JETS FROM SUBPARSEC TO KILOPARSEC SCALES: A PHYSICAL CONNECTION

F. Tavecchio and L. Maraschi
Osservatorio Astronomico di Brera, via Brera 28, 20121 Milan, Italy

R. M. Sambruna
Department of Physics and Astronomy and School of Computational Sciences, George Mason University, Fairfax, VA 22030

C. M. Urry
Department of Astronomy, Yale University, New Haven, CT 06520

C. C. Cheung
Department of Physics, Brandeis University, Waltham, MA 02454

J. K. Gambill
School of Computational Sciences, George Mason University, 4400 University Drive, Fairfax, VA 22030

AND

R. Scarpa
European Southern Observatory, Avenida Alonso de Cordova 3107, Vitacura, Casilla 19001, Santiago 19, Chile

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ABSTRACT

The Chandra discovery of bright X-ray emission from kiloparsec-scale jets allows insight into the physical parameters of the jet flow at large scales. At the opposite extreme, extensive studies of the inner relativistic jets in blazars with multiwavelength observations yield comparable information on subparsec scales. In the framework of simple radiation models for the emission regions we compare the physical parameters of jets on these two very different scales in the only two well-studied blazars for which large-scale emission has been resolved by Chandra. Notably, we find that the relativistic Doppler factors and powers derived independently at the two scales are consistent, suggesting that the jet does not suffer severe deceleration or dissipation. Moreover, the internal equipartition pressures in the inner jet and in the external X-ray–bright knots scale inversely with the jet cross section as expected in the simple picture of a freely expanding jet in equipartition.

Subject headings: galaxies: jets — quasars: individual (PKS 1510–089, 1641+399) — radiation mechanisms: nonthermal — X-rays: galaxies

1. INTRODUCTION

The study of extragalactic jets has been renewed recently by the Chandra discovery of numerous jets bright in X-rays on kiloparsec and larger scales (Chartas et al. 2000; Worrall et al. 2001; Siemiginowska et al. 2002; Sambruna et al. 2002). In powerful sources, the X-rays from the extended jet constitute a spectral component separate from the radio-to-optical synchrotron emission. The latter can be interpreted as inverse Compton (IC) scattered cosmic microwave background (CMB) photons produced by the same population of relativistic electrons that emit the radio to optical synchrotron radiation (Tavecchio et al. 2000a; Celotti et al. 2001; but see Dermer & Atoyan 2002 and Stawarz & Ostrowski 2002 for alternatives). The model requires that these X-ray–bright jets are still relativistic, with bulk Lorentz factors of 5–10, at distances of ≥100 kpc. Fitting the two spectral components with this kind of model and the additional hypothesis of equipartition constrains the main physical quantities of the jet, including the Doppler factor, the magnetic field, the density, the energy distribution, and, notably, the minimum Lorentz factor of the emitting relativistic electrons, $\gamma_{\text{min}}$.

On much smaller scales, the innermost regions of jets in the brightest blazars have been extensively studied through multi-frequency observations (e.g., Maraschi & Tavecchio 2001). The double-humped radio to $\gamma$-ray spectral energy distributions (SEDs) of these sources can be modeled as synchrotron plus IC emission, yielding robust estimates of the basic physical quantities of the emission region close to the central black hole (e.g., Ghisellini et al. 1998; Kubo et al. 1998; Sikora & Madejski 2000; Sikora 2001). From this type of model the jet power close to the central black hole was estimated (Ghisellini & Celotti 2002; Maraschi & Tavecchio 2003, hereafter MT03). Comparing the physical state of the plasma in the same jet on subparsec and kiloparsec scales can offer an important new window on the propagation of jets as they expand through the broad-line region on the host galaxy and into the intergalactic medium (e.g., Begelman et al. 1984; Bicknell 1994). As a first step in this direction, we discuss here such a comparison for the only two blazars, PKS 1510–089 ($z = 0.361$) and 1641+399 ($z = 0.591$), for which data are available for both the inner and outer regions of the jet. The blazar cores are well studied observationally and were modeled by Tavecchio et al. (2000b, 2002); X-ray and optical emission from the large-scale jets of both blazars was measured in the recent survey of bright radio jets with Chandra and the Hubble Space Telescope (HST; Sambruna et al. 2002; Sambruna et al. 2004, hereafter S04). The two sources were included in the survey because they...
satisfied the selection criteria of having radio jets of appropriate brightness and size, irrespective of their previously known blazar properties. The plan of this paper is as follows: in §2 we summarize the modeling on both scales, in §3 we compare the physical parameters derived independently on the two scales, and in §4 we discuss our results. Throughout this paper we assume $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $q_0 = 0.5$.

2. MODELING JETS ON SMALL AND LARGE SCALES

2.1. The Inner Jet Model

The SEDs of the unresolved blazar cores were modeled as synchrotron plus IC emission, allowing for both synchrotron and external photons as seeds for the IC process. The energy spectrum of the relativistic electrons is assumed to be a broken power law with indices of $n_1 < 3$ and $n_2 > 3$. A complete discussion of this model is given by MT03 and references therein. In the homogeneous case the model uniquely determines the main physical quantities (magnetic field, electron density and energy, size, and Doppler factor) if the spectral shapes around the peaks of the two spectral components are observationally determined and an upper limit to the size of the emitting region is derived from time variability. The absence of a spectral break between soft and hard X-rays indicates $\gamma_{\text{min}} \sim 1$ (e.g., Tavecchio et al. 2000b). The model parameters derived in MT03 for the two sources are reported in Table 1. Although not assumed in the modeling, we find a posteriori that the emitting regions are close to equipartition.

While $\delta$ is a direct outcome of the radiative model, the bulk Lorentz factor of the flow, $\Gamma$, depends on the viewing angle, $\theta$. For the most probable viewing angle, $\theta = 1/\delta$, this is the maximum angle allowed by the given Doppler factor, $\Gamma = \delta$. In addition, we report in Table 1 that the value of $\Gamma$ corresponding to a smaller (less probable) viewing angle, $\theta = 1/2\delta$.

2.2. The Outer Jet Model

The large-scale X-ray/optical radio data for the two sources are presented and discussed in S04. Both jets exhibit a knotty X-ray morphology. For our analysis we used radio, optical, and X-ray fluxes for the first knots that are well separated from the nuclei in the Chandra images: knot B for PKS 1510–089 and knot A for 1641+399, at projected distances of $2^{\prime\prime}9$ and $2^{\prime\prime}7$ (11.8 and 13.5 kpc) from the cores, respectively. The X-ray knots are unresolved by Chandra; their angular radii were fixed at $1^{\prime\prime}$, which represents an upper limit to the actual dimension. Radio and optical fluxes were extracted over the same area (see S04). The associated radio knots, however, appear to be resolved in high-resolution maps at the $0^{\prime\prime}.5$ level (C. C. Cheung et al., in preparation); thus, the adopted radius should not be far from the real one. The present analysis refers to a homogeneous approximation. The possible existence of strong inhomogeneities, advanced in Tavecchio et al. (2003) but questioned in Stawarz et al. (2004), would affect the results.

The SEDs of the knots are shown in Figure 1. The data, although sparse in wavelength coverage, clearly indicate the presence of two emission components, as in the prototypical case of IC/CMB jets, PKS 0637–052 (Tavecchio et al. 2000a). As in that case, we modeled each SED with a synchrotron plus IC/CMB model, assuming for the emitting electrons a single power-law energy distribution $N(\gamma) = K \gamma^{-\gamma}$ between $\gamma_{\text{min}}$ and $\gamma_{\text{max}}$. This assumption differs from that adopted for the blazar cores (broken power law). Because of the very limited spectral coverage, the higher energy part of a broken power law would be underestimated here. The comparison of the large-scale and small-scale jets is still meaningful, since the single power law adopted here closely corresponds to the lower energy branch of the broken power law.

The slope of the radio spectrum of the knots is $\alpha_r = 0.7 \pm 0.8$, which implies $n = 2.4 \pm 2.6$. In both cases the X-ray slope ($0.81 \pm 0.62$, $0.66 \pm 0.86$) is consistent with the radio slope within the large errors (S04). If, additionally, equipartition between the magnetic and electron energy densities is assumed, the observed fluxes provide a unique value for the physical parameters, $K$ and $B$, and the Doppler factor, $\delta$, for a fixed size of the emitting region (Tavecchio et al. 2000a).

In the absence of information on the spectral shape in the optical band, the optical flux (PKS 1510–089 has an upper limit available) can be attributed either to the synchrotron or to the IC component. Here we have chosen the first alternative for 1641+399 and the second for PKS 1510–089. In any case, the weakness of the optical flux constrains the minimum Lorentz factor of the emitting electrons. Given the steepness of the electron energy distribution, the latter quantity determines the total electron energy density. Generally not measurable with classical radio observations (because of self-absorption), $\gamma_{\text{min}}$ is important for the derivation of the kinetic power of the jet. In the present two cases, $\gamma_{\text{min}}$ must be less than $\sim 10$ in order to reproduce the observed X-ray flux and slope but larger than a few in order not to overpredict the optical flux. This is similar to the cases of the four jets reported in Sambruna et al. (2002) and other jets in the survey of S04, for which $\gamma_{\text{min}}$ falls in the range 5–10.
The spectral models for the multifrequency emission from the two knots computed with the equipartition assumption are shown in Figure 1. The corresponding model parameters are reported in Table 1.

3. THE CONNECTION BETWEEN SMALL AND LARGE SCALES

In the following section we discuss the inner and outer jet connection with regard to the bulk velocity, the transported (kinetic) power, and the internal energy density/pressure.

3.1. Bulk Motion

A comparison of the parameters independently derived for the inner and outer jets (see Table 1) shows that the values of the beaming factors ($\delta$) for the two widely separated regions are similar. As mentioned above, a determination of the bulk Lorentz factor $\Gamma$ requires an assumption about the viewing angle. Starting from the largest possible angle for a given value of $\delta$, $\theta_{\text{max}} \approx 1/\delta$, for which $\Gamma = \delta$, the minimum value of $\Gamma$ is $\delta/2$ for $\theta = 0$. Since $\theta = 0$ is unlikely and unpractical—for instance, for deprojecting—we report in Table 1 the range in $\Gamma$ corresponding to viewing angles between $\theta_{\text{max}}$ and $\theta_{\text{max}}/2$. Note that the value of $\Gamma$ for $\theta_{\text{max}}/2$ is very close to $\delta/2$, corresponding to $\theta = 0$. We discard the possibility of much larger values of $\Gamma$ that are also in principle allowed for angles smaller than $\theta_{\text{max}}$ but appear unreasonable in view of the higher implied kinetic powers (MT03).

That powerful jets remain relativistic at large scales was anticipated long ago on the basis of theoretical expectations (Blandford & Rees 1974) and observational evidence of jet one-sidedness and depolarization asymmetry (Laing 1988; Garrington & Conway 1991). From our analysis (summarized in Table 1) we derive the values of the Doppler beaming factors at subparsec and 100 kpc scales and find no significant difference. Although some deceleration cannot be excluded, the results do not suggest or require it. Recent numerical simulations for highly relativistic jets are in fact consistent with these conclusions (Scheck et al. 2002).

3.2. Kinetic Power

An important global quantity that can connect the jets at different scales is the transported power. Assuming that the central engine is stationary when averaged over an appropriately long timescale ($10^5-10^6$ yr), the transported power should remain constant or decrease along the jet. For instance, one could refer to the internal shock model applicable to both gamma-ray bursts and relativistic jets in radio sources (Spada et al. 2001). The instantaneous power emitted by the central engine fluctuates, but along the propagation path the fluctuations merge and are progressively smoothed into an almost continuous flow.

For both the inner, unresolved region and the still-relativistic resolved jet, the transported power can be computed using the expression

$$P_j = \pi R^2 \Gamma^2 (U'_B + U'_e + U'_p)c$$

(Celotti & Fabian 1993), where $R$ is the radius of a cross section of the jet and $U'_e$, $U'_p$, and $U'_B$ are the rest-frame energy densities of relativistic electrons, protons, and the magnetic field, respectively. The electron energy density $U'_e$ can be expressed as $U'_e = n_e(\gamma) m_e c^2$, where $n_e$ is the total electron density and $\langle \gamma \rangle$ is the average Lorentz factor.

In general there is little direct information about $U'_p$, the matter content of jets. For powerful blazars an indirect argument leads us to assume a significant proton content. In fact, the intrinsic radiative luminosity from the core exceeds the power computed assuming an $e^-e^+$ plasma, which would lead to substantial deceleration of the jet close to the nucleus.

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2 This is the approximated version (valid for $\gamma_{\text{min}} \gg 1$) of the general $U'_e = m_e c^2 \int_{\gamma_{\text{min}}}^{\gamma_{\text{max}}} N(\gamma)(\gamma - 1)d\gamma$. 
In Figure 2 we compare the powers resulting from different assumptions. The solid line represents the power computed by applying the IC/CMB model for different values of $\Gamma$ without assuming equipartition (each point along this curve implies a different model that reproduces the observed fluxes). The power increases rapidly at low $\Gamma$ because of the larger rest-frame energy densities required by the weaker beaming. For both sources it has a broad minimum in the range of $\Gamma$ allowed in Table 1.

In Figure 2 the equipartition condition (determined only by the synchrotron radio flux) is shown by the short-dashed line (calculated assuming a fixed value of $\gamma_{\text{min}} = 10$). The intersection of the solid and short-dashed lines marks the equipartition solution, which corresponds (approximately) to the parameters of Table 1 and to the spectral models shown in Figure 1.

For comparison, the dotted line in Figure 2 shows the power required if X-rays were emitted via the synchrotron self-Compton process (for which the only seed photons are the synchrotron ones). For that model, as noted for PKS 0637−052 by Schwartz et al. (2000), the required power would be extremely large and equipartition far from satisfied.

It is noteworthy that the kinetic power of the outer jet, for an IC/CMB model near equipartition, is close to the power estimated independently for the inner jet from the blazar SED (shown in Fig. 2 by the long-dashed line; see also Table 1).

### 3.3. Energy Densities and Pressure

The internal jet pressure (given by $p = U_p/3 + U_e/3$) in the inner, unresolved jet region can be compared with that estimated in the outer knots. Remarkably, the ratio of the inner and outer pressures ($20-6 \times 10^{10}$) scales approximately with an inverse square law with respect to the rest-frame size of the emission region $R (5-4 \times 10^5)$.

Assuming the inner region lies at $r \sim 0.1$ pc $\sim 3 \times 10^{17}$ cm (Ghisellini & Madau 1996), and computing the distance of the external knots from the angular distance, deprojected with the two values of the viewing angle, we find that the scale factors for $R$ and $r$ are similar within 1 order of magnitude. Thus we can formulate the hypothesis that the jet is almost conical over 6 orders of magnitude in scale.

Moreover, the inner and outer models independently indicate near equipartition. Thus our results are consistent with the very simple picture of a free jet in equipartition as described by Blandford & Königl (1979), in which the magnetic field should decay with the cross-sectional area of the jet, $A$, as $B \propto A^{-1/2}$, and the pressure should decrease as $p \propto A^{-1}$.

The fact that the jet is free is consistent with (and supports) the results of the conservation of jet power. The interaction with the external medium should be weak, so that only a small fraction of the jet power is dissipated.
fraction of the power can be dissipated through shocks. As a result the jet does not decelerate substantially (at most, by a factor of 2 in $\Gamma$). An interesting point about the jet pressure at large scales is that its value is of the same order as the pressure of the gas inferred for the hot halos at comparable distances in FR I and FR II host galaxies, for which profiles have been measured (e.g., Hardcastle & Worrall 2000; Worrall & Birkinshaw 2000), and for the cluster gas around some intermediate-redshift radio-loud quasars (e.g., Hardcastle & Worrall 1999; Crawford & Fabian 2003). This condition could be associated with the end of the phase of free expansion, $p_{\text{ext}} \sim 10^{-11}$ to $10^{-12}$ ergs cm$^{-3}$.

4. CONCLUSIONS
We have presented a case study of two blazars for which high-quality radio, optical, and X-ray observations of both the small-scale and the large-scale jets are available. The physical parameters in the blazar core region and in the outer knots are reasonably well—and independently—determined.

A comparison of the physical quantities at the two scales indicates that:

1. The jet appears to maintain an almost constant relativistic velocity from subparsec scales to distances of hundreds of kiloparsecs. A deceleration of a factor of 2 is allowed but not indicated by the derived parameters.
2. The transported power inferred for the outer jet is remarkably similar to that estimated close to the nucleus.
3. The pressure at the two scales is consistent with a simple scaling relation with the jet cross section, $p \propto A^{-\frac{1}{2}}$, and the jet geometry between the two scales is approximately conical.

Admittedly the results are model-dependent, and the quantitative validity of the derived parameters holds within factors of a few, except for the beaming factor $\delta$, which is better determined because all quantities depend strongly on it. Nevertheless, it is noteworthy that all the results are consistent with the simple scenario of a freely expanding jet in equipartition.

While other possibilities, such as magnetic confinement (e.g., Begelman et al. 1984), cannot be excluded, the conditions for a free expansion are certainly satisfied if we compare the derived pressures in the jet with that of an external medium. The bright external knots could ultimately derive from processes associated with the end of the validity of the conditions of free expansion.

The analysis presented here offers new elements relevant for the understanding of the global behavior of jets. Clearly, more observations are needed. While angular resolution, important in investigating the issue of sizes and locations of knots in jets, is not likely to improve significantly in the near future, deeper observations and the study of a larger number of sources will certainly provide a wider context for investigating the issues addressed here.

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