US /GRBK)

Summer Student Lecture 1971

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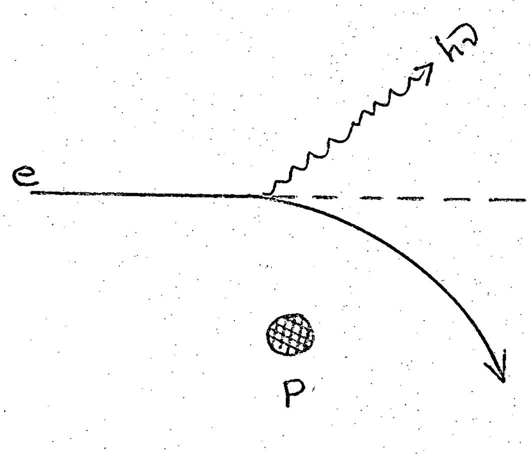
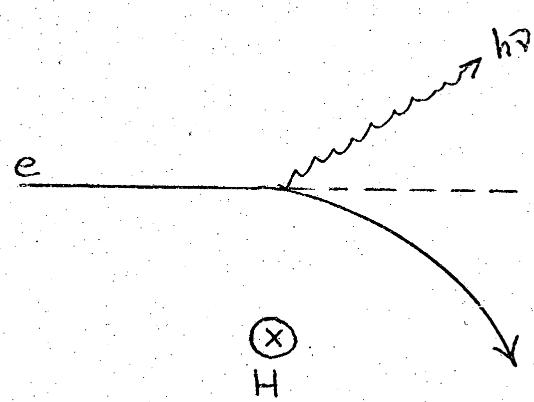
THE INVERSE COMPTON EFFECT

I. Background

Even in the early days of radio astronomy (ca. 1950's) it was recognized that the physical process responsible for the emission of "cosmic" radio waves was synchrotron radiation. This mechanism, which had its mathematical roots in a classic paper by J. Schwinger (Phys. Rev. 1948) who was interested in radiation losses suffered by particles in synchro-cyclotrons, was applied extensively to radio sources by the Russians Ginzburg, Syrovatskii, Shklovsky and others. These first authors referred to the process as "magnetic bremsstrahlung" because of the following analogy to the familiar coulomb bremsstrahlung:



Coulomb bremsstrahlung
(free-free emission)



Magnetic bremsstrahlung

In Coulomb bremsstrahlung a photon is emitted as the electron is deflected by a positive ion; in synchrotron radiation the electron is deflected by a magnetic field line causing the emission of a photon.

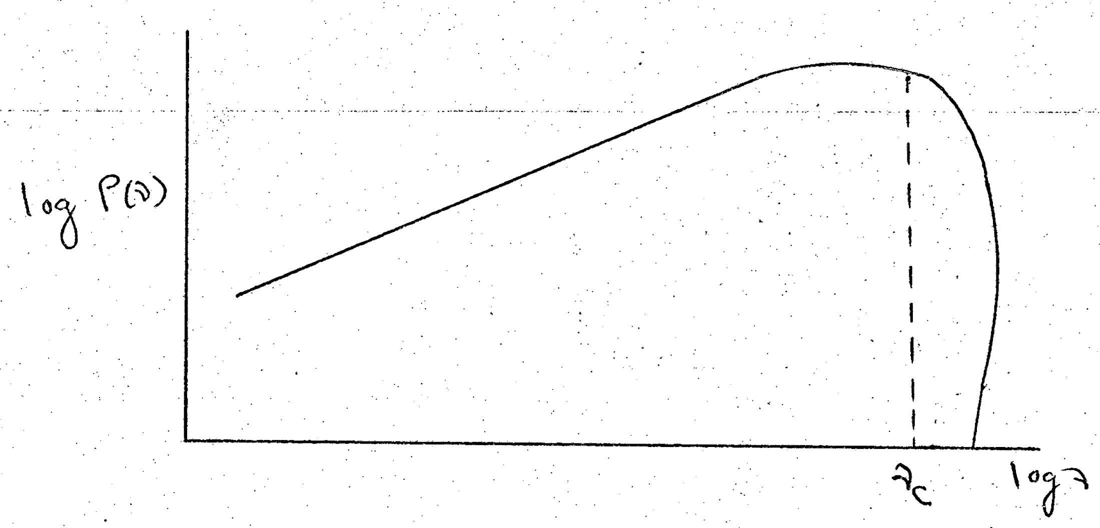
Consequently, observations of synchrotron radiation indicate the presence of two "ingredients":

a) energetic electrons

b) magnetic fields

How energetic are the synchrotron electrons?

The synchrotron power $P(\nu)$ radiated by a single electron of energy ε in a magnetic field H is schematically.



Most of the energy appears at a critical frequency

$$\nu_c = \frac{3e}{4\pi mc} H \left(E/mc^2\right)^2$$

$$= 1.61 \times 10^{-5}\ H\ E^2(\mathrm{eV})\ \mathrm{Hz}.$$

If ν_c is to be in the radio domain, $\nu_c \sim 10^9$ Hz then

$$E \sim \frac{10^7}{H^{1/2}}\ \mathrm{eV}$$

in ordinary radio sources, for example our own galaxy, the magnetic field is $\sim 10^{-5} - 10^{-6}$ gauss so that

$$E \sim 10^{10}\ \text{eV} \sim 10^{4}\ \text{MeV}$$

so that the electrons giving rise to synchrotron radio sources are highly relativistic indeed!

II. The Inverse Compton Effect

A. Consider what happens when one of these synchrotron electrons collides with a weakly energetic photon, for instance either a radio or a starlight photon which have energies of,

$$\text{Radio:}\quad E(\nu_R) = h\cdot 10^{9} \sim 6 \times 10^{-18} \sim 4 \times 10^{-6}\ \text{eV}$$

$$\text{Starlight:}\quad E(\nu_*) = h\cdot 10^{14} \sim 6 \times 10^{-13} \sim 0.4\ \text{eV}.$$

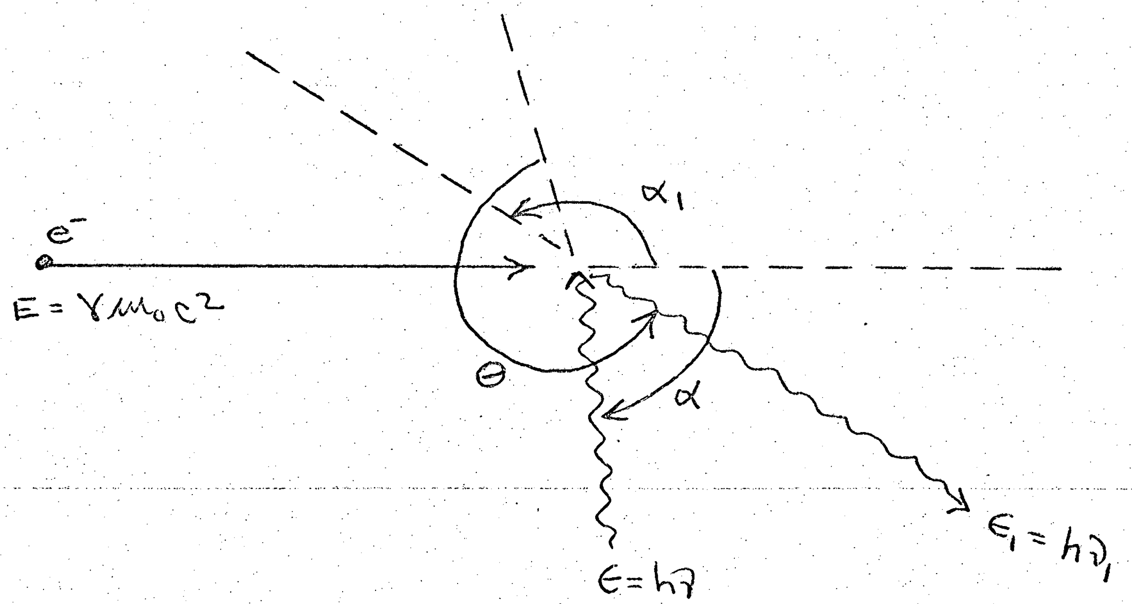
In such a collision one of two things may happen,

1) The photon is absorbed - synchrotron self absorption

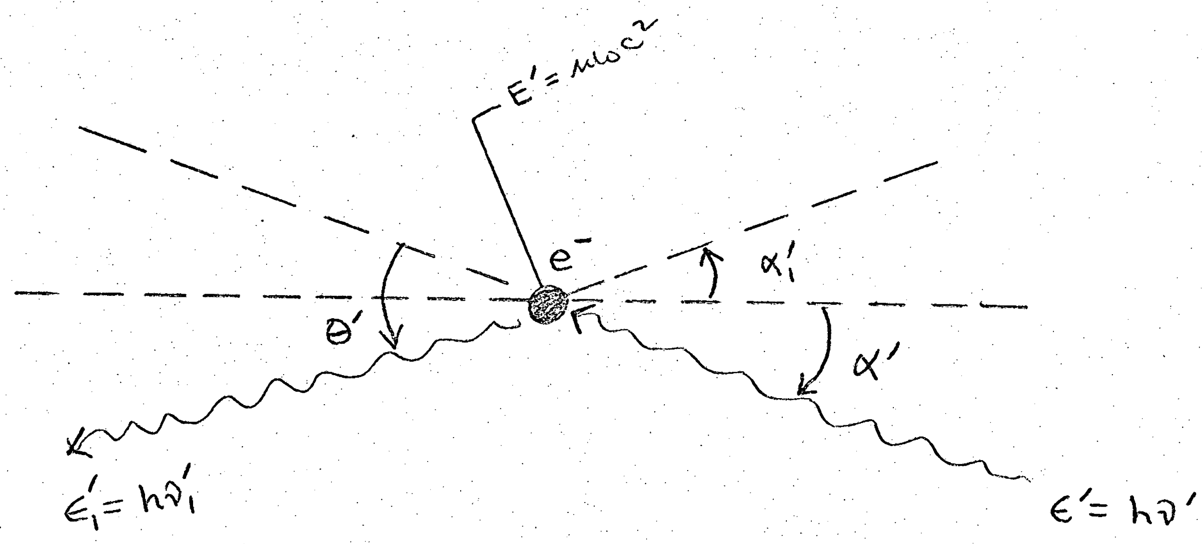
2) Elastic collision - photon gains energy from the electron.

Inverse Compton Effect $\equiv$ The collision of a fast electron and a low energy photon with the consequent production of a high energy recoil photon and a corresponding decrease in electron energy.

Lets look at this collision in two different coordinate frames.



a) Cosmic (Lab) Frame S



b) Electron Rest Frame S^1 (Ordinary Compton Scattering)

The angles at which the photon is incident on the electron α, α^1 in the two frames are related by the usual relativistic formula for the aberration of light,

$$\tan \alpha^1 = \frac{\sin \alpha}{\gamma (\cos \alpha + \beta)}$$

For highly relativistic electrons, $\beta \sim 1$, $\gamma >> 1$ which means that α^1 is very small except for $\alpha \sim \pi$. Physically this means that a photon flux isotropic in S will be seen in S^1 as a well collimated and almost unidirectional photon beam coming from the right in the diagram.

B. What is the Energy of the Recoil Photon in S?

The relativistic Doppler formula gives a transformation for the incident energies in S and S^1,

$$\varepsilon^1 = \gamma \varepsilon \; (1 + \beta \cos \alpha)$$

and similarly for the scattered photons

$$\varepsilon_1 = \gamma \varepsilon_1^1 \; (1 - \beta \cos \alpha_1^1)$$

In S^1 the process is precisely ordinary compton scattering so that the compton relation between the incoming and outgoing photon energies holds,

$$\varepsilon_1^1 = \frac{\varepsilon^1}{1 + (\varepsilon^1/mc^2)\;(1 - \cos \theta^1)} \quad .$$

Now substitute ε^1 and ε_1^1 from the Doppler relations into this equation and solve for ε_1 as a function of ε and we find that the energy of the recoil photon in the cosmic frame S is,

$$\varepsilon_1 = \frac{\gamma^2 \varepsilon (1+\beta \cos \alpha)\ (1-\beta \cos \alpha_1^1)}{1 + (\gamma\varepsilon/mc^2)(1+\beta \cos \alpha)(1-\cos \theta^1)}$$

recalling again that the photon energies ε<<1eV and the Lorentz factors for the electrons are large, $\gamma \sim 10^4$, we can apply the condition

$$\gamma\varepsilon << mc^2$$

and note that the angle factors above can all be set equal to 1. The recoil energy is now simply,

$$\boxed{\varepsilon_1 \simeq \gamma^2\ \varepsilon}$$

Through this relation one may observe the principle result of the inverse compton effect: soft photons can be raised to very high energies. As an example

(a) Radio photons, $h\nu \sim 10^{-5}$eV are converted to X-rays ($\sim 10^3$eV).

(b) Starlight photons, $h\nu \sim .1$eV become hard gamma rays (~10meV).

C. Total Compton Power Radiated by a Discrete Source

We have so far considered monoenergetic electrons. In most radio sources we find that the relativistic electron distribution has a power law form,

$$N(E)dE = N_o E^{-m} dE.$$

If we also consider the photon distribution to have a blackbody distribution characterized by an effective temperature T (e.g. for radio photons $T \sim 10^{-2}$°K; for starlight $T \sim 10^{3}$°K) then the total specific intensity resulting from compton collisions is

$$I_\nu \simeq 10^{-15} (3.66 \times 10^{-6})^{3-m} N_o R \rho T^{(m-3)/2} \nu^{(1-m)/2}$$

photons/cm^2-sec-sterad

where ρ is the total photon energy density and R is a measure of the size of the radiating volume. The details of this calculation may be found in Felten and Morrison, Ap. J., 146, 686 (1966).

The important result here, and one we shall have occasion to refer to later, is that the compton intensity is proportional to the normalization of the electron distribution and the frequency,

$$I_\nu \propto N_o \nu^{(1-m)/2}$$

III. Application of Inverse Compton Scattering To Radio Sources

In radio sources the inverse Compton effect manifests itself in two ways:

1) It produces high energy photons (X-rays, γ-rays)

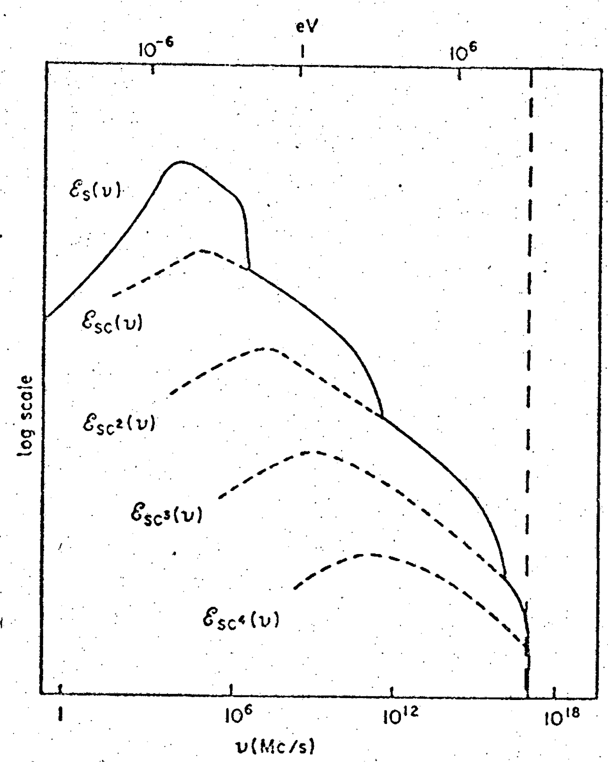
2) It limits the lifetime of the synchrotron electrons.

Lets look at each of these effects separately.

A. High Energy Photons

1. Total Spectrum of a Radio Source

If the radiation density due to synchrotron radiation is sufficiently intense to allow Compton scattering it is also possible that a particular photon may be scattered two or more times. In fact the number of scatterings is limited only by the form of the cross section which changes from the classical Thomson form to the Klein-Nishina expression for photon energies much in excess of 100 keV. There is also, of course, an absolute limit to the energy of the scattered photons determined by the maximum energy of the electron flux. If we account for all orders of Compton scatterings and refer to the resultant photon intensities as $\varepsilon_{sc}(\nu)$, $\varepsilon_{sc^2}(\nu)$, $\varepsilon_{sc^3}(\nu)$... (for once, twice, three times and higher order scatterings, etc.). Then the <u>total</u> spectrum of a radio source will have the following idealized shape



where $\varepsilon_s(\nu)$ is the radio synchrotron part of the spectrum. Notice also that as the energy per photon at the higher frequencies is much larger than that contained by the radio photons, the energy density in the twice scattered compton spectrum actually exceeds that in either the once scattered part or the integrated radio energy density. In fact, one has the following ratios

$$\varepsilon_s : \varepsilon_{sc} : \varepsilon_{sc^2} : \varepsilon_{sc^3} \sim 1:10:100:1/2.$$

These ratios don't increase indefinitely due to the change in cross section noted earlier.

It is to be expected, therefore, that strong, compact radio sources should be intense emitters of X-rays and γ-rays because of the inverse compton effect: such objects are the subjects for current searches at these energies.

2. Determination of the Magnetic Field in Radio Sources

Realizing that many radio sources emit through the synchrotron mechanism, it should be clear that a knowledge of the magnetic field in these objects is essential. Unfortunately such a determination is very difficult. There are three main ways of obtaining a value for this parameter in a particular source,

(1) observing a low frequency cut-off

(2) equipartition arguments

(3) observing inverse Compton X-rays

The theory of synchrotron radiation predicts that little radiation will be emitted at frequencies less than the so called "synchrotron self absorption frequency". This arises because electrons in spiraling about magnetic field lines can absorb photons as well as emit them (in order to conserve energy) and low frequency photons are preferentially absorbed (cf. Gringbueg and Syrovatskii, <u>The Origin of</u>

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Cosmic Rays). This cut-off in the radio spectrum is directly related to the magnetic field H and provides a means for its determination. Unfortunately such calculations are often unreliable because other effects such as a low energy cut-off in the electron distribution or the Razin effect can also produce a low frequency radio cut-off and its impossible to tell for certain that synchrotron self absorption is in fact present.

Equipartition arguments involve the following reasoning: A radio source is in a most energetically favorable position when the energy in relativistic particles exactly equals the energy in the magnetic field. Another way of looking at this is to say that the outward "pressure" of the relativistic particles is exactly balanced by the confining "pressure" of the magnetic field. The energy in relativistic electrons, ε_e, is easily derived from a knowledge of the radio spectrum and the usual synchrotron formulae. However, because of the much larger mass of the proton as compared to the electron, most of the energy in relativistic particles in a radio source resides with the protons not the electrons and the protons do not exhibit themselves in any observationally verifible way. One thus must resort to the assumption that a factor f more energy exists in relativistic protons than there is in relativistic electrons; the equipartition relation then is,

$$E_e + E_p = (1+f)E_p = H^2/8\pi .$$

One really has no way of knowing f but it is usually taken to be ~100 after some early calculations by Burbidge (1957). The magnetic field then follows immediately but is uncertain both because f is uncertain and because one has no way of knowing if equipartion holds or not in a particular source.

But now suppose X-rays are observed from a radio source and we specify that these X-rays arise from Compton scattering of synchrotron radiation. In this case, the Compton flux at a particular X-ray frequency ν_x is

$$\text{X-ray:} \quad I(\nu_x) \propto N_o \, \nu_x^{-\alpha} \quad \text{erg/Hz sec}$$

as we noted before. Similarly, the synchrotron radio flux observed at a frequency ν_R is

$$\text{Radio:} \quad I(\nu_R) \propto N_o \, H^{(1+\alpha)} \, \nu_R^{-\alpha} \quad \text{erg/sec Hz.}$$

Consequently, if the radio and X-ray flux can be measured in a particular source then we can unambiguously establish the magnetic field without knowing anything else about the source (e.g. the distance or size doesn't enter explicitely in this method as it does in those discussed previously):

$$H = \left[\frac{I(\nu_R)}{I(\nu_x)} \left(\frac{\nu_x}{\nu_R}\right)^{\alpha}\right]^{-(\alpha+1)}$$

We now have X-ray and radio measurements on several objects and are in a position to apply this method -- the fields that result are $10^{-6} - 10^{-7}$ gauss, values which are 10-100 times smaller than those got from either equipartition arguments or low frequency cut-offs. The reason for this discrepancy seems to be the different solid angles used to view the source in the radio and in the X-ray: When the angular resolution of X-ray detectors becomes comparable with that of radio telescopes one can expect more reliable measurements.

B. Inverse Compton Limits on the Lifetime of Synchrotron Electrons.

The relativistic electrons in radio sources will scatter any other radiation which is present as well as their own synchrotron radiation. The dominant form of radiation in many extended sources may be the primevial blackbody microwave radiation which presently has a temperature $T \sim 3°K$ and an energy density $U \sim 1eV/cm^3$. In all "big bang" cosmologies these quantities scale with redshift $Z = \lambda$ observed/λ emitted as

$$T = T_o \ (1+Z)$$
$$U = U_o \ (1+Z)^4 .$$

Because of the presence of this radiation the electrons will lose energy through the inverse Compton effect at a rate

$$\left(\frac{dE}{dt}\right)_{IC} = -10^{7.6} \ U \ (E/mc^2)^2 \quad \text{ergs/sec}$$

and it will also lose energy by synchrotron radiation in a similar way,

$$\left(\frac{dE}{dt}\right)_S = -10^{7.6} \ \frac{H^2}{4\pi} \ (E/mc^2)^2 \quad \text{erg/sec}$$

The lifetime of an electron will be

$$\tau(E) = \frac{10^{7.6} \ mc^2}{E(U+H^2/4\pi)} \quad \text{sec}$$

so the lifetime of a relativistic synchrotron electron is limited even as the magnitude of the magnetic field $H \to 0$! And since U scales with redshift this statement is particularly relevant at high Z: in fact losses due to Compton scattering will equal those due to synchrotron radiation when

$$H_c \sim 4 \times 10^{-6} (1+Z)^2 \text{ gauss}$$

For sources having fields $H \lesssim H_c$ we expect the inverse Compton effect to be important, i.e., we expect to be able to observe X-rays. The total spectrum of a radio source with arbitarily small H should have the following form when account is taken of Compton scattering of the relativistic electrons on the 3°K microwave background: