WITNESSING THE GRADUAL SLOW-DOWN OF POWERFUL EXTRAGALACTIC JETS: THE X-RAY - RADIO CONNECTION

M. Georganopoulos
Joint Center for Astrophysics, Physics Department, University of Maryland, Baltimore County
1000 Hilltop Circle, Baltimore, MD 21250
GEORGANO@UMBC.EDU
D. Kazanas
NASA/Goddard Space Flight Center, Laboratory for High Energy Astrophysics
Greenbelt, MD 20771
KAZANAS@MILKYWAY.GSFC.NASA.GOV

Abstract

Radio jets emanating from the central engine of powerful active galaxies start with relativistic velocities, as indicated by the superluminal velocities observed in their inner (pc) part. However, it is still not clear if the jets remain relativistic further out, a key question for their dynamics. Recently, it was shown that the *Chandra*-detected X-ray emission from knots in large scale ($\sim$ hundreds of kpc) powerful jets is best understood as Compton scattering off the cosmic microwave background from jets that flow relativistically (Lorentz factor $\sim$ 10–20). A puzzling feature of this X-ray emission is that it peaks in the inner part of the jet, decreasing outward, a behavior markedly opposite to that of the radio emission. Here we show that, this naturally results form a gradual deceleration of the jet flow, and that the offsets between different wavelength maps can reveal the deceleration profile. This matches another recent finding, namely that the jet flow feeding the hot spots - bright regions where the jets terminate colliding with the intergalactic medium - is still relativistic with a Lorentz factor of $\sim$ a few.

1 Introduction

The detection of active galactic nuclei jets by *Chandra* spawned a revolution in our understanding of jet physics. Schwartz et al. (2000) were the first to note that the X-ray emission from the knots of the jet of PKS 0637−752, at a projected distance $\sim$ 100 kpc from the quasar core, is part of a spectral component separate from its synchrotron radio-optical emission and is too bright to be explained through synchrotron-self-Compton emission from electrons in equipartition with the jet magnetic field. Mounting observational evidence indicates that these properties are common to other quasars' jets (e.g., Sambruna et al 2001; Marshall et al. 2001; Siemiginowska et al. 2002; Sambruna et al. 2004; Jorstad & Marscher 2004). Tavecchio et al. (2000) and Celotti et al. (2001) proposed that the X-ray emission can be explained as external Compton (EC) scattering of cosmic microwave background (CMB) photons off relativistic electrons in the jet, provided that the jet flow is sufficiently relativistic ($\Gamma \sim$ 10) to boost the CMB energy density in the flow frame (by Γ^2) at the level needed to reproduce the observed X-ray flux. Synchrotron models have also been proposed that require large scale relativistic motion. Dermer & Atoyan (2002) attribute the excess X-ray emission to the hardening of the upper end of the electron distribution to Compton losses of electrons with $\gamma \sim 10^{8-9}$ on the CMB in the Klein-Nishina regime, and some authors (e.g., Schwartz et al. 2000) suggest an additional, independent component in the electron distribution, whose synchrotron emission provides the observed X-ray flux.

A puzzling feature of the *Chandra*–detected quasar jets is that their X-ray emission decreases faster along the jet than their radio emission, resulting to an outward increasing radio to X-ray ratio. In some sources (e.g., 3C273 in Sambruna et al. 2001 and Marshall et al. 2001; PKS 1136−135 and 1354+195 in Sambruna et al. 2004; PKS 1127−145 in Siemiginowska et al. 2002; 0827+243 in Jorstad & Marscher 2004) this behavior is so extreme that the radio emission peak is located clearly downstream of that of the X-rays. The synchrotron X-ray model of Dermer & Atoyan (2002) naturally produces shorter sizes in X-rays than in radio. However, it also produces larger optical than X-ray sizes, something that has not been observed. This is also a rather unanticipated behavior for the EC model, given that the EC nature of the X-rays and the synchrotron radio emission are attributed to roughly the same electrons of the jet's non-thermal electron distribution. More important, given that in the EC model the electrons have cooling lengths longer than the observed jet size, the X-ray emission should remain constant along the jet, contrary to the observed knot emission. Here we argue that the observed differences in the relative radio - X-ray images at the knots of jets can be attributed to to large scale deceleration of the jets.

As was recently discussed (Georganopoulos & Kazanas 2004), the decrease in the flow Lorentz factor Γ leads to a decrease of the CMB photon energy density in the flow frame, which in turn leads to a decrease in the corresponding EC flux. At the same time, the decrease in Γ is accompanied by compression of the flow's magnetic field that results in a synchrotron emissivity which is largest where Γ becomes smallest, i.e., downstream of the maximum X-ray emission

2 A gradually decelerating relativistic jet

We study here the emission from a decelerating relativistic flow. We parameterize the jet flow assuming that its radius r scales as $r(z) = r_0 f(z)$, where $f(z)$ is a function with $f(z_0) = 1$ and r_0 is the jet radius at a fiducial point z_0 along the jet. Similarly, we assume that the flow decelerates as $\Gamma(z) = \Gamma_0 g(z)$, where $g(z)$ is a function with $g(z_0) = 1$ and Γ_0 is the bulk Lorentz factor at z_0. The evolution of the electron energy distribution (EED) along the jet is determined by the combination of adiabatic changes (losses for expansion and gains for compression), radiative losses, and particle acceleration. If the radiative losses of the electrons responsible for the X-ray and radio emission are negligible (as may be the case for the ($\gamma \sim$ a few hundreds) EC X-ray emitting electrons, or if we assume that some localized (e.g., shocks; Kirk et al. 2000) or spatially distributed (e.g., turbulence; Manolakou, Anastasiadis & Vlahos 1999) particle acceleration mechanism offsets the radiative losses, then the evolution of the EED can be treated as adiabatic. In this case, assuming that $\Gamma \gg 1$, the elementary volume dV scales as $dV = dV_0 f^2 g$, allowing for expansion or compression, while the adiabatic electron energy change rate with z is obtained from $\gamma' = -\gamma\left(2f'/f + g'/g\right)/3$, where the prime denotes differentiation with respect to z. The solution of the above equation is $\gamma(z) = \gamma_0 f^{-2/3} g^{-1/3}$. Assuming particle conservation, $n(\gamma, z) dV d\gamma = n(\gamma_0, z_0) dV_0 d\gamma_0$, the comoving EED $n(\gamma, z)$ can be written as

$$n(\gamma, z) = k\gamma^{-s} f^{-2(s+2)/3} g^{-(s+2)/3}, \qquad (1)$$

where $n(\gamma, z_0) = k\gamma^{-s}$ is the EED at z_0.

Following Georganopoulos, Kirk & Mastichiadis (2001), the EED in the local rest frame is $n(\gamma, z)\Delta^{2+s}$, where $\Delta(z)$ is the familiar Doppler factor $\Delta(z) = 1/(\Gamma(z)(1 - \beta(z)\cos\theta))$ and θ is the observing angle. Using this, and taking into account the cosmological corrections, we calculate the EC flux per dz in the δ-function approximation (Coppi & Blandford 1990; an electron of Lorentz factor γ upscatters seed photons of energy ϵ_0 only to an energy $4\epsilon_0\gamma^2/3$). Assuming flux conservation, the magnetic field $B(z)$ can be written as $B(z) = B_0/fg$. Using this, we calculate the synchrotron flux per dz in the δ-function approximation (an electron of Lorentz factor γ produces synchrotron photons only at the critical synchrotron energy $B\gamma^2/B_{cr}$). For a given observing energy and observing angle, one can find the radiating part of the jet and perform the optically thin radiative transfer by integrating the expressions for the EC and synchrotron emissivities along each line of sight for a two dimensional array of lines of sight that covers the source as projected on the observer's plane of the sky.

The results of such calculations are shown in Fig. 1, where it can be seen that the optical emission is confined at the base of the flow, due to the strong radiative losses of the high energy electrons, practically marking the site of strong particle acceleration. The morphology of the radio emission is angle dependent: at $\theta = 6°$ it covers the entire extend of the jet, while at $\theta = 12°$ the emission of its inner part is is dimmed because most of the radiation is beamed outside our line of sight. The X-ray emission at both angles peaks close to the base of the flow, due to the decrease of the comoving CMB photon energy density away from the flow base. Regarding the relative radio-X-ray morphology, while at $\theta = 12°$ the offset between the two images is very

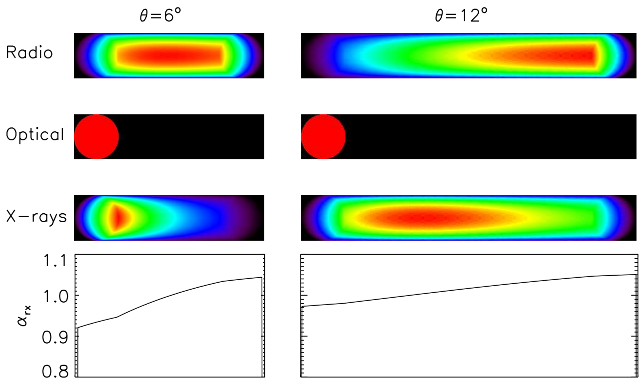

Figure 1: The radio (top), optical(middle), X-ray (bottom) maps and the radio to X-ray spectral index α_{rx} (below the X-ray map) for a decelerating flow observed under $\theta = 6°$ (left) and $\theta = 12°$ (right). The cylindrical flow, assumed to be at $Z = 0.3$, decelerates from $\Gamma_0 = 6$ to $\Gamma = 2$ with $\epsilon = 1$ and $B_0 = 3 \times 10^{-6}$ as it propagates a distance of 200 kpc. The EED is a power-law of index $s = 2$ and $\gamma_{max} = 10^6$ at the base of the flow. This calculation includes radiative losses. Each map is normalized with red indicating the maximum luminosity per unit area. The projected jet lengths are $\approx$ 21 kpc for $\theta = 6°$ and $\approx$ 42 kpc for $\theta = 12°$. Taken from Georganopoulos & Kazanas (2004).

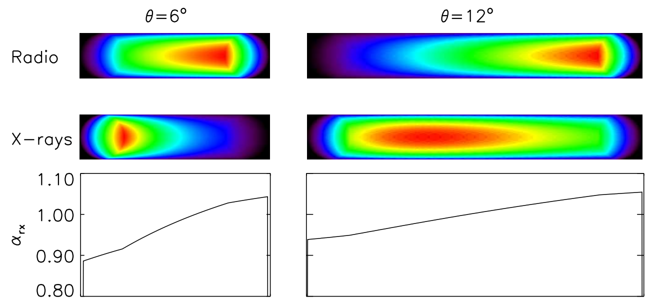

Figure 2: Radio (top), X-ray (middle), and the radio to X-ray spectral index α_{rx} (bottom) for a decelerating flow observed under 6° (left) and 12° angles, under the assumption that distributed re-acceleration offsets the radiative losses. The jet, assumed to be at redshift $z = 0.3$, decelerates from $\Gamma = 6$ to $\Gamma = 2$ as it propagates a distance of 200 kpc. Each map is normalized, with red indicating the maximum luminosity per unit area. Taken from Georganopoulos & Kazanas (2004).

large, at $\theta = 6°$ the two images overlap, although the radio image clearly extends further downstream. Also, as the radio-X-ray spectral index plots show, in both cases α_{rx} increases downstream in agreement with observations.

We compare now this picture with the one we would get from the same system if radiative losses were balanced by distributed re-acceleration. (Fig. 2). The X-ray images remain practically the same, because the radiative losses for the EC X-ray emitting electrons in this $Z = 0.3$, $\Gamma_0 = 6$ jet are negligible. The radio image however changes significantly, particularly so for the $\theta = 6°$ orientation. Now that the radio emitting electrons retain their energy the outer part of the jet is much brighter than the inner part, resulting to a clear separation between the radio and X-ray images.

3 Discussion

We proposed that the increase of the radio-to-X-ray flux ratio along the length of the jets of powerful quasars, as well as the occasional offset of the jet images in these wavelengths, are naturally accounted for in terms of relativistic flows that decelerate over the entire length of the jet. Despite this deceleration, the jets remain relativistic ($\Gamma \sim$ a few) to their terminal hot spots (Georganopoulos & Kazanas 2003), within which they eventually attain sub-relativistic speeds. Our proposal provides, for the first time, a means for deducing the jet kinematics through simple models of their multi-wavelength images; these can then be checked for consistency when coupled to the detailed hot spot emission, which as shown in earlier work (Georganopoulos & Kazanas 2003), depends on the value of Γ at this location.

The scenario we propose here finds further support from modeling jets with several sequential individual knots: Sambruna et al. (2001) and Jorstad & Marscher (2004) noted the need for a gradual decrease of the Doppler factor and/or an increase of the magnetic field in order to reproduce the emission from the knots along the jets of 3C273 and 0827+243 with simple one zone models. These knot to knot variations can be naturally incorporated within the context of a decelerating collimated flow, as we propose.

Acknowledgments

G. M. thanks the organizers of the meeting for waiving his registration fees.

References

Celotti, A., Ghisellini, G., Chiaberge M. 2001, MNRAS, 321, L1

Coppi, P. S., Blandford, R. D. 1990 MNRAS, 245, 453

Dermer, C. D., Atoyan, A. M. 2002, ApJ, 568, L81

Jorstad, S. G., Marscher, A. P. 2003, ApJ, submitted,

also in astro-ph/0405424
Georganopoulos, M., Kirk, J. G., Mastichiadis, A. 2001, ApJ, 561, 111
Georganopoulos, M., Kazanas, D. 2004, ApJ, 604, L81
Georganopoulos, M., Kazanas, D. 2003, ApJ, 589, L5
Kirk, J. G., Guthmann, A. W., Gallant, Y. A., Achterberg, A. 2000, ApJ, 542, 235
Manolakou, K., Anastasiadis, A., Vlahos, L. 1999, A&A, 345, 653
Marshall, H. L., et al. 2001, ApJ, 549, L167
Sambruna, R. M., Urry, M. C., Tavecchio, F., Maraschi, L., Scarpa, R., Chartas, G., Muxlow, T. 2001, ApJ, 549, L161
Sambruna, R. M., Gambill, J. K., Maraschi, L., Tavecchio, F., Cerutti, R., Cheung, C. C., Urry, M. C., Chartas, G. 2004, ApJ, 608, 698
Schwartz, D. E. et al. 2000, ApJ, 540, L69
Siemiginowska, A., Bechtold, J., Aldcroft, T. L., Elvis, M., Harris, D. E., Dobrzycki, A. 2002, ApJ, 570, 543
Siemiginowska, A., Smith R. K., Aldcroft T. L., Schwartz, D. A., Paerels, F., Petric, A. O. 2003, ApJ, 598, L15
Tavecchio, F., Maraschi, L., Sambruna, R., Urry, C. M. 2000, ApJ, 544, L23