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The radio-bright blazar PKS 1502+10: a possible neutrino source with a proton jet

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High energy neutrino (up to PeV) production in bright blazars within a parsec-scale jet and the presence of accelerated ultrarelativistic protons are being constantly discussed. In order to produce neutrinos, the presence of high energy protons in AGN jets is necessary. On the other hand, the lower ultrarelativistic energy part of the proton energy distribution (from GeVs up to TeVs) should generate synchrotron radio emission in the same parsec-scale jet, in addition (may be) to the electron synchrotron radiation. We report the results of testing the possibilities of numerical fitting the earlier suggested Hedgehog model for an electron jet or/and a proton jet in a strong longitudinal magnetic field to the multi-frequency radio spectrum of PKS 1502+106 obtained with RATAN-600 and other telescopes in the frequency range from ~0.1 GHz to 1000 GHz. For VLBI the proton jet can provide a magnetic field and brightness temperatures of $m_p/m_e = 1836$ times higher and an angular size of $\sqrt{m_p/m_e} = 43$ times less than those produced by the electron synchrotron jet.

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1. Introduction

After ultra-high energy neutrino events [1], active galactic nuclei (AGNs) have become intriguing candidates for astrophysical neutrino sources and effective proton accelerators. The sources of these neutrinos are still unknown, but it turned out that the sky areas from where the ultra-high-energy neutrinos are coming (IceCube) are statistically associated with VLBI bright quasar positions, and the moments of their arrival coincide with powerful flares of synchrotron emission in the compact jets of these objects [2-3]. This allows us to suggest that the neutrinos are produced in their central parsec-scale regions, probably in the proton-proton or proton-photon interactions.

We consider the proton synchrotron radiation based on the Hedgehog model. The model was suggested in 1969 by N.S. Kardashev for a jet in a strong longitudinal magnetic field [4-6]. The model is similar to the nonrelativistic model suggested by I. Shklovsky in [7-8] and was mathematically generalized by Van der Laan [9].

It can be said that the Hedgehog model, in fact, is the Shklovsky model in which the chaotic magnetic field of a cloud from an active nucleus of a galaxy or a quasar is replaced by a quasi-radial magnetic field of the jet from the active nucleus. Nevertheless, such substitution almost "automatically" requires a predominance of magnetic energy density $W_H = H^2/(8\pi)$ over the kinetic energy density $W_E \sim \rho c^2$ of synchrotron-emitting particles ($W_H \gg W_E$ as a result) in a relativistic jet with a continuous outflow of particles from the nucleus. It has been shown that there is also a possibility of apparent superluminal velocities of relativistic components in a radio source. Because of this energy requirement, the jet model differs significantly from the Blandford and Königl model [10], in which $W_H \sim W_E$. The aim is to study main VLBI features of proton synchrotron jets in comparison with jets of electron synchrotron emitters that have the same gamma factors and geometry of sources. The object PKS 1502+106 is used as an example of possible neutrino radio-bright VLBI blazar with a proton jet emitting neutrinos in the photon-proton process [2, 11]. An earlier similar comparison was made in [6, 12].

2. Magnetic field, brightness temperature, and angular diameter for electron/proton synchrotron radiation

The model dependence of the magnetic field B on the distance r along the jet is $B = B_0\,(r/r_0)^{-2}$. The task is to compare main jet parameters if its geometry and $\gamma_E = (E/m_e\,c^2) = (E/m_p\,c^2)$ are the same for the electron and proton jets that are observed within the same angle ϑ = const. The following spectra parameters have been estimated from fitting the jet model to the observed data: the frequency ν_m ($\lambda_m = c/\nu_m$) and the flux density S_m in the maximum of the jet spectrum, the indices γ_E and γ of the energy spectrum for electrons or protons. We use the equations obtained from the book by V.L. Ginzburg [13] to estimate the main jet parameters neglecting the redshift:

$$B_\perp/M_{2e} \sim 0.82 \cdot 10^{-6} \cdot \nu_m \cdot \gamma_E^{-2}, \tag{1}$$

$$T_b \sim 1.5 \cdot 10^8 \cdot \gamma_E \cdot M_{2e}\,, \tag{2}$$

$$\Theta \sim \lambda_m \left(\frac{2S_m}{\pi k_B T_b}\right)^{1/2}. \tag{3}$$

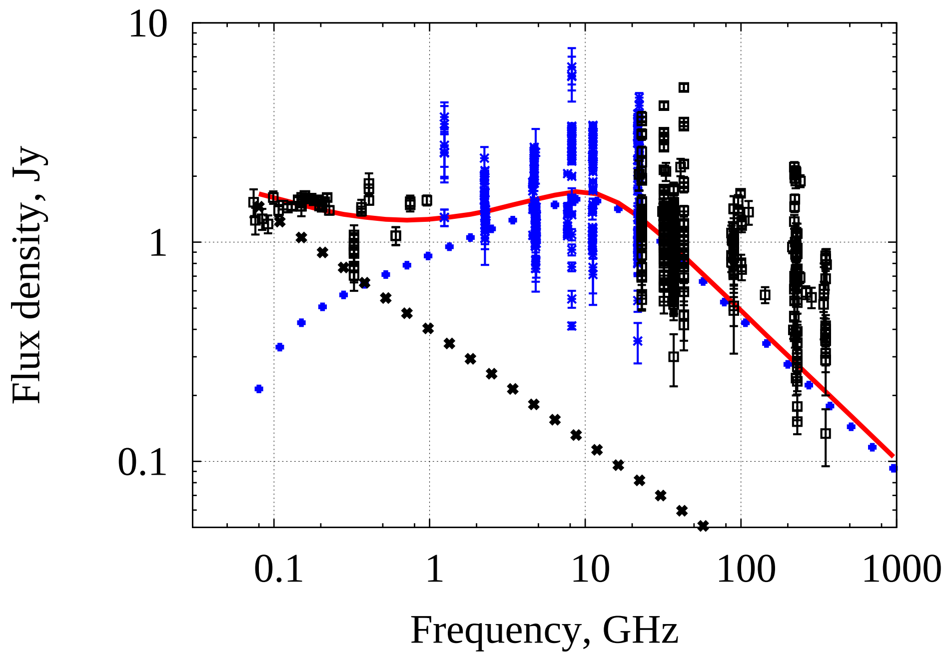

Figure 1: Broadband radio spectra of PKS 1502+106. The RATAN-600 and CATS (astrophysical CATalogs support System [14]) data are shown with the blue and black colors, respectively. The RATAN data were obtained at six frequencies (1.2, 2.3, 4.7, 8.2, 11.2, and 22.3 GHz) quasi-simultaneously in 2009–2021. The CATS data combine ~7600 radio measurements from 74 literature sources, covering a time period of about 40 years. The black dotted line represents the linear model fit for the synchrotron radiation in optically thin extended structures up to kpc scales. The blue dotted line represents the high-frequency model component with $dN(t)/dt = const$ [4] associated with the parsec-scale jet that dominates starting from ~ 0.3 GHz to higher frequencies. The red line is the sum of the black and blue dotted lines.

Here $B_\perp = B \sin\vartheta$, $M_{2e} = 1$ for electrons, and $M_{2e} = 1836$ for protons, Θ is the angular diameter of the emitting jet in the image plane, k_B is the Boltzman constant, T_b is brightness temperature. These equations are valid for the known approximation [13] in which the synchrotron emission of a particle with a charge e, mass M, energy E, and gamma-factor $\gamma_E = E/Mc^2$ in the magnetic field $H_\perp$ occurs at the frequency ν_0 of its spectral maximum, $\nu_0 \sim 0.29 \cdot \nu_C = 0.29 \cdot 3\, e\, H_\perp\, \gamma_E^2/(4\pi Mc)$ [13]. This gives equation (1). In the same approximation, relation (2) follows from the well-known equation for intensity through the coefficients of emission and reabsorption as well as through the optical thickness at the frequency ν_0. Relation (3) is obtained from the equation for the flux density through the intensity at the frequency ν_0 and the solid angle $\Omega \sim \pi\, \Theta^2/4$.

PoS(EVN2021)009

Table 1: Estimation of jet parameters.

Particle	B, Gauss	T_b, K	Θ, mas	$t_{1/2}$, s
$electrons$	7	$5 \cdot 10^{10}$	0.6	$1 \cdot 10^{8}$
$protons$	$1 \cdot 10^{4}$	$9 \cdot 10^{13}$	0.014	$2 \cdot 10^{11}$

3. Results

We tested the Hedgehog model numerical fitting to describe the average multi-frequency spectrum of PKS 1502+106, compiled from observed data of many epochs. The electron or proton synchrotron radiation was modelled for a jet with a strong longitudinal magnetic field. Such temporally average spectra could be obtained in the model if the continuous flux $dN/dt(t)$ of emitted particles across the base of the jet is constant during a long time (of the order of 10 years in general). The variability of this flux of protons or electrons emitting synchrotron radiation is converted in the model [4-6, 12] to variability of observed emission. The main results of our estimation of jet parameters using equations (1)–(3) and fitting the model to the observations (Fig. 1) are presented in the table. In the last column of the table, we also added the time $t_{1/2}$ of energy loss due to synchrotron radiation.

The general fitted parameters are the following: $\vartheta = 1^\circ$, $\nu_m = 13$ GHz, $S_m = 1.5$ Jy, $\gamma = 2.4$, $\gamma_E = 300$, $M_{2e} = 1$ (electrons), $M_{2e} = 1836$ (protons), $B^2/(8\pi) \gg W_E$ both for electrons and protons (W_E is the energy density of emitted particles).

4. Summary

The multi-frequency variable spectra of PKS 1502+106, averaged over many years, can be explained both by proton and electron synchrotron radio emission. If we explain them by emitting electrons or protons with equal gamma factor and jet geometry, then the magnetic field and brightness temperature of the proton jet can gain values up to $m_p/m_e = 1836$ times greater than those for the electron jet (m_p and m_e are the masses of proton and electron, respectively). The angular size of this proton jet can be up to ~ 43 times less than that for the electron jet. VLBA results are in agreement with these angular sizes.

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