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AGN winds and jets: a theoretical perspective

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Abstract. Our current theoretical understanding of the dynamical properties of AGN winds and jets is reviewed, with a focus on radiation-pressure and magnetic driving mechanisms. The implications to (1) the environmental impact of the outflows, (2) AGN unification schemes, (3) the nature of the underlying accretion flows, and (4) the relationship to other astrophysical accretion/outflow systems are highlighted.

Key words. Accretion, accretion disks – Hydrodynamics – *Magnetohydrodynamics* (MHD) – Galaxies: active – Galaxies: jets – X-rays: binaries

1. Introduction

This review focuses on the physical mechanisms likely responsible for driving active-galactic-nucleus (AGN) outflows from regions where the central black hole dominates the gravitational field (i.e., on scales $\lesssim$ 0.1 pc for quasars; e.g., Goodman 2003). It is convenient to divide these outflows into "outer-scale winds" and "inner-scale jets." The winds are observed largely through their thermal emission signatures and are launched on scales at least as large as that of the BELR, the broad emission-line region ($R_{\rm BELR} \approx 0.02\, L_{\rm opt,44}^{0.7}$ pc, where $L_{\rm opt,44}$ is the optical luminosity in units of 10^{44} ergs s^{-1}; e.g., Kaspi et al. 2005). The jets are detected mostly through their nonthermal emission and evidently originate in the vicinity of the central black hole (on scales of a few to $\lesssim 10^2$ times the gravitational radius $r_{\rm G}$). In the following discussion it is assumed that these outflows emanate from an accretion disk that is fed mass from larger scales. Various pieces of evidence (including observations of our own Galactic center; e.g., Genzel et al. 2003) indicate that real accretion flows may not have the homogeneous, equatorial structure envisioned in the idealized accretion-disk picture, and the way gas is fed into the AGN is also still an issue (e.g., Shlosman et al. 1990). However, these questions do not bear strongly on the topics addressed in this review.

Following a summary of the main properties and the likely environmental impact of AGN outflows (§ 2), the mechanisms proposed for driving winds and jets are discussed in § 3 and § 4, respectively. While it has been argued that radiation-pressure forces, and perhaps even thermal pressure forces, contribute to the driving of the outer-scale winds, there is a growing recognition that magnetic stresses probably play a critical role in this process. There is currently an even stronger consensus that magnetic fields are indispensable to the driving of the inner-scale jets. As jets are a universal phenomenon, it may be instructive to consider the driving of AGN jets in the context of their counterparts in gamma-ray

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burst (GRB) sources, Galactic X-ray binaries (XRBs), and young stellar objects (YSOs) — this is taken up in § 5.

2. Properties of AGN outflows

2.1. Winds

The evidence for gas outflows in Seyfert 1 (Sy 1) galaxies has come from high-resolution UV and X-ray spectroscopy, which indicates outflow speeds $\sim 10^2 - 10^3$ km s^{-1}, of the order of the escape speed from the BELR for typical black-hole mass values ($\sim 10^6 - 10^7\ M_\odot$). The outflowing gas is seen in absorption (with an inferred global source covering factor $\gtrsim 0.5$; e.g., Crenshaw et al. 1999) and separates into distinct kinematic components that exhibit a range of physical properties (ionization parameter, density) and FWHM widths. Since both the continuum and the broad emission lines are typically absorbed in the UV, the strongest UV absorption components evidently lie outside the BELR. The actual distances of the absorbers have been estimated in several sources based on direct determinations of the density from measurements of the relative strengths of metastable multiplet lines. The distances inferred in this way range from ~ 0.03 pc for component D+E in NGC 4151 (Kraemer et al. 2001), about an order of magnitude larger than $R_{\rm BELR}$ for this source, to ~ 25 pc for component 1a in NGC 3783 (Gabel et al. 2005), nominally within the inner narrow-line region of this galaxy. Similar values have been estimated on the basis of the recombination times of X-ray lines (e.g., Netzer et al. 2002, 2003), supporting the conclusion from detailed spectral modeling and simultaneous X-ray and UV observations (Kraemer et al. 2005) that the UV and X-ray components of the partially ionized "warm absorber" gas overlap. A UV/X-ray "warm absorber" is detexcted also in the more luminous QSOs.

Broad Absorption-Line QSOs (BALQSOs) exhibit a distinct outflow component, with speeds that are typically $\sim 10^3 - 10^4$ km s^{-1} but range up to $\sim 0.1\,c$. Similarly to the lower-velocity Sy 1 absorbing component, the absorbing gas has been inferred to lie (at least in part) outside the BELR and to have a fairly large ($\gtrsim 0.3$; e.g., Goodrich 1997) covering factor at the source. However, whereas Sy 1's are evidently viewed at a comparatively small angle to the symmetry axis, BALQSOs are typically interpreted as being observed at a relatively large angle (e.g., Lamy & Hutsemékers 2004). The so-called "associated" QSO absorption systems (e.g., Richards et al. 1999), which are blueshifted relative to the source by up to $\sim 0.1\,c$, could possibly also originate in the QSO, just like the BALQSO outflows. It is conceivable that these two types of outflow may be related, but this question has not yet been resolved.

A potentially important ingredient in AGN outflows is dust. The presence of dust within the wind has been inferred in some warm absorbers and BALQSOs, although most of the X-ray absorbing material is apparently not dusty. There is a direct indication from spectropolarimetry in the Sy galaxy NGC 1622 for dust moving toward us at a speed of $\sim 10^3$ km s^{-1} (Goodrich 1989). This galaxy is unusual in that its classification changed from Type 1.8 (characterized by a significantly reddened BELR) to Type 1 — probably the consequence of a rare viewing angle — which may be the reason why there has so far been no similar detections in other sources.

There also exists tentative evidence for an association of at least some of the BELR outflow components with a flattened mass distribution (a disk). The BELR emission is characterized by single-peaked lines and a variability pattern in which a change in the continuum flux produces an earlier response in the red wing of a line like Hβ than in the blue wing. These characteristics are most naturally interpreted in terms of a rapidly accelerated outflow from a rotationally supported disk (e.g., Chiang & Murray 1996). This interpretation is quite general and applies both in the case of disk radiation-pressure driving and the case of a centrifugally driven wind (e.g., Murray & Chiang 1997; Bottorff et al. 1997). A disk-like geometry for the BELR has been inferred also from an observed correlation between the peak width of certain lines and the radio-axis inclination to the line of sight in radio-loud

QSOs (e.g., Vestergaard et al. 2000; Hough et al. 2002; Aars et al. 2005) and is consistent with X-ray absorption measurements in certain Seyfert galaxies (e.g., Kraemer et al. 2005). An equatorial disk geometry has also been indicated for BALR outflows by spectropolarimetric observations of BALQSOs (e.g., Goodrich & Miller 1995; Cohen et al. 1995; Lamy & Hutsemékers 2004) as well as by the measured line profiles (e.g., Arav et al. 1999).

2.2. Jets

Apparent superluminal motions (with component-separation speeds as high as $\sim 40\,c$; e.g., Jorstad et al. 2001) and rapid Stokes-parameter variability point to a relativistic outflow component on scales $\lesssim 1$ pc in AGN radio jets. A growing body of data indicates that the bulk of the acceleration to relativistic speeds takes place on comparatively large ($\sim 0.1-10$ pc) scales. In particular, the absence of bulk-Comptonization spectral signatures in blazars has been argued to imply that Lorentz factors $\gamma \gtrsim 10$ must be attained on scales $\gtrsim 10^{17}$ cm (Sikora et al. 2005). In the case of the quasar 3C 345, Unwin et al. (1997) combined a VLBI proper-motion measurement of the jet component C7 with an inference of the Doppler factor from an X-ray emission measurement (interpreted as SSC radiation) to deduce an acceleration from $\gamma \sim 5$ to $\gamma \gtrsim 10$ over $r \sim 3-20$ pc. Piner et al. (2003) inferred an acceleration from $\gamma = 8$ at $r < 5.8$ pc to $\gamma = 13$ at $r \approx 17.4$ pc in the quasar 3C 279 jet using a similar approach. Extended acceleration in the 3C 345 jet has been independently indicated by the increase in apparent component speed with separation from the nucleus (Lobanov & Roland 2005) and by the observed luminosity variations of the moving components (Lobanov & Zensus 1999). Similar effects in other blazars (e.g., Homan et al. 2001) suggest that parsec-scale acceleration may be a common feature of AGN jets.

Although AGN jets may also contain nonrelativistic components, there is evidence that the relativistic component persists to large (kpc to Mpc) scales: this comes in part from the detection of apparent superluminal motions on such scales (e.g., in 3C 120; Walker et al. 2001) and from spectral indications of a deceleration from relativistic speeds in the termination radio lobes of these jets (Georganopoulos & Kazanas 2003, 2004). A proper modeling of these outflows requires a knowledge of their composition, but there is still no consensus on whether the plasma in any particular jet is made up primarily of electrons and protons or of electrons and positrons. It has, however, been argued that in the case of relativistic QSO jets protons dominate the mass flux whereas e^+e^- pairs dominate the particle flux (Sikora & Madejski 2000).

Although only a fraction of AGNs are radio loud and give rise to relativistic outflows, it is evidently the inner-scale jets (rather than the outer-scale winds) that dominate the inferred AGN mechanical heating of galaxy clusters (by offsetting the cooling in the cluster core and establishing an entropy "floor" on larger scales — e.g., Ruszkowski & Begelman 2002; Roychowdhury et al. 2004) and perhaps also the mechanical feedback on galactic bulges that was proposed to regulate the $M - \sigma$ relation (Begelman & Nath 2005).

3. Wind driving mechanisms

Various pieces of evidence suggest that continuum (bound-free) and line (bound-bound) radiation-pressure driving evidently play a role in accelerating AGN outflows (e.g., Arav 1996; Chelouche & Netzer 2003; Everett 2005). Both the central continuum and the local disk continuum may drive the flow, but *shielding* of the central continuum that reduces the ionization level of the gas is generally required for efficient acceleration. One possibility, first suggested by Murray et al. (1995), is that the radiatively driven disk outflows are self-shielded by their innermost "failed wind" zones. Subsequent numerical simulations (Proga et al. 2000; Proga & Kallman 2004) appeared to support this suggestion. However, in view of the various approximations employed by these simulations, this issue requires further scrutiny. What is needed, in particular, is a calculation that will incorpo-

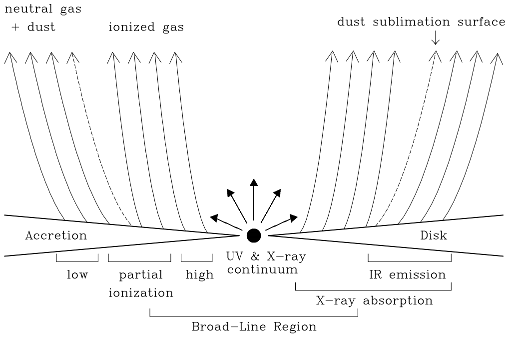

Fig. 1. Schematic representation of a centrifugally driven AGN disk wind.

rate the effects of the central continuum and of a realistic disk radiation field on the ionization state and the acceleration of the gas near the disk surface while taking into account as accurately as possible the radiative transfer (scattering and absorption) in the shield.

Disks threaded by open magnetic field lines can produce high-speed, high-momentum-discharge, centrifugally driven outflows (Blandford & Payne 1982). Such outflows may arise naturally in accretion disks since they are also efficient at transporting angular momentum. AGN disk winds of this type would have a strongly stratified vertical density profile and would be photoionized in their inner regions and dusty in their outer zones (see Fig. 1). [The dust could be uplifted by the outflow from the outer, likely molecular, regions of the disk; alternatively, as suggested by Elvis et al. (2002), it could be produced in the outflow itself beyond the dust sublimation surface.] As was demonstrated by Königl & Kartje (1994), these winds could naturally account for a variety of AGN properties and provide a physical basis for the proverbial "molecular torus" that underlies the Type 1 / Type 2 AGN unification scheme. In particular, centrifugally driven disk outflows can account for the visual obscuration and UV/X-ray attenuation inferred in Type 2 AGNs (see Fig. 2). In fact, this scenario implies an effective obscuring torus that is "fuzzy," as has been inferred in objects like NGC 4151 (Crenshaw et al. 2000). The comparatively high opacity of the dusty regions results in the "flattening" (by radiation pressure) of the "torus" in high-luminosity sources (a trend that has been inferred observationally), and the reprocessing of the central continuum radiation by the wind and disk in the dusty outer regions by and large reproduces the measured near/mid-infrared spectra of Seyfert galaxies (see Fig. 3). The predicted electron and dust distributions can also account for the distinct optical/UV continuum polarization

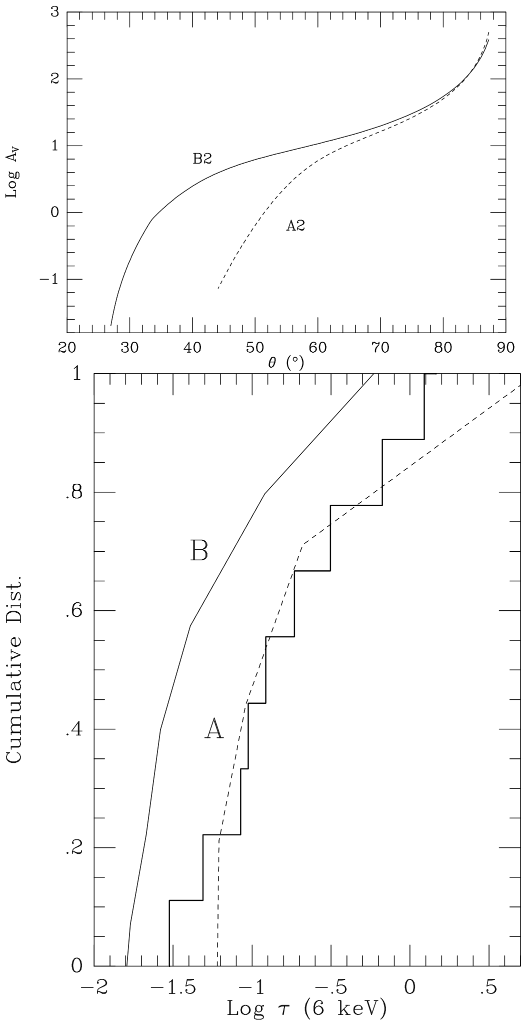

Fig. 2. Visual extinction as a function of polar angle θ (*top*) and comparison with data-based cumulative 6 keV optical depth distribution (*bottom*) for two centrifugally driven AGN disk-wind models.

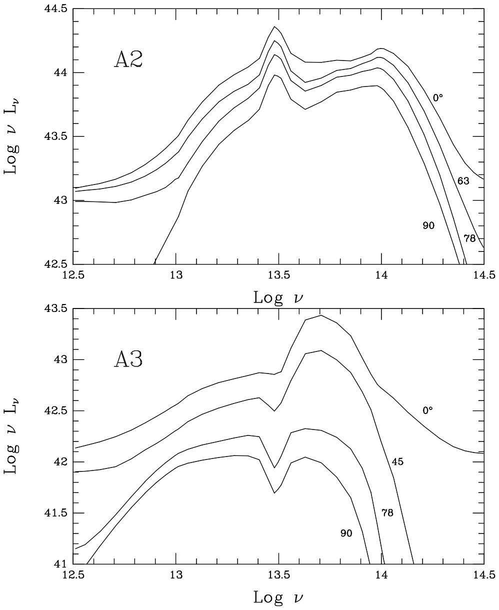

Fig. 3. IR spectra (labeled by the value of θ) for a comparatively tenuous disk-driven MHD wind (*top*) and for a comparatively massive outflow (*bottom*).

properties of Sy 1 and Sy 2 galaxies (Kartje 1995).

MHD driving (possibly complemented by the local disk radiation field) provides an attractive mechanism of uplifting gas from the disk surface and thereby producing a shield that enables matter further out to undergo efficient radiative acceleration by the central continuum source. AGN winds are thus likely to be driven by the joint action of MHD and radiation-pressure forces (e.g., Everett 2005), with the relative contribution of radiation pressure (which would raise the speed but reduce the degree of collimation of the outflow) increasing in more luminous sources.

The MHD perspective is also relevant to the interpretation of the growing evidence that AGN winds represent *multiphase outflows* (e.g., Everett et al. 2002; Kronglod et al. 2005; Chelouche & Netzer 2005; Steenbrugge et al. 2005). In fact, the two main explanations proposed for the inferred different phases have been that they correspond either to discrete clumps confined by the magnetic field of an underlying continuous outflow (e.g., Kartje et al. 1999) or to transient features in a medium that exhibits MHD turbulence (Bottorff & Ferland 2000).

Before concluding this section it is worth noting that X-ray–ionized and heated outflows can be driven by thermal pressure gradients to speeds as high as $\sim 10^3$ km s^{-1} when the Compton temperature and $L/L_{\rm Edd}$ (where $L_{\rm Edd}$ is the Eddington luminosity) are sufficiently high (Balsara & Krolik 1993; Woods et al. 1996). Chelouche & Netzer (2005), using a simplified model, proposed this mechanism as the origin of the warm-absorber outflow in the Sy 1 galaxy NGC 3783. However, a more detailed study (which, among other things, would explicitly address the question of how mass is fed into the outflow and would also consider other sources) is needed to validate this interpretation.

4. Jet driving mechanisms

The inferred large-scale accelerations in AGN jets are most probably not purely hydrodynamic, since in such models the acceleration would be expected to saturate on the (small) scale $r_{\rm G}$ of the central mass distribution, which sets the size of the sonic "nozzle." Extended acceleration is, however, a signature of MHD driving (e.g., Li et al. 1992; Vlahakis & Königl 2003). Exact solutions of the equations of special-relativistic ideal MHD can be obtained by generalizing the (spherical) radial self-similarity formalism originally developed in the nonrelativistic regime by Blandford & Payne (1982). (The two regimes are distinguished by the existence of a characteristic speed, c, in the relativistic case, which precludes the incorporation of gravity into the self-similar equations and a simple matching of the outflow solution to a particular — e.g., Keplerian — disk rotation law. Furthermore, in contrast to the nonrelativistic case, one cannot neglect the displacement current and the charge density in the formulation of the relativistic problem.)

Figure 4 shows a self-similar solution (from Vlahakis & Königl 2004) that provides an illustrative fit to the 3C 345 data presented

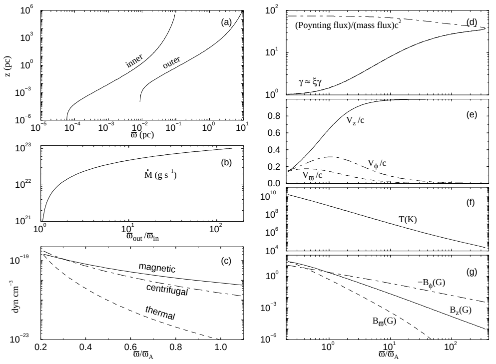

Fig. 4. Self-similar relativistic-MHD model of the superluminal jet in 3C 345. Panels (*c*)–(*g*) show the dependence of various quantities on $\varpi/\varpi_{\rm A}$ (a function of θ) along the outermost field line. Here $\varpi_{\rm out}$, $\varpi_{\rm in}$, and $\varpi_{\rm A}$ are the outermost and innermost disk radii and the cylindrical radius of the Alfvén lever arm, resp. (with $\varpi_{\rm A,out} = 150\,\varpi_{\rm A,in} = 4.1 \times 10^{-2}$ pc).

by Unwin et al. (1997,see § 2.2). Panel (*c*) depicts the force densities in the poloidal direction, showing that thermal and centrifugal effects are important only near the origin, with the B_ϕ magnetic pressure-gradient force rapidly becoming the dominant driving mechanism. Panel (*d*) shows that an approximate equipartition between the kinetic and Poynting fluxes is attained asymptotically and demonstrates that the model fit reproduces well the inferred acceleration of component C7. For the adopted fiducial parameters, this component is predicted to continue accelerating up to $\gamma \approx 35$. Interestingly, Lorentz factors of this order have been inferred in the more distant components (in particular C3 and C5) of the 3C 345 jet (Lobanov & Zensus 1999). Panel (*g*) shows that the magnetic field is primarily poloidal near the origin of the flow but becomes predominantly azimuthal further downstream. Asymptotically, $B_z \propto \varpi^{-2}$, $-B_\phi \propto \varpi^{-1}$, and also $B_\varpi << B_z$—a signature of cylindrical collimation. It is seen that jet collimation (and not just acceleration) takes place over an extended region (although the rate of field-line bending is reduced with increasing Lorentz factor as the effective inertia goes up and the electric force becomes nearly as large as — and almost cancels out — the transverse magnetic force). This predicted behavior is supported by observations of relativistic jets (e.g., M87; Junor et al. 1999). It is, however, also conceivable that a slower disk wind from the outer regions of the accretion disk (of the type considered in § 3) could aid in the collimation of the relativistic outflow from the innermost disk region (e.g., Bogovalov & Tsinganos 2005).

The rotational energy of the central black hole could supplement (or even supplant) that of the surrounding accretion disk as the source of energy for the jet (e.g.,, McKinney & Gammie 2004; De Villiers et al. 2005; Komissarov 2005). In either case the acceleration to the terminal Lorentz factor ($\gamma \gtrsim 10$) takes place on scales $\gg r_{\rm G}$, although the detailed structure of the flow is influenced by the specific boundary conditions at the source.

5. Relationship to other jet sources

Long-duration ($\gtrsim$ 2 s) GRBs have been inferred to arise in ultrarelativistic ($\gamma \sim 10^2 - 10^3$), highly collimated (opening half-angles $\sim 2^\circ - 20^\circ$) outflows of typical kinetic energy $E_{\rm K} \sim 10^{51}$ ergs. Early models of GRB outflows have interpreted them in terms of thermally driven "fireballs" powered by neutrino emission or magnetic field dissipation at the source. However, the current view is that magnetic fields provide the most plausible means of extracting the inferred energy on the burst time scale (e.g., Mészáros & Rees 1997; Di Matteo et al. 2002). Vlahakis & Königl (2003) verified that magnetic fields can also guide, collimate, and accelerate the flow. In particular, using exact semianalytic solutions of the special-relativistic, ideal-MHD equations, constructed within the same modeling framework that was employed in the fitting of superluminal AGN jets (see § 4), they demonstrated that Poynting flux-dominated GRB jets can transform $\gtrsim 50\%$ of their magnetic energy into kinetic energy of highly relativistic baryons. Similarly to the AGN jet models, the GRB outflow solutions exhibit an extended acceleration region — the distinguishing characteristic of MHD driving. However, only in AGN jets is the acceleration zone potentially resolvable (by radio interferometry), which could make it possible to use observations of blazar jets to test and constrain the generic magnetic outflow model.

As in the case of AGNs, it is as yet unclear whether GRB jets are powered by the rotational energy of the central black hole or of the surrounding accretion disk. Recent *Swift* observations might, however, shed light on this question (e.g., Granot et al. 2006), which could potentially have implications also to AGN outflows. The simplest interpretation of the new observations is that the gamma-rays are emitted with very high efficiency. This suggests that magnetic energy dissipation (rather than the conversion of kinetic energy into internal energy in shock waves, as in the popular "internal shocks" scenario) could contribute directly to the jet emissivity (and possibly also to the flow acceleration; Drenkhahn & Spruit 2002). Similar effects may occur also in AGN jets (e.g., Choudhuri & Königl 1986; Romanova & Lovelace 1997).

Turning now to XRBs, there has been a tantalizing recent claim that Galactic black-hole sources and AGNs obey the same scaling relation between the radio (L_R) and X-ray (L_X) luminosities, with the black-hole mass M providing a normalization:

$$\log L_\mathrm{R} \approx 0.60 \log L_\mathrm{X} + 0.78 \log M + 7.33$$

(Merloni et al. 2003; Falcke et al. 2004; Merloni et al. 2006). Galactic black holes exhibit this relation in the low/hard state; the radio emission is quenched when the X-ray luminosity grows to $\gtrsim 0.1\,L_\mathrm{Edd}$ and the source enters the high/soft state. Interestingly, a similar quenching of the radio emission has been inferred in AGNs, indicating that AGNs such as Narrow-Line Sy 1 galaxies may correspond to the high/soft state of XRBs (e.g., Maccarone et al. 2003).

The low/hard state in XRBs has been interpreted as an accretion phase during which steady-state jets carry away most of the liberated power (e.g., Fender et al. 2003). Transient jet outflows may occur at higher accretion rates during the very-high (or steep-power-law) state, of which powerful radio-jet sources may be the AGN analogs (e.g., Jester 2005). XRB jets typically exhibit only moderately relativistic apparent speeds, but there is already one measurement (in the neutron-star XRB Cir X-1) of a value ($\gtrsim 15\,c$; Fender et al. 2004) that is of the order of those found in superluminal AGN jets.

In view of the likely importance of ordered magnetic fields in driving the outflows (see § 4) it was proposed that jet dominance during the low/hard state might be brought about by the formation of a large-scale poloidal field configuration, possibly related to the thickening of the disk during a radiatively inefficient accretion phase (e.g., Meier 2001; Livio et al. 2003) or else resulting from magnetic flux advection through the disk (e.g., Tagger et al. 2004; Spruit & Uzdensky 2005). It is worth noting in this connection that YSOs have also been inferred to launch magnetically driven outflows from the inner regions of their associated accretion disks that quite possibly carry away most of the locally liberated power (e.g., Bacciotti 2004). In this case the large-scale field likely corresponds to interstellar field lines advected inward by the accretion flow.

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