Relativistic Electrons in High Energy Astrophysics

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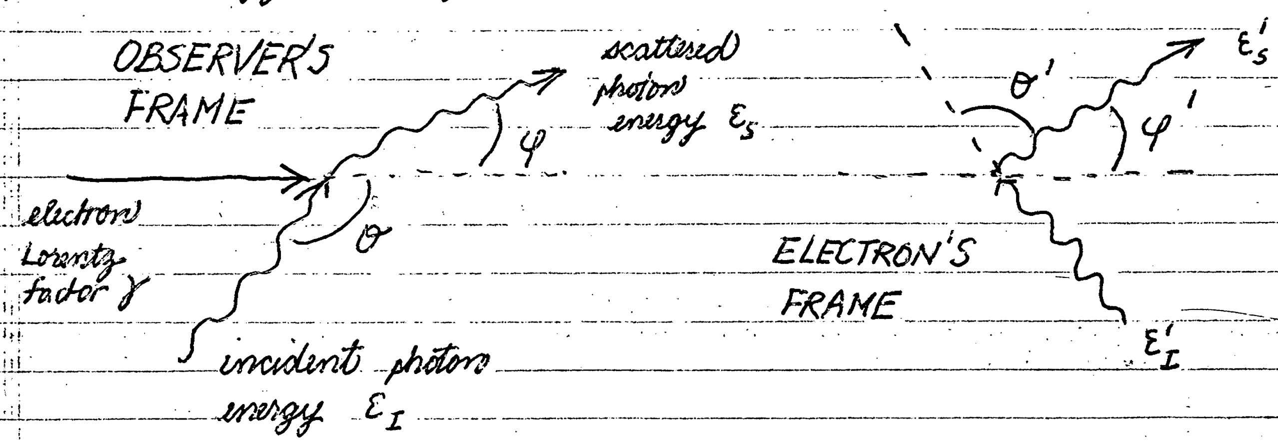
High Energy Astrophysics is too broad a subject to be covered in one lecture, so I will concentrate only on processes involving relativistic electrons ... since these particles are of most interest to radio astronomers.

Inverse Compton

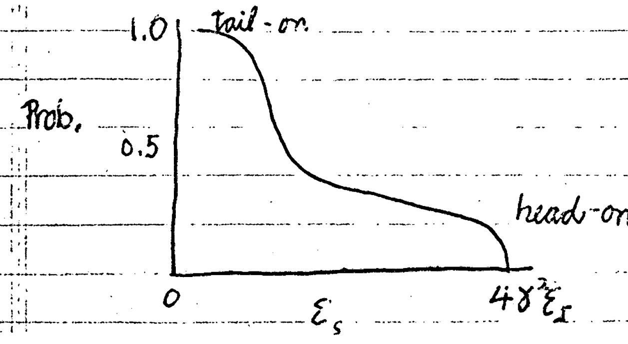
Inverse Compton emission is produced whenever relativistic electrons scatter lower energy photons. Since photons are ubiquitous in the universe, IC emission is generated wherever relativistic electrons are present — how much is determined by the number of electrons and their ambient photon energy density.



Using the Lorentz transformations you can show the energy of the scattered photon in the observer's frame is given by (see Blumenthal and Gould Rev. Mod. Phys. 42 237 (1970)):

$$\varepsilon_s = \frac{\gamma^2 \varepsilon_I (1+\beta\cos\theta)(1-\beta\cos\varphi')}{1 + \frac{\gamma\varepsilon_I}{mc^2}(1+\beta\cos\theta)(1-\cos\theta')}$$

The probably of scattering the photon to a given energy is (assuming an isotropic photon distribution in the observer's frame and $\gamma\varepsilon_I \ll mc^2$):



On the average, an isotropic distribution of electrons and photons produce IC photons with energy

$$\langle \varepsilon_s \rangle \simeq \frac{4}{3}\gamma^2 \langle \varepsilon_I \rangle$$

The IC power emitted by an electron with energy γmc^2 is given by:

$$P_{IC}(\gamma) = \underbrace{\frac{4}{3}\gamma^2\langle\varepsilon_I\rangle}_{\text{scattered photon energy}} \times \overbrace{n_{ph}\,\sigma_T\,c}^{\text{Scattering rate}}$$

n_{ph} ← number density of photons; σ_T ← Thomson cross-section; c ← speed of light

(rewriting)

$$= \frac{4}{3}\gamma^2\sigma_T c\, U_{rad.} = 2.6\times10^{-14}\gamma^2\left(\frac{U_{rad.}}{1\ \mathrm{eV\,cm^{-3}}}\right)\ \mathrm{eV/sec}$$

$U_{rad.}$ ← radiation density

Recall from synchrotron theory that the synch. power from an electron is:

$$P_{synch.}(\gamma) = \frac{4}{3}\gamma^2\sigma_T c\left\{\frac{B^2}{8\pi}\right\} = \frac{4}{3}\gamma^2\sigma_T c\, U_{mag}.$$

You can see that the two equations are quite similar. In fact, the two processes are closely related. [You can think of the synchrotron process as Compton scattering of virtual photons of the magnetic field and derive all the standard results of synchrotron theory.]

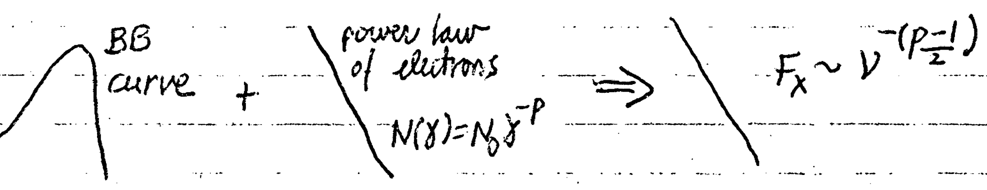
Combining the two equations we see the ratio of the luminosities from a collection of electrons is given by:

$$\frac{L_{IC}}{L_{synch.}} \doteq \frac{U_{rad.}}{\left\{\frac{B^2}{8\pi}\right\}}$$

Spectrum

If the ambient photon distribution is not too flat, a power law distribution of electrons, $N(\gamma) = N_0\gamma^{-p}$, will produce an IC spectrum with the same index as the synchrotron spectrum i.e. $\alpha = \left(\frac{p-1}{2}\right)$.

for example:



To prove this we make the often made δ-function approximation, that is, all the power is emitted at a single frequency given by

$$h\nu_s = \frac{4}{3}\gamma^2 \varepsilon_I \quad \Rightarrow P_{IC}(\gamma, \nu) \simeq \frac{4}{3}\gamma^2 \sigma_T c\, U_{ph}\, \delta(\nu - \nu_s)$$

erg sec^{-1} electron^{-1}

for blackbody $\langle \varepsilon_I \rangle \simeq h\nu_s = 3.6\,\gamma^2 kT$

let $\gamma_s \equiv \left(\frac{h\nu_s}{3.6kT}\right)^{1/2}$

$$\frac{dP_{IC}}{d\nu\, dVol.} = \int P_{IC}(\gamma, \nu)\, \underbrace{N_0 \gamma^{-p}}_{\text{electron distribution}} d\gamma$$

$$= \int \frac{4}{3}\gamma^2 \sigma_T c\, U_{ph.}\, \delta(\nu - \nu_s)\, N_0 \gamma^{-p} \frac{d\gamma}{d\nu_s} d\nu_s$$

$$= P(\gamma_s) N_0 \gamma_s^{-p} \cdot \{7.2\, \gamma_s (kT/h)\}^{-1}$$

$$\therefore \frac{dP}{d\nu\, dVol.} = \text{constant} \times N_0 U_{ph} T^{\left(\frac{p-3}{2}\right)} \nu^{-\left(\frac{p-1}{2}\right)} \quad \frac{\text{erg}}{\text{sec-cm}^3\text{-Hz}}$$

APPLICATION TO CLUSTER X-RAY SOURCES

Brecher & Burbidge (NATURE 237, 440, 1972) have suggested that the x-ray emission from clusters of galaxies is inverse Compton scattered 3K background photons.

They argued that if a significant concentration of relativistic electrons were present in intracluster space, these electrons could produce both the diffuse radio emission seen in clusters like Coma and the x-ray emission.

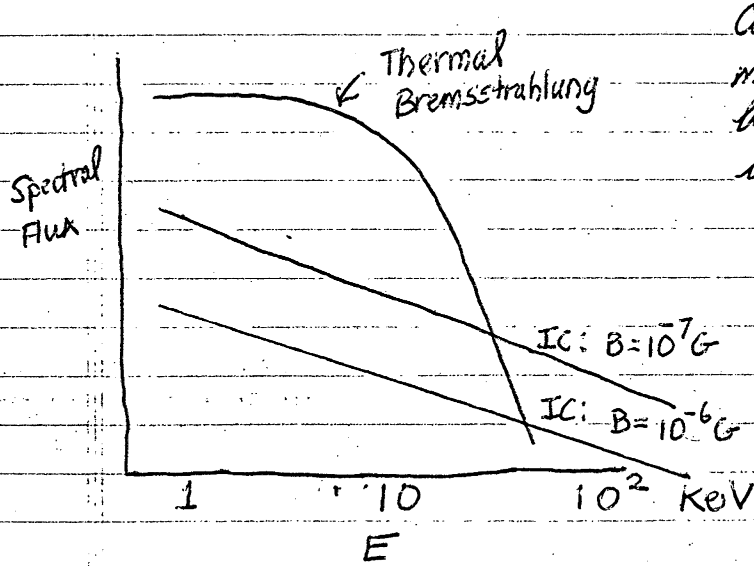
In Coma, for example, $L_{radio} \simeq 10^{41}$ erg sec^{-1} and $L_{x\text{-}ray} \simeq 8 \times 10^{44}$ erg sec^{-1} the required field strength is

$$\frac{L_{radio}}{L_{x\text{-}ray}} \cdot U_{rad} = \frac{B^2}{8\pi} \Rightarrow B \sim 3 \times 10^{-8} \text{ Gauss}$$

this is approx. an order of magnitude below equipartition so it requires lots of electrons

The important prediction of this model is that the x-ray spectrum ~~a~~ should be a power law — just like the radio.

In the past 5 years detailed studies of the x-ray spectra from many clusters have shown that the spectra in the 1–10 KeV range are not power laws. Instead, they closely fit the exponentials expected from thermal bremsstrahlung. This suggests that the emission is produced intraclusters by a hot gas (10^7–10^8 K) with density $n_e \sim 10^{-3}\ cm^{-3}$. The detection of iron line emission has strengthened this view.



Current thinking is that both mechanisms produce cluster x-rays but IC component is only important at high energies

In clusters that contain a radio halo, you can use limits on the high energy flux to put an upper limit on the intracluster field strength.

SELF-COMPTON IN COMPACT RADIO SOURCES

A number of sources have been seen that vary on timescales of years at low frequencies (~ 400 MHz)

this implies: ① no self-absorption turnover above ~ 400 MHz
② scale size ≲ light year

For the inferred size, the absence of a self-absorption turnover down to ~400 MHz requires an extremely small magnetic field (remember $\nu_T^{5/2} = \text{const.} \times F_{\nu_T} B^{-1/2} \theta^{-2}$).

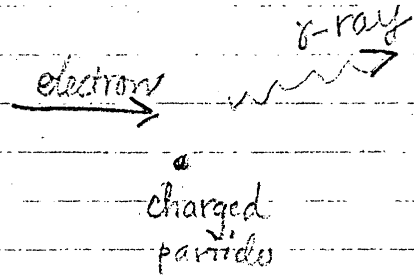
Relatively high radio luminosity + small B ⟹ lots of rel. electrons
" + small size ⟹ high energy density of synchro. photons
} ⟹ very luminous ~~[illegible]~~ IC x-ray source

⟹ Observed x-ray flux is much smaller than predicted if it's seen at all. This is the so-called Inverse Compton Problem.

Solution is: the sources have relativistic bulk motions so inferred size is much smaller than real size.

Non-Thermal Bremsstrahlung

Relativistic electron is scattered by a charged gas particle (could be another relativistic particle ~~by~~ but it's usually less likely) and produces a photon.



On the average the photon energy is $\sim \frac{1}{2} E_e$

The resultant photon spectrum has the same index as the electron spectrum.

This mechanism is the dominant source of $E_\gamma < 30$ MeV γ-rays in our galaxy (see e.g. Fichtel, Space Sci. Reviews 20 (1977) 191.)

"Producing these photons drains off an electron's energy at a rate:

$$-\frac{d\gamma_e}{dt} = 1.37\times10^{-16}\left(\frac{n_e}{1\ \mathrm{cm}^{-3}}\right)\gamma_e\left[\ln\gamma_e + 0.36\right]\ \mathrm{sec}^{-1}$$

(no screening approx.)

where n_e is the gas number density. Notice that this loss mechanism is only dominant for low energy particles because synchrotron and IC losses scale as γ_e^2.

"Ionization" Losses

Relativistic electrons also deposit energy in ambient gas by exciting and ionizing atoms or in ~~ionized~~ fully ionized plasma by exciting plasma oscillations.
For an application to heating of Intercluster medium see Lea & Holman Ap. J. 222 29 (1978)

Electrons lose energy at rate (in ionized gas)

$$-\frac{d\gamma_e}{dt} = 2.98\times10^{-14}\left(\frac{n_e}{3\times10^{-3}}\right)\left[40.3 + \ln\left\{18.26\,\gamma_e^{-\frac{1}{2}} n_e^{\frac{1}{2}}\right\}\right] \sec^{-1}$$

In our galaxy this is the dominant loss mechanism for electron with $E_e < 20$ MeV.

Figure 1 shows all the loss rates for an extragalactic site: the ICM of the Coma Cluster.

Evolution of Electron Spectrum

This subject has been discused by many authors, my favorite is (Kardashev Astron. Zh. 39 393 (1962)).

I would just like to remind you that to self-consistently calculate the emission from an ensemble of electrons you must include the effects of the energy losses.

The losses cause the electrons to "diffuse" in energy space... you must solve a continuity equation to really find a self-consistent solution.

$$\frac{\partial N_e(\gamma_e,t)}{\partial t} + \frac{\partial}{\partial\gamma_e}\left[N_e(\gamma_e,t)\frac{d\gamma_e}{dt}\right] + \frac{N_e(\gamma_e,t)}{T_L} = Q_e(\gamma_e,t)$$

Synchro. loss, etc.

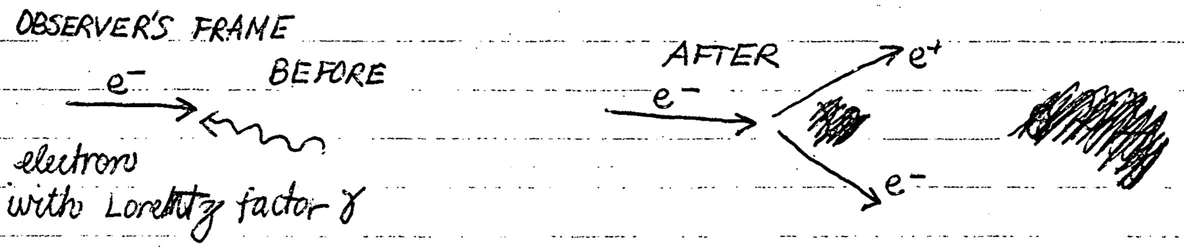
Catastrophic Losses like leakage

Source function

Pair Production

If a photon's energy in the rest frame of an electron exceeds $4m_ec^2$ ($2m_ec^2$ for a proton) it is energetically capable of pair production. If we let "CP" stand for charged particle, the reaction is

$$\text{photon} + CP \longrightarrow CP + e^+ + e^-$$



$$\sigma_{PP} \sim \frac{1}{137}\sigma_T$$

In an ultra-relativistic plasma this process and bremsstrahlung:

$$e + CP \rightarrow e + CP + \text{photon}$$

are the dominant reactions.

These reactions can produce a cascade wherein an ever-increasing amount of rest mass is generated at the expense of internal energy. To see this, suppose a bremsstrahlung interaction occurs. If the γ-ray optical depth is high, this γ-ray will produce a e^+-e^- pair. The net result of these reactions is ~~the production of pairs at the expense~~

bremsstrahlung: $e + CP \rightarrow e + CP + \gamma\text{-ray}$

pair production: $\underline{\gamma\text{-ray} + CP \rightarrow e^+ + e^- + CP}$

$$2CP + e + \gamma\text{-ray} \rightarrow 2CP + e + \gamma\text{-ray} + \underline{\underline{e^- + e^+}}$$

the production of pairs.

This loss mechanism can be quite important and have interesting consequences during the formation of superluminal radio sources. (see Vestrand et al. Ap.J. 245, 811 (1981)).