EXISTENCE OF LARGE SCALE SYNCHROTRON X-RAY JETS IN RADIO-LOUD ACTIVE GALACTIC NUCLEI

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ABSTRACT

In this paper, analytical arguments are presented that there exists a synchrotron X-ray jet on large scales in most radio-loud AGNs, based on the knowledge of the nature and physics of blazars. In blue blazars and blue-blazar-like radio galaxies, the large scale X-ray jet may get faint along the jet, while in most red blazars and red-blazar-like radio galaxies, the X-ray jet is bright on 10 kpc scales whether the jet is highly relativistic on large scales or not. In extreme red blazars in which the jet is still highly relativistic on large scales and the synchrotron peak of the inner jet lies in the infrared bands, the X-ray jet may get fainter along the jet from 10 kpc to 100 kpc scales while the optical and IR jet gets brighter. The predictions can be tested with the ongoing observations of the Chandra X-ray Observatory.

\textit{Subject headings:} galaxies: active — galaxies: jets — radiation mechanism: nonthermal — X-rays: galaxies

1. INTRODUCTION

Extragalactic jets are a spectacular feature associated with the activity of radio-loud active galactic nuclei (AGNs). They are pipelines through which the mass, momentum and energy are transported from the central nucleus to the extended radio lobes (e.g. Rees 1971; Begelman et al. 1984; Laing 1993), and naturally play an important role for understanding the nature and physics of the invisible central engine in AGNs which is widely believed to be an accretion disk surrounding a super massive black hole (e.g. Rees 1984). Jets are usually observed in the radio bands with VLA on kiloparsec (kpc) scales and with VLBI on parsec scales. A handful of radio jets have been detected in the IR/optical bands by the Hubble Space Telescope on kpc scales. At X-ray energies, about four nearby radio jets have been detected by EINSTEIN and ROSAT X-ray observatories in Cen A (Turner 1997; Feigelson et al. 1981), M87 (Neumann et al. 1997; Schreier and ROSAT X-ray observatories in Cen A (Turner 1997; Feigelson et al. 1981), M87 (Neumann et al. 1997; Schreier et al. 1982), 3C 273 (Röser et al. 2000; Harris and Stern 1987) and NGC 6251 (Mack et al. 1997), respectively.

Since it was launched in July 1999, Chandra X-ray Observatory (CXO) has detected several more radio jets on kpc scales with high spatial and spectral resolution at X-ray energies. While the radio (and probably the optical) emission of the jets is certain to be synchrotron, the radiation mechanisms responsible for the kpc scale X-ray jets have not been well understood yet. The X-ray jet in the distant quasar PKS 0637-752 has been explained in synchrotron self-Compton (SSC) models (Schwartz et al. 2000) and as inverse-Compton scattering of the cosmic microwave background (CMB, Tavecchio et al. 2000; Celotti et al. 2001). The X-ray jet in the famous quasar 3C 273 can be interpreted as synchrotron emission, or synchrotron self-Compton emission or inverse-Compton scattering of the CMB (Marshall et al. 2001; Sambruna et al. 2001; Röser et al. 2000). The X-ray jet in M87, Cen A and Pictor A has also been interpreted in several models (Neumann et al. 1997; Perlman et al. 2001; Turner et al. 1997; Wilson et al. 2001). All these explanations are based on spectral fitting in the X-ray band or broad band spectra from radio to X-rays, uncertainty of which is usually high due to the weak signal of the jet.

Blazars, including BL Lac objects and flat-spectrum radio quasars (FSRQs), are compact, flat spectrum radio sources with highly variable and polarized nonthermal continuum emission extending up to X-ray and often gamma-ray energies, which are generally understood as consequences of a relativistic jet oriented close to the line of sight (e.g. Blandford & Rees 1978; Blandford & Königl 1979; Marscher 1980; Ghisellini et al. 1993; Kollgaard 1994). The compact jet of a blazar which appears as a bright core in VLA maps but usually exhibits an elongated jet in VLBI maps, connects the central region with the outer, more extended, large scale jets and radio lobes, and dominates the radio emission of the source, as in the cases of 3C 273 and PKS 0637−752. Blazars have been observed intensively from radio to gamma-rays, and the radiation mechanisms of the inner jets (the compact, parsec and subparsec scale jets) have been almost certain. The broad band spectral energy distributions (SEDs) of blazars have two components, exhibiting a self-similar double-hump structure. Correlated variations across the SEDs are consistent with the picture that a single electron population in the relativistic jet gives rise to both components, via synchrotron at low energies and inverse-Compton scattering at high energies (e.g. Ulrich et al. 1997; Ghisellini et al. 1998). In red blazars (such as 3C 273 and PKS 0637−752) which have synchrotron peak at IR/optical wavelengths, the X-rays are inverse-Compton emission, while in blue blazars which have synchrotron peak at UV/X-rays, the X-rays are an extension of synchrotron emission (Padovani & Giommi 1996; Kubo et al. 1998). Besides the emission mechanisms, other aspects of the inner jets in blazars have been intensively studied as well.

The knowledge about the inner jet in blazars may serve as a starting point and a useful tool to study the emission

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mechanisms in the kpc scale jet. The kpc scale jet is an extension of the inner jet, connecting the inner jet to the radio lobe, and thus must be somewhat similar to the inner jet. Conclusions about the inner jet may be applied or generalized to the kpc scale jet, and the conservative quantities can be used to constrain the models for the kpc scale jet. In this paper, we argue that there exists a synchrotron X-ray jet on kpc scales in radio-loud AGNs, based on the knowledge of the inner jet in blazars.

2. X-RAY JETS IN BLAZARS

In blue blazars, the inner jet produces X-rays via synchrotron process. It is possible that the parsec scale synchrotron X-ray jet extends to the kpc scale, i.e., there may be a synchrotron X-ray jet on kpc scales. In red blazars, the inner X-ray jet is inverse-Compton emission, so it seems that red blazars cannot produce an X-ray jet on kpc scales through synchrotron process. Furthermore, for some sources, the trough between the synchrotron and Compton peak happens to lie in the range of X-rays, and consequently there are not any X-ray jets in these sources on kpc scales. However, it is probable that there exists a synchrotron X-ray jet in red blazars on kpc scales. Statistical studies for complete samples of blazars revealed spectral trends that as the bolometric luminosity increases, the luminosities of the emission-lines and Compton component increase but the frequency of the peak of the synchrotron component decreases (Sambruna et al. 1996; Fosati et al. 1998). These trends support a simple paradigm in which the electron acceleration is similar in both red and blue blazars but the relativistic electrons in the inner jet of red blazars suffer more Compton cooling because of larger external photon densities as indicated by the higher emission-line luminosity, leading naturally to lower characteristic electron energies and thus lower frequencies of the synchrotron peak (Ghisellini et al. 1998; Urry 1999). On kpc scales, the external photon densities of the jet in red blazars are much smaller, so the electrons may reach much higher characteristic energies. These high energy electrons may produce synchrotron X-ray jet on kpc scales, which can be seen below in detail.

2.1. Physics of the inner jet in blazars

Statistical analysis for all γ-ray loud blazars shows a strong correlation between the characteristic electron energy γ_{peak} and energy density (U_r + U_B) in the jet comoving frame for all γ-ray loud FSRQs (Ghisellini et al. 1998),

$$\gamma_{peak} \propto (U_r + U_B)^{-0.5\pm0.06} = C(U_r + U_B)^{-0.5\pm0.06},$$ (1)

where U_r and U_B = B^2/(8\pi) are the energy density of radiation (produced in or outside the jet) and magnetic field, respectively. If including γ-ray loud BL Lac objects, the correlation is γ_{peak} ∝ (U_r + U_B)^{-0.6\pm0.04}, slightly different from Eq. (1). The difference may be caused by the larger uncertainty of U_r, since BL Lac objects have weak or no emission lines, leading to larger uncertainties to the radiation energy density of the external radiation, U_{ext}.

The electrons must be accelerated in the regions where they produce radiation since the timescales of radiative energy losses of electrons are very short to both synchrotron and Compton processes. Assuming that the jet is composed of electrons and protons, and that the electron heating rate balances to cooling rate $\dot{\gamma}_{\text{heat}} = \dot{\gamma}_{\text{cool}}$. Eq. (1) can be deduced in the internal shock scenario (Ghisellini 1999), suggesting that γ_{peak} is the result of the balance between heating and cooling. Taking into account both synchrotron and inverse-Compton emission, the electron cooling rate in the jet is $m_e c^2 \dot{\gamma} = (4/3) \sigma_T c^2 \gamma^2 (U_r + U_B)$, where $m_e$ is the mass of electron and $\sigma_T$ is the Thomson cross-section. Using Eq. (1), at $\gamma = \gamma_{peak}$, $\dot{\gamma} \propto \gamma^2 (U_r + U_B) \sim \text{constant}$, i.e., at γ_{peak} the radiative cooling rate is nearly the same for all sources. This may suggest that electron acceleration is the same in both red and blue blazars, independent of luminosity, γ and U, and that only the cooling differs (Ghisellini et al. 1998; Urry 1999).

It is reasonable to assume that Eq. (1) can be applied to the kpc scale jet, and that the proportionality constant C is the same on small and large scales. The kpc scale jet is an extension of the inner jet. It can be treated as an “inner jet” originating from a weaker “nucleus”, the end of the inner jet. Furthermore, on kpc scales the jet is still relativistic as indicated by the observed jet–counterjet intensity asymmetry. The differences between the kpc scale jet and the inner jet are not more than the differences between red and blue blazars. Probably, the electron acceleration mechanism in the kpc scale jet is the same as that in the inner jet, and the electron heating rate balances to the cooling rate.

2.2. The kpc scale synchrotron X-ray jet in blazars

Given the relativistic electrons with γ_{peak} in the magnetic field B of a relativistic jet with speed β in units of the speed of light, Lorentz factor Γ and viewing angle θ, the peak frequency ν_{s} of synchrotron radiation in the observer’s frame is

$$\nu_s = 3.7 \times 10^6 \frac{\delta}{1+z} B_{\text{peak}}^2,$$ (2)

where z is the redshift of the source and δ is the Doppler factor $\delta = [\Gamma(1-\beta \cos \theta)]^{-1}$. For blue blazars, $U_r(pc) \sim U_B(pc)$ in the inner jet. According to Eq. (1), $\gamma_{\text{peak}} = C^2 [2U_B(pc)]^{-1} = 4C^2 \pi/B_{pc}^2$. Substituting γ_{peak} into Eq. (2) gives

$$\nu_s(pc) = 3.7 \times 10^6 \frac{\delta_{pc} 4\pi C^2}{1+z B_{pc}^2}.$$ (3)

On kpc scales, none of the jets shows any direct evidence of superluminal motion with one exception, MS7 (Biretta et al. 1999), so in most cases the kpc scale jet probably has only mildly relativistic speeds, i.e., $\Gamma(kpc)$ is slightly greater than 1. Since the inner jet is highly relativistic, the contribution of the emission from the inner jet to $U_e(kpc)$ cannot be neglected (Celotti et al. 2001). The emission of the kpc scale jet itself also contributes a main part of $U_e(kpc)$, but $U_r(kpc) \sim U_B(kpc)$ still holds. According to Eq. (1), $\gamma_{\text{peak}}^2 = C^2 [2U_B(kpc)]^{-1} = 4C^2 \pi/B_{kpc}^2$, yielding

$$\nu_s(kpc) = 3.7 \times 10^6 \frac{\delta_{kpc} 4\pi C^2}{1+z B_{kpc}}.$$ (4)

At point r of the jet, the magnetic flux $L_B$ is

$$L_B = \pi \psi^2 r^2 c \Gamma^2 U_B = \frac{c}{8} \psi^2 r^2 \Gamma^2 B^2,$$ (5)
assuming that the emitting region located at $r$ has a transverse dimension $R = \psi r$. Conservation of magnetic flux $L_B$ gives

$$\frac{B(kpc)}{B(pc)} = \frac{\Gamma_{pc}}{1000 \delta_{kpc}} \sim \frac{1}{100}, \quad (6)$$

i.e., $B(kpc) \sim 10^{-2}B(pc)$, assuming that $\psi$ is constant along the jet and $\Gamma_{pc} \sim 10$ (Blandford 1993; Marcher 1993; Celotti et al. 2001). Combining Eqs. (3), (4) and (6) yields

$$\nu_s(kpc) = 10^2 \nu_s(pc) \frac{\delta_{kpc}}{\delta_{pc}} \sim 10 \nu_s(pc). \quad (7)$$

The synchrotron emission of blue blazars peaks in the range of $\sim 0.01$ keV to $\sim 1$ keV, so on kpc scales, the synchrotron peak of the jet emission lies above 0.1 keV, suggesting that there exists a synchrotron X-ray jet in blue blazars on kpc scales.

For red blazars, $U_r/U_B$ is typically in the range of $10^{-10}$, so $\gamma_{\text{peak}}^2 \sim 4C^2\pi/(10B^2)$, yielding

$$\nu_s(pc) = 3.7 \times 10^6 \frac{\delta_{pc}}{1+z} \frac{4\pi C^2}{1+70Bpc} \times 10^5 \nu_s(pc). \quad (8)$$

On kpc scales, as in the case of blue blazars, $U_r(kpc) \sim U_B(kpc)$, and

$$\nu_s(kpc) = 3.7 \times 10^6 \frac{\delta_{kpc}}{1+z} \frac{4\pi C^2}{B_{kpc}} \times 10^5 \nu_s(pc). \quad (9)$$

Thus

$$\nu_s(kpc) = 10^3 \nu_s(pc) \frac{\delta_{kpc}}{\delta_{pc}} \sim 10^2 \nu_s(pc). \quad (10)$$

The synchrotron peak of red blazars lies in the range of $\sim 10^{13}$ Hz to $\sim 10^{15}$ Hz, so on kpc scales, the synchrotron peak of the jet emission lies above $\sim 0.01$ keV, which is like those blue blazars whose synchrotron peak lies in the UV and soft X-ray energies, suggesting that there exists a synchrotron X-ray jet in red blazars on kpc scales as well.

3. DISCUSSION

In Section 2, it has been argued that there exists a synchrotron X-ray jet in both blue and red blazars. Blue and red blazars are just the extrema of the blazar class. Similarly, there exists a synchrotron X-ray jet in intermediate blazars on kpc scales. Furthermore, according to the unified schemes, Fanaroff-Riley class I radio galaxies (Fanaroff & Riley 1974) are intrinsically the same as BL Lac objects, and Fanaroff-Riley class II radio galaxies and steep-spectrum radio quasars (SSRQs) are intrinsically the same as FSRQs, with the relativistic jet oriented at a larger angle to the line of sight than blazars (e.g. Urry & Padovani 1995). Therefore, radio galaxies and SSRQs have a synchrotron X-ray jet on kpc scales as well.

According to Eqs. (4), (5) and (9), the synchrotron peak of the emission of the large scale jet shifts gradually to higher frequencies along the jet for both red and blue blazars. Consequently, in blue blazars and blue-blazar-like radio galaxies, the X-ray jet may get faint along the jet. In typical red blazars and red-blazar-like radio galaxies, from $\sim 10$ kpc to $\sim 100$ kpc along the jet, the synchrotron peak may lie right in the energy range of the CXO, resulting in a relatively bright X-ray jet. This may account for the X-rays observed from the “inner jet” of 3C 273 between 5’’ and 10’’ from the core (Marshall et al. 2001). The viewing angle $\theta$ of the jet of 3C 273 to the line of sight is $\cos \theta = 0.95$ (Davis et al. 1991), so at the distance of 3C 273 ($z = 0.158$), 5’’ and 10’’ from the core of 3C 273 correspond to $\sim 38.43$ kpc and $\sim 76.86$ kpc from the core along the jet, respectively, assuming $H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$ and $q_0 = 0.5$. The X-rays from the “inner jet” of 3C 273 are thus probably synchrotron emission.

If in some cases (possibly in some powerful FSRQs) the jet is still highly relativistic on large scales, i.e., $\Gamma \sim \Gamma_{pc} \sim 10$, the energy density of the CMB, $U_{CMB}$, gets significant in the jet comoving frame. Assuming $L_B = 10^{43}$ erg/s and redshift zero, at $\sim 10$ kpc $U_{CMB} \sim U_B$, and at $\sim 100$ kpc $U_{CMB} \sim 100U_B$ (Celotti et al. 2001). From $\sim 1$ kpc to $\sim 10$ kpc along the jet, the above analysis is still valid, except that Eqs. (7) and (10) turn to be $\nu_s(kpc) = 10^2 \nu_s(pc)$ and $\nu_s(kpc) = 10^3 \nu_s(pc)$, respectively. On 100 kpc scales, $\nu_s(100kpc) \sim 10^{-1} \nu_s(10kpc)$, indicating that the synchrotron peaks gradually shift to lower frequencies from 10 kpc to 100 kpc scales. For extreme (and thus the most powerful) red blazars, in which the synchrotron peak of the inner jet lies in the infrared bands, the synchrotron peak of the large scale jet may shift back to the optical band on 100 kpc scales, and consequently the X-ray jet gets fainter along the jet from 10 kpc to 100 kpc scales, while the optical and IR jet gets brighter. If in some powerful Fanaroff-Riley class II radio galaxies (counterparts of powerful red blazars) the jet is still highly relativistic on large scales, and is viewed at a very large angle, Doppler beaming effects may cause the X-ray jet too weak to be detected.

4. CONCLUSIONS

In conclusion, we predict a detectable synchrotron X-ray jet on large scales in most radio-loud AGNs. In blue blazars and blue-blazar-like radio galaxies the large scale X-ray jet gets faint along the jet, while in typical red blazars and red-blazar-like radio galaxies the X-ray jet is bright on 10 kpc scales whether the jet is highly relativistic on large scales or not. In extreme red blazars in which the jet is still highly relativistic on large scales and the synchrotron peak of the inner jet lies in the infrared bands, the X-ray jet may get fainter along the jet from 10 kpc to 100 kpc scales while the optical and IR jet gets brighter.

These predictions can be tested with the ongoing observations of the Chandra X-ray Observatory. Although blazars are characterized by core-dominant morphology on kpc scales, there are still a handful of blazars showing VLA jet. These are blue blazars 0414+009, 548−2201+044, 2155−304 (Laurent-Muehleisen et al. 1993), 0829+089 and red blazars 3C 371 (Wrobel & Lind 1990), PKS 0521−365 (Keel 1986), 0954−658, 2007+777 (Kollgaard et al. 1992), 0752+258 (Antonucci & Ulvestad 1985). In all these sources we predict a detectable synchrotron X-ray jet on kpc scales. Apart from some powerful Fanaroff-Riley class II radio galaxies in which the jet may be highly relativistic on kpc scales ($\Gamma_{pc} \sim 10$) and oriented at a very large angle to the line of sight, we also predict a detectable synchrotron X-ray jet on kpc scales in radio galaxies and steep-spectrum radio quasars. As time
goes on, more and more radio-loud AGNs will be observed by the CXO. If a kpc scale X-ray jet is detected in each of these sources, the synchrotron origin of kpc scale X-ray jets will be verified.

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