Summer Student Notes

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Extended Extragalactic Radio Sources

Most extragalactic radio sources which have been discovered at low frequencies ($\nu \sim 178$ MHz) are found to have extended radio structure ranging from $\sim$1" to several degrees in size. The simplest and most common description of these structure is double.

At resolution only a few times better than the maximum size of the source, most extragalactic sources appear to consist of two approximately symmetric radio lobes with their optical counterpart directly between them. This is true for both radio galaxies and Q.S.O.'s. Also sources without optical identifications (blank fields) have a basically double structure. For this reason theoretical work on extended sources has concentrated on models which produce doubles. However, at higher resolution it becomes clear that significant differences exist between double sources as discussed later.

Classical Double Sources

Most models of extragalactic sources are aimed at explaining "classical double sources". High resolution observations of these sources reveal that each of the lobes is dominated by a compact knot of emission usually with a tail of lower brightness emission leading back to the optical identification. Usually there is also a compact bright spot centered on the identification as well. The spectrum of the outer lobes is usually a power law with a spectral index, α, ($S_\nu = k\, \nu^\alpha$ Jy) with $\alpha \sim -0.6$ to 1.2. The extended structure of the sources are usually linearly polarized with percentages varying from $\sim$1 to $\sim$20 percent.

The spectra, polarization, and surface brightness of the emitting regions strongly suggest that the radiation process is incoherent synchrotron emission (that is radiation produced by relativistic electrons spiraling in a magnetic field). The power law spectrum suggests that the energy distribution of the electrons is also power law.

Following Pacholczyk (1970) and Kellermann (1966), if one considers a cloud of relativistic electrons with a power law energy distribution

$$N(E)\, dE = KE^{-\gamma}\, dE \tag{1}$$

trapped in a magnetic field, H, the spectral density of synchrotron emission observed is given by

$$S_\nu \propto Kr^3 H_\perp^{(\gamma+1)/2} \left(\frac{\nu}{2c_1}\right)^{(1-\gamma)/2} \tag{2}$$

where r is the equivalent spherical radius of the cloud

$$c_1 = 3e/4\, m_e^3 c^5 = 6.27 \times 10^{+18} \tag{3}$$

and the region is assumed to be optically thin. The observed spectrum is thus also a power law with

$$S = k\nu^{+\alpha} \tag{4}$$

and

$$\alpha = (1-\gamma)/2 \tag{5}$$

A number of ways exist in which to further estimate the physical parameters of the source. The most common of these is to calculate the minimum total energy which could produce the observed radiation and the magnetic field strength which this condition implies. First one defines

$$E_{total} = E_p + E_e + E_H \tag{6}$$

where

E_p is the total proton energy

E_e is the total electron energy and

E_H is the magnetic field energy

Since one probably does not ever observe proton radiation, one must assume the ratio of proton to electron energies, k. Estimates of k range from $\sim$1, which is appropriate if annihilation of matter and antimatter is the source of the energy to accelerate the electrons, to $\sim$2000 from an induction-type acceleration mechanism. Probably k = 1 is now the most common assumption which is not to say we knew the acceleration process but that k = 1 seems to be the simplest assumption.

The magnetic field energy with a source of radius r is

$$E_H = \frac{H^2}{8\pi} \phi \frac{4}{3} \pi r^3 = \frac{H^2 \phi r^3}{6} \tag{7}$$

where ϕ is the fraction of the source's volume occupied by magnetic field and by relativistic particles.

The electron energy is given by

$$E_e = \int_{E_1}^{E_2} EN(E)dE = k \int_{E_1}^{E_2} E^{-\gamma+1} dE \tag{8}$$

The total observed radio luminosity is

$$L = 4\pi D^2 \int_{\nu_1}^{\nu_2} S_\nu d\nu \tag{9}$$

where D is the distance to the radio source.

From synchrotron theory,

$$L = -\int_{E_1}^{E_2} \frac{dE}{dt} N(E)dE = KC_2H_\perp^2 \int_{E_1}^{E_2} E^{-\gamma+2} dE \quad (10)$$

where $$c_2 = 2e^4/3\, m_e^4 c^2 = 2.37 \times 10^{-3} \quad (11)$$

Eliminating K between (8) and (10)

$$E_e = c_2^{-1} L H_\perp^{-2} \frac{\gamma-3}{\gamma-2} \frac{E_1^{-\gamma+2} - E_2^{-\gamma+2}}{E_1^{-\gamma+3} - E_2^{-\gamma+3}} \quad (12)$$

Now since the characteristic synchrotron frequency is related to the particle energy by

$$\nu_c = c_1 H_\perp E^2 \quad (13)$$

one finds

$$E_e = c_{12}\, (\alpha, \nu_1, \nu_2)\, H_\perp^{-3/2} L \quad (14)$$

where

$$c_{12} = c_2^{-1} c_1^{1/2} \frac{2\alpha-2}{2\alpha-1} \frac{\nu_1^{(1-2\alpha)/2} - \nu_2^{(1-2\alpha)/2}}{\nu_1^{(1-\alpha)} - \nu_2^{(1-\alpha)}} \quad (15)$$

Substituting (14) and (7) into (6)

$$E_{total} = (1+k)\, c_{12} H_\perp^{-3/2} L + \frac{H^2 \phi r^3}{6} \quad (16)$$

Equation (16) considered as a function of the magnetic field obtains a minimum when

$$E_H = \frac{3}{4} (1+k) E_e \quad (17)$$

This corresponds to a minimum total energy of

$$E_{total}^{(min)} = \frac{7}{4} (1+k) E_e = \frac{7}{4} (1+k) H^{-3/2} L \quad (18)$$

The corresponding magnetic field is equal to

$$H^{(min)} = (4.5)^{2/7} \, (1+k)^{2/7} \, c_{12}^{2/7} \, \phi^{-2/7} \, r^{-6/7} \, L^{2/7} \qquad (19)$$

Substituting (19) into (18)

$$E_{total}^{(min)} = c_{13} \, (1+k)^{4/7} \, \phi^{3/7} \, r^{9/7} \, L^{4/7} \qquad (20)$$

These quantities, while not necessarily the actual total energy or magnetic field values do give us a general idea of the likely parameters of a source. Some physical arguments along with other methods of estimating source parameters also usually given similar values for extended sources.

Source Models

Present models of extragalactic double sources can be divided into three classes: plasma clouds, relativistic beams, and supermassive objects. In plasma cloud models the source is usually produced by an explosion in the nucleus of the galaxy or Q.S.O. The cloud is then confined by the ram pressure $\rho_{ext} \, v^2$ produced by the surrounding medium where ρ_{ext} is the density of the gas through which the cloud is moving and v is the velocity of the cloud relative to that medium.

Relativistic beam models assume that instead of an explosion, quasi continuous production of a relativistic fluid occurs in the nucleus. This fluid either in the form of particles or very low frequency electromagnetic wave flows along a narrow channel out of the galaxy. At the end of the channel the fluid encounters a region of denser material and is decelerated. At this "working surface" highly relativistic electrons are generated and the local magnetic field is amplified, producing the observed radiation.

A third approach assumes that the radiating particles in the lobes of radio doubles are produced by condensed objects which have been thrown out of the parent galaxy. The model of this type currently most in favor is the slingshot model. This model proposes that as the result of a close three body encounter in the galactic nucleus supermassive black holes ($\sim 10^8\ M_\odot$) have been ejected. These objects then accelerated particles somehow, possible through processes related to the accretion disks which should form around them.

Other Extended Extragalactic Sources

In addition to classical double sources one finds other more relaxed-looking radio sources. These sources still often have generally double structure; but instead of having two bright knots at the outer edge of the radio emitting region the brightest regions of the source are near the galaxy with lower brightness regions extending further out. These sources are significantly lower in absolute luminosity than classical doubles and seem to be almost always found in clusters of galaxies. In general it seems likely that the higher gas densities and temperatures expected in clusters plus the motion of the parent galaxies with respect to the surrounding medium account for these differences, although the subject is certainly more complicated than this simple explanation implies.

Bibliography

For further reading about extragalactic sources

(1) De Young, D. S., "Extended Extragalactic Radio Sources", Annual Review of Astronomy and Astrophysics, Volume 14 (1976) preprint in library.

(2) Moffett, A., in Volume 9 of Stars and Stellar Systems (1976).

(3) Kellermann, K. I., "Radio Galaxies and Quasars", Chapter 12 of Galactic and Extragalactic Radio Astronomy (1974).

(4) Pacholczyk, A. G., Radio Astrophysics (1970).