Inverse Compton Scattering of Radiation from a Central Source as a Possible Mechanism for the Formation of X-Ray Radiation from Kiloparsec Jets of Core-Dominated Quasars

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\textbf{Abstract}—For the interpretation of X-ray radiation from kiloparsec jets of quasars, the inverse Compton scattering of the cosmic microwave background has been widely used for almost 20 years. A recent analysis of the Fermi-LAT observational data showed that this assumption is inapplicable for jets of several quasars. In this paper, we consider the inverse Compton scattering of photons from a central source as a possible mechanism for the formation of X-ray radiation from kiloparsec jets of the quasars PKS 0637–752, 3C 273, PKS 1510–089, and PKS 1045–188. Estimates of the angle between the line of sight and the velocity of kiloparsec jets are obtained. The predicted gamma-ray flux for all objects turned out to be below the upper limit on the flux from a kiloparsec jet obtained from the Fermi-LAT data. It is shown that our assumption about the mechanism of X-ray radiation from kiloparsec jets is consistent with all data of multiwavelength observations available to date.

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1. INTRODUCTION

Kiloparsec (kpc) jets of active galactic nuclei have been observed with a high angular resolution in the X-ray range by the Chandra space observatory since 2000 [1]. For the first discovered jet of the quasar PKS 0637–752, as well as for jets of other core-dominated quasars, the X-ray flux turned out to be higher than expected from the extrapolation of the synchrotron radio–optical spectrum to X-ray frequencies [1, 2]. This is an evidence of different processes that generate radiation in these ranges. In one of the first works, it was shown for the PKS 0637–752 quasar jet that the most probable mechanism of its high-frequency radiation is inverse Compton scattering (ICS) of self-synchrotron radiation [1]. However, from a comparison of fluxes in the radio and X-ray ranges, it followed that the condition of the equipartition of energy between the magnetic field and the particles is not fulfilled: a larger energy is contained in the emitting particles. The authors of [3, 4] suggested that the X-ray radiation of the jet of PKS 0637–752 is formed due to inverse Compton scattering of cosmic microwave background (IC/CMB). It was assumed that a kpc-scale jet, by analogy with a parsec (pc) jet [5], moves as a whole with an ultrarelativistic velocity at a small angle to the line of sight. In this case, the energy density of the cosmic microwave background (CMB) in the frame of reference of the kpc-scale jet increases, which leads to an increase in the flux in the X-ray range, the flux at radio frequencies being the same, and, consequently, to the fulfillment of the condition of equipartition of energy. This model of the formation of X-ray radiation, named “beamed IC/CMB,” later became widely used for the interpretation of X-ray radiation from kpc-scale jets of core-dominated quasars (see, e.g., [6–10]).

Recent studies have shown that the beamed IC/CMB model is inapplicable to high-frequency radiation from the kpc-scale jets of the quasars PKS 0637–752 [11] and 3C 273 [12], because, in the observational data of Fermi–LAT instrument in the gamma-ray range, there is no high constant radiation flux characterized by a hard spectrum, which must have been generated in kpc-scale jets. An indirect argument against the beamed IC/CMB model is the fact that there is no statistically significant difference in the distribution of the difference in the positional angles of
the pc- and kpc-scale jets of core-dominated quasars that have (27 objects) or do not have (23 objects) a detectable X-ray flux from a kpc-scale jet [13].

Alternative mechanisms for the formation of X-ray radiation from kpc-scale jets of quasars, e.g., such as synchrotron radiation, produced either by the second high-energy population of electrons [14] or by protons [15], introduce additional free parameters, by varying which one can obtain acceptable estimates of the physical conditions in the kpc-scale jets. In addition, these mechanisms require two different acceleration mechanisms to operate in one part (or in closely located parts) of the jet, which complicates the consideration of the physical nature of the jets.

On the other hand, if we dispense with the a priori small angle (<10°) between the kpc-scale jet and the line of sight, then the kpc-scale jets observed in projection are actually at a smaller distance from the active nucleus. Then, at least for the knots of kpc-scale jets nearest to the nucleus, X-ray radiation can be formed due to inverse Compton scattering of the radiation from the central source (IC/CS). By the term “knot” we mean a part in a jet with an increased surface brightness, which is probably caused by an increased density of emitting particles. Another reason for which IC/CS is becoming a more attractive mechanism for the formation of X-ray radiation is that the radiation of the CS at frequencies from radio to millimeter wavelengths is generated in a pc-scale jet [16] and, due to relativistic effects, is amplified in the frame of reference of a kpc-scale jet so that IC/CS contributes to the observed X-ray radiation significantly more than IC/CMB. As was shown for kpc-scale jets of the quasars 3C 273 [17] and PKS 1127–145 [18], IC/CS provides a natural explanation for the observed decrease with distance in the X-ray intensity of knots from the active nucleus and allows one, with a known CS spectrum, to determine both the physical parameters of the knots and the angle between the line of sight and the velocity of the kpc-scale jet [18]. Since a decrease in the X-ray intensity is often observed along the kpc-scale jets of quasars [2, 6], this may indicate the widespread occurrence of IC/CS. Previously, this mechanism was considered only for radio galaxies [4, 19–21].

In this paper, we investigate the applicability of IC/CS to the interpretation of X-ray radiation from kpc-scale jets of quasars. In Section 2, we explain our choice of objects and present the available observational data, which we use to determine the angle between the line of sight and the velocity of kpc-scale jets (Section 3). In Section 4, we estimate the magnetic field strength and the density of emitting electrons. The emission spectrum of jets in the X-ray and gamma-ray ranges is simulated for comparison with the upper bound of the flux from the kpc-scale jets in the gamma-ray range. A discussion of the results and conclusions is presented in Section 5.

2. OBJECTS AND METHOD OF RESEARCH

The selection of objects was made according to the following criteria. First, only core-dominated quasars were selected. Second, a decrease in the X-ray intensity of the knots along the kpc-scale jet, which is an indication of the possibility of IC/CS radiation, should be observed. In this case, jets with two or more knots observed both in the radio and in the X-ray ranges were selected. Third, it was necessary to have observational data of pc-scale jets, from which it is possible to estimate the apparent superluminal velocity of the components and, consequently, to estimate the velocity $\beta$ (in units of the speed of light $c$) and the angle of the pc-scale jet with the line of sight $\theta_{pc}$. To simplify the selection of objects, we used web pages containing data on X-ray jets$^1$ and observational data from the MOJAVE program.$^2$

These criteria are met by the following objects: 3C 273, PKS 1127–145, PKS 1045–188, and PKS 1510–089. The angle between the line of sight and the kpc-scale jet of the quasar 3C 273 within the IC/CS was determined in [17] by comparing the integral energy densities of the CS and CMB rather than by comparing the X-ray flux produced in IC/CS and IC/CMB. Therefore, 3C 273 was left for this study. The geometrical and kinematic parameters of the kpc-scale jet of the quasar PKS 1127–145 under the assumption of IC/CS were determined in [18] and will be used here for comparison. Despite the fact that the X-ray intensity of the knots of the pc-scale jet of the quasar PKS 0637–752 does not exhibit a distinct decrease with the distance from the core, we included this object in the collection: it is interesting as a prototype for which the beamed IC/CMB scenario was first suggested and then rejected.

In this study, we use formulae that were derived and thoroughly described in [18]. Here, we will emphasize only the main ones. To take into account the spectra of both relativistic electrons and scattered radiation, the expression for the scattered radiation flux density is found using the invariant kinetic Boltzmann equation for ICS [22–24]. Since the dominant part of the scattered radiation is formed in a relativistic pc-scale jet [16], in order to find the distribution function of scattered photons in the frame of reference of the kpc-scale jet from the observed spectrum of the quasar, appropriate transformations should be made. The transition to the reference frame of the pc-scale jet was carried out using the Doppler factor $\delta = \sqrt{1 - \beta_{pc}^2/(1 - \beta_{pc} \cos \theta_{pc})}$. The velocity $\beta_{pc}$ and angle of view $\theta_{pc}$ of a pc-scale jet is determined from the apparent velocity $\beta_{app}$ of its features from the expressions $\theta_{pc} = (1 + \beta_{app}^2)^{-0.5}$ and $\theta_{pc} \sim 1/\Gamma_{pc}$ (where

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1 http://hea-www.harvard.edu/XJET/
2 http://www.physics.purdue.edu/astro/MOJAVE/allsources.html
\[ \Gamma_{pc} = 1/\sqrt{1 - \beta_{pc}^2} \] is the Lorentz factor. For the transition to the reference frame of the pc-scale jet, we use the Doppler factor of the pc-scale jet \( \delta_j \) that would be observed from the pc-scale jet. The quantity \( \delta_j \) depends on the angle \( \theta_{pc}^{kpc} \) between the velocity vector of the pc-scale jet and the direction from the pc- to the kpc-scale jet (the prime denotes the values in the reference frame of the kpc-scale jet). In other words, \( \theta_{pc}^{kpc} \) is the angle of the actual bend of the jet that occurs between the pc- and kpc-scales. The bend angle \( \theta_{pc}^{kpc} \) in the observer’s frame of reference can be found from the difference in the positional angles of the pc and kpc-scale jets, using the results from [25, formula (1)]:

\[ \cot \theta_{pc}^{kpc} = \frac{\sin \varphi - \tan \Delta PA \cos \theta_{pc} \cos \varphi}{\tan \Delta PA \sin \theta_{pc}} \tag{1} \]

where \( \varphi \) is the azimuth bend angle (Fig. 1). Figure 1 shows a scheme of the jet bend between the pc- and kpc-scales and the direction of reference \( \varphi \) is determined. It can be seen that, if the pc-scale jet deviates from the pc-scale jet in the direction of the \( z \) axis, then \( \theta_{pc}^{kpc} \) can be at best determined in a certain interval, but, for a part of sources, only the lower bound of \( \theta_{pc}^{kpc} \) can be obtained. Therefore, the use of only the value of \( \theta_{pc}^{kpc} \) obtained from expression (1) in further calculations is justified. It should also be noted that there is observational evidence that kpc-scale jets have a moderately relativistic propagation velocity [30–33] and the smaller \( \beta_{kpc} \), the smaller the difference between \( \theta_{pc}^{kpc} \) and \( \theta_{pc} \).

To determine the distribution function of scattered photons, it is assumed that the emission spectrum is power-law (flux density of radiation \( F_\nu = Q\nu^{-\alpha} \), where \( \alpha \) is the spectral index). The spectra of the objects under consideration in the range from radio to millimeter wavelengths are shown in Fig. 3, from which it
can be seen that they can be described by several power-law parts. The indices “1” and “2” denote the parts of the CS's radiation spectrum that we associate with the radiation of a pc-scale jet generated in optically thick and thin media, respectively. Index “3” marks the parts that we associate with the low-frequency radiation of the kpc-scale jet. The model parameters of the CS’s radiation spectra are given in Table 2. For a more detailed description of the turn between parts 1 and 2, we used a function of the form

\[ F(\nu) \propto [b(\nu/\nu_0)^{-\alpha_1} + d(\nu/\nu_0)^{-\alpha_2}]^{-1} \]

where \( b \) and \( d \) are parameters; \( \alpha_1 \) and \( \alpha_2 \) are the spectral indices of parts 1 and 2, respectively; and \( \nu_0 \) is the turn-over frequency of the spectrum between parts 1 and 2. We took the observational data for each of the objects from the NED database;\(^4\) they are mainly presented in the papers [34, 35] for 3C 273, [16, 36–42] for PKS 1045–188, [38, 43, 44] for PKS 1510–089, and [26, 41, 45–47] for PKS 0637–752.

As shown in [18], for ICS of power-law photon and electron energy spectra, two cases are possible, each of which is characterized by its own spectral index of scattered radiation, \( \alpha_x \). In the first case, under the limitation from the photon spectrum, the main contribution to the scattered radiation at a given frequency is made by the ICS of photons with a frequency corresponding to one of the boundaries of the photon spectrum by electrons with energies far from the boundary values (see Fig. 4b). Then the spectral flux density of the scattered radiation is determined by the formula

\[
F(\omega_X) = (1 + z)^{\alpha - (\gamma - 1)/2} \\
\times A \frac{2(1 - \cos \theta_{kpc})}{(\gamma + 1)(\gamma - 2\alpha - 1)} \frac{\omega_{\text{cut}, \gamma}^{(\gamma - 1)/2 - \alpha} \omega_X^{-(\gamma - 1)/2}}{\omega_{\text{cut}, \gamma} - \omega_X} \tag{3}
\]

\( http://ned.ipac.caltech.edu/ \)
where $z$ is the redshift of the object, $\alpha$ is the spectral index of the scattering photon spectrum, $\gamma$ is the spectral index of the electron energy distribution, $r_e$ and $m_e$ are the classical radius and rest mass of the electron, $V$ is the volume of the radiating region (the knot of the kpc-scale jet), $\theta_{\text{pc}}$ is the angle between the kpc-scale jet and the line of sight, $R$ is the distance from CS to the considered knot of the kpc-scale jet, $\mathcal{H}$ is the coefficient of proportionality of the electron energy distribution, and $\omega_X$ is the observed X-ray frequency. If the spectral index of the radio radiation of the kpc-scale jet’s knot fulfills the condition $\alpha_R = (\gamma - 1) / 2 > \alpha$, then $\omega_{\text{cut}, j}$ corresponds to the upper bound of the power-law photon spectrum (the power-law region under consideration); otherwise, $\omega_{\text{cut}, j}$ is the lower bound. We assume an isotropic distribution of electrons in the knot. The index “$j$” denotes the frequency that a photon with a frequency $\omega_i$ has in the frame of reference of the kpc-scale jet:

$$\omega_i = \omega(1 + z)\delta_i / \delta.$$

### Table 1. Basic information on the analyzed quasars and their parsec jets

| Object      | $z$  | $D_L$, Mpc | kpc in $1^\alpha$ | $\beta_{\text{app}}$ | $\beta_{\text{pc}}$ | $\theta_{\text{pc}}$, deg | $\Theta_{\text{pc}}$, deg | $\Theta_{\text{kpc}}$, deg | $\Delta \Theta$, deg | $\theta_{\text{pc}}^\text{kpc}$, deg |
|-------------|------|------------|--------------------|-----------------------|----------------------|--------------------------|---------------------------|--------------------------|-------------------------|-----------------------------|
| PKS 0637–752| 0.653| 3909.3     | 6.94               | 13.3 ± 1.0 [26]       | 0.997               | 4                        | 273 [26]                  | 278 [1]                  | 5                        | 1                          |
| PKS 1045–188| 0.595| 3487.7     | 6.65               | 10.35 ± 0.32 [28]    | 0.995               | 6                        | 146 [27]                  | 125 [27]                  | 21                       | 3                          |
| 3C 273      | 0.158| 747.0      | 2.70               | 8.09 ± 0.06 [28]     | 0.992               | 7                        | 238 [27]                  | 222 [27]                  | 16                       | 3                          |
| PKS 1510–089| 0.36 | 1907.0     | 5.00               | 18.4 ± 2.4 [28]      | 0.999               | 3                        | 328 [27]                  | 163 [27]                  | 165                      | 1                          |

The columns represent: (1) object; (2) redshift; (3) luminosity distance (in this article, we use a $\Lambda$CDM model with the following parameters: $H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.27$, and $\Omega_\Lambda = 0.73$ [29]); (4) correspondence between angular and linear scales; (5) the apparent average velocity of the pc-scale jet parts; (6, 7) the velocity and the angle with the line of sight of the pc-scale jet, respectively, estimated from $\beta_{\text{app}}$; (8, 9) positional angles of pc- and kpc-scale jets, respectively; (10) the difference between the positional angles of pc- and kpc-scale jets; (11) the actual bending angle of the jet between the pc- and kpc-scales in the observer’s frame of reference. The data in columns (7–11) are in degrees.

$$A = \left(\frac{\delta_i}{\delta}\right)^{3+\alpha} \frac{r_e^2}{R^2} V \sin^2 \theta_{\text{pc}} \left(\frac{m_e c^3}{1-\gamma}\right)^{1-\gamma} \mathcal{H} Q,$$
In the second case, there is a limitation imposed by the electron spectrum, which consists in the fact that practically all scattered radiation at a given frequency is formed due to the scattering of photons with a frequency far from the boundary values by electrons with an energy corresponding to one of the boundary values of the power-law distribution (Fig. 4c). Then, the spectral flux density of the scattered radiation has the form

\[ F(\omega) = A \frac{2(1 - \cos \theta_{\text{kepc}})}{2(\alpha + 1)[2\alpha - \gamma + 1]} (\Gamma_{\text{cut}})^{2\alpha - \gamma + 1 - \alpha} \omega^{-\alpha} \]  

\[ \omega = \Gamma \omega_{\text{cutoff}} \]  

where \( \Gamma_{\text{cut}} \) corresponds to the lower bound of the power-law electron energy spectrum if \( \alpha_R > \alpha \); otherwise, \( \Gamma_{\text{cut}} \) is the upper bound.

The choice between formulae (3) and (5) is carried out by comparing the spectral indices of the radiation of a certain knot of the kpc-scale jet in the radio and X-ray ranges and the spectral indices of the marked power-law regions of the spectrum of the corresponding central source. If the spectral indices of radio and X-ray radiation of the knot are close to each other, then we used expression (3). If \( \alpha_X \neq \alpha_R \), then \( \alpha_X \) was compared with the spectral indices of the power-law parts of the CS’s spectrum, and, if \( \alpha_X = \alpha_R \), expression (5) was used with the substitution of parameters \( \alpha \) and \( Q \) corresponding to the 4th part of the CS’s spectrum. For the sources under study, either the first or the second possibility was realized. The situation with \( \alpha_R \neq \alpha_X \) and \( \alpha_X \neq \alpha_i \) can be explained within IC/CS by the presence of a break in the X-ray spectrum.
spectrum of a knot, caused by the transition from the limitation from the photon spectrum to the limitation from the electron spectrum, as, e.g., it occurs in the high-energy spectrum of the knots of the kpc-scale jet near the core of the quasar PKS 1127–145 [18].

3. THE ANGLE BETWEEN THE LINE OF SIGHT AND THE VELOCITY OF KILOPARSEC JETS

With increasing distance from CS, the density of IC scattering photons decreases, which, with a similar density of ultrarelativistic electrons in the knots, results in a decrease in their X-ray intensity. In the knots located further than a certain distance from CS, the density of CS photons decreases to such an extent that the main source of photons for ICS becomes the cosmic microwave background. As a result of the constant density of CMB photons, the X-ray intensity of these knots is approximately the same, as in the case of the kpc-scale jet of the quasar 3C 273 [48, 49]. Namely, in the two knots nearest to CS, the X-ray intensity decreases with distance from CS, while in the ones it has a small, approximately constant value. The jets of the other selected objects, with the exception of PKS 0637–752 [1], exhibit only a decrease in the X-ray intensity of the knots with distance from CS [8, 6, 50]. Therefore, we assume that the X-ray radiation of all the knots of the jets of PKS 0637–752, PKS 1045–188, and PKS 1510–089 is formed due to IC/CS. In the farthest knots of these jets detected in the radio range, X-rays are not detected, and it is possible that IC/CMB occurs in them. From a comparison of the flux densities of scattered radiation generated as a result of IC/CS with limitation from the photon spectrum and IC/CMB, it becomes possible to determine the angle between the kpc-scale jet and the line of sight (see details in [17, 18]) or at least its lower bound [18]:

\[
\theta_{kpc}^{\gamma+1} \geq \frac{2\gamma+1}{\gamma + 3} L_{CMB}^{\frac{1}{4}} \left(\frac{\alpha_{CMB}}{\alpha_{CMB_{cut}}}\right)^{(\gamma-1)/2-1}, \tag{6}
\]

where \(\gamma\) is the spectral index of the electron energy distribution in the farthest knot, located at a projection distance \(R\) from CS, the X-ray radiation of which is formed due to the IC/CS, \(\alpha_{CMB}\) and \(W_{CMB}\) are the frequency of the maximum and the energy density of CMB at the redshift of the object under consideration, respectively, and

\[
L_{CMB} = 4\pi(1+z)^{3+\alpha}\left(\frac{\delta}{\delta_{CMB}}\right)^{3+\alpha} D_{L}Q_{\alpha}^{-\alpha+1} \tag{7}
\]

is the luminosity of CS in the reference frame of the kpc-scale jet, \(D_L\) is the luminosity distance of the object, and \(Q\) and \(\alpha\) are the coefficient of proportionality and the spectral index of the power-law part of the CS’s spectrum, the scattering of photons of which makes the main contribution to the observed X-ray radiation from a given knot. Changing the sign of inequality in expression (6), which corresponds to the dominance of IC/CMB over IC/CS, and taking \(R\) equal to the distance of the nearest knot, the X-ray radiation of which is presumably formed due to IC/CMB, we determine the upper bound of \(\theta_{kpc}\): The angles of the kpc-scale jets of the quasars under consideration, obtained in this way, are presented in Table 3. It should be noted that, for the kpc-scale jets of PKS 0637–752, PKS 1045–188, and PKS 1510–089, the X-ray radiation from which we estimate the lower bound of the angle with the line of sight is received from the straight part of the jet. With increasing distance from the central source behind the straight part of the jets, a bend appears on the radio maps and the angle with the line of sight of the jet part after bend can be greater.

It is worth noting that the angles \(\theta_{kpc}\) are several dozen degrees, while the angles with the line of sight of the pc-scale jets of these sources are not greater than 7° (see Table 1). This difference can be explained by the effect of the relativistic aberration, when a truly straight jet slows down between the pc- and kpc-scales [18]. Then, the Doppler factor of the kpc-scale jets, \(\delta_{kpc}\), can be estimated, the value of which on average for all sources is 2 (see Table 3). Knowing \(\delta_{kpc}\) and \(\theta_{kpc}\), one can estimate the velocity of the kpc-scale

| Object          | \(\theta_{kpc}\), deg | \(\delta_{kpc}\) | \(\beta_{kpc}\) | \(\Gamma_{kpc}\) |
|-----------------|------------------------|-----------------|----------------|----------------|
| PKS 0637–752    | 27*                    | 2.19            | 0.87           | 2.0            |
|                 | 37**                   | 1.65            | 0.98           | 4.7            |
| PKS 1045–188    | 34*                    | 1.79            | 0.81           | 1.7            |
|                 | 44**                   | 1.44            | 0.70           | 1.4            |
| 3C 273          | 25–26                  | 2.37            | 0.90           | 2.3            |
|                 | 3C 273                 | 25–26           | 0.91           | 2.4            |
| PKS 1510–089    | 24*                    | 2.43            | 0.88           | 2.1            |
|                 | 34**                   | 1.77            | 0.94           | 2.9            |
| PKS 1127–145*** | 35                     | 1.74            | 0.8            | 1.7            |

* The lower bound of the angle \(\theta_{kpc}\). **The value of \(\theta_{kpc}\) exceeding by 10° the minimum is given for comparison. ***The angle with the line of sight and the velocity of the kpc-scale jet were determined in [18] and are presented here for comparison.
As the Thomson scattering cross section, the electron charge, the spectral index of radio emission, and the observed flux at the frequency of the electron spectrum can be obtained from synchrotron radio, infrared, and optical radiation and from IC/CS using the relation between the energies of interacting particles,

\[ B \propto \left[ \frac{32\pi^2D^2}{c\sigma_TV^3\alpha_k} \right]^{1/2} \left[ \frac{3e}{2m_e} \right]^{-1/2} \left[ \frac{\omega_R}{\omega_k} \right]^{1/2} F_R(\omega_R) \]

where \( \sigma_T \) is the Thomson scattering cross section, \( e \) is the electron charge, \( \alpha_k \) is the spectral index of radio emission, and \( F_R \) is the observed flux at the frequency \( \omega_R \). The normalization factor \( \mathcal{Z} \) of the electron spectrum is expressed from the observed spectral flux in the X-ray range by formulae (3) or (5), which makes the estimate of \( B \) independent of the volume of the radiating region and the density of emitting electrons. The values of \( B \), determined in this way turn out to be one or two orders of magnitude smaller than the values of the magnetic field corresponding to the equipartition condition of energy between the emitting electrons and the magnetic field (see Tables 4–8). In this case, the values of \( B \) are approximately two times greater than the magnetic field determined from IC/CMB.

In the case of IC/CS with a limitation imposed by the photon spectrum, the formula for the spectral flux density of scattered radiation (3) includes one of the boundaries of the power-law energy spectrum of scattering photons. This frequency can be determined from the observed CS's spectrum (see (4)). While, the expression for \( F(\omega_X) \) under the limitation imposed by electron spectrum (5) includes one of its boundaries, which is unknown. Some estimates for the boundaries of the electron spectrum can be obtained from synchrotron radio, infrared, and optical radiation and from IC/CS using the relation between the energies of interacting particles,

\[ \Gamma^2 = \frac{\omega_X}{k_{IC}\omega_j} \]

where \( k_{IC} = 4/[3(1+z)] \). Let us consider each object in more detail.

### 4.1. PKS 0637–752

The morphology of the kpc-scale jet of the quasar PKS 0637–752 is thoroughly described in [1, 5]. In the radio range, the jet is directed to the west and, starting from the distance \( \approx 10'' \) from the core, bends to the north. To the east of the core there is a counter-lobe.
X-rays are detected from the jet knots WK 5.7, WK 7.8, WK 8.9, and WK 9.7, located at a distance of 5ʺ–10ʺ from the core. In the optical range, knots WK 7.8, WK 8.9, WK 9.7 are found [51]; for the first two, infrared radiation was detected [52]. For the region from 3ʺ to 10ʺ from the core, the spectral index in the radio range is \( \alpha_R = 0.81 \) [5]. In the X-ray range, for the region located within 4.0ʺ–6.5ʺ from the core, the spectral index is \( \alpha_X = 1.1 \pm 0.3 \), while, for the region centered at the WK 8.9 knot and having a radius of 2.5ʺ, \( \alpha_X = 0.85 \pm 0.1 \) [5]. Since, for the knots WK 7.8, WK 8.9, and WK 9.7, within the errors, the spectral indices of radio and X-ray radiation are equal, \( \alpha_R = \alpha_X \), then in these knots, the X-ray radiation is formed due to ICS of photons belonging to the second part of the CS’s spectrum under the limitation from the photon spectrum. Since, for the spectral index of the radiation of the second part of the CS’s spectrum is \( \alpha_2 > \alpha_R \), expression (3) implies that the main contribution to the X-ray radiation at the observed frequency \( \omega = 1.5 \times 10^{18} \text{ s}^{-1} \) (photon energy 1 keV) is made by ICS of photons with a frequency corresponding to the lower bound (see Table 2). In this case, scattering occurs on electrons belonging to a power-law distribution with a spectral index \( \gamma = 2\alpha_R + 1 \approx 2.6 \). We denote by \( \omega_{\text{br}} \), the frequency corresponding to the upper boundary of the 1st part and the lower boundary of the 2nd part of the CS’s spectrum in the reference frame of the kpc-scale jet. Then, as can be seen from Fig. 4b, the lower boundary of the electron spectrum, \( \Gamma_{\text{min}} \), is smaller than the Lorentz factor of electrons.

The nomenclature reflects the belonging of the knots to the jet located west of the core and their angular distance from the core.
scattering photons with \( \omega_{0,j} \) to the frequency \( \omega_{X} \). Expression (9) implies that \( \Gamma_{\min} < 400 \). We took this into account in further estimates of the magnetic field strength and the density of emitting electrons. These estimates were carried out using observational data [5, 51] and formulae (3) and (8) for the upper bound of the knots’ size of 0.4” [5]. The magnetic fields under the energy equipartition condition and under the assumption of IC/CMB were estimated using expressions (9) in [18] and (10) in [17] (corrected by \( z \) and a factor of 0.29), respectively. The obtained values of these parameters are presented in Table 4 and illustrated by Figs. 5 and 6. If the actual size of the radiating region is smaller than 0.4”, then the values of the magnetic field and electron density are somewhat greater.

For the knot WK 5.7, within the measurement errors, we have \( \alpha_{X} = \alpha_{R} \). Consequently, X-ray radiation is formed due to ICS of the 2nd part of the CS’s spectrum by electrons with an energy corresponding to one of the boundaries of the power-law distribution (see formula (5)). Since \( \alpha_{R} < \alpha_{2} \), this is the upper boundary. If the X-ray spectrum measured in the frequency range from \( \omega_{0} \) to \( \omega_{X} \) (corresponding to the photon energies of 0.2 and 4 keV) is power-law, then electrons with the Lorentz factor \( \Gamma_{\max} \) must scatter photons with a frequency \( \omega_{\max,i} \) corresponding to the upper boundary of the 2nd part of the spectrum are scattered to frequencies greater than \( \omega_{2} < \omega_{\max,i} \Gamma_{\max}^{2} \). Consequently, the range of possible values is \( \Gamma_{\max} = 36–189 \), which is very small, since electrons in a magnetic field, e.g., of \( -10^{-5} \) G [2] cannot create the observed synchrotron radiation.

Then, in the indicated range of X-ray radiation, the spectrum, possibly, has a break, associated with the transition from the limitation from the photon spectrum to the limitation from the electron spectrum with an increase in the observation frequency. This break will occur at a frequency corresponding to the scattering of photons with \( \omega_{0,j} \) by electrons with \( \Gamma_{\max} \). Using (9), we found that \( \sqrt{\omega_{0}/(k_{ic}\omega_{0,j})} = 189 < \Gamma_{\max} < 847 = \sqrt{\omega_{2}/(k_{ic}\omega_{0,j})} \). From the knot WK 5.7, radio radiation at a frequency of 8.6 GHz was detected [5]. Synchrotron radiation at this frequency by electrons with \( \Gamma_{\max} = 840 \), the required magnetic field strength is 0.01 G. This magnitude of the magnetic field corresponds to parsec jets (see, e.g., [53]), but is very large for kiloparsec jets [2]. Possibly, the electron energy spectrum in the knot WK 5.7 has a break similar to the break in other knots. The smaller value of the Lorentz factor at which the break occurs in comparison with other knots can be interpreted by the fact that the knot WK 5.7 is closer to the CS and, therefore, the IC/CB

| Knot    | \( R_{arcsec} \) | \( F_{0.5-7} \) | \( F_{1} \) | \( \alpha_{X} \) | \( F_{R} \) |
|---------|-------------------|-----------------|-------------|----------------|-------------|
| A       | 4                 | 1.07 x 10^{-14} | 1.46 x 10^{-32} | 0.87 ± 0.38 | 24.4 |
| B       | 7                 | 4.76 x 10^{-15} | 6.06 x 10^{-33} | 0.78 ± 1.37 | 78.3 |

The columns represent: (1) the knot; (2) \( \theta_{kpc} \) used in calculations; (3) the electron densities for \( 10^{10} \) and \( 10^{10} \) cm^{-3}, respectively; (4) the magnetic field determined from the ratio of fluxes in the radio and X-ray ranges; (5) the flux density at a frequency of 1.43 GHz [66].
losses are greater. Then, the spectrum in the radio range must be steeper. Based on the available data on the radio spectrum of the entire western jet up to its bend, it is difficult to draw any conclusions about the radio spectrum of the knot WK 5.7.

On the other hand, within the measurement errors. Then, in the knot WK 5.7, as well as in the other ones, ICS occurs in the 2nd part of the CS’s spectrum with limitation from the photon spectrum. The electron density and the magnetic field strength found in this case are given in Table 4.

Let us consider the spectrum of scattered radiation at frequencies exceeding the Chandra operating range. With increasing $\omega_x$, the spectrum of scattered radiation $\alpha_x = (\gamma - 1)/2$ will persist up to the frequency

$$\omega_{x,br} = k_{IC} \omega_{j,br} \Gamma_{br}^2,$$

where $\Gamma_{br}$ is the upper boundary of the electron energy distribution with the index $\gamma = 2.6$. Synchrotron infrared and optical radiation detected from the knots WK 7.8, WK 8.9, and WK 9.7 is characterized by the spectral index $\alpha_{IR,Opt} = 1.6$ [52], which indicates a break in the electron energy spectrum, most likely arising from the radiation losses of the electron energy, which are most significant for electrons with higher energy. Electrons with a Lorentz factor smaller than the Lorentz factor $\Gamma_{br}$ at which the break occurs emit due to the synchrotron mechanism in the radio range, and electrons with a Lorentz factor greater than $\Gamma_{br}$ emit in the infrared and optical ranges. Based on this, one can estimate $\Gamma_{br}$. For example, with a magnetic field of $5 \times 10^{-6}$ G, the Lorentz factor of the break is within $2 \times 10^4 - 7 \times 10^5$. The IC/CS by electrons with $\Gamma > \Gamma_{br}$ does not make a significant contribution to the scattered radiation up to the frequency $\omega_{x,br}$; otherwise, it would be reflected in the value of $\alpha_x$.

At frequencies higher than $\omega_{x,br}$, the total flux of scattered radiation with taking into account the relation specified by expression (9) has two components: namely, ICS of the 2nd part of the CS’s spectrum by electrons with $\Gamma_{br}$ and ICS of photons with a frequency $\omega_{br,j}$ by electrons with $\Gamma > \Gamma_{br}$. Substituting into expressions (5) and (3) the corresponding quantities and taking into account the continuity in the total distribution of electrons, one can make sure that the con-
distribution of ICS by the high-energy electron distribution to the scattered radiation is insignificant. The total spectrum of the scattered radiation generated in the knots WK 5.7, WK 7.8, WK 8.9, and WK 9.7, plotted with the parameters \( \Gamma_{br} = 5 \times 10^3 \) and \( \Gamma_{min} = 50 \), is shown in Fig. 7. The ICS of photons with a frequency \( \omega_{ij} \) by electrons with \( \Gamma_{min} \) and the ICS of photons with a frequency \( \omega_{max,ij} \) by electrons with \( \Gamma_{br} \) determine, according to expression (9), the low- and high-energy cutoffs of the high-frequency spectrum of the knots, respectively. It can be seen that the assumption about IC/CS as a mechanism of high-frequency radiation of the kpc-scale jet of the quasar PKS 0637–752 cannot be refuted by the available observational data in the gamma-ray range [11].

### 4.2. 3C 273

One of the nearest quasars with an extended one-sided kpc-scale jet (up to 23") 3C 273, was intensely observed in radio (see, e.g., [54, 55]), infrared [56], optical [57, 58], ultraviolet [59], and X-ray [48, 49, 60, 61] ranges. In the radio range, knots of jet are found up to =23" from the core. Starting from the distance of =12" from the core, where the jet begins to be detected at other frequencies, the radio intensity sharply increases and continues to increase with distance, reaching a maximum in the hot spot located at 22". In the optical range, the maximum intensity is also observed in the region corresponding to the hot spot, but approximately 1" closer to the core than the peak intensity in the radio range. For the rest knots, the optical intensity is approximately the same (see, e.g., [58]). In the X-ray range, the intensity is maximal in the knot A,\(^6\) nearest to the core; then it decreases by half at the knot B2;\(^7\) and, in subsequent knots, it decreases by almost an order of magnitude and has an approximately constant value. Farther than 21" from the core, X-ray radiation is not detected (see [48, 49, 62]). In [17], it was assumed that, for the knots A and

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\(^6\) Here, we adhere to the nomenclature of knots used in [58].

\(^7\) Note that we do not distinguish the region located between the knots A and B2 as a separate knot, since it has a low intensity at all observed frequencies and the position of its peak brightness strongly depends on frequency. This behavior requires additional explanation, which is beyond the scope of this work.
B2, X-ray radiation is generated due to IC/CS and, in other knots, via IC/CMB. The spectral indices of the knots A and B2 in the radio and X-ray ranges are (according to the data of [54, 63]) and differ from the spectral indices of the CS’s radiation (see Table 2). Therefore, according to expression (3), the main contribution to the observed X-ray flux comes from the scattering of photons with a frequency by electrons with energies far from the boundary values. Formula (9) implies that . The results of the estimates of the electron density and the magnetic field strength are presented in Table 5 and Figs. 8 and 9.

In the high-frequency spectrum of the knots A and B2 (Fig. 10), as well as in the spectrum of the knots of the PKS 0637–752 jet, at the frequency

\[ \omega_{X, br} = k_{IC} \omega_{\text{max}, j} \Gamma_{\text{min}}^2, \]  

there is a break caused by the transition from the limitation from the electron spectrum to the limitation from the photon spectrum. The low-energy boundary of the high-frequency spectrum is determined by ICS on electrons with the Lorentz factor \( \Gamma_{\text{min}} \). Only for the knots A and B2, the scattered frequency is \( \omega_{br, j} = 1.8 \times 10^{11} \) s\(^{-1}\); for other knots, \( \omega_{\text{CMB}} = 1.2 \times 10^{12} \) s\(^{-1}\). Since \( \omega_{br, j} < \omega_{\text{CMB}} \), the low-frequency cutoff of the spectrum of the knots A and B2 is at a lower frequency than that for the distant knots. This explains the observed difference in the energy distribution in the spectrum of the near and far knots [63] by the fact that, in the infrared and optical radiation of the knots A and B2, a significant contribution is made by the radiation due to IC/CS. For example, the ICS of the 2nd part of the CS’s spectrum by electrons with \( \Gamma_{\text{min}} \) (see expression (5)) can reproduce the observed flux in the optical range for the near knots with an accuracy better than 10% and give \( \approx 50% \) of the flux in the infrared range for \( \Gamma_{\text{min}} = 40 \). With \( \Gamma_{\text{min}} = 10 \), IC/CS will give up to 70% of the observed flux in the infrared range, whereas, for the distant knots, the X-ray spectrum generated via the IC/CMB is cutoff at the optical frequencies.

The difference in the maximum possible frequencies of photons the ICS of which makes the main contribution to the X-ray radiation of the near and far knots leads to different frequencies of the high-energy cutoff of the spectra for the same values of \( \Gamma_{\text{max}} \) in the knots. When modeling the spectrum of scattered radiation, we adopted \( \Gamma_{\text{max}} = 10^5 \). It can be seen from Fig. 10 that the model spectrum of the knots A and B2 at frequencies corresponding to the photon energy of 1–10 GeV is approximately equal to the upper bound of the expected flux from the kpc-scale jet of 3C 273, established in [12]. If the value of \( \Gamma_{\text{max}} \) for these knots is taken smaller or a detailed study of the CS’s spectrum shows lower values of the maximum frequency of
the 2nd part, then the high-energy cutoff of the spectrum will occur at lower frequencies. Then, the gamma-ray flux will be significantly lower than the upper bound of the expected gamma-ray flux from the kpc-scale jet determined from the Fermi-LAT data [12]. Therefore, based on the available data, the assumption about IC/CS as a mechanism for the formation of X-ray radiation of the knots A and B2, nearest to the quasar, cannot be refuted.

4.3. PKS 1510−089

In the X-ray range in the quasar PKS 1510−089 jet, knots A, B, and C (in order of increasing distance from CS) are detected; they correspond to the knots in the radio range, except the last, most distant knot [6]. The X-ray intensity of the knots decreases with the distance from CS, which suggests that IC/CS is the mechanism of X-ray radiation of all the knots. Let us

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig8.png}
\caption{The density of emitting electrons in the nearest to CS knots A and B2 of the 3C 273 quasar jet. The values were obtained within IC/CS and $\theta_{\text{kpc}} = 27^\circ$.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig9.png}
\caption{Magnetic field in the nearest to CS knots of the 3C 273 jet: (solid line) the magnetic field strength under the energy equipartition condition; (dashed lines) the magnetic field strength obtained from a comparison of radio and X-ray fluxes within the IC/CS; (dotted line) the magnetic field determined under the assumption of IC/CMB. All values of the magnetic field are shown for $\delta_{\text{kpc}} = 1$ and $\theta_{\text{kpc}} = 27^\circ$.}
\end{figure}
consider the scattered radiation and its spectrum for each knot separately.

The X-ray spectral index of the knot A is \( \alpha_X = \alpha_i \neq \alpha_R \); therefore, the main contribution to the X-ray flux from the knot is made by ICS of the 1st part of the CS’s spectrum under the limitation from the electron spectrum. Since \( \alpha_X = 0.09 \pm 0.43 \) [6] and \( \alpha_R = 0.6 \) (for the entire jet) [64], electrons with \( \Gamma_{\text{min}} \) are scattered most efficiently. This process produces photons with frequencies ranging from \( k_{\text{IC}} \omega_{\text{min}, i} \Gamma_{\text{min}}^2 \) to \( \omega_{X, \text{br} 1} = k_{\text{IC}} \omega_{\text{br} 1} \Gamma_{\text{min}}^2 \). If we consider the spectrum of scattered radiation in the range corresponding to the photon energy of 0.5–8 keV to be power-law, then we have \( 1.4 \times 10^3 < \Gamma_{\text{min}} < 1.7 \times 10^4 \). At the frequency \( k_{\text{IC}} \omega_{\text{min}, i} \Gamma_{\text{min}}^2 \), the scattered radiation spectrum is cut-off. At frequencies from \( \omega_{X, \text{br} 1} \) to \( \omega_{X, \text{br} 2} = k_{\text{IC}} \omega_{\text{br} 2} \Gamma_{\text{max}}^2 \), radiation is formed due to ICS of photons with a frequency \( \omega_{\text{br} 2} \) on electrons of a power-law energy distribution. The spectral index of this radiation is \( (\gamma - 1)/2 \). The ICS of the 2nd part of the SC’s spectrum by electrons with \( \Gamma_{\text{max}} \) (since \( \alpha_R < \alpha_i \)) produces radiation at frequencies from \( \omega_{X, \text{br} 2} \) to \( k_{\text{IC}} \omega_{\text{max}, j} \Gamma_{\text{max}}^2 \), above which the spectrum of scattered radiation is cutoff.

The X-ray spectral index of the knot B, \( \alpha_X = 0.81 \pm 0.62 \) [6], was determined with low accuracy. Therefore, it can be equal to \( \alpha_i \) and \( \alpha_R \). The large error in \( \alpha_X \) can partly be caused by the break in the X-ray emission spectrum. If \( \alpha_X = \alpha_i \), then the X-ray radiation of the knot B is formed due to the scattering of the 2nd part of the CS’s spectrum on electrons with \( \Gamma_{\text{max}} \). In this case, the minimum frequency of the scattered radiation, according to formula (9), must be \( k_{\text{IC}} \omega_{\text{br} 1} \Gamma_{\text{max}}^2 \leq \omega_X \). This condition yields \( \Gamma_{\text{max}} \leq 5 \times 10^5 \). This value seems to be too small even if we assume that it corresponds to the Lorentz factor of the break in the electron energy spectrum. Then, possibly, \( \alpha_X = \alpha_R \) and X-ray radiation is formed due to ICS with the limitation imposed by the photon spectrum. Considering ICS of the 1st and 2nd parts by electrons with a power-law energy distribution, we found that the scattering of photons with a frequency \( \omega_{\text{br} 1} \) makes the main contribution to the observed X-ray radiation.

The radio and X-ray spectral indices of the knot C are approximately equal; therefore, X-ray radiation is formed due to ICS with a limitation imposed by the photon spectrum, as well as in the knot B. The shape of the scattered radiation spectrum of the knots B and C is similar to the case of the knot A, taking into account that \( \omega_{X, \text{br} 1} \) and \( \omega_{X, \text{br} 2} \) depend on the parameters of the electron energy distribution, which may be different in these two knots. Taking into account the specificities of IC/CS in the knots of the PKS 1510–089 jet, we estimated the density of emitting electrons.
The spectrum of scattered radiation of the knot A and the total emission spectrum of the knots B and C are shown in Fig. 13. The values of $\Gamma_{\text{min}}$ and $\Gamma_{\text{max}}$ were chosen so as, firstly, to exclude the production by IC/CS of an optical flux at a level sufficient for detection; secondly, the breaks in the spectrum of scattered radiation of the knots should not occur in the middle of the observed X-ray range; thirdly, the integral theoretically expected gamma-ray flux from the knots A, B, and C should be consistent with the upper bound of the constant flux. This upper bound can be taken equal to the minimal flux from the entire object observed by Fermi-LAT. We adopted this flux at the level of $5 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ in the range 0.1–100 GeV, based on both 8-year data with weekly averaging and the data from the 3FGL catalog [65] with one month averaging over the first four years of Fermi-LAT observations. With $\Gamma_{\text{max}} = 10^6$ for the knot A and $\Gamma_{\text{max}} = 10^4$ for the knots B and C, the total flux from the knots in the Fermi-LAT operating range is $3 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$. This value can be lower if $\Gamma_{\text{max}}$ is taken smaller, especially for the knots B and C. Thus, from the limitation on the gamma-ray flux, an estimate of the maximum energy of ultrarelativistic electrons in the knots can be obtained.

### 4.4. PKS 1045–188

The quasar PKS 1045–188 jet in the X-ray range is detected up to the scales of $\approx 8''$ [8, 66] and is not detected in the jet region after the bend observed on the VLA radio maps at a frequency of 1.4 GHz [27]. For this object, there are no published data on the spectral index and spectral flux from the knots in the X-ray range. We found these parameters by processing the Chandra observations no. 15037 using the CIAO...
The flux and spectral index were determined for two knots from the parts bounded by circles with a diameter of , located at distances of and from the central source. The obtained values are given in Table 7.

There are also no published data on the spectral index of the radiation of the kpc-scale jet in the radio range, but, assuming that the main contribution to the low-frequency ( ) part of the CS’s spectrum (Fig. 3) is made by the radiation generated in the kpc-scale jet, we adopt for further calculations . For example, a similar situation takes place for 3C 273 and PKS 0637–752, because the spectral indices of these kpc-scale jets correspond to the spectral indices obtained by linear approximation of the low-frequency (part 3 in Fig. 3) CS’s spectra.

Within the determination errors, for the knot A, we have  and . In the latter case, the X-ray radiation is formed due to ICS of the 2nd part of the CS’s spectrum by electrons with (see formula (5) and the explanations to it). Then, using expression (9), from the absence of a break in the spectrum of scattered radiation in the frequency range corresponding to photon energies of 0.5–7 keV, we find the limitations 200 ≤ Γ_{max} ≤ 900. These values are small even if we assume that they correspond to the Lorentz factor at which a break in the power-law electron energy distribution occurs.

In the case of , the X-ray radiation of the knot A, as well as the knot B, is formed due to the scattering of photons with a frequency on electrons with the power-law energy distribution. The estimated values of the density of emitting electrons and the magnetic field strength at the knots of the PKS 1045–188 jet are consistent with similar values obtained by us for the jets of other sources and are presented in Table 8 and Fig. 14.

Figure 15 shows the calculated spectrum of scattered radiation from the knots A and B. The radiation of the low-frequency part of this spectrum is formed due to ICS of the 1st part of the CS’s spectrum by electrons with Γ_{min}. The spectral index of this radiation is . At the middle frequencies, including the Chandra operating range, radiation is formed due to ICS of photons with on electrons of the power-law energy spectrum. In this case, . High-frequency radiation is formed due to ICS of the 2nd part of the CS’s spectrum by electrons with Γ_{max}. In this case, . Figure 15 also shows the upper bound of the gamma-ray flux from the kpc-scale jet, which we estimated based on the following. The radio source PKS 1045–188 is not positionally associated with any

![Graph showing scattered radiation spectrum](image-url)
of the detected gamma-ray sources in the sky within an error of 95%, according to Fermi-LAT data [67]. Moreover, it is not in the plane of the Galaxy ($b = 35^\circ$). Therefore, as the upper bound of the flux from this object, the sensitivity of the telescope was set according to the typical photon index of quasars, $\alpha_\gamma = 1.5$ [67], which is about $4.6 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ at energies above 100 MeV [67]. The integral flux from the knots A and B in the range 0.1–100 MeV depends on $\Gamma_{\text{max}}$, since this quantity determines the position of

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**Fig. 14.** (a) Density of emitting particles and (b) magnetic field strength in the knot A of the quasar PKS 1045–188 jet. Left panel: (solid line) $\theta_{\text{kpc}} = 34^\circ$ and (dashed line) $\theta_{\text{kpc}} = 44^\circ$. Right panel: (dashed lines) the magnetic field found from a comparison of the observed radio and X-ray fluxes within the IC/CS; (thick dashed line) $\theta_{\text{kpc}} = 34^\circ$ and (thin dashed line) $\theta_{\text{kpc}} = 44^\circ$; (solid line) the magnetic field under the energy equipartition condition; (dashed line) the magnetic field obtained within IC/CMB for $\delta_{\text{kpc}} = 1$.

**Fig. 15.** (Dashed line) Spectrum of scattered radiation from the knots A and B of the kpc-scale jet of the quasar PKS 1045–188. The spectrum was plotted for the parameters $\Gamma_{\text{min}} = 100$ and $5 \times 10^5$, (black dot) the total observed flux from the knots A and B, (filled triangles) errors of determination of the spectral index, (solid vertical lines) the Chandra and Fermi-LAT operating ranges; (thick solid line) the minimum flux considered as the upper bound of the constant gamma-ray flux from the kpc-scale jet at the energy spectral index $\alpha_X = 1.5$, and (dashed vertical lines) the frequencies of the break in the spectrum of scattered radiation caused by the transition from the limitation imposed by the electron spectrum to the limitation imposed by the photon spectrum (low-frequency break) and from the limitation imposed by the photon spectrum to limitation imposed by the electron spectrum (high-frequency break).
the high-frequency cutoff in the spectrum of scattered radiation. At $\Gamma_{\text{max}} = 5 \times 10^5$, the integral theoretical flux is equal to $2 \times 10^{-8}$ erg cm$^{-2}$ s$^{-1}$, which is smaller than the estimate for the flux from the kpc-scale jet, while, at $\Gamma_{\text{max}} = 10^6$, the theoretically expected flux on the level of $8 \times 10^{-8}$ erg cm$^{-2}$ s$^{-1}$ exceeds the upper estimate for the flux from the kpc-scale jet.

5. DISCUSSION AND CONCLUSIONS

We have considered the inverse Compton scattering of radiation from a pc-scale jet on ultrarelativistic electrons of a kpc-scale jet as a mechanism for the formation of the observed X-ray radiation from the jets of the quasars PKS 0637–752, 3C 273, PKS 1510–089, and PKS 1045–188. For all the sources, we have obtained adequate estimates for the density of emitting particles ($\sim 10^{-3}$ cm$^{-3}$) and the magnetic field strength ($\sim 10^{-5} - 10^{-6}$ G for $\delta_{\text{pc}} = 1$). If we take into account the moderate relativistic motion of the kpc-scale jets, then the magnetic field in the frame of reference of the kpc-scale jet will be several times stronger. However, for all the sources considered here, as well as for PKS 1127–145 [18], the condition of equipartition is not fulfilled: the energy density of the particles is greater than the energy density of the magnetic field. This inequality becomes even stronger if we assume the presence of other particles in the kpc-scale jet besides the electron–positron plasma. The possibility of such a deviation from equipartition for kpc-scale jets was noted in [51]. An extremely high brightness temperature, exceeding the maximum permissible value under the condition of equipartition excluding the Compton catastrophe, was detected by the ground–space radio interferometer RadioAstron for several active nuclei [68–72], including 3C 273 [73]. This result can be explained either by the large ($\sim 100$) Doppler factor of the pc-scale jets, or by the fact that the energy density of the emitting particles is higher than the energy density of the magnetic field even in the pc-scale. Therefore, in our opinion, the requirement of energy equipartition cannot be dominant in determining the mechanism of formation of X-ray radiation in the kpc-scale jets of quasars.

Unlike other models, IC/CS explains without additional assumptions the observed decrease in the X-ray intensity of the knots with the distance from the CS. For the outer knots of the 3C 273 jet, the X-ray intensity has a small and approximately constant value. This fact is interpreted in [17] by the X-ray generation in these knots due to IC/CMB. From the comparison of the flux densities formed by IC/CS and IC/CMB, an interval of the angles of the kpc-scale jet with the line of sight of $25^\circ$–$26^\circ$ has been found. For the kpc-scale jets of the quasars PKS 0637–752, PKS 1045–188, and PKS 1510–089, the observed X-ray radiation from the knots of which is formed only due to IC/CS, a lower bound of the angle between the jet and the line of sight ($\sim 25^\circ$) has been obtained. The difference in the angles between the line of sight and pc-scale jets, estimated from the apparent superluminal motion of their features [26, 28], and the angles between the line of sight and kpc-scale jets can be explained by the deceleration of jets between the pc- and kpc-scales. It is possible that this deceleration already manifests itself at distances of about 100 pc from the core [30, 74]. In this case, the value of the Lorentz factor change is $\Gamma/\Gamma_{\text{max}} = 10^{-3} - 10^{-2}$ [30] and, if that changes insignificantly, then, over a time of hundreds to thousands of years in the reference frame of the source, the jet can slow down from the Lorentz factor from 10 to 1. We have found that the kpc-scale jets make up an angle of $\geq 25^\circ$ with the line of sight and have an average velocity of $(0.6–0.95)c$. The velocities are consistent with other independent estimates of the velocities of the kpc-scale jets of the active galaxies [31–33].

IC/CS predicts the existence of breaks in the spectrum of scattered radiation. These breaks are caused by the transition from the limitation imposed by the electron spectrum to the limitation imposed by the photon spectrum and vice versa. The detection of breaks in the X-ray spectrum of the knots of the kpc-scale jets both will prove the action of IC/CS, and will make it possible to determine the parameters of the electron spectrum.

Within IC/CS, for each source, the gamma-ray flux was simulated. The flux obtained in the frequency range corresponding to the photon energies of 0.1–100 GeV depends on the choice of the maximum Lorentz factor of electrons. For adequate values of $\Gamma_{\text{max}}$, it turns out to be lower than the estimate of the constant flux obtained from the Fermi–LAT data. On the assumption that this constant flux is generated in a kpc-scale jet, IC/CS does not contradict the available observational data.

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