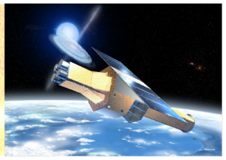
Astro-H Summer Workshop for Science



Non-thermal Radiation Processes

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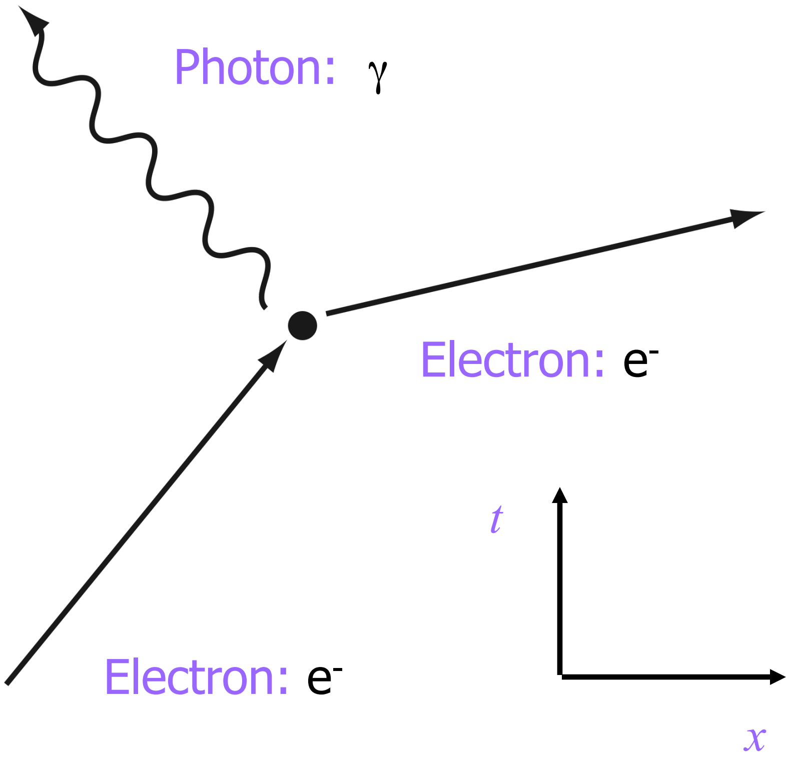
With help from Drs. Eskandarian, Maximon and Parke (GWU) and Harrus (NASA HQ)

Making Photons

A basic Feynman diagram.

All radiative transitions can be understood in this way; if you get confused, this can be a good way to regain your grounding.



Making Photons

- Bound particles have quantized energies E_i. Transitions of charges from excited states to lower-energy bound states makes photons with energies peaked at $\Delta E = E^*_i - E_j$. X-rays and gamma rays are possible from
  - Atomic transitions for tightly-bound electrons
  - Nuclear photo-transitions
  - Spin flip in strong B fields
  - Landau level changes in strong B fields
- "Unbound particles" have a "continuum" of possible energies; Acceleration of these can produce a continuum of photon energies.

Introduction

Non-thermal radiation creates a continuum, rather than lines.

Relevant Processes:

- Synchrotron radiation
- Compton & Inverse Compton radiation
- Thick-target Bremsstrahlung

Assumptions

- We will make some initial assumptions about our "astrophysical plasmas":
  - They are dominated by H and He, with trace metals.
  - Nuclear transitions are insignificant.

However, magnetic fields play an important role, and it is not always be true that electrons have a Maxwellian velocity distribution!

Cyclotron/Synchrotron Radiation

- **Radiation emitted by charge moving in a magnetic field**.
- First discussed by Schott (1912). Revived after 1945 in connection with problems on radiation from electron accelerators.
- Very important in astrophysics: 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…

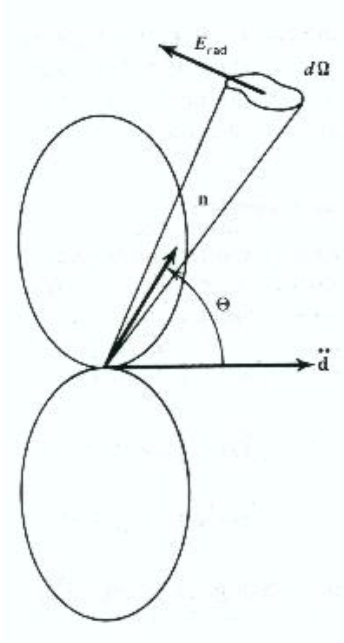
Cyclotron/Synchrotron Radiation

- Cyclotron radiation comes from a non-relativistic electron, gyrating in a magnetic field, while synchrotron radiation is by definition relativistic.
- In the non-relativistic case, the frequency of gyration in the magnetic field is

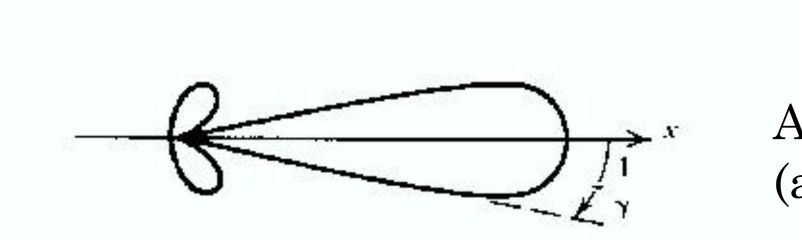
$$\omega_L = eB/m_e c$$

$$= 2.8\ B_{1G}\ \mathrm{MHz}\ (\mathrm{Larmor})$$

- The frequency of the emitted radiation is $\boldsymbol{\omega_L}$



Synchrotron Radiation



Angular distribution of radiation (acceleration ⊥ velocity). [Rybicki & Lightman]

- Synchrotron radiation comes from relativistic electrons interacting with a magnetic field. In this case, the emitted radiation is "beamed" along the velocity vector, with an opening angle

$$\Delta\theta \sim 1/\gamma$$

- Gyration frequency $\omega_B = \omega_L/\gamma$
- Observer sees radiation for duration $\Delta t <<< T = 2\pi/\omega_B$
- This means that the spectrum includes higher harmonics of ω_B.
- The maximum is at a characteristic frequency which is:

$$\omega_c \sim 1/\Delta t \sim \gamma^2 e B_\perp / mc$$

Synchrotron Radiation

The total emitted power is:

$$P = \frac{2e^4 B_\perp^2}{3m_e^2 c^3 \beta^2 \gamma^2} = \frac{2}{3} r_0^2 c \gamma^2 B_\perp^2$$ when $\gamma >> 1$

Or, alternatively $P \propto \gamma^2 c \sigma_T U_B \sin^2\theta$ (where U_B is the magnetic energy density

and so $P \sim 1.6 \times 10^{-15} \gamma^2 B^2 \sin^2\theta \ \mathrm{erg/s}$

Electron lifetime: $\tau \propto E/P \sim 20/(\gamma B^2)$ yr

This is sometimes called "electron burn-off"; in the Crab Nebula, the lifetime of an X-ray producing electron is only 20 years (!)

Note that $P \propto 1/\mathrm{mass}^2$: synchrotron is negligible for massive particles.

Synchrotron Radiation

Synchrotron radiation comes from relativistic electrons spiraling around magnetic fields. Can we use X-ray measurements to determine either the:

- electron distribution?
- magnetic field?

Synchrotron Radiation

Assume the energy spectrum of the electrons between energy E_1 and E_2 can be approximated by a power-law:

$$N(E) = K\,E^{-\rho}\,dE \quad \text{(isotropic, homegeneous).}$$

where N(E) is the number of e^- per unit volume

Intensity of radiation in a homogeneous magnetic field:

$$I(\nu,k) = \frac{\sqrt{3}}{\rho+1}\Gamma\left(\frac{3\rho-1}{12}\right)\Gamma\left(\frac{3\rho+19}{12}\right)\frac{e^3}{mc^2}\left(\frac{3e}{2\pi m_e^2 c^5}\right)^{(\rho-1)/2} K\,[B\sin\theta]^{(\rho+1)/2}\,\nu^{-(\rho-1)/2}$$

This complex result does lead to one simple conclusion:

$$I(\nu) \propto \nu^{-(\rho-1)/2}$$

or, equivalently $$I(E) \propto E^{-(\rho-1)/2}$$

Synchrotron Radiation

$$N(E) = K\, E^{-\rho}\, dE \quad \text{for } E_1 < E < E_2$$

We know ρ; can we get K, E_1,E_2, or B?

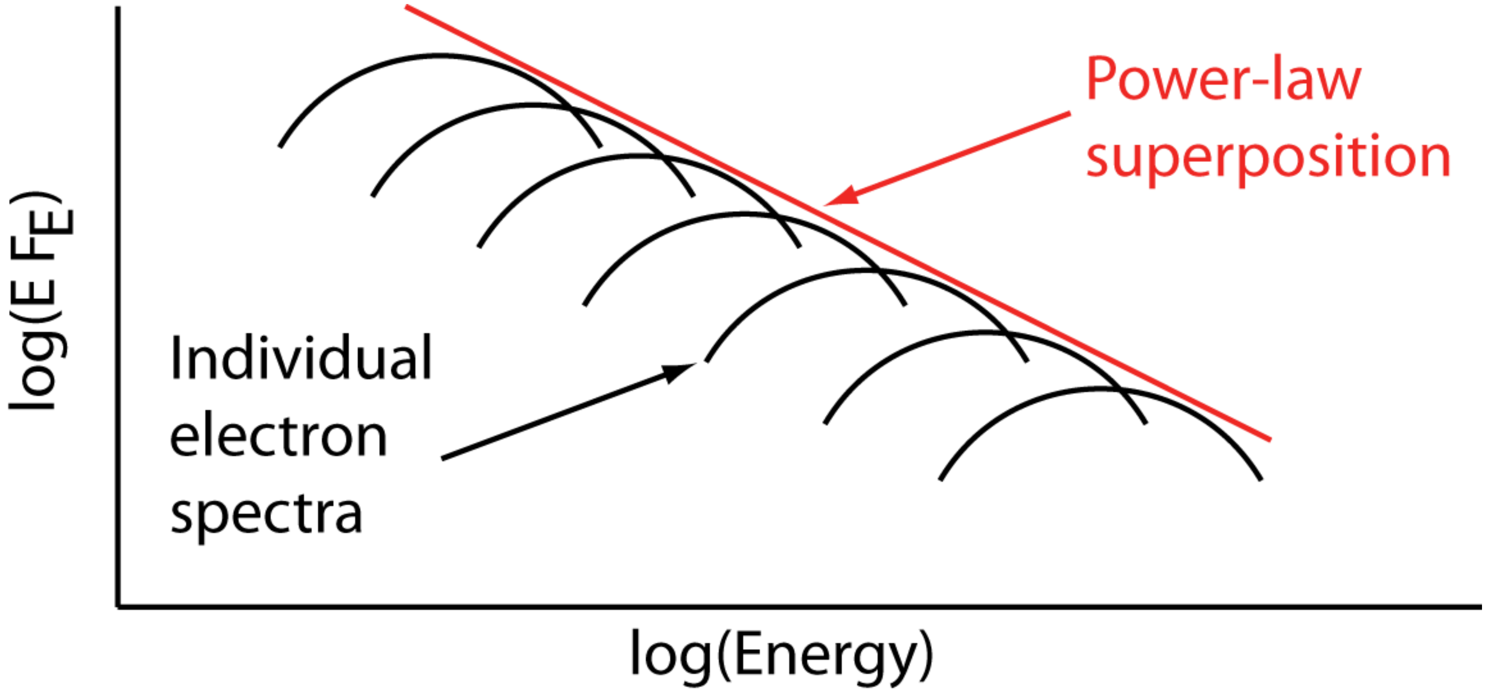
Average the previous equations over all directions of magnetic field (for astrophysical applications), where L is the size of the radiating region:

$$I(\nu) = a(\rho)\frac{e^3}{m_e c^2}\left(\frac{3e}{4\pi m_e^3 c^5}\right)^{(\rho-1)/2} B^{(\rho+1)/2} K L \nu^{-(\rho-1)/2} \ \text{erg cm}^{-2}\text{s}^{-1}\text{sr}^{-1}\ \text{Hz}^{-1}$$

where $$a(\rho) = \sqrt{\frac{3\cdot 2^{(\rho-1)}}{\pi}\frac{\Gamma(\frac{3\rho-1}{12})\Gamma(\frac{3\rho+19}{19})\Gamma(\frac{\rho+5}{4})}{8(\rho+1)\Gamma(\frac{\rho+7}{4})}}$$

Synchrotron Radiation

The spectrum from a single electron is **not** a power-law, but if the energy distribution of the electrons is a power distribution, the result appears to be one:



(from Shu, Part II, p 178)

Synchrotron Radiation

Estimating the two boundaries energies E_1 and E_2 of electrons radiating between ν_1 and ν_2 can be done using the following results:

$$E_1(\nu) \leq m_e c^2 \sqrt{\frac{4\pi m_e c \nu_1}{3eBy_1(\rho)}} = 250\sqrt{\frac{\nu_1}{By_1(\rho)}}\mathrm{eV}$$

$$E_2(\nu) \leq m_e c^2 \sqrt{\frac{4\pi m_e c \nu_2}{3eBy_2(\rho)}} = 250\sqrt{\frac{\nu_2}{By_2(\rho)}}\mathrm{eV}$$

Tabulations of $y_1(\rho)$ and $y_2(\rho)$ are available. Note that if

$\nu_2/\nu_1 << y_1(\rho)/y_2(\rho)$ or if $\rho<1.5$ this is only rough estimate

Synchrotron Radiation

As one might expect, synchrotron radiation can be quite polarized. The total polarization:

$$\frac{P_{\perp}(\omega) - P_{||}(\omega)}{P_{\perp}(\omega) + P_{||}(\omega)} = \frac{\rho + 1}{\rho + 7/3}$$

can be very high (more than 70%).

Synchrotron Self-absorption

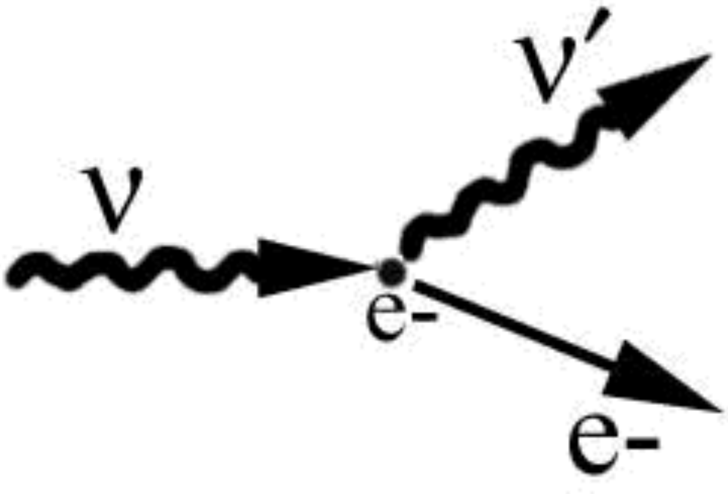
The principal of invariance under time reversal suggests that any emission process can also be an absorption process.

Here, a photon interacts with a charged particle in a magnetic field and is absorbed; the process is stronger at low frequencies/energies. Below the "break frequency" ν_m, we have the result that

$$F \propto \frac{\nu^{5/2}}{\sqrt{B}}$$

independent of the spectral index.

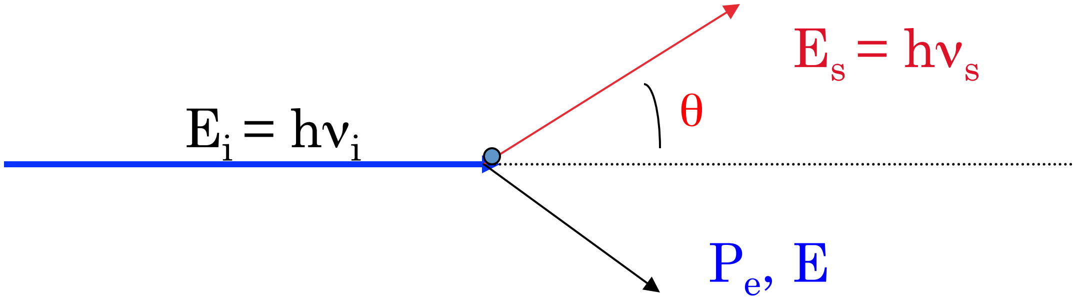
Compton Scattering



$$\nu' < \nu$$

Compton Scattering

For low energy photons ($h\nu << mc^2$), scattering is classical Thomson scattering (E_i=E_s; $\sigma_T = 8\pi/3\ r_0^2$)



$E_s = h\nu_s$

θ

$E_i = h\nu_i$

P_e, E

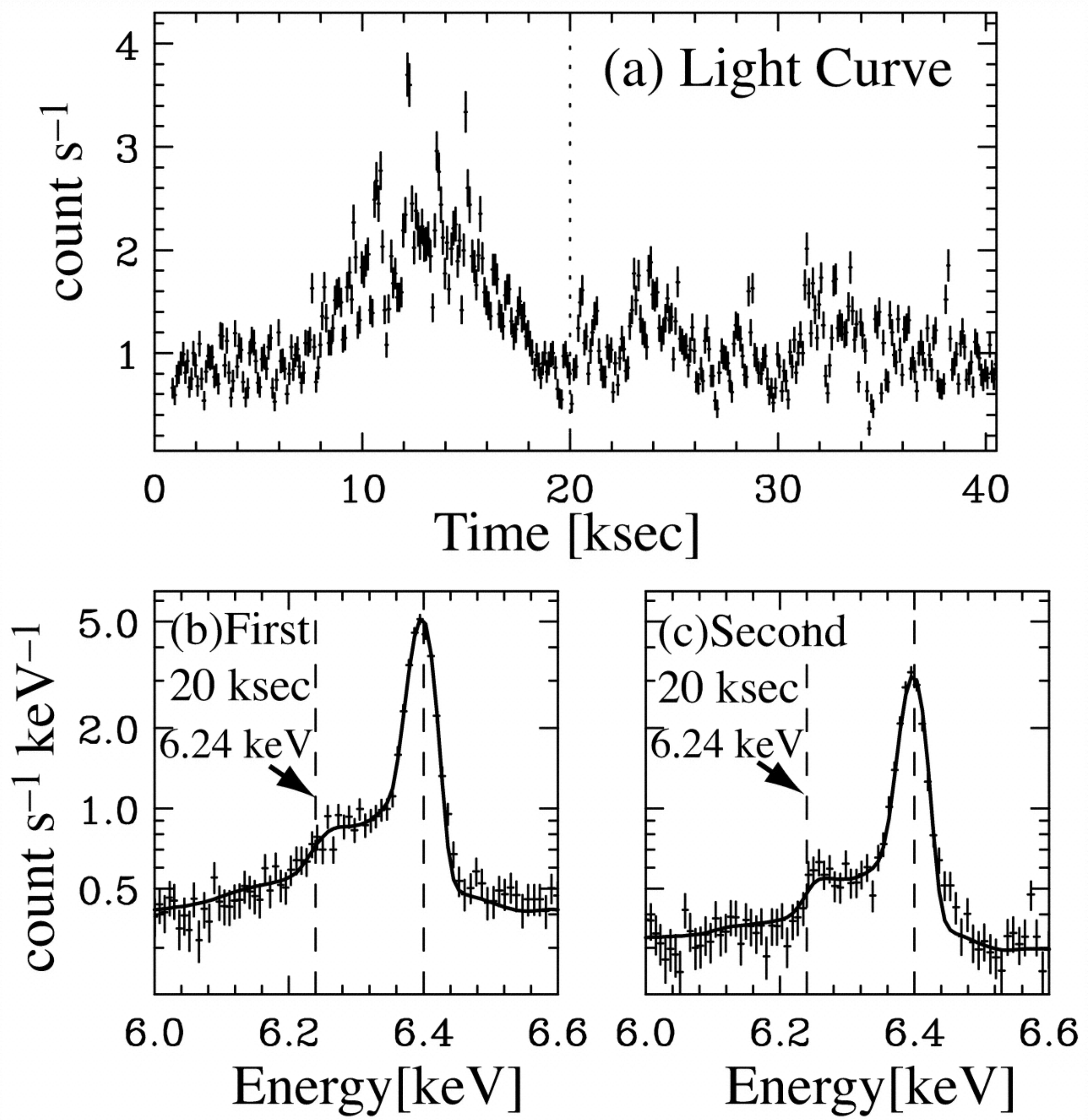
where $E_s = \dfrac{E_i}{1 + \frac{E_i}{m_e c^2}(1 - \cos\theta)}$ or

$$\lambda_s - \lambda_i = \lambda_c(1 - \cos\theta) \qquad \lambda_c \equiv \frac{h}{m_e c} = 0.02426\,\text{Å}$$

Note that E_s is always smaller than E_i

Compton Scattering

This has been detected using the Chandra HETG and the Fe K 6.4 keV fluorescence line from the XRB GX301-2 (Watanabe et al. 2003)

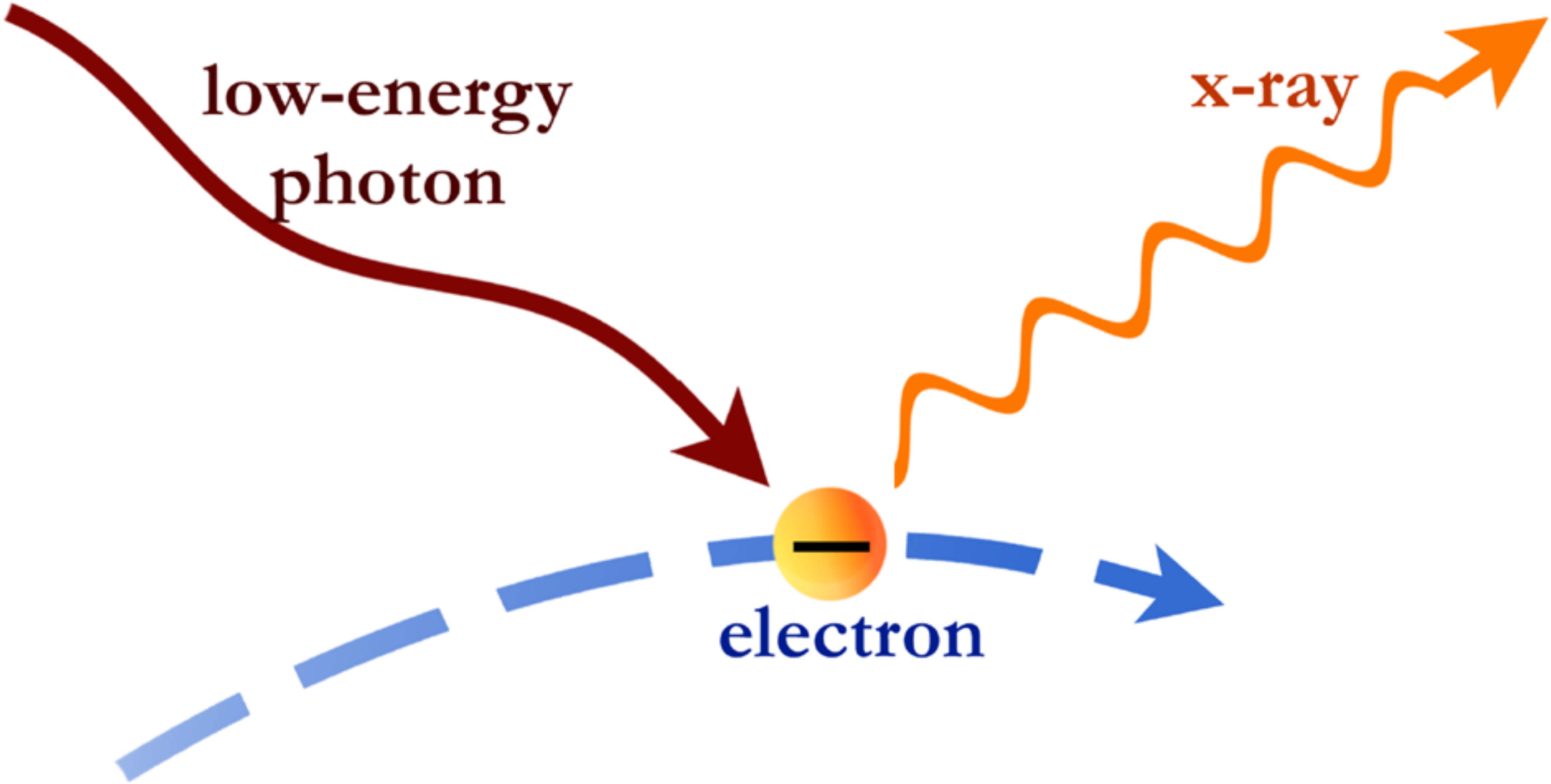


Here E = 6.4 keV, so
$\lambda = 12.398/E = 1.937$Å

$$\lambda_s - \lambda_i = \lambda_c(1 - \cos\theta)$$

$\lambda_s = \lambda + 2\lambda_c = 1.986$ Å or
E = 6.24 keV (if $\Theta = 180^o$)

Inverse Compton Scattering



Inverse Compton Scattering

If the electron kinetic energy is large enough, energy can be transferred from the electron to the photon:

Inverse Compton

Use the previous formula (valid in the rest frame of the electron) and then Lorentz transform:

$$E_i^{foe} = E_i^{lab}\gamma(1- \beta \cos\theta)$$

$$E_s^{foe} = f_{comp}(E_i^{foe})$$

$$E_s^{lab} = E_s^{foe}\gamma(1+\beta\cos\theta')$$

which means that $E_s^{lab} \propto E_i^{lab}\, \gamma^2$ (potentially quite large!)

Inverse Compton Scattering

The total power emitted via this process is:

$$P_{\rm comp} = \frac{4}{3}\sigma_T c\gamma^2 U_{\rm ph}(1 - f(\gamma, E_i^{\rm lab}))$$

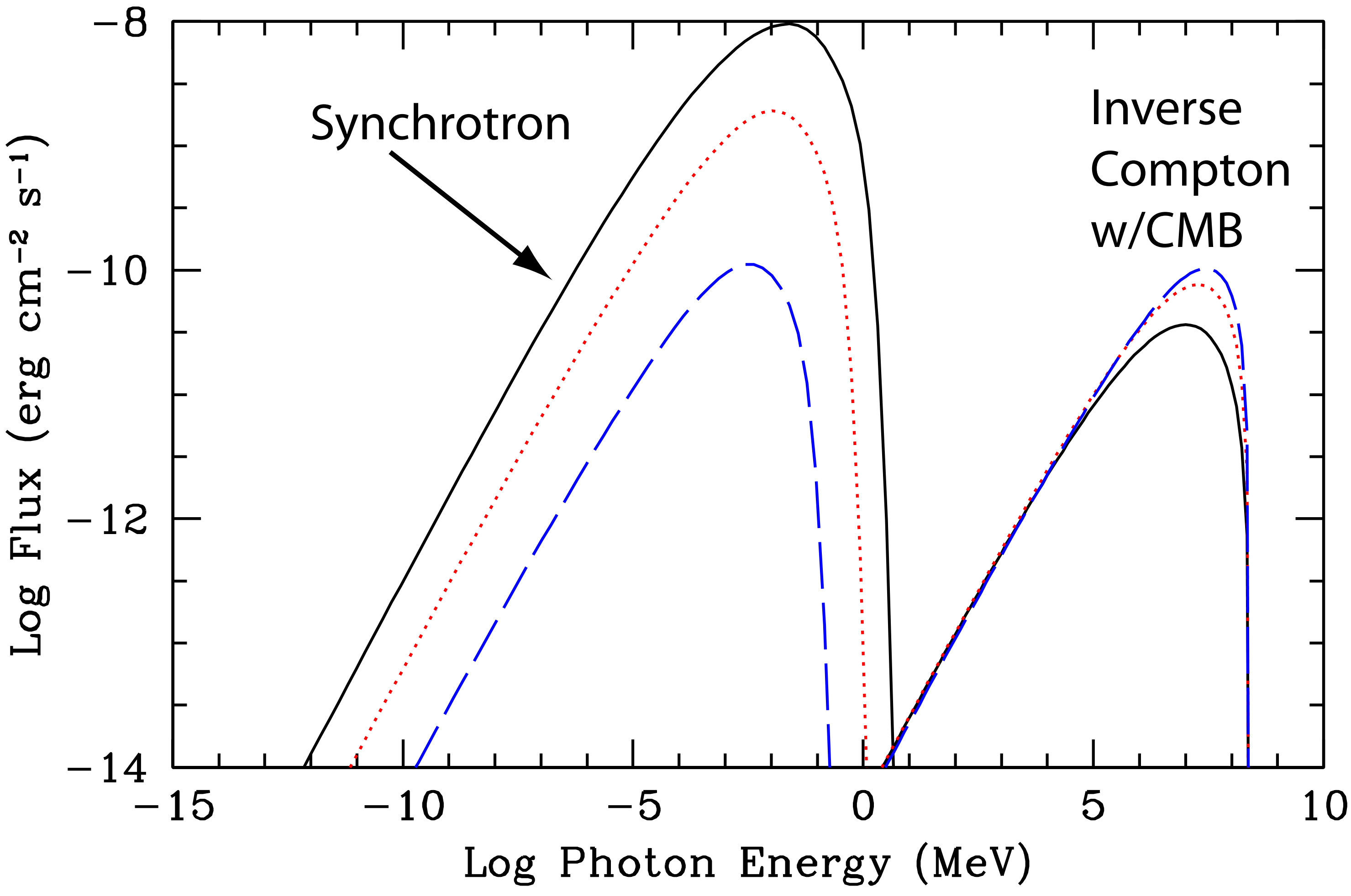
or $$P_{\rm comp} \sim \frac{4}{3}\sigma_T c\gamma^2 \beta^2 U_{\rm ph}$$

where U_{ph} is the initial photon energy density

Remember that $$P_{\rm sync} \propto \gamma^2 c\sigma_T U_B$$

So: $$\frac{P_{\rm sync}}{P_{\rm comp}} = \frac{U_B}{U_{ph}}$$

So synchrotron radiation can be thought of as inverse Compton radiation from the "virtual" photons in the magnetic field.

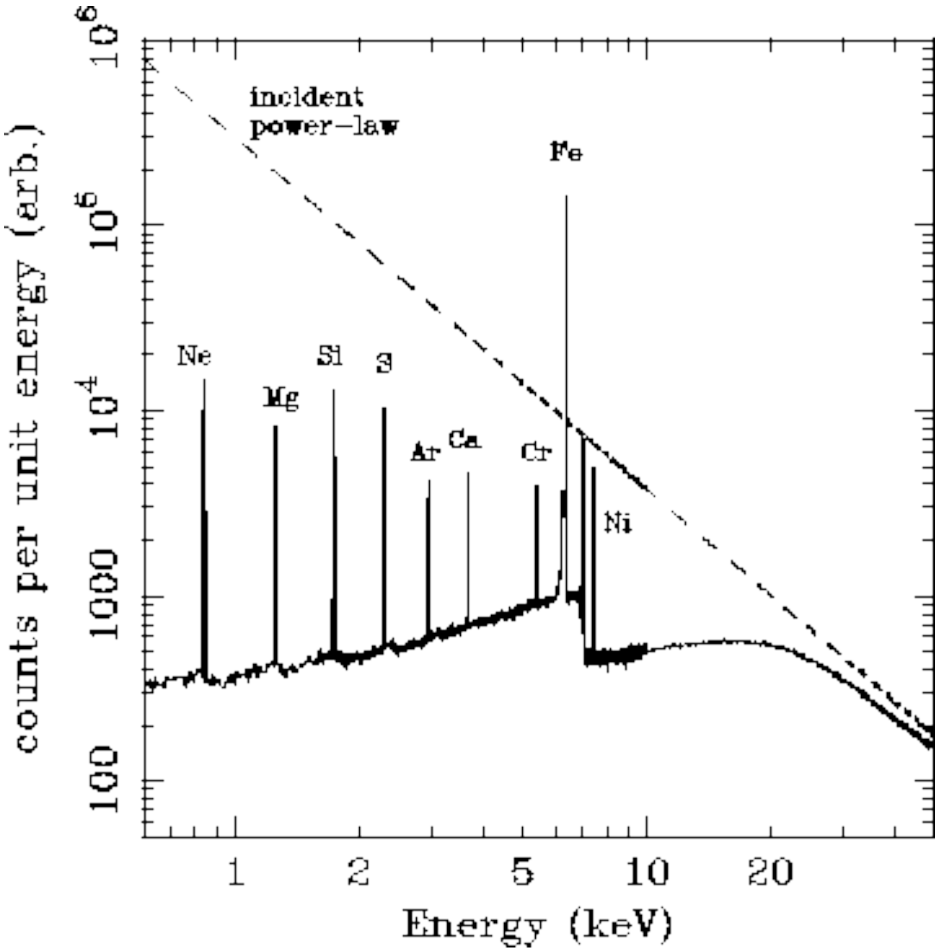

Synchrotron
Inverse Compton w/CMB
Log Flux (erg cm⁻² s⁻¹)
−8
−10
−12
−14
Log Photon Energy (MeV)
−15
−10
−5
0
5
10

Reflection

The ``reflection'' of an incident power-law X-ray spectrum (shown as a dashed line) by a cold and semi-infinite slab of gas with cosmic abundances.

Fluorescent lines below 10 kev, and the Compton ‘hump’ at ~20 keV are clearly visible

(Reynolds 1996)

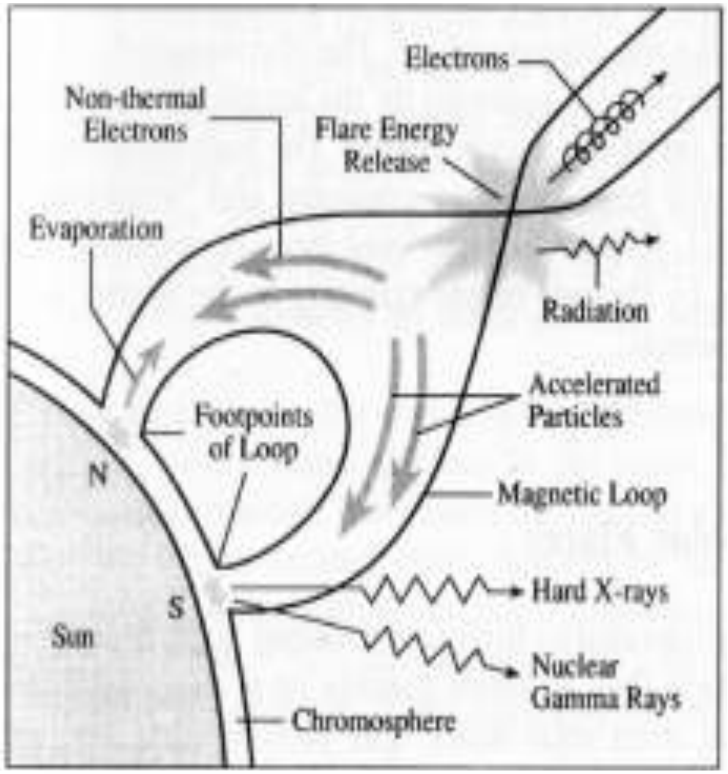


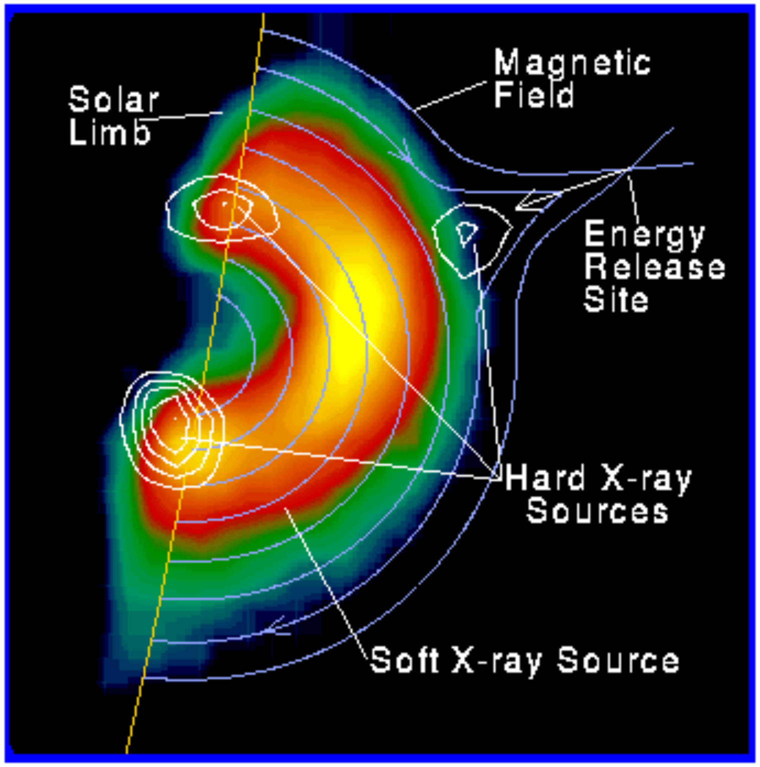
Books and references

- Rybicki & Lightman "Radiative processes in Astrophysics"
- Longair "High Energy Astrophysics"
- Shu "Physics of Astrophysics"
- Tucker "Radiation processes in Astrophysics"
- Jackson "Classical Electrodynamics"
- Pacholczyk "Radio Astrophysics"
- Ginzburg & Syrovatskii "Cosmic Magnetobremmstrahlung" 1965 Ann. Rev. Astr. Ap. 3, 297
- Ginzburg & Tsytovitch "Transition radiation"

Thick-Target Bremsstrahlung

- Occurs when relativistic electrons impact a ‘solid’ surface – such as the photosphere of a star.
- Typically important in solar or stellar flares
- Heating in the corona excites electrons, which collide in the chromosphere, emitting hard X-rays via TTB, and heating the plasma so that it also emits soft X-rays.
- Called the ‘Neupert effect’





Yohkoh X-ray Image of a Solar Flare, Soft X-rays with Hard X-ray Contours Jan 13, 1992.

Conclusions

- Distinguishing between different types of non-thermal emission can be difficult based solely on moderate-resolution spectra.
- A broad bandpass is vital.
- Understanding the underlying physical processes is necessary if you wish to extract much from your spectrum.