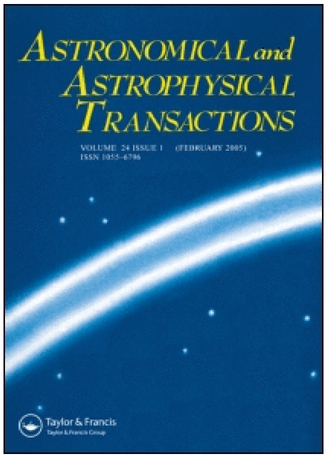

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Investigations of physical conditions in AGNs by the radio astronomy method

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This is a concise review of investigations of AGNs by the interplanetary scintillation method made in Pushchino Radio Astronomy Observatory.

Keywords: Compact radio source; Active galactic nucleus; Physical conditions; Interplanetary scintillations

1. Introduction

Many compact radio sources located in AGNs have low frequency cutoffs in their spectra. An analysis of physical mechanisms responsible for the spectral cutoffs has shown that synchrotron self-absorption of the radiation is the most likely mechanism for many radio sources. In that case we can estimate magnetic field strengths, relativistic electron number densities, and corresponding magnetic field and relativistic plasma energies in the AGNs where these radio sources are located. The method for the estimation of the physical parameters has been developed in [1] on the basis of the uniform synchrotron source model.

To obtain the physical information we must have the radio spectrum of the compact radio source and its angular diameters at high and at low frequencies. Therefore, we need observations of compact radio sources with high resolution at both high frequencies and at low frequencies (in particular in the metre radio wave range). The low frequency observations are necessary to detect low frequency cutoffs in spectra of compact radio sources.

At present there are no VLBI systems working in the metre radio wave range. The lowest frequency observations of compact radio sources are now carried out at PRAO by the interplanetary scintillation (IPS) method. The observations are performed with the Large Phased Array (LPA) at a frequency of 111 MHz (until 1999, at 102 MHz). The effective area of the antenna in zenith is $\sim$20000 m^2 ($A_{\rm geom} = 70000$ m^2). The sensitivity of the IPS observations is $\sim$0.1 Jy.

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The reduction of IPS observations with LPA was published in [2]. We estimate angular diameters of the scintillating sources from power spectra of the IPS. By comparing the observed spectrum with theoretical spectra (for different angular diameters θ), we determine the angular diameter of the scintillating radio source. To exclude fluctuation of the solar wind velocity we take the mean spectrum averaged for 7–10 days of observations.

The resolution of the IPS method depends on the signal to noise ratio. The limiting resolution of the method in the case of extremely strong sources when $S > 100$ Jy (in the regime of saturation) is $\sim 0.01''$. Typical resolution for weak sources ($S \sim 1$ Jy) is $\sim 0.1''$.

2. Results of the early investigations

1. At present we have obtained physical parameters for a few tens of AGNs. The magnetic field strength estimates are in the range 10^{-1}–10^{-5} G at the scale 1–10^2 pc. In spite of the roughness of the estimates, they are sufficient to show that energy equipartition is not in effect in many AGNs.
2. A correlation was found between physical conditions in AGNs and the morphological types of their host galaxies. Magnetic field strengths are smaller in the AGNs in spiral galaxies (accordingly the relativistic electron number densities are higher) than in the AGNs in elliptical galaxies.
3. Observations of five giant radio galaxies (3C 236, 3C 219, DA 240, NGC 315, NGC 1275) point to a possible relationship between radio structures of the radio galaxies and physical conditions in the nuclei of their parent galaxies. For radio galaxies of classical morphology (where giant radio clouds are connected by thin jets with the nucleus) the energy of the magnetic field in the nuclei considerably exceeds the energy of relativistic electrons. The opposite is true for jetless radio galaxies; for radio tailed galaxies an approximate equipartition is observed.

A concise review of these investigations was published in [3].

3. Necessity for the new method of investigation

Formerly we emphasized that the old method of investigations [1] was based on a uniform model of the synchrotron source. The spectrum of a uniform synchrotron source (with a power-law distribution of relativistic electron energies $N(E) = N_0 E^{-\gamma}$) is composed of two parts. At high frequencies, where the optical depth $\tau < 1$, the flux density $S \sim \nu^{-\alpha} (\alpha = (\gamma - 1)/2)$ and at low frequencies, where $\tau > 1$, $S \sim \nu^{2.5}$. This simple spectrum was a reasonably good approximation of real compact radio source spectra when observational data were deficient. But at present we have detailed spectra of the sources from VLBI observations at many frequencies, and it has become clear that the low-frequency spectra of the sources generally differ from that expected of a single uniform source, and the theoretical maximum slope of 2.5 is very rarely observed. Apparently the uniform synchrotron source is not a suitable model for real radio sources. It is necessary to invoke a more complicated source model to interpret radio astronomy observations.

Some sources have undulating spectra (similar to 3C 273 and NRAO 140). In principle, the spectra of these sources may be explained as the superposition of the spectra of a small minority of self-absorbed components, peaking at different frequencies (if uniform sources are present in nature).

But many compact sources have smooth spectra (within the observational uncertainties) that are flat or inverted. Of course, such spectra could result from the superposition of spectra of a large number of uniform components (located in the plane that is perpendicular to the line of sight), but they also can be produced by a single non-uniform source. The last possibility is more attractive than the sum of a large number of uniform sources.

It was shown [4–7] that the spectra of non-uniform synchrotron sources are comprised of three parts. At high frequencies ($\nu > \nu_2$) where the source is transparent ($\tau < 1$) $S \sim \nu^{-\alpha}$, at low frequencies ($\nu < \nu_1$) where the source is completely opaque ($\tau >> 1$)$S \sim \nu^{2.5}$, and there is the intermediate region ($\nu_2 - \nu_1$) where the source is partially transparent ($\tau \geq 1$). If relativistic electron density $N(r)$ and magnetic field $H(r)$ are power laws then at the intermediate frequencies the source spectrum is a power law too: $S \sim \nu^{-\alpha_{lf}}$. The low frequency spectral index α_{lf} lies in the range $-\alpha < \alpha_{lf} < 2.5$. This gives us the possibility to approximate practically any observed low frequency cutoff in the real source spectrum by a theoretical spectrum.

A need arose for developing a new method of physical parameter estimation of compact radio sources, located in AGNs, on the basis of a non-uniform source model.

4. New method of physical parameters estimation

We have developed a new method to estimate the physical parameters of radio sources [8]. This method is based on a non-uniform synchrotron source model. Real magnetic field strength and the relativistic electron density are approximated by the functions:

$$H(r) = \frac{H(0)}{1 + k_H (r/R)^m},$$

$$N(E, r) = E^{-\gamma} \frac{N(0)}{1 + k_N (r/R)^n}$$

for $r < R$ and $H(r) = 0$, $N(r) = 0$ for $r > R$. R is the source radius. This model has been chosen from physical considerations [7]. Model parameters are the following eight: γ, $H(0)$, m, k_H, $N(0)$, n, k_N, R.

All model (physical) parameters are determined from radio astronomy observations. To obtain the physical information we must have the spectrum of the radio source $S(\nu_i)$ with the high frequency cutoff at a frequency ν_2 and the low frequency cutoff at a frequency ν_1, the low frequency spectral index α_{lf}, angular diameters of the radio source at different frequencies (no less than one frequency) and red shift of the host galaxy.

From observations at higher frequencies, where a source is transparent and $S \sim \nu^{-\alpha}$, we have $\gamma : \gamma = 2\alpha + 1$.

The coefficient k_H is connected with the length of the intermediate frequency range ($\nu_2 - \nu_1$). We have it from the model catalogue [7] if we know $\nu_2 - \nu_1$ from observations.

The value of $\alpha_{\rm lf}$ we take from the observed radio source spectrum. From theory [5]

$$\alpha_{lf} = \frac{13 - 5n - 3m - 2m\gamma + 2\gamma}{2 - 2n - 2m - m\gamma}.$$

With γ and α_{lf} known, we have the connection between m and n. Parameters m and n lie in finite intervals which correspond to physical realized source models [8]. To simplify the work we adopt $n = 0$ and $N(E) = N_0 E^{-\gamma}$. Usually from observations we have an angular diameter estimation at one frequency. As was shown by [8] in this situation we have the minimum magnetic field strength estimation and the maximum particle density estimation. The maximum magnetic field strength must be one and half order or two order higher and the minimum particle density estimation must be one order lower [8].

To estimate H(0), N_0 and R we use the system of equations:

$$\begin{cases} \tau(\nu_2) = \int_{-R}^{R} c_6(\gamma) N_0 H^{\gamma+2/2}(x) \left(\dfrac{\nu_2}{2C_1}\right)^{-\gamma-4/2} dx \approx 1 \\ S(\nu) = \int_{\Omega} I(\nu,\omega) Cos\theta d\omega \approx \int_{\Omega} I(\nu,\omega) d\omega \\ I(\nu_\theta, r_\theta)/I(\nu_\theta, 0) = \dfrac{1}{2}. \end{cases}$$

ν_θ is the frequency at which the angular diameter was measured.

$I(\nu)$ is obtained from the numerical solution of the transfer equation:

$$I(\nu, r) = \int_{-L}^{L} c_5(\gamma) N_0 H^{\gamma+1/2}(x) \left(\frac{\nu}{2C_1}\right)^{1-\gamma/2} e^{-\int_x^L c_6(\gamma) N_0 H^{\gamma+2/2}(x')(\nu/2C_1)^{-4-\gamma/2} dx'} dx$$

So we have all model parameters. It is necessary to emphasize that because of the paucity of observation data it is possible to obtain only interval estimations of the physical parameters.

5. Results of the new investigations

Using the new method, we have investigated the physical conditions in nuclei of the nearby radio galaxies 3C 111 and 3C 465 [9]. A strong non-uniform magnetic field distribution was found in the nuclei of these radio galaxies. In the central regions of the nuclei at the scale $r \le 0.1$ pc the magnetic field strengths lie in the interval $10^2 < H < 10^4$ G. The minimum mean H in 3C 111 is $\langle H \rangle \sim 10^{-2}$ G at the scale 20 pc and in 3C 465 $\langle H \rangle \sim 10^{-1}$ G at the scale 4 pc. No energy equipartition was found in nuclei of the radio galaxies. The magnetic field energy is greater than the relativistic electron energy.

Using the same method, we have investigated the physical conditions in the nucleus of 3C 274 [10]. This is one of the nearest radio galaxies. It was found that the magnetic field distribution in the nucleus of 3C 274 is very non-uniform too. In the centre of the nucleus, on the scale $r < 0.01$ pc, it is $0.4 < H < 40$ G compared with the mean $\sim 10^{-3}$–10^{-4} G. In contrast with 3C 111 and 3C 465, everywhere in the nucleus the relativistic electron energy is much higher than the magnetic field energy, whereas near the centre it is possible energy equipartition is in effect.

Note that different physical conditions in the nuclei of these radio galaxies correlate with different forms of radio jets in the galaxies. Perhaps the magnetic field plays an important role in the forming of radio jets.

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