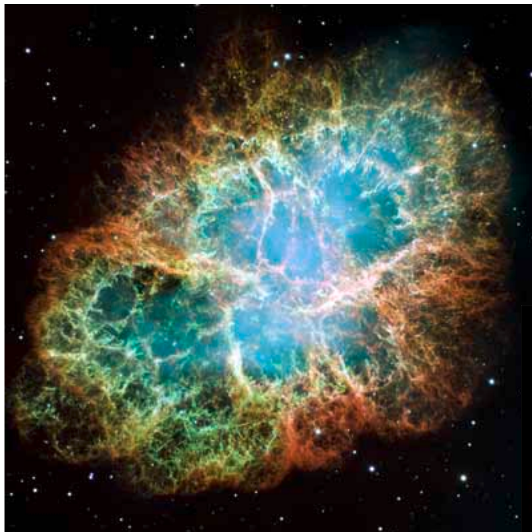


Fig. 1.— Artist's conception of synchrotron radiation. Cool figure from http://www.gemini.edu/gallery/science/m87/Synchrotron_Radiation_med.jpg

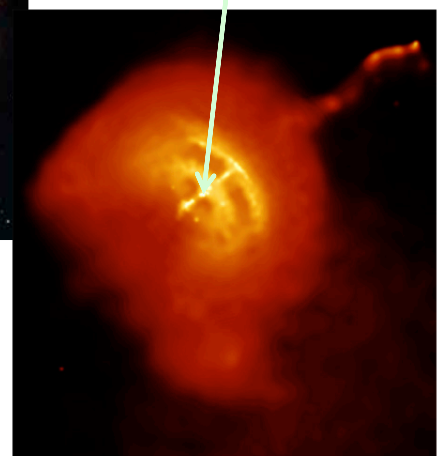
Synchrotron radiation-lit nebulae (Plerions)

Crab Nebula-optical IR and X-ray image

Supernova in 1054 AD

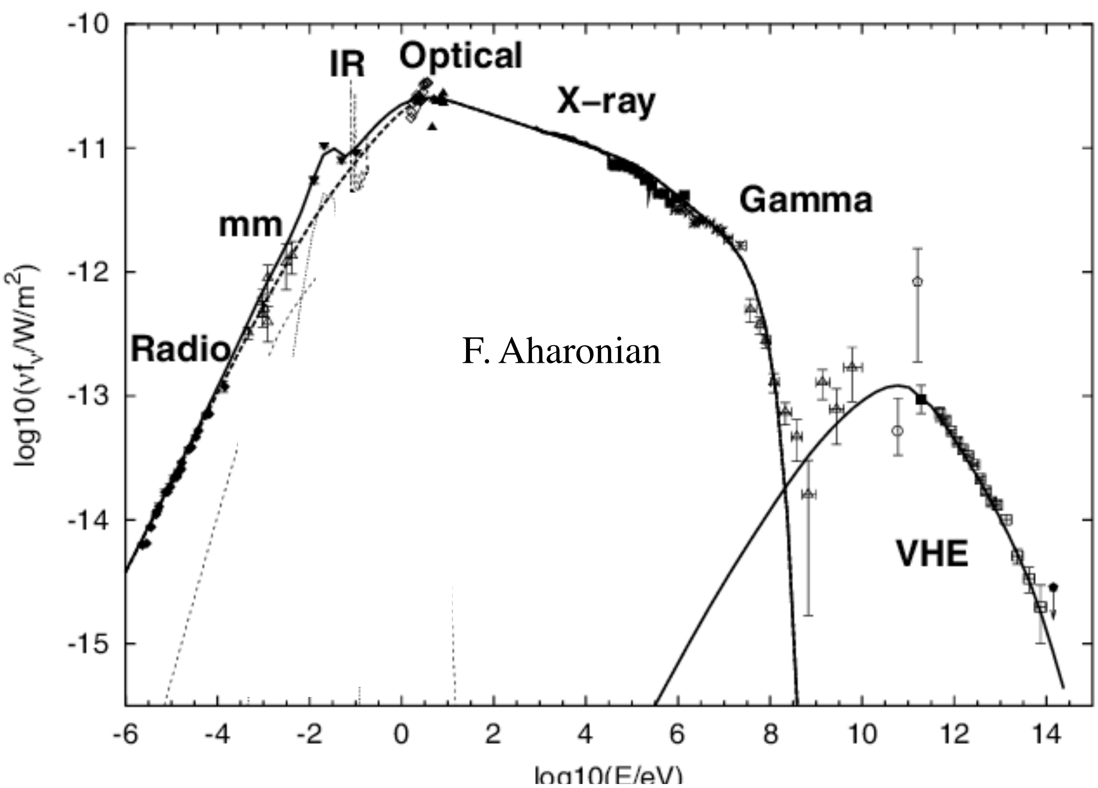


Pulsar-rotating, non-accreting Neutron star



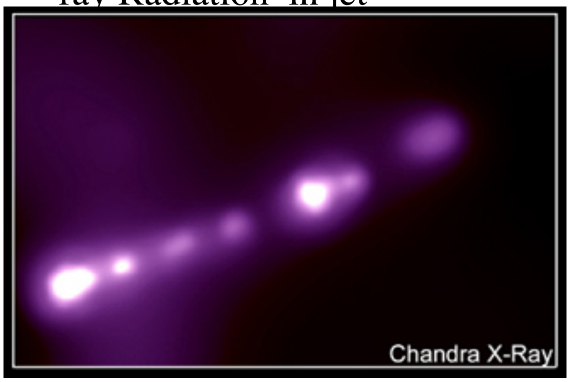
X-ray image of Vela pulsar

Broad Band Spectrum of Crab Nebula

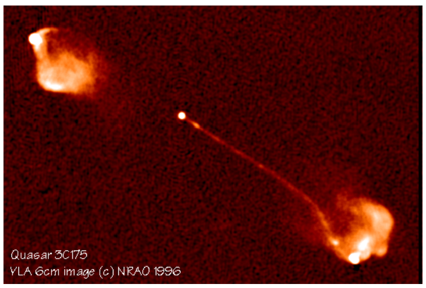


Synchrotron Radiation Examples

Image of M87 Synchrotron X-ray Radiation in jet



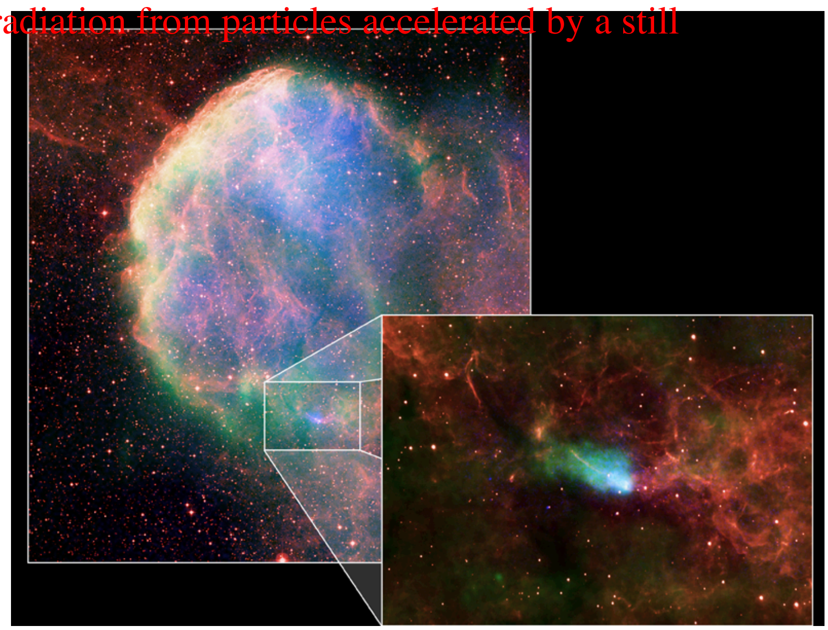
~1.5kpc=5x10^{21}cm long



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

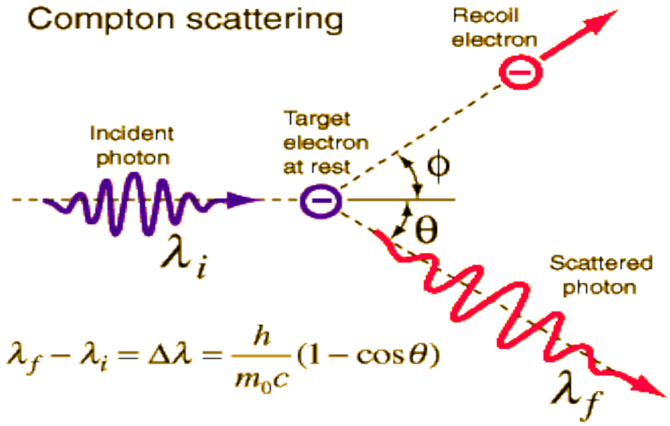


Compton Effect(s) Longair 9.2 RB Ch 3.8, Kaiser Ch 14, Bradt (Astrophysical Processes Ch 9

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

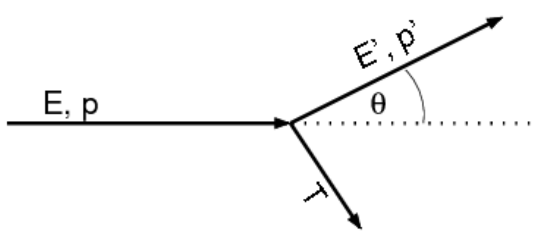
Whether the photon gives energy to the electron or vice versa

In Thomson scattering, there is no change in the frequency of the radiation.
a good approximation if d the energy of the photon is much less than the rest mass energy of the electron.



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

Compton Scattering



$\Longrightarrow$ 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:

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

and

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

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

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

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

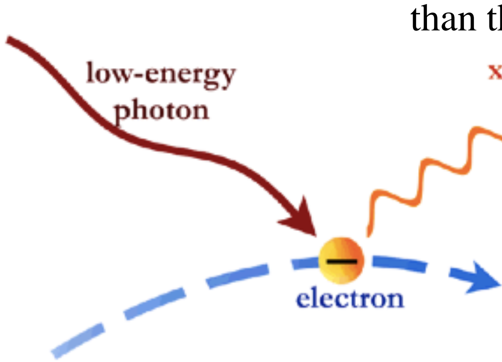
- http://pulsar.sternwarte.uni-erlangen.de/wilms/teach/radproc/radproc0177.html

INVERSE COMPTON EMISSION

Longair 9.3

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

the electrons lose energy rather than the photons.



dE/dt= $\sigma_T c U_{Rad}$, U_{Rad}=energy density of radiation

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

9.51 Longair

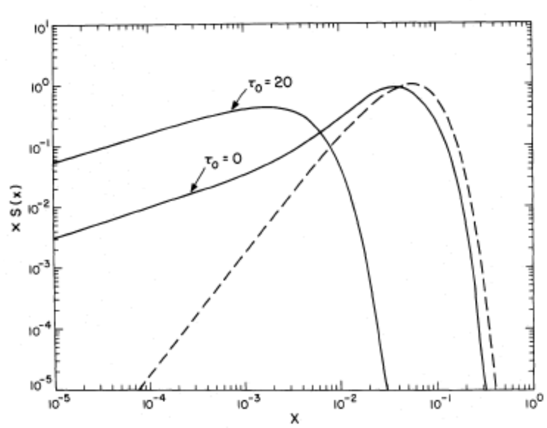
Examples in X-ray astronomy: active galactic nuclei (AGN), X-ray binaries

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.
- Thermal Comptonization
  - 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

the frequency of photons scattered by ultra-relativistic electrons is $\nu \sim \gamma^2 \nu_0$

COMPTONIZATION BY COLD ELECTRONS



INVERSE COMPTON EMISSION

- Results depend on source geometry

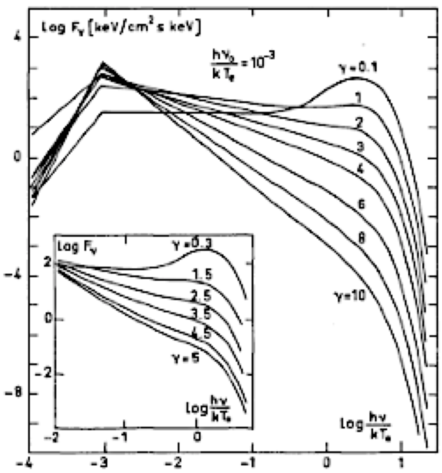


Fig. 5. The spectrum resulting from comptonization of low-frequency photons ($h\nu_0 = 10^{-3}$ kT$_e$) in a high temperature plasma clouds with different parameters γ (14)

Sunyaev & Titarchuk 1980

- ***Power law***

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

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

A,B normalizations

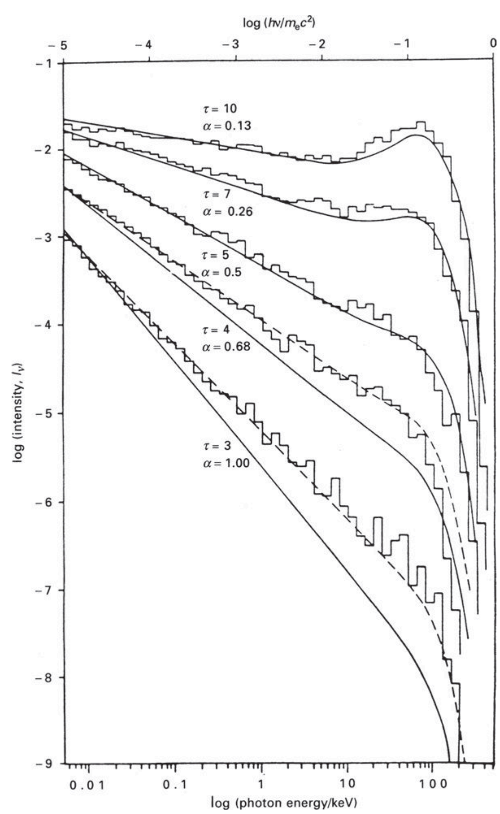
F,Γ ***photon*** flux photon index

I,α ***energy*** flux, index (α=Γ-1)

E_c=*kT*=cutoff energy

- Comptonization from a thermal distribution can produce a power law distribution of photons (fig 9.9 Longair) with a spectral index
- $m = -3/2 + [9/4 + y]^{1/2}$
- $y = \pi^2/3\ [m_e c^2/(\tau+2/3)^2\ kT_e]$

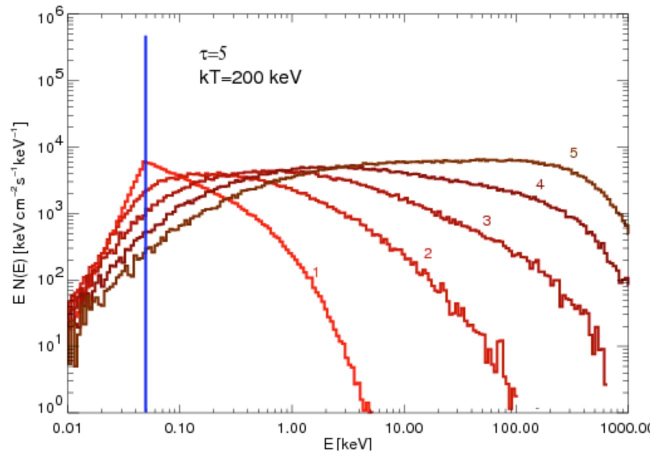
9.102 Longair



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 Comptonized spectrum with $kT_e \sim 100$ kev, $y \sim 1$ ($y=4kT_e/m_ec^2(\max(\tau,\tau^2))$)

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.

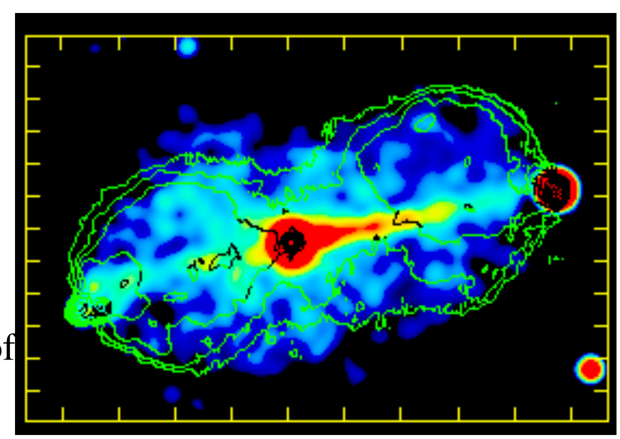
Synchrotron power
$P_{synch}=4/3\sigma_T c^2 U_B\beta^2\gamma^2$

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

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

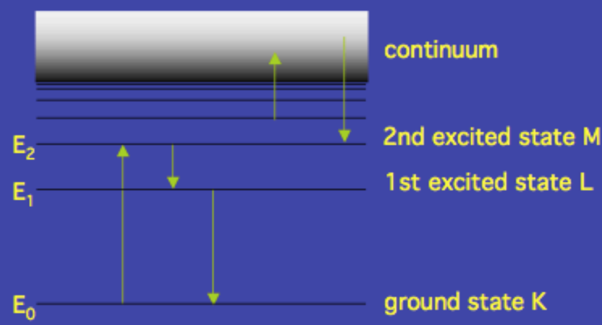
Ratio of Synchrotron to Compton is U_B/U_{rad}

'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.