Implications of Bulk Velocity Structures in AGN Jets

Jianping YANG
National Astronomical Observatories, Yunnan Observatory, Chinese Academy of Sciences, Kunming 650011, China
Graduate School of the Chinese Academy of Sciences, China; Yunnan Agricultural University, Kunming 650201, China
yangjp@mail.ynao.ac.cn

Jiancheng WANG
National Astronomical Observatories, Yunnan Observatory, Chinese Academy of Sciences, Kunming 650011, China

Benzhong DAI
Department of Physics, Yunnan University, Kunming 650091, China

and

Xiaoyan GAO
National Astronomical Observatories, Yunnan Observatory, Chinese Academy of Sciences, Kunming 650011, China

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Abstract

Synchrotron self-Compton (SSC) models and External Compton (EC) models of AGN jets with continually longitudinal and transverse bulk velocity structures have been constructed. The observed spectra show complex and interesting patterns in different velocity structures and viewing angles. These models were used to calculate the synchrotron and inverse Compton spectra of two typical BL Lac objects (BLO) (Mrk 421 and 0716+714) and (one) Flat Spectrum Radio Quasars (FSRQs) (3C 279), and to discuss the implications of jet bulk velocity structures in a unification of the BLO and FR I radio galaxies (FRI). By calculating the synchrotron spectra and SSC spectra of BL Lac object jets with continually bulk velocity structures, we have found that the spectra are much different from those in jets with a uniform velocity structure under increasing viewing angles. The unification of BLO and FRI is less constrained by the viewing angles, and would be imprinted by velocity structures intrinsic to the jets, themselves. By considering jets with bulk velocity structures constrained by the apparent speed, we discuss the velocity structures imprinted on the observed spectra for different viewing angles. We find that the spectra are greatly impacted by longitudinal velocity structures, because the volume elements are compressed or expanded. Finally, we present the EC spectra of FSRQs and FR II radio galaxies (FRII), and find that they are weakly affected by the velocity structures compared to synchrotron and SSC spectra.

Key words: galaxies: jets — radiation mechanisms: nonthermal

1. Introduction

It is well known that AGN jets radiate strong nonthermal emission from the radio to the gamma-ray range. Their spectral energy distribution (SED) consists of two bumps, attributed to synchrotron and inverse Compton (IC) emission of ultrarelativistic particles. A simple one-zone homogeneous jet model usually provides a good framework to explain the emissive spectra of AGN jets. However, a realistic case is that the jet has bulk velocity structures in the longitudinal and transverse directions to its axis (Blandford & Levinson 1995). To explain the spectral properties of some AGNs, several authors have proposed many inhomogeneous jet models (Marscher 1980; Ghisellini et al. 1985; Georgakopoulous & Marscher 1998; Wang et al. 2004; Georgakopoulous et al. 2005; Tavecchio & Ghisellini 2008). For example, to reproduce the spectra of TeV blazars, Georgakopoulous and Kazanas (2003a) have presented a jet model characterized by a deceleration of the bulk velocity along the jet axis. Their model is also used to explain X-ray phenomena in kiloparsec jets of powerful radio galaxies and quasars (Georganopoulos & Kazanas 2003b). Giroletti et al. (2004a) have proposed a transverse velocity structure model, described by a slower external flow surrounding a faster spine, to explain a limb-brightening morphology in Mrk 501 observed by Very Long Baseline Interferometry (VLBI). Ghisellini and Tavecchio (2008) have used a needle/jet model, which harbors small active regions (needles) inside a large jet to account for the 2–3 min fast variability of PKS 2155–304. Recent observations of TeV blazars raise new questions regarding the one-zone uniform jet model, such as the unreally high Lorentz factor (about 50) demanded by avoiding γ–γ absorption for TeV blazars (Krawczynski et al. 2002; Konopelko et al. 2003; Henri & Sauge 2006; Begelman et al. 2008; Finke et al. 2008), which can not match the much slower speeds required by VLBI observations (Piner & Edwards 2004; Piner et al. 2008). Therefore, it is argued that the jet should have velocity structures to mediate the inconsistence of bulk motions obtained by different wavebands (Chiaberge et al. 2000; Trussoni et al. 2003).

For the unification of BL Lac objects (BLO) and FR I radio galaxies (FRI), velocity structures have also been suggested by Chiaberge et al. (2000). By analyzing the core emissions of FRI observed by the Hubble Space Telescope, they have found that the observed fluxes of the FRI nucleus are over-luminous by a factor of 10–10^4 than ones predicted by a simple one-zone model, in the radio and optical bands.
Therefore, they proposed a jet-velocity structure, which has a fast spine surrounded by a slow layer, to reconcile the unification scheme.

In this paper we present Synchrotron self-Compton (SSC) and External Compton (EC) models of AGN jets with continually longitudinal and transverse bulk velocity structures. Our study is not completely new, but we include new ingredients and results. Firstly, the observed apparent speed is obtained by flux convolution over the whole emitting region with bulk velocity structures. Secondly, each part of the jet contributes its spectrum to the observed SED; some important characteristics are ignored in simple models with two-zone velocity structures. Thirdly, some parameters of the jet velocity structures can be constrained by the jet power or apparent speed; our models are more realistic for discussing the emissive properties of jets with velocity structures than previous models. Fourthly, the jet velocity structures can reasonably solve the problem of unifying BLO and FRI faced by all one-zone models. Fifthly, we find that the effects of the velocity structures on the observed synchrotron and SSC spectra strongly depend on the viewing angles. Sixthly, we find that the longitudinal velocity structures, with the volume elements being compressed or expanded, have great influences on the observed spectra. Finally, the observed EC spectra are weakly affected by the velocity structures compared to the observed synchrotron or SSC ones.

In section 2 we present velocity structures of jets for calculating models, and place these modifications in the context of the emission mechanisms in section 3. We show model applications to two BLO (Mrk 421 and 0716+714) controlled by the same jet power in section 4, which focusing on unifying BLO with FRI sources. We then discuss the apparent speeds that govern the velocity structures of a jet to constrain the observed spectra in section 5. In section 6, we employ the SSC and EC models to one quasar (3C 279), and discuss the effects of the velocity structures on the EC spectra. We finish with discussions and conclusions in section 7.

2. Velocity Structures

We only select a part of a stationary jet to study. For simplicity, we adopt the following assumptions: (1) The length of the studied region is on a small scale (i.e., about $1 \times 10^{17}$ cm) compared with the whole jet. Although the whole jet may be conical or have other morphologies, a cylinder jet is a good approximation within a short length scale. (2) In the studied region, the jet is assumed to have bulk velocity structures in the longitudinal or transverse directions to the jet axis. The velocity structures are not resolved by the VLBI observation. (3) We assume that the jet is stationary, and that relativistic electrons are injected continuously with a power-law energy spectrum, $N(\gamma, z_0) = N_0 \gamma^{-\delta} \exp(-\gamma/\gamma_{min})$ (Finke et al. 2008). Here, we mainly pay attention to the influence of the velocity structures on the radiative spectra, and ignore the radiative energy loss of the electrons on the studied jet scale. However, for jets with the longitudinal velocity structures, because volume elements are compressed or expanded, the electron energy distribution and the magnetic field in the jet will be changed following Georganopoulos and Kazanas (2004):

$$\gamma(z) = \gamma_0 (z/z_0)^{-\delta/3}, \quad N(\gamma, z) = N(\gamma, z_0)(z/z_0)^{-(\delta+2)/3}, \quad \text{and} \quad B(z) = B_0(z/z_0)^{-\delta},$$

where $\xi$ is the index of the longitudinal velocity structures (see the next part), and subscript “0” denotes the values at the studied jet base. (4) For transverse velocity structures, the magnetic fields are assumed to have an isotropic distribution in the comoving frame.

2.1. Longitudinal Velocity Structures

For a jet with longitudinal velocity structures, we take the Lorentz factor along the jet to be $\Gamma(z) = \Gamma_0 (z/z_0)^{\xi}$, where $\Gamma_0$ is the Lorentz factor at the base, and $\xi$ is the index of the longitudinal velocity structures. This power-law form was earlier given by Marscher (1980), and subsequently adopted by Ghisellini et al. (1985), Georganopoulos and Marscher (1998), and Li and Wang (2004). $\xi = 0$, $\xi > 0$, and $\xi < 0$ correspond to the transition, acceleration, and deceleration phases respectively.

VLBI measurements of the apparent motion for parsec-scale radio knots have often been employed to constrain a combination of the Lorentz factor and the viewing angles (Vermeulen & Cohen 1994). Although VLBI monitoring of the radio knots in blazar jets has revealed several sources containing knots with apparent speeds extending out to 30c (Piner et al. 2007), the typical values for TeV blazars are found to be much more modest, under 5c (e.g., Giroletti et al. 2004b; Piner & Edwards 2004). Gopal-Krishna et al. (2004) have shown that the slow apparent speeds of the knots of blazars observed by VLBI can be reconciled with the extremely relativistic bulk motion, inferred from TeV flux variations (Krawczynski et al. 2002), if one considers a modest full opening angle for the parsec-scale jets. They have also shown that the actual viewing angles, $\theta$, of such conical jets from the line-of-sight can be substantially larger than those commonly inferred by VLBI proper motion data (Gopal-Krishna et al. 2006). Recently, they evaluated the role of the jet opening angle on certain key parameters (i.e., the viewing angle, apparent speed and Doppler factor), which were inferred from VLBI radio observations of blazar nuclear jets (Gopal-Krishna et al. 2007). In these papers, they have argued that the Doppler boosting of an ultrarelativistic jet, as well as the apparent proper motions, can greatly vary across the jet’s cross-section, and thus it is important to carry out an integration of various quantities across the jet cross-section. Therefore, they performed an integration of the (boosted) flux-weighted apparent velocity over the jet cross section to obtain a weighted observed value of the apparent velocity of the jet, when the width of a knot cannot be resolved by VLBI observations.

For longitudinal velocity structures, the observed apparent speed ($\beta_{app} = \beta_{app} = \beta_{app} = \beta_{app} = \beta_{app}$) is decided by (Gopal-Krishna et al. 2004, 2006, 2007)

$$\beta_{app, obs} = \int \beta(z) \delta(z) dF_{sync}(z),$$

where $F_{sync}$ is the observed flux, and $dF_{\nu}(z)$ is the comoving flux in $z$. In this equation, we take the radio spectral index to be 0.

Through radio observations, Giroletti et al. (2004b) have found that the mean value of $\Gamma$ is 3 in TeV sources. Piner
and Edwards (2004) have presented that the jets of TeV blazars have only mildly relativistic motion that is less than 5c on parsec-scales. Piner et al. (2007) have found that the apparent speed distribution shows a peak at low speed for BLO. We then take a speed of $\beta_{\text{app,obs}} = 3.6c$ to limit $\Gamma_0$.

2.2. Transverse Velocity Structures

For a jet with transverse velocity structures, we suppose the jet bulk velocity to be $\Gamma(R) = \Gamma_c - (\Gamma_c - \Gamma_m)(R/R_0)$, where $\Gamma_c$ and $\Gamma_m$ are the Lorentz factor of the central and marginal region, respectively. In this work, we have only adopted $\xi$ to be 0 and 1, corresponding to different transverse velocity structures.

We take the apparent speed to be given by $\beta_{\text{app,obs}} = 3.6c$ in order to restrict $\Gamma_c$ and $\Gamma_m$. We also use the jet power given by (Celotti et al. 1997; Ghisellini et al. 2005), $P_{\text{jet}} = \int_0^{R_0} \Gamma^2(R) U\beta(R) c \pi R dR$, to limit $\Gamma_c$ and $\Gamma_m$, where $U = U_{\text{B}} + U_e + U_p$ is the total energy density in the jet frame.

3. Radiation Mechanisms

In this section, the radiation models of continually longitudinal and transverse velocity structures are constructed, respectively.

3.1. Radiation Model of Longitudinal Velocity Structures

We present a modified homogeneous SSC model to reproduce the entire spectral energy distribution. In the following, a prime accent denotes a parameter expressed in the comoving frame.

For an isotropic electron distribution, the synchrotron emission coefficient is given by

$$j'_s(v'_s, z) = \frac{1}{4\pi} \int N_e(y, z) P_e(v'_s, y) d\gamma,$$

where $v'_s$ is the frequency in the comoving frame, and $P_e(v'_s, y)$ is the mean emission coefficient for a single electron averaged over an isotropic distribution of the pitch angles. The differential synchrotron luminosity between $z$ and $z + dz$ is then given by

$$dL'_{\text{sync}}(v'_s, z, \theta) = 4\pi^2 R_0^2 j'_s(v'_s, z)e^{-\alpha'_s(v'_s, z)/R_0} dz,$$

where $R_0$ is the radius of the jet, and $\alpha'_s(v'_s)$ is the absorption coefficient (Rybicki & Lightman 1979), as follows:

$$\alpha'_s(v'_s, z) = -\frac{1}{8\pi m_e v'_s^2} \int \gamma^2 d\gamma \frac{N_e(y, z)}{y^2} P_e(v'_s, y) d\gamma.$$

The Doppler factor is given by $\delta(z, \theta) = \frac{\Gamma(z)}{\Gamma(z) + \beta(z) \cos \theta}$ and $\Gamma(z) = \Gamma_0(\frac{1}{\sqrt{1 - \beta^2(z)}})$, where $\Gamma(z) = [1 - \beta^2(z)]^{-1/2}$ is the bulk Lorentz factor and $\beta(z)$ is the velocity in units of $c$. Then, the synchrotron flux density in the observer’s frame is simply given by

$$dF_{\text{sync}}(v_s, z, \theta) = \frac{1}{4\pi d_l^2} \delta(z, \theta)[1 + z_{\text{rs}}] dL'_{\text{sync}}(v'_s, z, \theta),$$

where $\alpha$ is the spectral index, which is taken as 1.0. $d_l$ is the luminosity distance and $z_{\text{rs}}$ is the redshift. We transfer $v'_s$ into the observer’s frame as follows:

$$v_s(z, \theta) = \frac{\delta(z, \theta)}{1 + z_{\text{rs}}} v'_s.$$

Finally, we obtain the total flux density through integrating equation (5).

Calculating the differential SSC emission between $z$ and $z + dz$, we need to compute the soft photon density produced at layers with different Lorentz factors, which is given by $u_{\text{ph}}' = u_{\text{ph}} R_0^2$ (Dermer 1995; Georganopoulos & Kazanas 2003a). $\Gamma_{\text{rela}}$ is the relative Lorentz factor between soft photons and IC electrons. $u_{\text{ph}}'$ is the soft photon energy density in the local frame. The photon energy density, $u'(v'_s, z, \theta)$, is given by the sum of a local contribution (Kataoka et al. 1999),

$$u'_\text{loc}(v'_s, z) = \frac{3}{4} \frac{4\pi j'_s(v'_s, z)}{c \alpha'_s(v'_s, z)} [1 - \exp(-\alpha'_s(v'_s, z) R_0)],$$

and an external contribution,

$$u'_\text{ext}(v'_s, z, \theta) = \frac{j'_s(v'_s, z) \pi R_0^2}{c} \left\{ \int_{z_0}^{z} \frac{\Gamma_{\text{rela}}(z, \theta)}{\Gamma^2(z, \theta)} \exp(-\alpha'_s(v'_s, z)(z - z_0))dz_0 \right\}$$

$$\left. + \int_{z + R_0}^{z_{\text{max}}} \frac{\Gamma_{\text{rela}}(z, \theta)}{\Gamma^2_{\text{rela}}(z, \theta)} \exp(-\alpha'_s(v'_s, z)(z_0 - z))(z_0 - z) \frac{dz_0}{(z_0 - z)^2} \right\}.$$

Then, the emission coefficient is given by (Inoue & Takahara 1996; Kataoka et al. 1999; Katarzynski et al. 2001)

$$j'_s(v'_s, z, \theta) = \frac{h}{4\pi} \epsilon'_s q(\epsilon'_s, z, \theta),$$

where $q(\epsilon'_s, z, \theta)$ is the production rate of the differential photon,

$$q(\epsilon'_s, z, \theta) = \int d\gamma' n_{\text{ph}}(\epsilon'_s, z, \theta) \int d\gamma N(\gamma, z) C(\epsilon'_s, \gamma, \epsilon'_s).$$

$C(\epsilon'_s, \gamma, \epsilon'_s)$ is the Compton kernel given by Jones (1968),

$$C(\epsilon'_s, \gamma, \epsilon'_s) = \frac{2\pi r_e^2 c}{\gamma^2 \epsilon'_s} [2\ln(k) + (1 + 2k)(1 - k)]$$

$$\left. + \frac{(4\epsilon'_s y)k^2}{(2(1 + 4\epsilon'_s y)k)}(1 - k), \right\}$$

where

$$k = \frac{\epsilon'_s}{4\epsilon'_s y} \left( \frac{\gamma}{\epsilon'_s} - 1 \right),$$

and $r_e$ is the classical electron radius. The integration of equation (10) follows the condition

$$\epsilon'_s \leq \epsilon'_s' \leq \gamma - \frac{4\epsilon'_s y}{1 + 4\epsilon'_s y}.$$

We can then integrate $dL'_{\text{sync}}(v'_s, z, \theta)$ to obtain the total flux density.
In calculating the differential EC emission between \( z \) and \( z + dz \), we need to know the soft photon energy density produced by an external radiation field, so we mainly consider photons reprocessed by the Broad Line Region (BLR) (Sikora et al. 1994). The photons are assumed to be distributed as a blackbody with temperature \( T_{\text{ext}} \). In the comoving frame of each layer the mean soft photon energy is blueshifted to \( \epsilon_{\text{ext}} \sim \Gamma(z)\epsilon_{\text{in}} \sim \Gamma(z)k_B T_{\text{ext}} \), where \( k_B \) is the Boltzmann constant. The photon energy density is given by \( u'_{\text{ph,ext}} = u_{\text{ph,ext}} \Gamma^2(z) \).

3.2. Radiation Model of Transverse Velocity Structures

To the transverse velocity structures, we replace equation (3) by

\[
\begin{align*}
\frac{dL'_s}{dR} (v_s, R, \theta) &= 8\pi^2 R j'_s(v_s)(z_{\text{max}} - z_0) e^{-\frac{\epsilon_{\text{in}}(v_s) R_0}{R}} dR. \quad (14)
\end{align*}
\]

The soft photon energy density is given by

\[
\begin{align*}
u'(v_s, R, \theta) &= 2\pi j'_s(v_s) \int_0^{z_{\text{max}}-z_0} dz \int_0^{R_0} dR_s \gamma_{\text{rel}}(R_s, R, \theta) \frac{R_{\text{rel}} \exp\left[-\alpha'(v_s)(R^2 + z^2)^{1/2}\right]}{(R^2 + z^2)^{1/2}}. \quad (15)
\end{align*}
\]

where \( R_s \) is the radius of producing the soft photons. Since the studied length is assumed to be short compared to the whole jet, we take the soft photon density at \( z_{\text{max}}-z_0 \) for different \( z \) as an approximation. We find that this simplicity is reasonable in the following calculation.

4. Velocity Structure Constrained by Jet Power

In this section, we apply the transverse velocity structures constrained by jet power to the SEDs of Mrk 421 and 0716+714, and discuss their properties in the unification of BLO and FRI.

We selected the well-observed Mrk 421, which is a typically high-energy peaked BL Lac (HBL). The SED of Mrk 421 was obtained by fitting the observed core data [for the quiescent state of Mrk 421, the data was from the Macomb et al. (1995) and NED] with our model. The SEDs of its parent population were then given by increasing the viewing angles. In this work, we adopted two kinds of transverse velocity structures, \( \zeta = 0 \) (uniform velocity structures) and \( \zeta = 1 \) (bulk Lorentz factor linearly lessen from the center to the margin). The observed data of Mrk 421 were fitted using the parameters listed in table 1. Its corresponding SEDs in different viewing angles were calculated to show the implications of the velocity structures. Konopelko et al. (2003) used the one-zone SSC model to fit the lower state SEDs of Mrk 421, and obtained parameters of \( s = 1.75, \gamma_{\text{max}} = 3 \times 10^3, B = 0.10 G; \) Blazejowski et al. (2005) presented parameters of \( \delta = 10, B = 0.50 G, R = 0.7 \times 10^{16} \text{cm}. \) The parameters in our model are comparable to theirs. We set \( \Gamma_c = \Gamma_{\text{in}} = 10 \) for a jet with a uniform structure and \( \Gamma_m = 3 \) for a jet with a velocity structure (Giroletti et al. 2004a, 2005; Tavecchio & Ghisellini 2008). Assuming the same jet power for the two structures, we could obtain \( \Gamma_c \) for the jet with the velocity structure. The SEDs of Mrk 421 are shown in figure 1. The SEDs of two velocity structures show a very small difference in the small viewing angle (3\(^\circ\)). Under the viewing angle of the parent population (FRI I (60\(^\circ\)), the SEDs have a large difference, in which the flux with a velocity structure is much larger than those with an uniform structure. The velocity structure can resolve the problem that the observed FRI nuclei are over-luminous by a factor of \( 10^{-10^4} \) than those predicted by a simple one-zone model in the optical and radio bands. In order to compare the observed and predicted fluxes of the parent population, we also present two vertical lines denoting the optical (\( V' \) band) and 5 GHz radio band, respectively, in figure 1. It is noted that the radio fluxes given by the model are extrapolated from the infrared fluxes.

0716+714 is a typical low-energy peaked BL Lac (LBL). We also list the parameters in the table 1. Giommi et al. (1999) gave the magnetic field to be \( B > 0.9 G; \) Tagliaferri et al. (2003) obtained parameters of \( B = 2.5 G, R = 2 \times 10^{16}, \theta = 3.4. \) These parameters are consistent with those given by our model. The SEDs of 0716+714 given by the model are shown in figure 2. It is shown that the SEDs have an obvious difference for the two velocity structures under large viewing angles (40\(^\circ\) or 60\(^\circ\)).

In figure 3, we give the luminosity ratio between the jets with \( \zeta = 1 \) and \( \zeta = 0 \) in three bands: radio (9 Hz), optical (\( V' \) band), and X-rays (1 keV) for Mrk 421, 0716+714, and their parent population. It is shown that the ratio can reach 2–9 in the

| Objects          | \( n_0 \)  | \( \gamma_{\text{max}} \) | Index | \( z_0 \)  | \( z_{\text{max}} \) | \( R \)   | \( B \) | \( \theta \) |
|------------------|----------|-----------------|-------|----------|-----------------|-------|-------|--------|
| Mrk 421 (\( \zeta = 0.1 \)) | 3.9 \times 10^2 | 8.0 \times 10^4 | 1.8   | 1 \times 10^{16} | 6 \times 10^{16} | 1 \times 10^{16} | 0.18   | 3°     |
| Mrk 421 (\( \zeta = 0 \))   | 4.3 \times 10^2 | 8.0 \times 10^4 | 1.8   | 1 \times 10^{16} | 6 \times 10^{16} | 1 \times 10^{16} | 0.24   | 3°     |
| Mrk 421 (\( \zeta = -1 \)) | 1.0 \times 10^2 | 7.0 \times 10^4 | 1.8   | 1 \times 10^{16} | 6 \times 10^{16} | 1 \times 10^{16} | 0.1    | 3°     |
| Mrk 421 (\( \zeta = 1 \))   | 1.0 \times 10^2 | 7.0 \times 10^4 | 1.8   | 1 \times 10^{16} | 6 \times 10^{16} | 1 \times 10^{16} | 0.9    | 3°     |
| 0716+714 (\( \zeta = 0.1 \)) | 4.6 \times 10^4 | 8.0 \times 10^3 | 2.0   | 1 \times 10^{16} | 6 \times 10^{16} | 1 \times 10^{16} | 0.1    | 3°     |
| 0716+714 (\( \zeta = 0 \))   | 5.0 \times 10^4 | 8.0 \times 10^3 | 2.0   | 1 \times 10^{16} | 6 \times 10^{16} | 1 \times 10^{16} | 1.2    | 3°     |
| 0716+714 (\( \zeta = -1 \)) | 1.0 \times 10^4 | 7.0 \times 10^3 | 2.0   | 1 \times 10^{16} | 6 \times 10^{16} | 1 \times 10^{16} | 0.7    | 3°     |
| 0716+714 (\( \zeta = 1 \))   | 1.0 \times 10^3 | 6.0 \times 10^3 | 2.0   | 1 \times 10^{16} | 6 \times 10^{16} | 1 \times 10^{16} | 1.2    | 3°     |
| 3C 279 (\( \zeta = 0 \))     | 8.0 \times 10^3 | 1.0 \times 10^3 | 2.0   | 1 \times 10^{16} | 2 \times 10^{17} | 1 \times 10^{17} | 0.1    | 3°     |
| 3C 279 (\( \zeta = -0.5 \))  | 1.0 \times 10^3 | 9.0 \times 10^2 | 2.0   | 1 \times 10^{16} | 2 \times 10^{17} | 1 \times 10^{17} | 0.35   | 3°     |
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Fig. 1. Approximate fitting for data of Mrk 421 [from Macomb et al. (1995) and NED] and the extrapolated SEDs of the parent population. The solid lines represent the emission of a jet with uniform velocity structures ($\zeta = 0$), and the dash lines denote a jet with velocity structures ($\zeta = 1$). The upper two curves report the emission at angles of $3^\circ$; the mid and lower two curves are the cases of the parent population of BL Lacs extrapolating the viewing angles to $40^\circ$ and $60^\circ$.

Fig. 2. Approximately fitting for NED data of 0716+714 and the extrapolated SEDs of parent population. The solid lines represent a jet with uniform velocity structures ($\zeta = 0$) and the dash lines denote a jet with velocity structures ($\zeta = 1$). The upper two curves report emission at angles of $2^\circ$; the mid and lower two curves are the cases of the parent population of BL Lacs extrapolating the viewing angles to $40^\circ$ and $60^\circ$.

Fig. 3. Ratio of the luminosity between $\zeta = 1$ and $\zeta = 0$ under different band and viewing angles.

The debeaming case

three bands under large viewing angles, corresponding to the parent population. Understanding these properties, we present the variations of the Doppler factors along the jet radius, $R$, for different velocity structures under viewing angles of $3^\circ$ and $60^\circ$, shown in figures 4 and 5. Under $3^\circ$ (see the figure 4), the Doppler factor of the jet with the velocity structure rapidly decreases with $R$, and is smaller than those of the jet with a uniform velocity structure when $R > 0.6 R_0$. However, the increase of the Doppler factor with $R$ appears at under $60^\circ$ (figure 5).

In the unification scheme, it is believed that the appearance of AGNs strongly depends on the viewing angles and obscuration instead of the intrinsic physical properties. For low-luminosity radio-loud objects, such as BLO and FRI, the relativistic beaming effects caused by the viewing angles should play an important role in observations. However, Chiaberge et al. (2000) have found that the observed FRI nuclei are over-luminous by a factor of $10^4$–$10^5$ than those predicted by a simple one-zone model in the radio and optical bands. They have argued that a radial velocity structure, which is a fast spine surrounded by a slow layer, can reconcile the above contradiction. We applied the velocity structures described previously to the unification of BLO and FRI. In figure 6, we show debeaming trails with different velocity structures in the radio-optical luminosity plane for Mrk 421 and 0716+714. For Mrk 421, when the viewing angle is increased to $60^\circ$, the predicted optical and radio luminosity nearly come into the region of FRI in the case of the velocity structure; however, they are less-luminous in the case of a uniform structure. For 0716+714, the predicted luminosity fully falls into the region of FRI in different velocity structures.

The $\alpha_{\text{opt}}-\alpha_{21}$ planes for Mrk 421, 0716+714, and FRI are presented in figure 7, in which the lines denote the debeaming trails of Mrk 421 and 0716+714. The plotted data of FRI and BLO are from Fossati et al. (1998) and Trussoni et al. (2003). For 0716+714, the debeamed indices fall into the region of FRI under different velocity structures. However, the debeamed indices of Mrk 421 are marginally in the region of FRI. This implies that some intrinsic physical difference exist between HBL and LBL.

5. Velocity Structure Constrained by Apparent Speed

In this section, we use the observed apparent speed to constrain the jet velocity structures, and discuss its effect on the SEDs of BLO shown in Mrk 421 and 0716+714.
Fig. 4. Under $\theta = 3^\circ$, the Doppler factors vary with $R$ for different velocity structures. The solid line denotes the case of uniform velocity structures, and the dash line is in velocity structures.

Fig. 5. Under $\theta = 60^\circ$, the Doppler factors vary with $R$ for different velocity structures. The solid line denotes the case of uniform velocity structures and the dash line shows the case of velocity structures.

Fig. 6. Debeaming trails with models of continual velocity structures in the radio-optical luminosity plane for Mrk 421 and 0716$+$714 (the solid lines denote $\zeta = 0$ and dash ones are $\zeta = 1$), where the upper pentagrams correspond to the luminosity of BL Lacs at $\theta = 2^\circ$ or $3^\circ$ and the lower ones are the predicted luminosity of the parent population at $\theta = 40^\circ$ and $60^\circ$. The three regions enclosed by curves respectively describe the range for three samples, i.e., HBL (dash curves), LBL (dot curves), and FRI (solid curves) in realistic observations (Chiaberge et al. 2000).

We took $\beta_{\text{app}} = 3.6c$ to limit the longitudinal and transverse velocity structures, and calculated the SEDs of the jet with velocity structures to fit the observed data of Mrk 421 and 0716$+$714. Under $\beta_{\text{app}} = 3.64c$, adopting $3^\circ$ or $2^\circ$ as the viewing angles, we obtained $\Gamma_0$ for three kinds of longitudinal velocity structures, e.g., uniform ($\zeta = 0$), decelerating ($\xi = -1$), and accelerating ($\xi = 1$), which are listed in the figures. The SEDs of Mrk 421, 0716$+$714 and their parent populations under different velocity structures are shown in figures 8, 9, 10, and 11. It is shown that the elementary volume expansion ($\xi > 0$) or compression ($\xi < 0$) changes the electron energy distribution in longitudinal bulk velocity structures, and cause the parameters fitting the observed data to have large differences between the uniform and velocity structure models (see the table 1). In the decelerating velocity structures, we used smaller parameters of $N_0, \gamma_{\text{max}}$, and $B$ to fit the observed SEDs compared to the uniform structure. On the contrary, we must use larger parameters in the accelerating models to fit the SEDs. When velocity structures exist, the flux, $vF_v$, decreases slowly along with an increase of the viewing angles (such as $40^\circ$ or $60^\circ$). However, $vF_v$ decreases quickly in the uniform structure. In figures 12 and 13, we give the luminosity...
Fig. 8. Under $\beta_{\text{app}} = 3.6c$, the approximate fitting for data of Mrk 421 [from Macomb et al. (1995) and NED] and the extrapolated SEDs of the parent population (note that we use different parameters for different velocity structures, see the table 1). The solid lines represent the emission of a jet with uniform velocity structures ($\xi = 0$), and the dash lines denote a jet with velocity structures ($\xi = -1$). The upper curves show the emission at angles of $3^\circ$; the red and green curves present the parent population of BL Lacs with viewing angles of $40^\circ$ and $60^\circ$.

Fig. 9. Under $\beta_{\text{app}} = 3.6c$, the approximate fitting for data of Mrk 421 [from Macomb et al. (1995) and NED] (note that we use different parameters for different velocity structures, see the table 1) and the extrapolated SEDs of parent population. The solid lines represent the emission of a jet with uniform velocity structures ($\xi = 0$), and the dot lines denote a jet with velocity structures ($\xi = 1$). The upper curves report emission at angles of $3^\circ$; the red and green curves present the parent population of BL Lacs with viewing angles of $40^\circ$ and $60^\circ$.

Fig. 10. Under $\beta_{\text{app}} = 3.6c$, an approximate fitting for NED data of 0716+714 (note that we use different parameters for different velocity structures, see the table 1), and the extrapolated SEDs of the parent population. The solid lines represent a jet with uniform velocity structures ($\xi = 0$) and the dash lines denote a jet with velocity structures ($\xi = -1$). The upper curves report the emission at angles of $2^\circ$; the red and green curves present the parent population of BL Lacs with viewing angles of $40^\circ$ and $60^\circ$.

Fig. 11. Under $\beta_{\text{app}} = 3.6c$, the approximate fitting for NED data of 0716+714 (note that we use different parameters for different velocity structures, see the table 1), and the extrapolated SEDs of the parent population. The solid lines represent a jet with uniform velocity structures ($\xi = 0$), and the dotted lines denote a jet with velocity structures ($\xi = 1$). The upper curves report emission at angles of $2^\circ$; the red and green curves present the parent population of BL Lacs with viewing angles of $40^\circ$ and $60^\circ$.

The ratio between different viewing angles in the same band. In a uniform jet, the ratio changes greatly with the viewing angles. The electron energy density and magnetic fields energy density do not necessarily satisfy the energy equipartition (Hardcastle et al. 1998). We found that for the acceleration velocity structures, $U_e/U_B$ has a larger value (about 300) outside of studied jet scale; however, for the deceleration velocity structure, $U_e$ is larger than $U_B$ at the inner region of the studied jet scale along the jet, and $U_B$ becomes dominant at the outer region (see the figure 14).

Regarding the transverse velocity structures (figures 15 and 16), we adopted two kinds of velocity structures: $\xi = 0$ (uniform velocity structure) and $\xi = 1$ (bulk Lorentz factor linearly decreases from the center to the margin). We set
Fig. 12. Ratio of luminosity between different viewing angles under different $\xi$ and bands for Mrk 421.

Fig. 13. Ratio of luminosity between different viewing angles under different $\xi$ and bands for 0716+714.

$\Gamma_m = 3$ and obtained $\Gamma_e$, restricted by $\beta_{\text{app}} = 3.6$, which is listed in corresponding figures. The SEDs of Mrk 421 and 0716+714 at different viewing angles are shown in figures 15 and 16. We show that the lower luminosity is common to the jets with a uniform velocity structure at large viewing angles, and that the way of solving the paradox of BLO and FRI unification is to consider the velocity structure, where all photons are not produced according to the same Doppler factor.

6. EC Spectra with Velocity Structure

Piner et al. (2007) have proposed that the mean fastest apparent speed for quasars is $6.8 \pm 1.1c$; as in the previous discussion we will use this observed apparent speed to constrain the parameters of the velocity structures (i.e., $\Gamma_0 = 19.6$ for the $\xi = -0.5$; $\Gamma_0 = 8.4$ for the $\xi = 0$). In figure 17, under $\beta_{\text{app}} = 6.8c$, we present a fit for the data of FSRQ 3C 279 (Inoue & Takahara 1996). In this model, we set $T_{\text{ext}} = 10$ eV (near the energy of hydrogen Lyman-$\alpha$ photons) and $U_{\text{ext}} = 6.6 \times 10^{-5}$ erg cm$^{-3}$ for external photons; other parameters are given in the table 1. The solid lines represent a jet with uniform velocity structures ($\xi = 0$), and the dotted lines denote a jet with velocity structures ($\xi = -0.5$). The upper curves show emission with an angle of $3^\circ$; the mid and lower curves correspond to the parent population of quasars with viewing angles of 40$^\circ$ and 60$^\circ$. From this figure, firstly, we find that the observed EC component is weakly affected by the velocity structures compared to the synchrotron or SSC ones. The reason is that for a continual jet, the luminosity, $L_{\text{EC}}$, has the relation $L_{\text{EC}} \sim N_e \delta^3 \gamma_{\text{EC}}^2 \sim N_e \delta^3 U_{\text{ext}} \sim \Gamma^2 \delta^3 U_{\text{ext}} N_e$; the integration of $\Gamma^2 \delta^3$ over $z$ gives a smaller discrepancy between the models of $\xi = -0.5$ and $\xi = 0$.

7. Discussions and Conclusions

In this work we mainly considered the influence of bulk velocity structures on the radiative spectra, and ignored the radiative energy loss of electrons in the studied jet scale. It is reasonable if we suppose that ongoing particle acceleration in situ can compensate the radiative loss. However, radiative losses become important for high-energy electrons that produce the high-energy part of the synchrotron and IC emission, when the particles-acceleration mechanism does not offset the radiative loss. In this situation, the high-energy part of the synchrotron and IC emission will mainly originate at the base of the jet, and their spectra will be steeper with the distance.

In this work, the synchrotron self-Compton (SSC) models and External Compton (EC) models of AGN jets with continuously longitudinal and transverse bulk velocity structures were constructed. However, our models can not discriminate a lateral or longitudinal deceleration scenario. For the former scenario, we might observe the limb brightening in VLBI (Giroletti et al. 2004a). For the longitudinal deceleration scenario, there should exist an outward-increasing radio-to-X-ray ratio (Georganopoulos & Kazanas 2003b). However, they might be interrelated, for example, in a faster spine and a slower layer model when the IC power is compared with the total bulk kinetic power. The Compton rocked effect will cause the spine to recoil and decelerate, and form longitudinal
velocity structures (Ghisellini et al. 2005). Similarly, if gradual entrainment from an external medium causes jet deceleration, it would produce velocity gradients across the jet. A faster spine and a slower sheath have been formed. Rapid TeV flares observed for PKS 2155−304 and Mrk 501 (Aharonian et al. 2007; Albert et al. 2007) appear to indicate large bulk Lorentz factors. The systematic differences of the Doppler factors, inferred from different waveband observations, indicate that the jet holds velocity structures within sub-parsec to parsec scale. Based on our calculation, a large bulk Lorentz factor in the base of the jet for longitudinal velocity structures, or in the spine for transverse velocity structures, can allow TeV photon escape, where the apparent speed is moderate.

In unified schemes, we find that beside the viewing angles, the bulk velocity structures play an important role in the Doppler beaming pattern. Firstly, from the observed data to deduce the intrinsic quantities, the velocity structures and the viewing angles should be considered at one time. In fact, if the jets have velocity structures, their intrinsic flux will be deduced with difficulty under different viewing angles. Secondly, the velocity structures also cause some statistical
discrepancy between observations and theory in a simple one-zone model (Chiaberge et al. 2000; Henri & Sauge 2006). In the one-zone model, if $\theta \leq 1/\Gamma$, one has $1 \leq \delta \leq 2\Gamma$, except for $\delta \approx 1/\Gamma$. This means that for a few Doppler amplified sources, one can expect a large number of unbeamed counterparts. In this work, we found that under larger viewing angles the velocity structures limited by the apparent speed have larger effects on the observed flux. The statistics of the flux limited sources will provide a framework to explore the velocity structures of AGN jets.

In figure 18, also given by Urry and Padovani (1995), we present relations between the Doppler factor, Lorentz factor and viewing angle. The curve lines for different Lorentz factors cross each other within viewing angles of $1^\circ$ to $10^\circ$. They show that a large bulk Lorentz factor does not always produce a large Doppler factor when the viewing angle increases. Furthermore, the Doppler factor with a large Lorentz factor decreases quickly under an increase of the viewing angles. These properties cause complex effects on the emissive spectra.

The observed apparent speed might be results of flux convolution over the resolution region, which can solve the inconsistency of bulk motions obtained in different wavebands. We find that the influences of the velocity structures upon the observed spectra heavily depend on the viewing angles. Under a jet with a velocity structure constrained by the jet power and the apparent speed, we show that the SEDs have a large difference for jets with and without velocity structure in a large viewing angle. For a jet with a transverse and longitudinal deceleration velocity structure, its flux is much larger than that with a uniform structure. Especially, in longitudinal bulk velocity structures, as an elementary volume expansion ($\xi > 0$) or compression ($\xi < 0$) greatly change the electron energy distribution, we have used smaller values of $N_0$, $\gamma_{\text{max}}$ and $B$ than the uniform ones to fit the SEDs; on the contrary, we must use larger values for the accelerating models to obtain a fitting. We find that for the deceleration velocity structures, $U_e$ is larger than $U_B$ at the inner region of the studied jet scale; along the jet, $U_B$ becomes dominant at the outer region. The EC-observed spectra are weakly affected by the velocity structures compared to synchrotron and SSC ones.

Nowadays, VLBA can not resolve velocity structures on the sub-parsec to parsec scale; the AGN’s unified schemes show a large uncertainty. TeV blazars should have jet bulk velocity structures within the sub-parsec to parsec scale.

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