FINE STRUCTURE OF JET KNOTS OF COSMIC RADIO SOURCES IN THE SYNCHROTRON AND COMPTON MECHANISMS OF RADIATION

E. Yu. Bannikova\textsuperscript{1,2} and V. M. Kontorovich\textsuperscript{1,2}

\textsuperscript{1} Institute of Radio Astronomy of the National Academy of Science of Ukraine, 4 Chervonoproporna Str., 61002 Kharkov, Ukraine
\textsuperscript{2} Kharkov National University, 4 Svobody Sqr. 61077 Kharkov, Ukraine

Received: 2004 December 1; revised 2005 May 13

**Abstract.** A method of obtaining jet physical parameter combinations (such as magnetic field strength, jet or knot velocity, etc.) is offered by studying knot “flares” in radio- and X-ray domains.

**Key words:** galaxies: active – galaxies: nuclei – galaxies: jets – radio galaxies

1. INTRODUCTION

Radio galaxies and quasars are investigated with high angular resolution in a wide range of frequencies from radio to X-ray domain\textsuperscript{1}. Some of them demonstrate jets with local knots (Kn) and hot spots (HS), which often have fine structure in the form of asymmetrical “flares”. The latter might be interpreted in terms of Kn or HS motion.

2. DIFFUSION MODEL WITH A MOVING KNOT OR HOT SPOT

In this work, the Kn or HS are considered as localized moving sources of ultra relativistic electrons propagating into a cloud or jet where they lose their energy due to synchrotron or/and Compton radiation. We use the kinetic equation (KE) describing these processes for the distribution function of relativistic electrons (EDF) with a given moving source and restriction to diffusion as a mode of electron propagation (Valtaoja 1982; Gestrin et al. 1987; Bannikova & Kontorovich 2003). By exchanging variables in the $t - E$ plane (or a Laplace transformation on time) we can reduce the KE (in terms of the new variables) in the case of a space-uniform decay to a diffusion equation for which the solution is known. The final expression for the EDF with a moving (point) source at $\mathbf{r}(t)$, where $x$ and $y$ are coordinates in a picture plane (Figure 1), gives us the possibility to find the intensity of both the synchrotron radiation and the radiation due to the inverse Compton effect for a resolved source. The resolution required can be achieved by a radio telescope such as VLA or by the modern space X-ray telescope (Chandra) (Marshall et al. 2005; Sambruna et al. 2002). We consider only the transparent region of the

\textsuperscript{1} See the Harris list of radio sources with jet-related X-ray emission: http://hea-www.harvard.edu/XJET

© Teorines fizikos ir astronomijos institutas
source. The injection spectrum is supposed to follow the power law \((E^{-\gamma})\) with 
\(\gamma_0 = 2\) in the range of energies \(E_1 < E < E_2\) and to be equal to zero outside.

The injection is switched on at the moment of time \(t = 0\) which corresponds to the beginning of effective particle acceleration. Thus, if we know the EDF \(N(E,t,r)\), it is possible to reproduce the distribution of emission intensity. By varying model parameters, we aim at achieving similarity of the model and the images of the source observed at a fixed frequency. The distributions demonstrated below have been calculated by the method described. The characteristic synchrotron and Compton frequencies are \(\nu_s = \frac{3}{2} \nu_H \left( \frac{E}{mc^2} \right)^2\), \(\nu_C = \nu_{ph} \left( \frac{E}{mc^2} \right)^2\), where \(\nu_H = eH/(2\pi mc)\), \(H\) is the magnetic field projection on the picture plane, \(\nu_{ph}\) is a typical frequency of the low frequency photon distribution corresponding to the scattering process. Such scattering can occur either on the CMB (relic) radiation, or on the radiation from the central source, or on the own synchrotron photons (Wilson 2003). The parameters we obtain are the “life time” \(\tau\) of an electron of the energy \(E\), \(\tau \approx \frac{1}{\beta E}\), where \(\beta = \frac{32\pi}{9} \left( \frac{\rho^2}{mc^2} \right)^2 \frac{W_H + W_r}{m^2 c^4}\), \(W_H + W_r\) denotes the energy density of the chaotic magnetic field and radiation; the “diffusion length” is \(\lambda_{\text{diff}} \approx \sqrt{D_0 \tau}\), and the ”diffusion velocity” is \(V_{\text{diff}} = \sqrt{D_0 / \tau}\). Here \(D_0\) is the coefficient of diffusion. The ratio of the transverse velocity of HS or Kn to the longitudinal velocity \(V\) governs the cloud geometry at a given frequency. We base a qualitative analysis and preliminary estimates on “geometrical” considerations. The \(H\) and \(E\) of the electron radiation at a given frequency can be expressed as a function of the known geometric form and velocity of the knot. So, if we know the longitudinal \(L\) and the transverse \(l\) sizes of Kn then the relative velocity can be estimated as \(V \approx \beta E (L-l)\). If \(W_H \gg W_r\), \(H\) is connected with \(E\) according to the expression for the life time of an electron as \(H^2 \cdot E \approx 2 \cdot 10^{-6} V/10^{20}\text{cm/s} \frac{(L-l)/\text{pc}}{(L-l)/\text{pc}}\) (in the CGS system). On the other hand, from \(\nu = \nu_s\) it follows that \(H \cdot E^2 \approx 5 \cdot 10^{-19} \nu\).

3. THE KNOT STRUCTURE OF THE JET IN M87

Using the diffusion model we reconstruct intensity distributions (Figure 2) for two knots, A and B, of the kiloparsec jet in M87 as observed at a wavelength of 6 cm (Biretta et al. 1995) and in X-rays (Wilson & Yang 2002). The parameters found are the velocity components for the radio knot A: \(V_{Ax} = 0.509 \cdot c, V_{Ay} = -0.083 \cdot c\); for the knot B: \(V_{Bx} = 0.62 \cdot c, V_{By} = -0.16 \cdot c\) and \(D_0 = 5 \cdot 10^{29}\text{ cm}^2/\text{s}\) and \(H = 10^{-5}\text{ G}\). Specifically, for the velocity \(V_{Ax}\) of the knot A, the parameters are \(\tau = 8 \cdot 10^{10}\text{ s}, \lambda_{\text{diff}} = 2 \cdot 10^{20}\text{ cm}\) and \(V_{\text{diff}} = 2 \cdot 10^9\text{ cm/s}\). In the X-ray domain, the shape of knots is close to a sphere. Knowing the intensity distribution, it is also possible to find the spectral index distribution for a given frequency \(\nu\): 
\[
\alpha = -\nu \frac{d \log I / d \nu}{\log (\nu_1/\nu_2)}
\]

for two different frequencies \(\nu_1\) and \(\nu_2\): 
\[
\alpha_{\nu_1-\nu_2} = \frac{\log (I_1/I_2)}{\log (\nu_1/\nu_2)}.
\]
Fig. 2. The intensity distribution calculated for the knots A+B in the jet of M 87 (left); the southern component of the microquasar 1E 1740-2942 (center); the parsec-scale jet in 3C 270 (right).

In our calculations, the radio spectral index increases from an expected value of 0.5 (0.3 in some calculations) with the distance to the knot.

4. THE JET OF THE MICROQUASAR 1E1740–2942

In the microquasar 1E1740-2942, which is located close to the Galactic Center, two jet components are observed (Mirabel et al. 1992). We model the Southern component (Figure 2) by obtaining the intensity distribution for the following parameter values: $V_x = -0.65 \cdot c$, $V_y = -0.25 \cdot c$, $D_0 = 3 \cdot 10^{27}$ cm$^2$/s, $t = 1.5 \cdot 10^8$ s, $\lambda = 20$ cm and $H = 0.6$ G, corresponding to $\tau = 9 \cdot 10^7$ s, $\lambda_{\text{diff}} = 5 \cdot 10^{17}$ cm and $V_{\text{diff}} = 6 \cdot 10^9$ cm/s.

5. THE PARSEC-SCALE JET IN NGC 4261/3C 270

The “flare” in the VLBI-jet observed at a frequency of $\nu = 8.387$ GHz is directed from the center to the periphery. It might be the result of a fixed shock or a shock with a small velocity compared to the velocity of the jet. For defining the jet velocity, it is sufficient to consider the framework in which Kn moves and the jet is at rest, and apply the technique described above. Taking into account the jet velocity $V = -0.52 \cdot c$ (Piner et al. 2001), we get the map of intensity distribution (Figure 2) for the following parameters: $D_0 = 3 \cdot 10^{27}$ cm$^2$/s, $t = 1.5 \cdot 10^8$ s, $\nu = 8.387$ GHz and $H = 10^{-2}$ G. Note that such relatively large values of $H$ may have some physical grounds (Beskin & Pariev 1993). In the model, the transverse size of the “flare” increases slightly with the distance from the shock, while in the observations it decreases with the distance. Such a discrepancy implies that in this object the prevailing role in electron propagation may belong to hydrodynamic flow from a finite-size injection region. The account of flow is especially essential at low frequencies and far from the source of electrons. Besides, a parameter of importance, in general, is the angle at which the jet moves to (or from) the observer.

6. DISCUSSION AND CONCLUSIONS

A comparison of the characteristic (cyclotron $\nu_H$ and radiation $\nu_{\text{ph}}$) frequencies shows that the electrons of the same energy could be responsible for the synchrotron radiation (in radio domain) and the inverse Compton (in X-rays). As a consequence, they have lifetimes of the same order, and similar images of

© Teorines fizikos ir astronomijos institutas
"flares" should be observed in both the domains. The differences can arise due to refraction of a radio image, impact of heterogeneity in $H$ (Bannikova & Kontorovich 2004) or the radiation field. This opens a possibility of studying of these parameters. If the images are formed by the electrons with substantially different lifetimes (for example, at prevalence the synchrotron radiation both in radio and X-ray domains, as is apparently the case for M 87), we could observe in the latter image not a "flare" but a finite (true) size of the sources of injection.

ACKNOWLEDGMENTS. The work was supported in part by the INTAS grant 00-00292.

REFERENCES
Bannikova E. Yu., Kontorovich V. M. 2003, Space Science and Technology, 9, No. 2, 304
Beskin V. S., Parjev V. I. 1993, Uspekhi Fiz. Nauk, 163, No. 6, 95

© Teorines fizikos ir astronomijos institutas