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# Are Quasar Jets Matter or Poynting Flux Dominated?

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**Abstract.** If quasar jets are accelerated by magnetic fields but terminate as matter dominated, where and how does the transition occur between the Poynting-dominated and matter-dominated regimes? To address this question, we study constraints which are imposed on the jet structure by observations at different spatial scales. We demonstrate that observational data are consistent with a scenario where the acceleration of a jet occurs within $10^{3-4}R_g$. In this picture, the non-thermal flares – important defining attributes of the blazar phenomenon – are produced by strong shocks formed in the region where the jet inertia becomes dominated by matter. Such shocks may be formed due to collisions between the portions of a jet accelerated to different velocities, and the acceleration differentiation is very likely to be related to global MHD instabilities.

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## 1. INTRODUCTION

Extragalactic jets are perhaps the most spectacular products of accretion activity in quasars and radio galaxies. Yet, despite decades of observations and intensive theoretical studies, their most fundamental aspects are still mysterious. It is unclear how they are launched, accelerated and collimated; why in some active galactic nuclei (AGNs) they are strong (as a fraction of the total energy output), while in others they are weak; and whether they are dominated dynamically by matter or magnetic fields. Various models address these issues, but uncertainties about the initial and boundary conditions, as well as the extremely complex physics of magnetized relativistic outflows, have not allowed a consensus to be reached concerning the nature of AGN jets.

Recent developments in high-energy astronomy, however, are starting to provide a way out of this impasse. X-ray and $\gamma$-ray observations of blazars, combined with our approximate knowledge of the central environments in quasars, allow us to estimate the number and energy flux of electrons/positrons in quasar jets. The latter is found to be too small to power the observed $\gamma$-ray flares or to support the energetics of radio lobes [63]. Therefore, the energy flux in jets must be dominated by protons or magnetic fields, but with the number of $e^+e^-$-pairs greatly exceeding the number of protons. We argue in §2

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that production of such jets may involve mass loading and initial acceleration (in the sub-Alfvénic region) by radiation pressure, and further acceleration by magnetic stresses. In §3, observational constraints on intensity and structure of magnetic fields in different spatial scales of quasar jets are discussed. In §4, we speculate about possible connection of the blazar activity with the conversion of the Poynting flux to matter dominated jets. A more detailed discussion of these issues can be found in [61].

## 2. LAUNCHING A JET

The most promising scenario for launching quasar jets involves rotation of large-scale magnetic fields. The idea of driving outflows by large-scale magnetic fields, originally proposed by Weber & Davis[85] to explain the spindown of young stars, was successfully applied to pulsar winds [48, 20] and became a dominant mechanism in theories of relativistic jets in AGNs [55, 11, 12, 42, 38, 81]. Powerful, magnetically dominated outflows can be driven from both an accretion disk and a black hole magnetosphere. Such outflows can become relativistic if the total to rest-mass energy flux ratio $\mu \equiv L_j/\dot{M}c^2 \gg 1$, where $L_j = L_B + L_{kin}$ is the total energy flux, $L_B$ is the magnetic energy flux, $L_{kin} = (\Gamma - 1)\dot{M}c^2$ is the kinetic energy flux, and $\dot{M}$ is the mass loading rate. Following the work by Blandford & Payne[8], it is often claimed that without sufficient thermal pressure the MHD outflows from the disk can be produced only for magnetic field lines inclined at $i > 30$ degrees to the disk rotation axis. For such angles the effective potential is decreasing along magnetic field lines and the outflow can be launched and driven away by centrifugal forces even for very low coronal temperatures. This may lead to very efficient mass loading and, therefore, to non-relativistic terminal velocities [54, 79]. For $i < 30$ degrees, the coronal plasma cannot be freely driven by centrifugal forces: instead, it must first overcome the effective-potential barrier, which can have its maximum far away from the disk. Therefore, a strong thermal or radiative assistance is required to initiate outflows in such a geometry. The latter can be particularly efficient in quasars that radiate at a significant fraction of the Eddington rate and have pair rich coronae. Preliminary studies of launching and developing outflows with $\mu \gg 1$ have been recently performed both analytically and numerically [46, 47, 37, 80, 43, 44], but none of these works addressed the issue of mass loading and acceleration in the sub-Alfvénic region for typical quasar conditions.

A basic question regarding scenarios for the formation of powerful, relativistic MHD jets by accretion disks concerns the origin of the strong poloidal magnetic field. Two possibilities have been considered in the literature: one is that such magnetic fields are advected inward from the interstellar medium by accreting matter [8], and the other one is that they are generated locally by a dynamo [83]. The first one is often questioned because the dragging of magnetic fields inward requires the magnetic Prandtl number to be unrealistically large [45, 22]. However, this argument applies only if the accretion is driven by viscous torques in the turbulent disk. If the angular momentum is carried away by the MHD wind, then the magnetorotational instability (MRI) that drives the turbulence is suppressed and magnetic field advection can become efficient. The second possibility is often criticized because the large-scale fields produced by the dynamo are expected to be predominantly toroidal [77, 49, 32]. Under certain circumstances,

however, an inverse cascade of reconnecting magnetic loops could produce a dominant poloidal component [75, 40] and accretion could then be driven by the torque exerted on the disk by the MHD outflow.

The production of very strong and relativistic jets requires a large fraction of the gravitational energy of accreting matter to be converted to Poynting flux. This condition can be satisfied only in the very central region, but the collimation of such a jet requires the disk to be threaded by a poloidal magnetic field over much larger scales [66]. The collimation/confinement of central, weakly mass-loaded, electromagnetic outflows is then provided by slower and more massive MHD outflows, launched at larger disk radii by centrifugal forces [76, 9]. One particular version of such a hybrid outflow model has been suggested by Sol, Pelletier & Asseo[64].

## 3. MAGNETICALLY DOMINATED OVER WHICH SCALES?

If a jet is launched magnetically, does it remain magnetically dominated over all scales up to the termination shock, or does it undergo conversion to a kinetic energy-dominated state? The theory of axisymmetric, steady-state ideal MHD outflows predicts that the conversion process works efficiently up to the classical fast-magnetosonic surface, $z_f$, which is located at a few light cylinder-radii [59, 38, 5]. At this distance, the ratio of Poynting flux to kinetic energy flux, $\sigma$, drops to the value $\sim \mu^{2/3}$. This means that for $\mu \gg 1$ the flow still remains strongly Poynting flux-dominated at $z_f$. Whether and how fast the conversion can proceed beyond this point depends on the very uncertain boundary conditions [4, 21, 81, 6]. Below, we discuss whether there is any observational evidence of the dynamical dominance of magnetic fields on any scale in quasar jets.

### 3.1. The blazar zone

Blazar variability timescales of $\sim 1$ week in the optical band and similar or even shorter fluctuations with larger amplitudes in the $\gamma$-ray band [82, 52] show that most of non-thermal radiation in quasar jets is produced within a few parsecs from the center. This is independently confirmed by the location of the cooling break in blazar spectra [50]. Polarization of the variable optical, infrared and mm radiation suggests the dominance of perpendicular magnetic fields in the blazar jets [26, 18, 13, 69, 53]. Such an orientation is consistent with a toroidal magnetic field geometry, but can also result from compression of a tangled magnetic field in a transverse shock. Such shocks have been proposed to result from collisions between velocity inhomogeneities propagating down a matter-dominated jet [62, 65]. This internal shock scenario is 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 [50]. This contrasts strongly with the narrow energy distributions of accelerated electrons predicted by the magnetic reconnection models [87, 35].

## 3.2. Parsec scales

There are phenomenological arguments in favor of the dynamical domination of magnetic fields in parsec-scale jets. Some of these arguments are based on VLBI observations of the superluminal propagation of radio features. If such features were carried by a Poynting flux-dominated jet, they should be accelerating. Homan et al.[24] claim that in sources having multiple components with measurable proper motion, the innermost components are significantly slower than the others. If true, this would suggest that indeed the flow is accelerating. However, the assertion about slower moving innermost components seem to contradict the finding that there is a systematic decrease in apparent velocity with increasing wavelength [29]. 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. Noting also that some outflows bend or change their opening angle, one should not be surprised to see both increasing and decreasing projected speeds. In these cases, one learns little about the intrinsic kinematics of the source from the motion of the surface-brightness-peak of the radio component. This is because such peaks probably do not represent the real component centers, due to the relativistic aberration and Doppler effects from intrinsically expanding finite-size sources. Furthermore, 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 energy dissipated in shocks and partially returned to the flow, or can be represented by shocks formed on the interface between a jet and a clump of matter entering the jet from outside and being accelerated by the relativistic flow. Finally, the features that appear as moving on the VLBI scale may represent moving patterns rather than the real flow speeds. Noting all the above, we would consider as premature claims that "accelerating" individual features in 3C 279 [56] and 3C 345 [78, 41] indicate magnetic domination of parsec-scale jets in these objects.

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.[68] to prove acceleration of a jet in NGC 6251; however, the reality of the counter-jet detection in this object is questioned by Jones & Wehrle[28]. Furthermore, it should be emphasized that this method is based on the assumption that the jet is steady, whereas parsec scale jets are usually variable. For unsteady jets, even if they are intrinsically symmetric, the respective flux ratios are expected to vary due to light–travel–time effects and, therefore, multiple observing campaigns are needed to verify any premises about the flow acceleration.

The presence of strong, ordered magnetic fields in jets could eventually be diagnosed by studies of gradients of the rotation measure (RM) across a jet. Using this method, Gabuzda, Murray & Cronin[17] found evidence for toroidal field in several BL Lac objects. The RM gradient was found also in quasar 3C 273 [1, 86, 2]. However, the fact that Faraday rotation in many objects follow the '$\lambda^2$-rule', even in objects with rotation exceeding 1 radian imply its external origin. On another hand, the time variability [86] and the rapid decrease of the RM gradient with distance down the jet [2] indicate that Farady screen is located very nearby the jet. The screen can be provided by slower moving outer portions of the structured jet.

The presence of the toroidal magnetic component in quasar jets is indicated by measurements of the circular polarization [84, 25, 23]. However, as was demonstrated by Ruszkowski & Begelman[58], the observed circular polarization features can be explained without invoking strong, ordered magnetic fields.

## 3.3. Kiloparsec scales

Often-used arguments 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 fast-cooling ultra-relativistic electrons responsible for synchrotron radiation in the optical and X-ray band [36, 7]. However, high polarization does not necessary require large scale mean magnetic fields; it can be produced in shocks and in boundary shear layers [68], where initially tangled/turbulent magnetic fields are ordered by compression and stretching, respectively [33, 34, 14]. The parallel magnetic field orientation indicated by polarimetry of large-scale radio jets in FRII radio galaxies and quasars [10] suggests that shear layers play a dominant role in powering the emission from large-scale jets. Direct support for this scenario is provided by measurements of intensity and polarization profiles across jets in a number of nearby objects [71]. The perpendicular electric vector orientation in respect to the jet axis can result also from compression of tangled magnetic fields by oblique shocks. This can explain the perpendicular polarization of optical light in 3C 273 jet [57, 74]. Since formation of strong oblique shocks is unlikely to take place in the presence of a magnetically dominated jet, confirmation of the perpendicular orientation of the electric vector in the optical band in 3C 273 and other quasars can prove that in kilparsec scale jets, $\sigma \ll 1$.

The hydrodynamical nature of the large scale jets is also indicated by numerical simulations of their propagation. As Clarke, Norman, & Burns[15] and Lind et al.[39] demonstrated for non-relativistic jets and Komissarov[30] showed for relativistic jets, magnetically dominated jets 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 form such nose-cones. They are broad and their morphologies agree very well with the cocoons predicted by numerical simulations of light, supersonic, unmagnetized jets. Although there are a few radio quasars that possess a nose-cone radio morphology, this by itself does not prove the dominance by magnetic fields. As Komissarov & Falle[31] pointed out, a nose-cone morphology can also result if a jet is heavy, i.e., if its co-moving density multiplied by the Lorentz factor is larger than the density of the ambient plasma. This condition can be satisfied, for example, if the source is intermittent and the jet is restarted into the old, expanded cocoon — the remnant of an earlier epoch of activity. Stawarz[67] has proposed such an interpretation for the unusual morphology of 3C 273.

## 4. CONCLUSIONS

Quasar jets are presumably launched by rotating magnetic fields in the vicinity of supermassive black holes and, as MHD theories predict and bulk-Compton constraints support, are magnetically dominated over at least three distance decades. There appears to be no evidence of magnetic field domination on parsec and larger scales, and this suggests that the conversion of a magnetically-dominated to matter dominated jet takes place within the blazar zone. Such a location of the conversion is independently supported by data on kinematics of a jet. Radiation models of high energy flares in blazars give a bulk Lorentz factor $\Gamma \sim 10 - 20$ [19]. Lorentz factors of the same order are directly monitored by radio interferometers on parsec scales [24, 27, 29] and inferred from X-ray and optical observations on kiloparsce scales [72, 73, 60]. On the other hand, the lack of signatures of bulk-Compton radiation in the blazar spectra implies much slower flows prior to the blazar zone [63, 51]. It is tempting to speculate that short term, high amplitude flares in blazars are related to MHD instabilities [16, 3], developed in a jet during its final stages of acceleration.

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