Advances in Astronomy and Space Physics, **2**, 49-52 (2012)

X-ray and radio emission of kiloparsec jets at large redshifts

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For some jets of core dominant quasars we assumed that the X-ray emission of the nearest to the core knots is produced by the inverse Compton scattering on the quasar emission whereas the X-ray emission of distant knots is formed by the inverse Compton scattering on the cosmic microwave background as it takes place for the 3C 273 jet. Competition of the scattered radiation allows to estimate the luminosity of quasars and the angle between the jet and the line of sight. This angle for a jet of the quasar 1745+624 is $24^\circ \div 34^\circ$. We found that the ratio of X-ray to radio flux densities conforms to the expected dependence on redshift for the knots of PKS 1127–14 and 1745+624 jets.

Key words: radiation mechanisms: non-thermal; scattering; quasars: individual: 1745+624, PKS 1127-14

INTRODUCTION

The PKS 0637-752 jet is the first one detected by Chandra X-ray Telescope. Its X-ray emission was explained by the inverse Compton scattering (IC) on the cosmic microwave background (CMB). The small angle between the jet and the line of sight and the high bulk Lorentz-factor are needed to conform with the energy equipartition between the magnetic field and the particles [11]. This model became favour also for other jets of FRII radio sources, but different physical parameters of jet knots are required to explain the distribution of radio and X-ray intensity along individual jet [8]. Other possible X-ray emission mechanism is the IC on the self synchrotron photons. It occurs in the hot spots of several jets [4].

On the other hand, alternative X-ray emission mechanism for the 3C 273 jet was proposed [1, 5]. According to it the IC on the core emission produces the X-rays in the nearby to the quasar knots, while the IC/CMB forms the X-ray emission from the distant knots. Different emission scattering mechanisms are the simplest way to explain the variations of observed parameters of the knots within the jet without changing their intrinsic properties [5, 7]. But in this case the equipartition hypothesis fails, possibly except the farthest knot (hot spot), where the X-ray emission is not yet observed.

Some jets of core dominant quasars (1745+624 [3], PKS 1127–145 [10]) have distributions of X-ray and radio intensity similar to those of 3C 273 jet [6]. For each of them the radio intensity increases along the jet and has maximum at the terminal jet knot, while the X-ray brightness decreases and drops to undetectable level near the jet end. So, the X-ray emission mechanism of these jets is similar to that suggested for the 3C 273 jet [1, 5].

THE ANGLE BETWEEN THE JET AND THE LINE OF SIGHT

Competition of the scattered emission gives a possibility to define an angle θ between the jet and the line of sight (Fig. 1). This angle is needed to determine a physical size of a jet. The knot denoted “d” must be sufficiently distant from the core in order to provide the excess of the CMB energy density over the energy density of the quasar emission:

$$W_0\,(1+z)^4 > \frac{L}{4\pi c R_d^2}\sin^2\theta,$$

where $W_0 = 4.2\cdot 10^{-13}$ erg/cm^3 is the local energy density of the CMB, z is the redshift of the object, L is the luminosity of the core, R_d is the projected distance of the knot “d” from the quasar. However, the knot denoted “n” must be located close enough to the active nucleus in order to provide the excess of the energy density of the quasar emission over the CMB energy density.

Electrons emitting in X-ray and radio bands have almost equal energy. Therefore, if the X-ray emission is produced by the IC/CMB, then its spectral index has to coincide with the radio one. For 1745+624 ($z = 3.89$) it takes place in the terminal knot K2.5 [3]. So, we supposed that the X-ray emission is produced by the IC/CMB only in this knot. The IC on

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the core emission occurs in the remaining knots. The intensity of X-rays is proportional to the electron concentration and the energy density of the scattered emission (see (3)). The X-ray flux from the knots and the energy density of the CMB are known (see Table 1). The ratio of electron concentration of the knots K1.4 and K2.5 is

$$\frac{\mathcal{N}_{K1.4}}{\mathcal{N}_{K1.8}} = \frac{F_{K1.4}}{F_{K1.8}} \cdot \frac{W_{ES}^{K1.8}}{W_{ES}^{K1.4}} = \frac{F_{K1.4}}{F_{K1.8}} \cdot \left(\frac{R_{K1.4}}{R_{K1.8}}\right)^2 \approx 0.9,$$

where $F_{K1.4}$, $F_{K2.5}$ are the X-ray flux densities of the knots K1.4 and K2.5 correspondingly [3]. Hence, the electron concentration is assumed to be equal in all knots. Then the energy density of the quasar emission in the knot K1.4 is:

$$W_{ES}^{K1.4} = \frac{F_{K1.4}}{F_{K2.5}} W_0 (1+z)^4 \approx 4.4 \cdot 10^{-10}\,(\mathrm{erg/cm^3}).$$

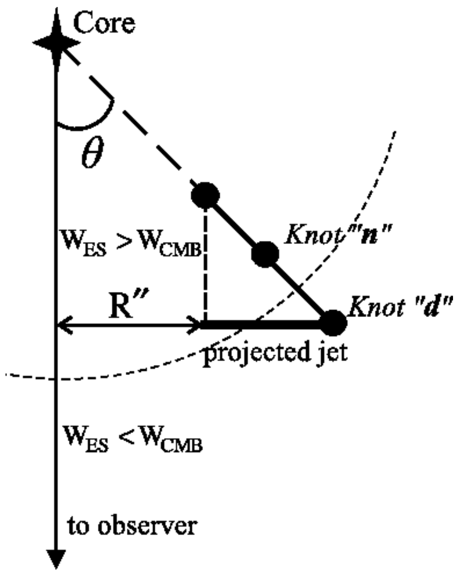

Fig. 1: The scheme of the jet orientation with respect to the observer. The observer, the core and its jet lie at the one plane.

Hence, the luminosity of synchrotron source in the active nucleus was estimated as:

$$L \approx 4\pi c R_{K1.4}^2 W_{ES}^{K1.4} / \sin^2\theta \approx \approx 1.5 \cdot 10^{47} / \sin^2\theta \;(\mathrm{erg/s}) \quad (1)$$

The derived result (1) agree well with an independent estimation of bolometric luminosity $L = 7.8 \cdot 10^{47}$ erg/s [3]. The angle between the jet and the line of sight was found to be $\theta = 24^\circ \div 34^\circ$ from comparing W_{ES} and W_{CMB}.

For the PKS 1127–14 jet ($z = 1.18$) we assumed that the IC/CMB occurs at the knot C. The observed difference between α_X and α_R for this knot is possibly caused by large errors of the X-ray spectral indices determination.

The core luminosity was derived in similar way. We supposed that the electron concentration in knots is equal because of the following relation:

$$\frac{\mathcal{N}_A}{\mathcal{N}_B} = \frac{F_A}{F_B} \cdot \frac{W_{ES}^B}{W_{ES}^A} = \frac{F_A}{F_B}\left(\frac{R_A}{R_B}\right)^2 \approx 0.9,$$

where F_B, F_C are the X-ray flux densities of the knots B and C correspondingly (see Table 2, [10]).

The energy density of the core emission at the knot B is

$$W_{ES}^B = \frac{F_B}{F_C} W_0 (1+z)^4 \approx 4.6 \cdot 10^{-11}\,(\mathrm{erg/cm^3}).$$

Then the quasar luminosity is:

$$L \approx 4\pi c R_B^2 W_{ES}^B / \sin^2\theta \approx \approx 3.9 \cdot 10^{48} / \sin^2\theta \,(\mathrm{erg/s}). \quad (2)$$

The result (2) sufficiently exceeds the other estimation $L = 8 \cdot 10^{46}$ erg/s mentioned in [10]. This discrepancy can be explained. Firstly, the concentration of the emitting electrons in the knot C can be essentially smaller than that in the knot B. In this case the parameters of the knot C is closer to the equipartition hypothesis then ones of the knot B. Secondly, the flux density of the quasar emission at the jet direction will be greater then that along the line of sight.

THE RATIO OF X-RAY TO RADIO FLUX DENSITIES

If the IC on the CMB occurs then the ratio of X-ray to radio flux densities should increase with the redshift because the CMB energy density increases [9]. In fact, jet knots do not satisfy this dependence. It was explained by the variation of the magnetic field strength H and the variation of the Doppler-factor [4]. However, the IC on the core emission can produce the X-ray emission in some knots.

We used the well-known expression for the electron energy looses:

$$\left(-\frac{dE}{dt}\right) = \frac{4}{3} c\,\sigma_T\, W\,\Gamma^2 \qquad \text{and} \qquad \omega = \tilde{\omega}\Gamma^2$$

where σ_T is the Thomson cross-section, Γ is the electron Lorentz-factor. In the case of synchrotron mechanism $W = H^2/8\pi$ is the energy density of the magnetic field and $\tilde{\omega} = 0.29 \cdot 3eH/2mc$ (e, m are the charge and the mass of the electron). For the IC, W is the energy density of the CMB and $\tilde{\omega} = 4\omega_0 (1+z)/3$ ($\omega_0 \approx 10^{12}$ s^{-1} is the frequency of the CMB maximum at $z = 0$). The electron energy spectrum was assumed to be described by the power law $N(E) = \mathcal{K}E^{-\gamma}$, where $\gamma = 2\alpha + 1$. Using the formula for the flux density:

$$F(\omega)\,d\omega = \frac{l_z}{4\pi}\left(-\frac{dE}{dt}\right) N(E)\,d\Omega dE,$$

where l_z is the knot size along the line of sight, Ω is the observed solid angle of the knot, and making substitutions mentioned above we obtained the uniform formula for the flux density of synchrotron and IC/CMB emission:

$$F(\omega)\,d\omega = \\ = \frac{l_z}{4\pi}\frac{2}{3}\,c\,\sigma_T W(\gamma-1)\,\mathcal{N}\Gamma_{min}^{\gamma-1}\,\tilde{\omega}^{\alpha-1}\omega^{-\alpha}d\omega. \quad (3)$$

Hence, the expression for the ratio of the flux densities of X-ray and radio emission is

$$\frac{F_X}{F_R} = (1+z)^{3+\alpha}\,8\pi W_0 H^{-1-\alpha}\times \\ \times\left(\frac{8\omega_0 mc}{0.29\cdot 9e}\right)^{\alpha-1}\left(\frac{\omega_X}{\omega_R}\right)^{-\alpha}. \quad (4)$$

Authors of [2] presented a similar to (4) result with the spectral index $\alpha = 1$ for all sources.

The magnetic field strength was derived from (4): for the knot K2.5 of the 1745+624 jet $H = 85\ \mu$G ($\alpha = 1.3$), for knot C of the PKS 1127–14 jet $H = 79\ \mu$G ($\alpha = 1.3$) or $H = 30\ \mu$G ($\alpha = 0.9$).

The dependence of F_X/F_R on the redshift (4) and the observed ratio of X-ray to radio flux densities for discussed sources are shown in Fig. 2. The parameters used to plot these dependencies correspond to the observed data for the knot C1 of the 3C 273 jet ($\alpha = 0.8$, $H = 1.5\ \mu$G [5]) and for the knot K2.5 of the 1745+624 jet. The ratio F_X/F_R increases both with growth of the spectral index and decrease of the magnetic field strength.

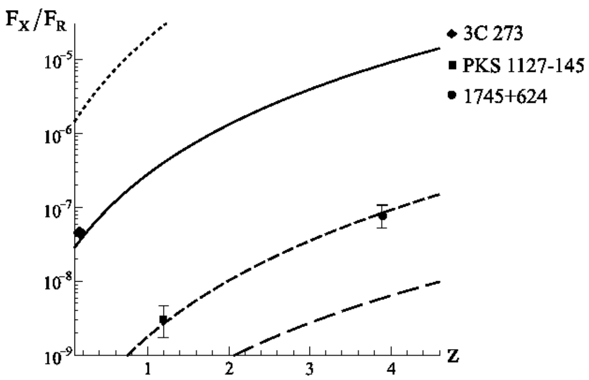

Fig. 2: The ratio of X-ray to radio flux densities versus the redshift. Each curve is plotted with the different parameters: dotted line – $\alpha = 1.3$, $H = 1.5$ mG; solid line – $\alpha = 0.8$, $H = 1.5$ mG; short dashed line – $\alpha = 1.3$, $H = 85$ mG; long dashed line – $\alpha = 0.8$, $H = 85$ mG.

The knot C of the PKS 1127–14 jet and the knot K2.5 of the 1745+624 jet correspond to the same dependence (Fig. 2). The values of the magnetic field and the spectral index in these knots also coincide. It proves that their X-rays emission is formed by the IC/CMB with the subrelativistic jet motion. Let us note, that for the ultrarelativistic jet in the IC/CMB model [11] the difference between knots parameters arises: $H \approx 209\ \mu$G, $\delta \approx 5$ [3] for the knot K2.5 of 1745+624 and $H \approx 15$, $\delta \approx 4.2$ [10] for the knot C of PKS 1127–14. The detailed analysis of the dependence on the redshift will be possible if the number of detected jets in the X-ray band increase.

CONCLUSIONS

The difference in the nature of the scattered photons easy explains the observed distributions of the radio and the X-ray intensities along the selected jets. It explains the distribution of the X-ray spectral index too. The competition of the scattered radiation allows to determine the angle between the jet and the line of sight. If the dependence of the ratio F_X/F_R on the redshift is defined then it is necessary to take into account the fact that IC on core emission occurs in some jet knots. It was shown that the 1745+624 and PKS 1127-14 jets have not bulk relativistic velocities. The X-ray emission of its distant knots is produced by the IC/CMB while the IC on the core emission takes place in the nearby to the active nuclear knots.

ACKNOWLEDGEMENT

We thank Victor M. Kontorovich for helpful discussions of this work.

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Table 1: The observed data of the 1745+624 jet. The flux densities F_R and F_X were measured at $\nu_R = 5$ GHz and $\nu_X = 2.41 \cdot 10^{17}$ Hz (the photon energy is 1 keV), correspondingly [3]. α_R and α_X are the spectral indexes in the radio (between 1.5-14.9 GHz) and in the X-ray (2-10 keV) bands. $1''$ corresponds to the projected distance 6.97 kpc.

Knot	distance, R''	F_R, mJy	F_X, nJy	α_R	α_X
K1.4	$1.4''$	6.8 ± 1.0	4.7 ± 0.5	0.96 ± 0.03	–
K1.8	$1.8''$	9.3 ± 1.4	3.1 ± 0.4	1.15 ± 0.2	–
K2.5	$1.5''$	32.3 ± 3.2	2.5 ± 0.6	1.28 ± 0.1	1.1 ± 0.6

Table 2: The observed data of the PKS 1127–14 jet. The flux densities F_R was measured at $\nu_R = 5$ GHz, the flux F_{2-10} was measured within the 2-10 keV range in units of 10^{-15} erg cm^{-2} s^{-1} [10]. α_R and α_X are the spectral indexes in the radio (between 1.5-8.5 GHz) and in the X-ray (2-10 keV) bands. $1''$ corresponds to the projected distance 8.11 kpc.

Knot	distance, R''	F_R, mJy	F_{2-10}	α_R	α_X
A	$11.2''$	1.2 ± 0.2	6.8 ± 0.7	1.32 ± 0.17	0.66 ± 0.15
B	$18.6''$	14.4 ± 1.4	2.6 ± 0.3	0.91 ± 0.07	1.0 ± 0.2
C	$28.5''$	16.7 ± 1.7	0.54 ± 0.2	0.85 ± 0.08	1.2 ± 0.5

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