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Are quasar jets dominated by Poynting flux?

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ABSTRACT

The formation of relativistic astrophysical jets is presumably mediated by magnetic fields threading accretion disks and central, rapidly rotating objects. As it is accelerated by magnetic stresses, the jet's kinetic energy flux grows at the expense of its Poynting flux. However, it is unclear how efficient is the conversion from magnetic to kinetic energy and whether there are any observational signatures of this process. We address this issue in the context of jets in quasars. Using data from all spatial scales, we demonstrate that in these objects the conversion from Poynting-flux-dominated to matter-dominated jets is very likely to take place closer to the black hole than the region where most of the Doppler boosted radiation observed in blazars is produced. We briefly discuss the possibility that blazar activity can be induced by global MHD instabilities, e.g., via the production of localized velocity gradients that lead to dissipative events such as shocks or magnetic reconnection, where acceleration of relativistic particles and production of non-thermal flares is taking place.

Subject headings: quasars: jets — radiation mechanisms: non-thermal — MHD

1. INTRODUCTION

The most promising scenario for launching astrophysical relativistic jets involves large-scale magnetic fields anchored in rapidly rotating compact objects. The idea of driving outflows by rotating magnetic fields, originally invented by Weber and Davis (1967) to explain the spindown of young stars, was successfully applied to pulsar winds (Michel 1969; Goldreich

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& Julian 1970) and became a dominant mechanism in theories of relativistic jets in active galactic nuclei (AGNs) (see, e.g., Phinney 1983; Camenzind 1986, 1987; Li, Chiueh, & Begelman 1992; Vlahakis & Königl 2004) and gamma-ray bursts (e.g., Thompson 1994; Spruit, Daigne, & Drenkhahn 2001; Vlahakis & Königl 2001). Powerful jets in quasars can be powered by innermost portions of an accretion disks and/or by rapidly rotating black holes. They can become relativistic if the total to rest-mass energy flux ratio $\mu \equiv L_j/\dot{M}c^2 \gg 1$, where $L_j = L_B + L_K$ is the total energy flux, L_B is the magnetic energy flux, $L_K = (\Gamma - 1)\dot{M}c^2$ is the kinetic energy flux, and $\dot{M}$ is the mass loading rate.

Theories of axisymmetric, steady-state ideal-MHD jets predict that the conversion process transforming electromagnetic energy into plasma kinetic energy works efficiently only up to the classical fast-magnetosonic surface, z_{fm}, located at a few light cylinder-radii (Sakurai 1985; Li et al. 1992a; Beskin, Kuznetsova, & Rafikov 1998). At this distance, the ratio of Poynting flux to kinetic energy flux, σ, drops to the value $\sim \mu^{2/3}$. This means that for $\mu \gg 1$ the flow still remains strongly Poynting flux-dominated at z_{fm}. Whether and how fast the conversion can proceed beyond this point is unclear, firstly because of theoretical and numerical difficulties in treating the strongly nonlinear differential equation which combines the evolution of the flow along the magnetic surfaces (Bernoulli equation) and the cross-field-force balance (Grad-Shafranov equation), and secondly because of the very uncertain boundary conditions at the base of the outflow and along the outermost magnetic surface (Begelman 1998; Heyvaerts & Norman 2003; Vlahakis & Königl 2003a, b).

Signatures of the presence of dynamically strong, ordered magnetic fields have been pursued observationally, by tracing magnetic field structure (using polarization information) and kinematics of kiloparsec- and parsec-scale jets and by studying morphology of extended radio sources. The results of these efforts are critically reviewed in §2. We demonstrate that there is no convincing evidence for dynamically important magnetic fields in quasar jets on scales larger than a few parsecs. In §3, we extend the above studies down to subparsec regions, by using multi-wavelength observations of blazars. In particular, the X- and γ-ray data allow us to estimate the leptonic and total energy flux, which in turn provides an upper limit for the magnetic dominance and a lower limit for the pair content. Finally, in §4, we investigate constraints imposed on the jet dynamics by the lack of signatures of the bulk Compton radiation in the blazar spectra. Implications of our results for the global jet dynamics and for jet launching scenarios are discussed in §5.

2. MAGNETIC FIELDS IN RADIO JETS

2.1. Kiloparsec-scale jets

Arguments used in favor of the dynamical dominance of magnetic fields over large spatial scales include the high linear polarization of kiloparsec-scale jets, and the need for *in situ* energy dissipation to provide the power for acceleration of fast-cooling ultra-relativistic electrons/positrons responsible for synchrotron radiation in the optical band, and in some objects also in the X-ray band (see, e.g., Lesch & Birk 1998; Birk & Lesch 2000). However, neither the energy dissipation nor the high polarization require large scale mean magnetic fields: energy can be dissipated in shocks and in boundary shear layers and high polarization can result from compression and stretching of initially tangled/turbulent magnetic fields (Laing 1980, 1981; Cawthorne et al. 1993). Furthermore, any large scale mean magnetic fields on parsec and larger scales are expected to be strongly dominated by the toroidal component, even if they started as purely poloidal. This arises from the fact that due to conservation of the magnetic flux, the poloidal component drops with distance $\propto 1/r^2$, while due to conservation of the magnetic *energy* flux, the toroidal component drops $\propto 1/r$, where r is the distance in a conical jet (Begelman, Blandford, & Rees 1984). This is in contrast to inferences based on polarimetry of large-scale jets in FRII radio galaxies and quasars, which indicate a parallel magnetic field orientation (Bridle et al. 1994). Such magnetic fields can be generated by a dynamo in the turbulent shear layers (Urpin 2002). The turbulence, driven by a shear, can be also responsible for acceleration of relativistic electrons producing nonthermal radiation in kiloparsec scale jets (Stawarz & Ostrowski 2002). Direct support for such a scenario is provided by measurements of intensity and polarization profiles across jets in a number of nearby FRII radiogalaxies (see Swain, Bridle, & Baum 1998, and references therein). There, the lack or deficit of radiation from the jet spine can result from the Doppler deboosting, because the flow in the jet spines can move faster than the flow in the boundary/shearing layers. Indeed, these spines are presumably the regions that produce X-ray radiation seen in some large-scale quasar jets oriented at small angles to the line of sight. Models of this radiation predict jet Lorentz factors significantly larger than those derived from the radio brightness asymmetries of jets and counter-jets (Tavecchio et al. 2004).

The hydrodynamical nature of large scale jets is also indicated by numerical simulations of their termination. As was demonstrated by Clarke, Norman, & Burns (1986) and Lind et al. (1989) in the non-relativistic case, and by Komissarov (1999) in the relativistic case, jets with strong toroidal magnetic components do not develop substantial back-flowing cocoons. Instead, the shocked jet plasma, being confined by magnetic stresses, forms a "nose cone"–shaped head. The cocoons observed in classical FR II radio sources do not appear to have such nose-cones. They are broad and their morphologies agree very well with those predicted theoretically (Scheuer 1974; Begelman & Cioffi 1989) and confirmed via numerical simulations for light, supersonic, unmagnetized jets. It should be noted, however, that all numerical simulations of strongly magnetized jets have been performed assuming ideal MHD flows, whereas the current closure condition requires a large fraction of magnetic fields to be resistively dissipated (Benford 1978; Lesch, Appl, & Camenzind 1989). Whether this can lead to formation of very compact hot spots observed in radio lobes remains very unclear, particularly because no strong terminal shocks are expected to be produced by jets with $\sigma > 1$.

2.2. Parsec-scale jets

As was pointed out by Blandford (1993), the toroidal component of magnetic fields in Poynting flux-dominated jets can be indicated by gradients of the Faraday rotation across parsec-scale jets. Such gradients have been found in several BL Lac objects (Gabuzda, Murray, & Cronin 2004) and in quasar 3C273 (Asada et al. 2002). However, the quality of these data, particularly regarding 3C273, is still very poor due to limited resolution of the transverse jet structure. And, as a strong counterexample, we refer to the only quasar for which there is reasonably good transverse resolution, B1611+343. No Faraday rotation gradient is seen in this object (Zavala & Taylor 2003). Furthermore, Faraday rotation can be produced in an external non-uniform medium, provided that such a medium is located in close proximity to the jet as required by ~ 1 year variations of the rotation measure in 3C 273 and 3C 279 (Zavala & Taylor 2001). The external origin of Faraday rotation is strongly indicated by the fact that in most objects the rotation follows the λ^2-rule, where λ is the wavelength of the electromagnetic radiation (Gabuzda et al. 2004; Zavala & Taylor 2004). That rule is followed even in objects with rotation exceeding 1 radian, which cannot be the case if produced co-spatially with the radiation (Burn 1966; Gardner & Whiteoak 1966). Furthermore, observations of optically thick radio cores at different wavelengths indicate that position of the polarization angle is the same at different synchrotron photospheres, which indicates that it doesn't depend on a distance from the center (Zavala & Taylor 2004). This can be reconciled with theoretically predicted strong dependence of the rotation measure on a distance in the laterally expanding jet ($RM \propto 1/r^2$ for conical jets), only if the Faraday depth of the parsec scale jets is negligible.

Arguments based on kinematics are also used in the literature to argue in favor of the dynamical domination of the magnetic fields in parsec-scale jets. The detection of any systematic acceleration of the flow would provide a strong argument for the conversion of the Poynting energy into kinetic energy. Homan et al. (2001) claim that such acceleration is indicated by VLBI observations of sources having multiple components with proper motion. They point out that in such objects the innermost components are significantly slower than the others. However, within the same sample of sources, the authors are not able to identify any clear case of individual components that are speeding up. Moreover, the above claims about slower-moving innermost components seem to contradict the finding that there is a systematic decrease in apparent velocity with increasing wavelength (Kellermann et al. 2004). The simplest interpretation of this is that the observations at longer wavelengths cover more extended portions of the jet structure, and therefore that the radio components decelerate, rather than accelerate. Alternatively, it is possible that a jet possesses a transverse structure and that the central portions of the jet, which presumably move faster than the boundary layers, contribute more radiation at the shorter wavelengths. Noting also that some jets appear curved, one shouldn't be surprised to see sometimes both increasing and decreasing projected speeds (see, e.g., Jorstad et al. 2004). It should also be emphasized that if such sources are intrinsically expanding, their surface-brightness peaks do not represent the real component centers and the apparent offset can change with time. In this case, one learns little about the intrinsic kinematics of the source from the motion of the surface-brightness-peak of the radio component. Furthermore, the features that appear as moving on the VLBI scale may represent moving patterns, rather then the real flow speeds. This is clearly documented, for example, by observations of a parsec-scale jet in Mrk501. There, the one-sidedness of the jet and the lack of superluminal motion of the VLBI features strongly suggest that the the knots represent stationary or very slowly moving patterns, presumably oblique shocks (Giroletti et al. 2004; Ghisellini, Tavecchio, & Chiaberge 2004). Finally, even if some apparent acceleration events are real, they are not necessarily related to the conversion of magnetic energy to kinetic energy. Acceleration events can be produced also in matter-dominated jets, e.g., at the expense of internal energy dissipated in shocks and partially returned to the flow, or due to the collision of the flow with an external cloud. Given the above, we regard as somewhat premature the claims that two "accelerating" individual features, in 3C 279 (Piner et al. 2003) and 3C 345 (Unwin et al. 1997; Lobanov & Zensus 1999), respectively, prove the magnetic domination of parsec-scale jets in these objects as asserted e.g. by (Vlahakis & Königl 2004).

Another approach to studying the dynamics of a jet is based on comparing its surface brightness distribution with that of its counterjet. This method was applied by Sudou et al. (2002) to the parsec-scale two-sided jet in the radio galaxy NGC 6251. They found that the jet–to–counterjet intensity ratio increases with distance from the center and using these data derived the acceleration of the flow, with $v \simeq 0.13c$ at a distance $r \simeq 0.53$pc and $v \simeq 0.42c$ at $r \simeq 1$pc. However, the reality of the counterjet detection in NGC 6251 is questioned by

Jones & Wehrle (2002). In particular, they did not confirm the presence of the conterjet at 15 GHz, the frequency at which their observations had a similar angular resolution to those by Sudou et al. (2002).

Both methods, involving the jet/counterjet brightness ratio and the apparent speed of the radio-emitting features, have been used by Cotton et al. (1999) to derive the dynamics of a parsec-scale jet in radio galaxy NGC 315. They infer an acceleration from $0.77c$ at a distance 3.3 pc to $0.95c$ at a distance 9.5 pc. However, as the authors point out, the present data are insufficient to determine whether the observed emission is from the main body of a jet or from its slower outer layers.

3. STRUCTURE OF "BLAZAR JETS"

3.1. Polarization properties and dissipative events

Short variability timescales — of the order of 1 week in the optical band and similar or even shorter with larger amplitudes in the γ-ray band (von Montigny et al. 1995; Mukherjee et al. 1997) — show that most of the non-thermal radiation from blazars is produced in a region with a size $R \leq 10^{17}(t_{fl}/3\,\mathrm{days})(\Gamma/15)$ cm, too compact to be transparent in the radio band (Sikora et al. 1994). Such a compactness, combined with the transparency of blazars to high-energy γ-rays and the lack of γ-radiation from the radio lobe-dominated quasars, implies that most of the high-energy radiation from blazars originates in well-collimated and relativistic (sub)parsec-scale jets.

Polarimetry measurements of the variable optical, infrared and mm radiation suggest that at subparsec distances, magnetic fields are dominated by the transverse component (Impey, Lawrence, & Tapia 1991; Gabuzda & Sitko 1994; Cawthorne & Gabuzda 1996; Stevens, Robson, & Holland 1996; Nartallo et al. 1998). Such an orientation is consistent with a toroidal magnetic field geometry, but can also result from compression of a tangled magnetic field in transverse internal shocks. The internal shocks have been proposed to result from collisions between velocity inhomogeneities propagating down a matter-dominated jet (Sikora et al. 1994; Spada et al. 2001). The internal shock scenario seems to be supported by the very broad energy distributions of relativistic electrons/positrons. They cover 3-4 decades in energy and are injected with approximately equal amounts of energy per decade (Moderski et al. 2003). This contrasts strongly with the narrow energy distributions of accelerated electrons predicted by the magnetic reconnection models (Zenitani & Hoshino 2001; Larrabee, Lovelace, & Romanova 2003). However, it should be emphasized here that acceleration mechanisms for electrons/positrons still await quantitative theories, with regard to both reconnection and shock scenarios, if the inertia of the matter is dominated by protons.

3.2. Leptonic flux

Shortly after the discovery of variable and strong γ-rays from blazars by the *Compton Gamma-Ray Observatory* (CGRO), it was realized that the exceptionally high γ-ray luminosities of quasar-hosted blazars can result from Comptonization of external radiation fields by ultra-relativistic electrons/positrons injected in sub-parsec scale jets propagating with a bulk Lorentz factor $\Gamma \sim 10 - 20$ (Dermer, Schlickeiser & Mastichiadis 1992; Dermer & Schlickeiser 1993; Sikora, Begelman, & Rees 1994; Blandford & Levinson 1995). Indeed, the data collected during the entire period of the CGRO mission strongly support this idea. All main features of the high-energy spectra of blazars during γ-ray flares can be explained naturally in terms of the external-radiation-Compton (ERC) model (Moderski, Sikora, & Błażejowski 2003). In particular, the distances at which short-duration flares are produced, inferred from their variability time-scales (t_{fl}) to be $z_{fl} \simeq ct_{fl}\Gamma^2 \simeq 1.7 \times 10^{18}(t_{fl}/3d)(\Gamma/15)^2$ cm, agree with the distance estimates obtained assuming that high-energy spectra of blazar flares are produced by Comptonization of broad emission lines and that the spectral break between the hard X-ray and soft γ-ray spectral ranges, observed in the $1 - 30$ MeV range, is due to cooling effects.

Spectra below the break are hard, with a power-law index of the energy flux, $F_\nu^{-\alpha}$, in the range $0.3 \leq \alpha \leq 0.8$ (Reeves & Turner 2000; Donato et al. 2001; Giommi et al. 2002). In the mid/soft X-ray bands the spectra often soften, presumably due to the contribution from the synchrotron-self-Compton (SSC) component (Sikora et al. 1994; Kubo et al. 1998). However, there are several blazars for which the spectra are well-fit by a single, very hard power-law function over all X-ray bands (Tavecchio et al. 2000). These objects provide an exceptional opportunity to study the energy distribution of relativistic electrons/positrons down to their lowest energies. (Note that the radiation by such electrons cannot be detected in the synchrotron and SSC spectral components, in the former because of synchrotron-self-absorption, in the latter because the low-energy tail of the SSC spectrum is hidden by the synchrotron component.) If X-rays in these blazars are indeed produced by Comptonization of broad emission line light, then the X-ray spectra provide evidence that there is no low-energy cutoff in the energy distribution down to mildly relativistic energies.

Since even the hardest X-ray spectra in blazars have radiation energy indices $\alpha > 0$, the total number of electrons and positrons involved in an outburst, N_e, is well determined by soft/mid X-ray observations. This is because, for a number distribution $N_\gamma \propto \gamma^{-s}$, with $s = 2\alpha + 1 > 1$, $N_e = \int_{\gamma_{min}} N_\gamma \, d\gamma$ is insensitive to the upper limit of the integral and the details of the particle distribution at higher energies. The most stringent limit on the particle content of the jet arises from considerations of the bulk-Compton radiation, where the "cold" electrons carried along in the jet Compton-upscatter the broad emission line photons. For an apparent luminosity $\nu_{sx} L_{\nu_{sx}}$, determined at $h\nu_{sx} = h\nu(\gamma_{min} \sim 1) \sim 2$ keV$(\Gamma/15)^2(h\nu_{diff}/10$ $eV)$, one finds that the electron number flux is (Sikora & Madejski 2000)

$$\dot{N}_e \sim \frac{N_e}{t_{fl}} \sim \frac{\nu_{sx} L_{\nu_{sx}}}{c\sigma_T u_{BEL} t_{fl} \Gamma^6} \sim 10^{50} \frac{(\nu_{sx} L_{\nu_{sx}})_{46}}{(t_{fl}/3d)(\Gamma/15)^6} \ \mathrm{s}^{-1} \, , \tag{1}$$

where $u_{BEL} \simeq 3 \times 10^{-3}$ erg cm^{-3} s^{-1} is the radiation energy density in the broad emission line region (Kaspi et al. 2000) and $\nu_{sx} L_{\nu_{sx}} \equiv 10^{46} \times (\nu_{sx} L_{\nu_{sx}})_{46}$ erg s^{-1}.

The leptonic flux can be also estimated indirectly, using data from the γ-ray band where radiation is produced in the fast cooling regime. Assuming a single power-law electron injection function, with $\gamma_{min} \sim 1$ and the index $p = 2$ corresponding to the high energy γ-ray spectrum slope $\alpha_\gamma \simeq 1$ (Pohl et al. 1997), we have (see Eq.12 in Moderski et al. 2004)

$$\dot{N}_e \sim 10^{51} \frac{(\nu L_\nu)_{48}}{(\Gamma/15)^3} \ \mathrm{s}^{-1}, \tag{2}$$

where $(\nu L_\nu)_{48} \equiv (\nu L_\nu)/10^{48}$erg s^{-1} is the apparent luminosity of the radiation produced at some frequency in the fast cooling regime.

3.3. Energetics

Modeling of the observed high-energy spectra in blazars within the context of the ERC model gives the average energy of the accelerated electrons/positrons $\bar{\gamma}_{inj} \sim 10$. Heating the plasma by such a factor requires the total energy flux prior to the dissipative event to be at least $\bar{\gamma}_{inj}$ times larger than

$$L_e = \dot{N}_e m_e c^2 \Gamma \simeq 10^{45} \dot{N}_{e,50} (\Gamma/15) \ \mathrm{erg\ s}^{-1} \, . \tag{3}$$

In principle, this energy could be provided by the bulk motion of electrons/positrons and dissipated via shocks formed due to interactions with the external medium. This, however, would require the initial bulk Lorentz factor to be $\Gamma_0 \sim \bar{\gamma}_{inj}\Gamma \sim 150$. Such a relativistic e^+e^--beam would produce a very strong spectral peak around $\Gamma_0^2\, h\nu_{UV} \sim 200$ keV due to Compton boosting of the external UV photons by a factor Γ_0^2. No such peaks have been observed so far. In addition, electron/positron jets, even if they can be successfully produced with $\Gamma_0 > 100$, would be immediately decelerated down to $\Gamma < 10$ by radiation drag in the compact central region (Phinney 1987; Sikora et al. 1996). The dissipative events cannot be powered by internal shocks, either, if the flow consists purely of pair plasma. The internal shocks can be, at most, mildly relativistic, even for very large ratios of the bulk Lorentz factors of the colliding inhomogeneities (Komissarov & Falle 1997; Moderski et al. 2004). Therefore, the acceleration of electrons/positrons to energies higher than $\bar{\gamma}_{e,inj} \sim 2$ by shocks requires the energy flux in the flow to be dominated by protons. Alternatively, if the energy flux in a jet is dominated by magnetic fields, the pairs can be accelerated at sites of magnetic field reconnection. In both cases, the jet power can be estimated using the formula

$$L_j \simeq \frac{\bar{\gamma}_{inj} L_e}{\eta_{diss}\eta_e} \sim 10^{47} \frac{(\bar{\gamma}_{inj}/10) L_{e,45}}{(\eta_{diss}\eta_e/0.1)} \text{ erg s}^{-1} \,, \tag{4}$$

where η_{diss} is the efficiency of the energy dissipation in the blazar zone (the region where most of the blazar radiation is produced) and η_e is the fraction of the dissipated energy converted to relativistic electrons. Jet powers inferred from the energetics of radio lobes and hot spots cluster around 10^{46} erg s^{-1} (Rawlings & Saunders 1991; Willott et al. 1999; D'Elia, Padovani & Landt 2003; Maraschi & Tavecchio 2003). These estimates are mutually consistent, considering that the latter value is time-averaged whereas the blazar energetics is determined from flares.

3.4. Pair content

Assuming that the energy flux of protons $L_p \simeq \dot{N}_p m_p c^2 \Gamma$ is $\gg L_e$ one can find that the pair content of quasar jets is $n_{pairs}/n_p = (n_e/n_p - 1)/2$, where

$$\frac{n_e}{n_p} \equiv \frac{\dot{N}_e}{\dot{N}_p} = \frac{m_p}{m_e}\frac{L_e}{L_j}(1+\sigma) \simeq 20(1+\sigma)\frac{(\eta_{diss}\eta_e/0.1)}{\bar{\gamma}_{inj}/10} \,, \tag{5}$$

where $\sigma \simeq L_B/L_p$. The pair content is minimal for $\sigma \ll 1$, with $n_e/n_p \sim 20$. In this case $L_p \gg L_B$ and the blazar dissipative events are likely to be dominated by internal shocks.

For $L_B > L_p$, shocks cannot be sufficiently strong to provide efficient particle acceleration and, therefore, the dissipative events are more likely to originate via the reconnection of magnetic field. Since the minimum kinetic energy flux is given by L_e (cf. Eq. 3), jets which are most severely dominated by magnetic field would have, prior to the blazar dissipative zone, $\sigma \simeq L_B/L_e \simeq 100 L_{j,47}/L_{e,45}$. In these jets $L_p < L_e$, i.e., $n_p < (m_e/m_p) n_e$. Such jets would remain strongly Poynting-flux-dominated even after passing through the dissipative blazar zone, with $\sigma \simeq 10 L_{j,47}/[(\bar{\gamma}_{inj}/10) L_{e,45}]$.

4. WITHIN THE FIRST $10^3 - 10^4$ GRAVITATIONAL RADII

4.1. Bulk-Compton radiation

Another interesting constraint provided by blazar observations concerns the efficiency of the jet acceleration process. Electrons/positrons, dragged through the very central region by protons and/or magnetic fields with bulk Lorentz factor $\Gamma \geq 5$, would Comptonize the direct radiation from the accretion disk, producing a strong soft X-ray bump (Begelman & Sikora 1987; Sikora & Madejski 2000), or, in the case of a non-stationary flow, soft X-ray precursors of the non-thermal flares (Moderski et al. 2004). The absence of such features in blazar spectra indicates that the acceleration of jets up to $\Gamma \geq 10$ must take at least $\sim 10^3$ gravitational radii.

4.2. The conversion distance

If blazar activity is related to the internal shocks formed in unsteady, matter-dominated jets, the efficient energy dissipation and particle acceleration imply $\sigma \ll 1$. This means that the magnetic-to-kinetic energy conversion of the flow should take place within a distance $z_{fl} \sim (t_{fl}/3d)(\Gamma/15)^2$ pc. Is this achievable by an ideal MHD flow? In some circumstances, acceleration by the magnetic nozzle effect can work: this can give $\Gamma/\Gamma_{fm} \sim \ln(z/z_{fm})$, where $\Gamma_{fm} \sim \mu^{1/3}$ is the Lorentz factor at the fast magnetosonic surface located at a distance $z_{fm} \sim \mu^{2/3} z_c$, and z_c is the distance at which a given magnetic flux tube crosses the corresponding light-cylinder (Li et al. 1992; Begelman & Li 1994; Beskin, Kuznetsova, & Rafikov 1998). From the assumption that in the blazar zone the jet is dynamically dominated by protons, we have $\mu \simeq L_p/\dot{M}_j c^2 \simeq \Gamma$ and find that the jet conversion can eventually occur at a distance

$$z_{conv} \sim z_{fm} \exp(\Gamma/\Gamma_{fm}) \sim (z_c/30R_g) M_9 \,\mathrm{pc}\,. \quad (6)$$

This result ($z_{conv} \sim z_{fl}$) may indicate a physical connection between the jet conversion process and dissipative processes responsible for flaring activity of blazars. Such an activity is likely to be induced by pinch and kink instabilities, developed in the phase when a jet is still dominated by the Poynting flux (Eichler 1993; Begelman 1998). MHD instabilities can differentiate the flow speed and this in turn can lead to the formation of shocks. An advantage of such a scenario is that it avoids the need for modulation of the outflow by the central engine. Any modulation of powerful jets at the base would require strong instabilities in the main body of the accretion disk (the corona is too tenuous to affect the jet dynamically) which in turn are very likely to produce rapid ($\sim$ few days) and high amplitude variations of the UV-bump. However, no such variations are indicated by optical observations of nuclei of radio lobe-dominated quasars (Stalin et al. 2004). (We would like to comment here, that short term flaring activities are observed in blazars during both high states and low states (see, e.g., Webb et al. 1990), and that small average amplitudes of short term variations can result from contamination of flares by radiation from larger distances in a jet or from superposition of a varying number of flares observed at once. An important factor determining brightness of individual flares can be related to the non-axisymmetry of the kink instability, which may cause the matter involved in different dissipative events to move in somewhat different directions relative to the line of sight.)

Alternatively, blazar activity can be directly related to magnetic energy dissipation processes, without involving shock formation. The largest uncertainty with this scenario is related to two questions: whether it can lead to acceleration of electrons with a very broad energy distribution, as indicated by the blazar spectra; and whether in the acceleration sites the magnetic field geometry is dominated by the transverse component, as indicated by the blazar polarimetry. Since the magnetic energy dissipation can involve fragmentation of long current sheets into nonlinear smaller structures of all sizes, generation of broad power-law electron spectra may be feasible, but an important question still remains: will enough of the transverse magnetic field orientation persist in order to provide linear optical polarization, which in some objects can reach a value up to 20-40 % and is preferentially aligned with a jet?

5. DISCUSSION AND CONCLUSIONS

As it was demonstrated in §3, X-ray and γ-ray observations of blazars, combined with our best guesses regarding the central environments in quasars, allow us to estimate the leptonic and total energy fluxes. The former is found to be too small to power the observed γ-ray flares or to support the energetics of the radio lobes. Therefore, the energy flux in blazar jets must be dominated by protons or magnetic fields, but with the number of e^+e^--pairs greatly exceeding the number of protons. In two extreme cases we have: (A) a proton dominated jet, with a leptonic content $n_e/n_p \sim 20(\eta_{diss}\eta_e/0.1)/(\bar{\gamma}_{inj}/10)$ (see Eq. 4); or (B) a Poynting flux-dominated jet, with $\sigma \simeq 10L_{j,47}/[(\bar{\gamma}_{inj}/10)L_{e,45}]$ and $n_e/n_p > m_p/m_e$.

The lack of soft X-ray excesses in blazar spectra, and of soft X-ray precursors to non-thermal flares in blazar light curves — both predicted to be produced by Comptonization of external radiation by cold electrons in a jet (see §4) — indicate that jet Lorentz factors are much smaller at distances from the black hole $\lesssim 10^3 R_g \sim 10^{17}$cm than in the blazar zone. There is no convincing evidence that the jet acceleration continues on larger scales: similar bulk Lorentz factors to those deduced from blazar models are inferred in parsec scale jets (Jorstad et al. 2001), while bulk Lorentz factors deduced from modeling optical and X-ray production in kiloparsec-scale jets are at most comparable to the blazar values (see, e.g., Scarpa & Urry 2002; Tavecchio et al. 2004). Hence, kinematical data from all spatial scales and the lack of bulk Compton radiation suggest that the jet acceleration saturates around the blazar zone. In case (A) above, this implies that the conversion of Poynting flux to kinetic energy takes place near or within the blazar zone. In case (B), the jet should stay strongly magnetically dominated over all scales.

The presence of hot spots — very compact features marking the abrupt termination of relativistic jets — as well as the polarimetry of kiloparsec scale jets, seem to favor large scale jets with $\sigma < 1$ and, therefore, case (A). This leads us to speculate that the strongly enhanced activity of the jet in the blazar zone may be related to the final stages of the conversion of a magnetically dominated jet to a kinetic energy-dominated jet. The dynamical events in blazars such as flares can be driven by shocks, which are favored because of the resulting broad energy distribution of electrons. However, efficient dissipation and particle acceleration appear to require strong shocks, and, therefore, $\sigma \ll 1$, and it is quite unlikely that such σ can be reached within the blazar zone by an ideal MHD flow (Begelman & Li 1994). This difficulty can be overcome by postulating dissipative enhancement of the conversion process. The magnetic dissipation can be stimulated and amplified by kink and pinch instabilities, which seem to be unavoidable ingredients of Poynting flux-dominated jets (Eichler 1993; Begelman 1998). Alternatively, one can consider a direct connection of the blazar activity with the magnetic dissipation events, provided they can result in production of electrons with a broad energy distribution. Since in this case the conversion to $\sigma \ll 1$ is not required, the jets may propagate to larger distances keeping toroidal magnetic fields close to the equipartition value.

In both shock and magnetic dissipation scenario of blazar activity, inertia of the matter is dominated by protons and, therefore, the jet is very likely to be powered by an accretion disk rather than the magnetosphere of a Kerr black hole. It can be loaded by protons evaporating from the disk surface or injected into the disk corona by magnetic eruptions, and enriched by pairs created by high energy photons produced in localized disk flares (Stern et al. 1995), in the entire corona (Beloborodov 1999), or following interaction of the proto-jet with the external radiation field (Sikora & Madejski 2000). Since for $n_e/n_p \gg 1$ the effective radiation pressure can be super-Eddington even for sub-Eddington accretion rates, the MHD outflow can be launched even for nearly vertical magnetic field lines, in contrast to the > 30 degree tilt required for magnetocentrifugal acceleration (Blandford & Payne 1982). In this case, the outflow can be driven mainly by radiation pressure within the sub-Alfvenic region, while the main part of acceleration is provided by magnetic stresses in the super-Alfvenic region and enhanced by dissipative processes supported by MHD instabilities.

In summary, we conclude:

• The kinetic energy flux of leptons, estimated from the emissivity of blazar events, is too small to support energetics of blazars and of radio lobes in quasars;

• Studies of kinematics and dynamics of quasar jets indicate that their power on the parsec- and kilo-parsec scales is likely dominated by protons, but the present data do not allow us to distinguish between the cases $\sigma \lesssim 1$ and $\sigma \ll 1$;

• Dynamical events associated with the blazar phenomenon and the lack of evidence for acceleration of jets beyond the blazar zone suggest that blazar activity can be related to the final stages of the conversion of initially Poynting flux dominated-jets into proton-dominated jets. MHD instabilities may play a key role in this process;

• Magnetic reconnection scenarios must be better understood and quantitative theories for the acceleration of electrons in the presence of protons — both in shocks and in reconnection sites — are needed to determine the nature of dissipative events responsible for the blazar activity;

• Domination of the matter inertia by protons suggests that accretion disks have the primary role in powering quasar jets. A large pair content — deduced from the emissivity and energetics of blazar events and provided by high energy processes in the hot accretion disk corona — guarantees launching of MHD outflow even in the case of nearly vertical magnetic field lines.

• As indicated by the lack of bulk-Compton features in the spectra of blazars, acceleration of a jet takes at least 10^3 gravitational radii.

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