August 1976

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Compact Radio Sources

The first extragalactic radio sources discovered generally turned out to be rather extended in comparison with their associated optical objects, usually either galaxies or QSO's. These extended radio sources can generally be characterized by dimensions $\sim 10^4 - 10^6$ pc. Because these sources are so large, they do not change significantly on a human timescale.

In the mid 1960's it became apparent that some extragalactic radio source did indeed change on the timescale of a few years or less. These necessarily compact sources were found, of course, to be very much smaller than the extended sources, and generally to lie inside the nucleus of the associated galaxy or within the associated optical QSO. Recent VLBI (very long baseline interferometry) techniques have establish that such sources generally have characteristic angular sizes ~ 0.001 arc second, which typically corresponds to a few parsecs or less. In addition to their much smaller sizes, compact sources generally have spectra which are either ~~flat~~ relatively flat or actually inverted (rising to high frequencies) at least over some range of frequencies. It is this ~~[illegible]~~ distinctive spectral shape which is most often used to recognise them.

Our understanding of these sources is still very rudimentary. Because they are so small and we are just beginning to get useful information about the way they appear and evolve, models of their origin and evolution are still very crude.

Compact sources are frequently found in optical active sources (for example 3C279 and 0235+16 have undergone optical outbursts of more than five magnitudes), and ~~so~~ in some cases there is a suggestion that optical and radio sources are related, but the connection is not yet clear.

Physical schemes to account for the radio activity generally fall into two rough categories:

1) Explosions in a galactic nucleus, accompanied by the ejection of matter and/or energy.

2) Activity in a static "atmosphere" of a very massive but very compact object.

There are various pros and cons for each of these schemes, but at this time all such models are highly speculative. So in the rest of this lecture I would rather concentrate on simpler, and hopefully better understood aspects of the problem.

Since all ~~I~~ we know about these sources comes via the radiation, it is fundamental to our understanding that we understanding the radiation processes themselves.

Synchrotron radiation

Synchrotron emission was proposed more than 20 years ago to account for the emission from extended sources. It is also ~~likely~~ the most widely accepted (hence canonical) emission process for compact sources. Other processes have been suggested (e.g. plasma radiation, curvature radiation) but the conditions for synchrotron emission are better understood than most and this process is the most successful overall.

Since extended sources usually have spectra which resemble power laws, and compact sources sometimes do, over a more limited frequency range, it is useful to ~~I~~ see how this might come about.

Suppose we have electrons of energy E which radiate a power spectrum $p(E,\nu) = p(\nu/\nu_c)$ where ν_c is some characteristic (energy dependent) frequency. Suppose $\nu_c = \nu_0 (E/E_0)^n$, which is true for many processes including bremsstrahlung as well as synchrotron and compton emission. If the electron energy spectrum can be written $dN/dE = N(E)$ in the interval $[E_0, E_1]$, the emission from an ensemble of electrons is

$$P_\nu = \int_{E_0}^{E_1} N(E) p(E,\nu)\, dE = \frac{E_0}{n}\left(\frac{\nu}{\nu_0}\right)^{1/n} \int_{\gamma_1}^{\gamma_0} \gamma^{-\left(\frac{1+n}{n}\right)} p(\gamma)\, N\left[E_0\left(\frac{\nu}{\nu_0}\right)^{1/n} \gamma^{-1/n}\right] d\gamma$$

with $\gamma = \nu/\nu_c$. If the electrons have a spectrum which resembles a power law, $N(E) = N_0 (E/E_0)^{-s}$, the result is

$$P_\nu = \frac{E_0 N_0}{n}\left(\frac{\nu}{\nu_0}\right)^{-\left(\frac{s-1}{n}\right)} \int_{\gamma_1}^{\gamma_0} \gamma^{\left(\frac{s-1-n}{n}\right)} p(\gamma)\, d\gamma \qquad (1)$$

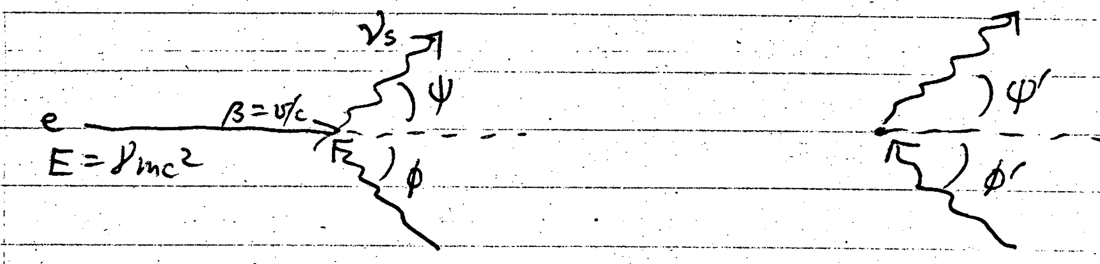
If the integrand vanishes at the limits (i.e., if there is little emission at ν from E_0 or E_1,

$$P_\nu \propto \left(\frac{\nu}{\nu_0}\right)^{-\left(\frac{s-1}{n}\right)} \qquad (2)$$

So, the observed power-law spectral form would appear to be more an indication of the nature of electron spectrum than of the radiation process.

To connect this result directly to a synchrotron source, let us look first at the closely related process, Compton scattering. If a moving electron scatters a photon, the frequency of the scattered photon is Doppler shifted, much as radar bouncing off a moving car. Provided $E h\nu/(mc^2)^2 << 1$ (the electron doesn't recoil) the scattered frequency is

$$\nu_s = \gamma^2 \nu (1+\beta\cos\phi)(1+\beta\cos\psi'). \quad (3)$$



observer's frame   electron's frame

For most values of ψ' and ϕ $\nu_s \sim \gamma^2 \nu$, So in the ~~above~~ derivation of equations (1) or (2) $n=2$ for Compton scattering. Since the frequency tends to increase when a moving electron scatters a photon, the process is sometimes called inverse-Compton scattering, but this is somewhat misleading since it is the same process as Compton scattering.

One can look at the motion of an electron in a magnetic field as a continual deflection of the electron scattering "virtual" photons each with energy $h\nu_B$, with $\nu_B = \frac{1}{2\pi}\frac{eB}{mc}$, the cyclotron frequency. Thus the characteristic frequency of the scattered "virtual photons", which are the synchrotron emission of the electron is $\nu_c \sim \gamma^2 \nu_B$, and again $n = 2$ in equation 2.

Now the spectra of compact sources characteristically curl over toward low frequencies (or equivalently sometimes appear to rise to high frequencies. This could be due to a number of effects, but the most likely is that the source has become self-absorbed.

Synchrotron self-absorption

The principle of detailed balance (time reversal invariance) says that any radiation process has to ~~be~~ have an associated absorption process. So synchrotron electrons must also absorb some radiation (synchrotron self-absorption, SSA). This results (as for a black body) in a limiting intensity to the radiation.

To see this we look at the equation of transfer for radiation (= the continuity equation for photons)

$$\frac{dI_\nu}{dz} = \epsilon_\nu - \varkappa_\nu I_\nu \qquad (4)$$

with I_ν the intensity, ϵ_ν the emissivity (emission per unit volume per solid angle) and $\varkappa_\nu$ is the absorption coefficient. For a uniform source this equation has a solution

$$I_\nu = S_\nu(1-e^{-\tau}) \qquad (5)$$

with $S_\nu = \epsilon_\nu/\varkappa_\nu$ and $\tau = \varkappa_\nu z$. Hence the limiting brightness is S_ν. For a thermal source $S_\nu = B_\nu = \frac{2\nu^3}{c^2}(e^{h\nu/kT}-1)^{-1}$, the Planck function. When $h\nu/kT \ll 1$ (valid at radio frequencies provided $T >$ a few degrees) the familiar result (Rayleigh - Jeans) is

$$I_{\nu_{max}} = \frac{2\nu^2}{c^2} kT \qquad (6)$$

This expression can also be generalized to nonthermal electron distributions. To see how, note that for a thermal distribution

$$N(E) \propto \exp(-E/kT), \text{ so}$$

$$kT = -dE/d\ln N,$$

and a more general expression is

$$I_{\nu_{max}} = -\frac{2\nu^2}{c^2}\, dE/d\ln N \,. \qquad (7)$$

For a power law electron spectrum $dE/d\ln N = -E/s$ so in a nonthermal source we expect

$$I_{\nu_{max}} = \frac{2\nu^2}{c^2}\frac{E}{s} \qquad (8)$$

Unfortunately the energy E appropriate to a given ν is not uniquely ~~very well~~ defined for synchrotron emission. However, to a first approximation $E = E_0 (\nu/\nu_0)^{1/2}$, so

$$I_{\nu_{max}} \simeq \frac{2\nu^2}{c^2}\frac{E_0}{s}\nu^{5/2}\nu_0^{-1/2} .$$

Further $\nu_0 \simeq \left(\frac{E_0}{mc^2}\right)^2 \nu_B$, and

$$I_{\nu_{max}} \simeq \frac{2\nu^2}{c^2}\frac{mc^2}{s}\nu^{5/2}\nu_B^{-1/2} \qquad (9)$$

(note that this expression could be used to derive $\mathcal{K}_\nu$ and that immediately $\mathcal{K}_\nu \propto \nu^{-(\frac{s+4}{2})}$.)

Putting all this together one would expect the flux of a homogeneous compact synchrotron source to have the form

$$F_\nu = \Omega_s I_\nu \simeq \Omega_s \frac{2\nu^2}{c^2} \frac{mc^2}{5} \nu^{5/2} \nu_B^{-1/2} (1 - e^{-\tau}) \quad (10$$

with $\tau \propto \nu^{-(\frac{s+4}{2})}$ and Ω_s the solid angle of the source.

Things are rarely so simple, but this picture allows us a means of calculating physical conditions in a source. Given F_ν, Ω_s and the frequency at which $\tau = 1$ one can calculate the magnetic field strength, ~~the~~ estimate the number and energy content of electrons and a variety of other quantities of interest.

With one more relation we actually have a test of this picture. Remembering ~~that~~ the connection between synchrotron and Compton scattering, we will realize that the relativistic electrons must also Compton scatter their own radiation. ~~This radiation~~ The resulting emission will be mostly at frequencies $\sim \gamma^2$ larger than those of the synchrotron.

The relative power going into Compton and synchrotron emission is

$$\frac{P_{compton}}{P_{synch}} \sim \frac{U_{rad}}{U_B} \quad (11)$$

with $U_{rad} \simeq \frac{4\pi}{c} \langle I \rangle$, the energy density in radiation and $U_B = B^2/8\pi$ the energy density in magnetic field. So if we can estimate $P_{compton}$ we have another relation between I and B and equations (10) and (11) can be solved simultaneously for Ω_s and B. This has been done for a variety of sources and the result is reasonable agreement between Ω_s and that suggested by VLBI observations. This is probably the best evidence to date that the radiation we are looking at is indeed synchrotron.

Physical characteristics

The derived physical size, magnetic field strength and total (electron + field) energy contents of several compact sources are:

Source	Radius (pc)	B (Gauss)	U (erg)
3C 84	0.6	0.1	10^{54}
BL Lac	0.5	0.01	10^{53}
3C 273	1	.001	10^{57}
3C 454.3	50	.0005	10^{58}

Variability

The variability often observed in ~~some~~ compact sources is one of the outstanding problems remaining to our understanding. Of course, at the lowest level, these variations represent changes in the number of radiating electrons and/or their energies and/or changes in magnetic field and/or changes in source structure. But ~~the~~ a real understanding of ~~these var~~ the causes and relative importance of these various possibilities is still in the future.

One of the most intriguing problems is the timescale on which some variations seem to occur. The variations fall into two catagories 1) variations of structure, 2) variations in flux. We would anticipate that because matter does not move at speeds greater than c, our sources will not appear to change more rapidly than the time light needs to travel across the source. However, some sources seem to be doing just that.

Possible explanations fall into three broad catagories

1) for rapid flux variations, perhaps some emission is not electron synchrotron

2) phase effects due to finite speed of light.

3) Our distance estimates are wrong.

References

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