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A Probe of the Matter Content of Quasar Jets

M. Georganopoulos[1,2], D. Kazanas[2], E. S. Perlman[2] and F. W. Stecker[1]

[1] Department of Physics, Joint Center for Astrophysics, University of Maryland-Baltimore County, 1000 Hilltop Circle, Baltimore, MD 21250, USA. e-mail: markos@milkyway.gsfc.nasa.gov

[2] Laboratory for High Energy Astrophysics, NASA Goddard Space Flight Center, Code 661, Greenbelt, MD 20771, USA

Abstract. We propose a method for estimating the matter content of quasar jets which exhibit *Chandra* - detected knots in their kpc scale jets. The method relies on measuring the component of the Cosmic Microwave Background (CMB) radiation that is bulk-Comptonized (BC) by the cold electrons in the relativistically flowing jet. We apply our method to PKS 0637 – 752, a superluminal quasar with an one – sided *Chandra* – detected large scale jet. What makes this source particularly suited for such a procedure is the absence of significant non-thermal jet emission in the *bridge*, the region between the core and the first bright knot, guaranteeing that most of the electrons in the bridge are cold, and leaving the BC scattered CMB radiation as the only significant source of photons in this region. At $\lambda = 3.6 - 8.0\ \mu m$, the most likely band for the BC scattered emission to appear, the angular resolution of *Spitzer* ($\sim 1'' - 3''$) is considerably smaller than the bridge of PKS 0637 – 752 ($\sim 8''$), making it possible to both measure and resolve this emission.

Key words. galaxies: active — quasars: general quasars: individual: PKS 0637 – 752 — radiation mechanisms: nonthermal — X-rays: galaxies

1. Introduction

The composition of extragalactic jets continues to remain elusive. A number of attempts (e.g. Reynolds et al. 1996, Wardle et al. 1998) have been made over the years toward measuring, or at the least constraining, the matter content of jets, and in particular the fraction of kinetic energy stored in protons and low energy or cold leptons, whose low radiative efficiencies fail to provide direct evidence of their presence.

A direct estimate of the cold lepton content of blazar jets was proposed by Sikora & Madejski (2000): The observed non-thermal blazar emission is thought to be produced at distances $\sim 10^{17} - 10^{18}$ cm from the central engine; the jet leptons providing the blazar emission at these distances need to be transported practically cold by a relativistic flow of bulk Lorentz factor $\Gamma \sim 10$ from the black hole vicinity to the blazar emission site; as these cold jet leptons propagate through the blazar broad line region (BLR) they would Compton – scatter the BLR optical-UV photons to energies ~ 1 keV, to produce a black – body type hump in their X-ray spectra. The fact that such a feature is not observed in the inverse-Compton dominated X-ray spectrum of blazars, led the above authors to conclude that the jet power is carried mainly by protons, although cold leptons dominate the number of particles in the jet.

While this idea is well founded and appealing, concrete answers are hindered by unknowns such as the distance at which the jet is formed, its sub-pc scale opening angle and the actual photon energy density of the BLR, as well as by the presence of a strong X-ray non-thermal continuum that apparently could "hide" the proposed bulk-Comptonized component.

2. Using the CMB as a seed photon source

Arguments based on the BC emission can be applied to any astrophysical site involving relativistic flows. One can then obtain more concrete conclusions provided that the flow geometry and the target photon density are better determined. Such a site is presented by the large scale jets of *Chandra* – detected superluminal quasars such as PKS 0637–752 (Schwartz et al. 2000; Chartas et al. 2001). The jet of PKS 0637–752, which is resolved and is found to be well collimated, propagates through a well understood photon field: the CMB. The source exhibits radio, optical, and X-ray emission from the quasar core and then from well separated knots along the jet at angular distances $\sim 8''$. The fact that the bridge, the region between the core and the first knot WK7.8, radiates weakly in radio, optical, and X-ray energies is very important because: (*i*) it shows that most of the leptons propagating in the bridge are cold and (*ii*) it provides a region free from unwanted contamination by unrelated broad band non-thermal radiation.

The luminosity L_{BC} of the BC emission depends on the power L_e carried by cold leptons in the bridge, the length l of the bridge, the bulk Lorentz factor Γ of the flow, and the angle θ formed between the jet axis and the line of sight. It can be shown (Georganopoulos et al. 2004) that

$$L_{BC} \approx 1.4\ 10^{-4}\, l_{100Kpc}\Gamma_{10}^{3}(1+z)^4 L_e, \qquad (1)$$

where z is the redshift of the source and we have assumed the typical for superluminal sources $\theta = 1/\Gamma$. The BC component peaks in the IR regime

$$\nu_{BC} \approx 4\ 10^{13}\ \Gamma_{10}^{2}\ \text{Hz}, \qquad (2)$$

regardless of z. The BC emission, therefore, requires an estimate of the jet power and kinematics. These can be provided by the spectrum and luminosity of the *Chandra* – detected knots, once the knot X-ray emission mechanism has been established.

2.1. The X-ray emission mechanism

Schwartz et al. (2000) noted that the X-ray emission from knots at a projected distance of ~ 100 kpc from the core of PKS 0637 – 752 is part of a spectral component separate from the synchrotron radio-optical emission and it is too bright to be explained through synchrotron self Compton SSC emission from electrons in energy equipartition with the jet magnetic field. Tavecchio et al. (2000) and Celotti et al. (2001) argued that the X-ray emission is due to external Compton (EC) scattering of 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) to the level needed to reproduce the observed X-ray flux. This was the first suggestion that powerful jets retain significantly relativistic velocities at large distances from the core, a very important feature because it boosts the level of the anticipated BC emission by $\sim \Gamma^2$. We adopt here this interpretation of the X-ray emission; the reader can find a discussion of the alternatives in Georganopoulos et al. (2004).

2.2. Minimum power conditions

A set of constraints for the jet power and beaming based on multiwavelength observations of knots has been presented by Dermer and Atoyan (2004, hereafter DA). These authors model the knots as homogeneous sources moving with a Lorentz factor Γ at an angle θ to the line of sight. The knot matter content is described through the ratio of power carried by protons to power carried by a power law lepton distribution. Assuming that the X-rays are due to EC scattering off the CMB and that $\delta = \Gamma$, DA calculate (their Eq. (12)) the Doppler factor δ_{min} that minimizes the power needed in

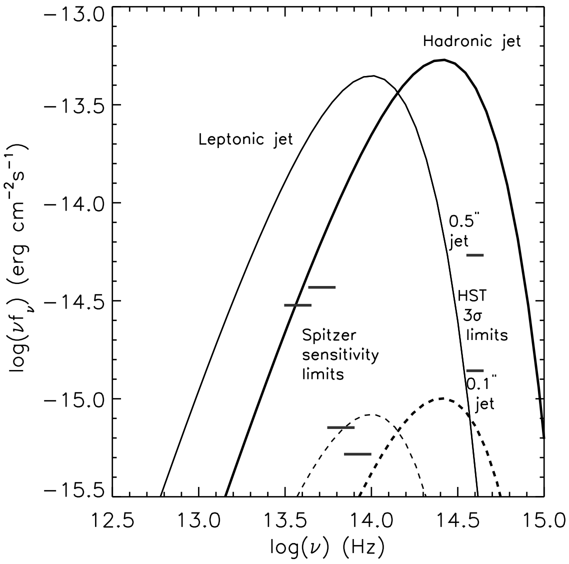

Fig. 1. The BC emission for an $e^{\pm}$ $(e-p)$ jet composition of PKS 0637-752 is plotted with a solid thin (thick) line for case A, in which the lepton power L_{lept} required in the knot is provided by the cold leptons in the beam. The dashed lines correspond to case B, in which the jet provides simply the number of leptons needed in the knot, with the thin (thick) line representing an $e^{\pm}$ $(e-p)$ jet composition. The *Spitzer* sensitivity limits and existing 3σ *HST* limits from Schwartz et al. (2000) assuming a $0.1''$ or a $0.5''$ jet radius are also shown.

the knot to produce the X-ray flux. Because the minimized quantity is the total knot power and *not* the power in relativistic electrons and magnetic field only, δ_{min} *depends on the matter content of the jet, and it is higher for* $e-p$ *jets* (Georganopoulos et al. 2004).

2.3. The BC emission of PKS 0637-752

Using the formalism of DA we derive minimum power Doppler factors $\delta_{min} = 17.4$ for a $e^{\pm}$ composition and $\delta_{min} = 27.8$ for an $e-p$ composition of knot WK7.8. These correspond to a jet minimum power $L_{min} = 9.7 \times 10^{45}$ erg s^{-1} for a $e^{\pm}$ jet and $L_{min} = 6.3 \times 10^{46}$ erg s^{-1} for an $e-p$ jet. The corresponding lepton power is $L_{lept} = 3.7 \times 10^{45}$ erg s^{-1} for a $e^{\pm}$ jet and $L_{lept} = 6.8 \times 10^{44}$ erg s^{-1} for an $e-p$ jet; these numbers are only weakly affected by our choice of the low energy cutoff γ_{min} of the electron power law as long as $\gamma_{min} > 10$, a condition imposed by the requirement that EC does not overproduce the observed optical flux. Assuming $\theta = 1/\Gamma$, at $z = 0.651$ $1''$ corresponds to 6.9 Kpc and the actual bridge length is $l \approx 930$ Kpc for a $e^{\pm}$ jet and $l \approx 1.5$ Mpc for an $e-p$ jet. We calculate the BC flux for an $e-p$ and an $e^{\pm}$ composition for two cases.

Case A: The lepton power L_{lept} required in the knot is provided by the cold leptons in the beam ($L_e = L_{lept}$). This requires that only a minority of the leptons get accelerated in the knot, and it is an optimistic estimate of the anticipated BC emission.

Case B: The most conservative case for the anticipated BC emission, according to which the jet provides simply the number of leptons needed in the knot, and the leptons are accelerated in the knot using energy exclusively from other agents such as the magnetic field and/or the jet hadrons.

As can be seen in Figure 1, in case A the emission for a $e^{\pm}$ jet peaks at mid IR energies, while that for an $e-p$ jet peaks at near IR - optical energies. For both compositions the anticipated mid IR flux is above the *Spitzer* sensitivity limits; the $e-p$ case however violates the *HST* 3σ detection limits for both a $0.5''$ and $0.1''$ thin jet. In case B the BC emission is still above the *Spitzer* sensitivity limit for the two shorter wavelength bands. However, the existing *HST* optical limits cannot be used to argue against an $e-p$ jet in this case. At $\lambda = 3.6 - 8.0\ \mu m$, the most likely band for the BC scattered emission to appear, the *Spitzer* angular resolution ($\sim 1'' - 3''$) is considerably smaller than the $\sim 8''$ bridge, and we anticipate that *Spitzer* will resolve the BC emission along the bridge.

3. Discussion

Existing *HST* limits for PKS 0637-752 already disfavor case A $e-p$ models. Additional constraints for pure $e-p$ jets come from the large Lorentz factors required. Although values of $\delta_{min} \sim 30$ are compatible with the superluminal motions observed in some blazars (e.g. Jorstad et al. 2002), the number of such highly relativistic sources should not overproduce the parent (misaligned) population (e.g. Lister 2003). Additionally, the large Doppler factors required for pure $e-p$ jets, suggest that the actual jets are over 1 Mpc long, a value reached by only the largest radio galaxies. An assumption made in our calculations is that the Doppler factor of the jet flow in the bridge between the core and the knot is the same as the Doppler factor of the knot. This can happen if the flow does not decelerate substantially at the knot. This seems to be the case in PKS 0637-752, where VLBI observations of superluminal velocities with $v_{app} = 17.8 \pm 1\, c$ in the core of the source (Lovell et al. 2000) set limits of $\Gamma > 17.8$, $\theta < 6^\circ.4$, in agreement with the Doppler factor $\delta = 17.4$ derived from minimizing the jet power in an $e^{\pm}$ jet. As was first discussed by Schwartz (2002) the X-ray emission due to EC off the CMB will remain visible at the same flux level independently of redshift. This is also the case for the BC emission. This suggests an exciting possibility for jets that have a very low radiative efficiency past the core: their IR-optical BC emission will be detectable independent of redshift, and it will be the only observable signature of these otherwise invisible jets.

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