# PART 16.

# Discussion And Conclusions

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# The Formation Of Astrophysical Jets

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**Abstract.** It is assumed that the acceleration and collimation mechanisms of jets are the same in all the classes of astrophysical objects which are observed to produce jets. These classes now include: active galactic nuclei, young stellar objects, massive x-ray binaries, low mass x-ray binaries, black hole x-ray transients, symbiotic systems, planetary nebulae, and supersoft x-ray sources.

On the basis of this assumption, an attempt is made, to identify the necessary ingredients for the acceleration and collimation mechanism. It is argued that: (i) jets are produced at the center of accretion disks which are threaded by a vertical magnetic field, (ii) the production of *powerful* jets requires, in addition, an energy/wind source associated with the central object. Tentative explanations for the presence of jets in some classes of objects and absence in others are given. Some critical observation that can test the ideas presented in this paper are suggested.

## 1. INTRODUCTION

Highly collimated jets are observed in a variety of astrophysical objects, ranging from active galactic nuclei (AGN) to young stellar objects (YSOs). In the present work, I will make the assumption that the jet *formation* mechanism, namely, the mechanism for acceleration and collimation, *is the same in all of the different classes of objects which exhibit jets.* Adopting a strictly phenomenological approach, I will then attempt to determine to which constraints such an assumption can lead. Previous attempts of this nature were made, for example, by Königl (1986), Pringle (1993), and Blandford (1993), however, with the discovery of new classes of objects which produce jets (see § 2 below) and with recent developments in theoretical work, the constraints become more meaningful. It should be noted right away that the *emission mechanisms* which render jets visible in the different classes of objects, are very different in objects like, for example, YSOs and AGN. Here, I therefore concentrate only on acceleration and collimation.

I should also note that bipolar, only weakly collimated outflows, are observed in many objects, such as: luminous blue variables, planetary nebulae, novae in outburst and post asymptotic giant branch stars. Models for the formation of these bipolar outflows exist (*e.g.* Balick 1987; Nota *et al.* 1995; Paresce *et al.* 1995; and see Livio 1996 for a review), but they will not be discussed in the present work.

TABLE 1: Systems Which Exhibit Collimated Jets

| Object | Physical System |
|---|---|
| **Stellar** | |
| Young Stellar Objects | *Accreting* young star |
| Massive X-Ray Binaries | *Accreting* neutron star |
| Black Hole X-Ray Transients | *Accreting* black hole |
| Low Mass X-Ray Binaries | *Accreting* neutron star |
| Symbiotic Stars | *Accreting* white dwarf |
| Planetary Nebulae Nuclei | *Accreting* nucleus<br>(or "interacting winds") |
| Supersoft X-Ray Sources | *Accreting* white dwarf |
| Pulsars (?) | Rotating neutron star |
| **Extragalactic** | |
| Active Galactic Nuclei | *Accreting* supermassive black hole |

## 2. DISKS AND JETS

In this section, I present all the classes of objects which exhibit jets, and discuss some aspects of the observational evidence for a connection between accretion disks and jets.

### 2.1. Which Systems Have Highly Collimated Jets?

In Table 1, I give a list of all the types of objects in which collimated jets have been observed, and the nature of the physical system involved. A few of these objects (symbiotic stars; low mass x-ray binaries with a neutron star accretor; pulsars) require a little clarification, one class (planetary nebulae), has not yet routinely made it into the normal jet literature, and one class (supersoft x-ray sources) is entirely new.

Systems which have been traditionally associated with jets are: many AGN and YSOs and some massive x-ray binaries (HMXBs), such as SS 433 (*e.g.* Margon 1984), Cyg X-3 (*e.g.* Strom, van Paradijs, & van der Klis 1989) and the Galactic center source 1E140.7-2942 (Mirabel *et al.* 1992). More recently, black hole x-ray transients have been added as a class (*e.g.* GRS 1915 + 105, Mirabel 1994; GRO 1655 − 40, Hjellming & Rupen 1995).

So far, the only low mass x-ray binary (LMXB) with a neutron star accretor in which a jet has been observed is Cir X-1 (Stewart *et al.* 1993), and even in that case it is not clear how collimated the flow really is. However, one of the models proposed for the recently observed KHz Quasi Periodic Oscillations in some LMXBs (*e.g.* see van der Klis, these proceedings) involves jets.

The only symbiotic system in which a jet has been observed, both in the optical and in the radio, is R Aqr (Burgarella & Paresce 1992; Dougherty *et al.* 1995).

The reason isolated pulsars are listed in Table 1 (with a question mark), is that the variable brightening observed above the Crab pulsar (Hester & Scowen 1996) has been interpreted as resulting from a shock formed at the interaction of a collimated jet with material in the pulsar's environment. However, further observations will be required, to confirm (or disprove) this interpretation.

I now turn to the new classes of objects which should, in my opinion, be from now on routinely included in any discussion of jets. In planetary nebulae (PNe), jets have now been directly observed in K1-2 (*e.g.* Bond & Livio 1990; Pollacco & Bell 1996), in M1-92 (Trammell & Goodrich 1996), in NGC 6543 (Harrington & Borkowski 1994), and possibly in NGC 7009 (*e.g.* Schwarz, Corradi, & Melnick 1992). In addition, several "point-symmetric" PNe have been interpreted as resulting from precessing jets (Livio & Pringle 1996, and references therein).

The newest exciting addition to the classes of objects which produce jets are the supersoft x-ray sources (SSS). These are luminous ($L_{bol} \sim 10^{37} - 10^{38}$ erg s$^{-1}$) objects, with a characteristic radiation temperature of $(1-10) \times 10^5 K$ (*e.g.* Hasinger 1994; Kahalka & Trümper 1996), in which probably a white dwarf accretes mass from a subgiant companion at such a high rate that it burns hydrogen steadily (*e.g.* van den Heuvel *et al.* 1992). Recent spectroscopic observations of the LMC source RX J0513.9-6951 (Fig. 1) reveal a bipolar collimated outflow with a velocity of $\sim 3800$ km s$^{-1}$ (Pakull 1994; Crampton *et al.* 1996; Southwell *et al.* 1996). The similarity of the spectral features corresponding to the outflow to those observed in SS 433 (*e.g.* Vermeulen *et al.* 1993) is striking. It should be noted, that some hints for the existence of a collimated outflow were also observed in the SSS CAL 83 (Crampton *et al.* 1987).

An examination of Table 1 reveals that with the possible exception of the Crab pulsar (*if* it indeed produces a jet), all the objects which exhibit jets contain *accreting* central objects (some models for jets in PNe do not involve accretion, see § 2.2, but others do); this leads us naturally to the question in the next section.

## 2.2. Do Jets *Require* an Accretion Disk?

Clearly a complete answer to this question is difficult, since it requires both a demonstration that disks can produce jets in all the different classes of objects and that other mechanisms cannot produce them. Since I have adopted a phenomenological approach, I will rather attempt to answer the simpler question: has a disk been observed in all of the classes of objects which produce jets?

In the case of YSOs, the answer is clearly: *yes*, (*e.g.* Beckwith & Sargent 1993) with the most dramatic manifestation being the disk and jet recently observed in HH 30 (Burrows *et al.* 1996). Similarly, disks have unambiguously been observed in all the classes of x-ray binaries (HMXBs, LMXBs, SSS, and

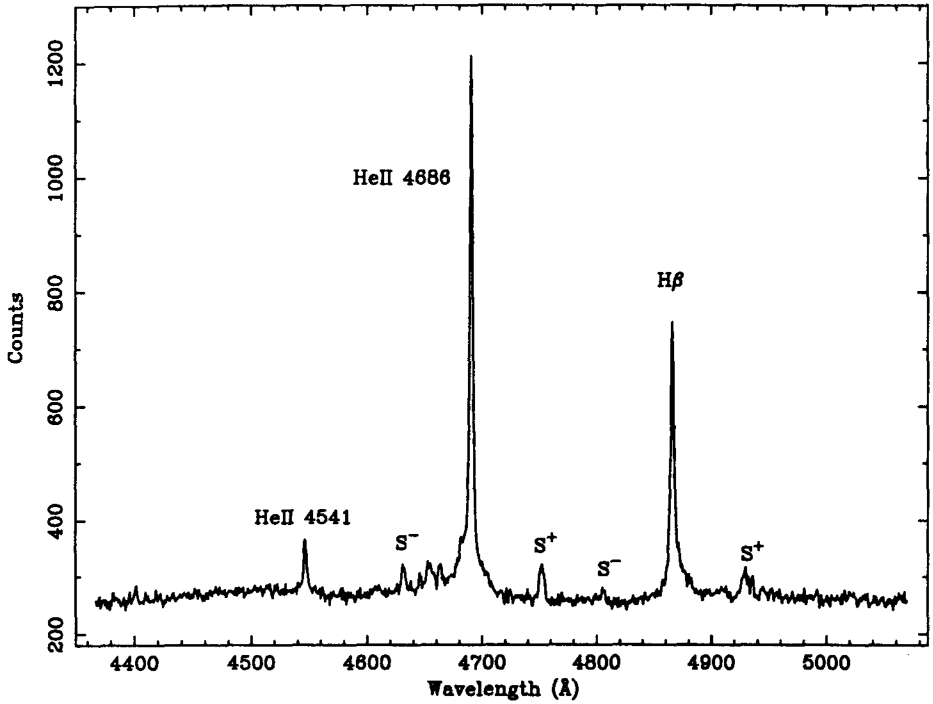

Figure 1. Spectrum of the supersoft x-ray source RX J0513.9-6951 revealing a bipolar collimated outflow (from Southwell *et al.* 1996).

black hole x-ray transients; *e.g.* van Paradijs & McClintock 1995; Southwell *et al.* 1996). The situation with AGN is somewhat more frustrating. Although almost all of the researchers in this field agree that there are accretion disks in AGN, the evidence is somewhat circumstantial (*e.g.* Netzer 1992; Kinney 1994), and every now and then there are even attempts to cast doubt on their existence (*e.g.* Barvainis 1992). Here I would merely like to mention a few recent pieces of evidence for the presence of disks in AGN, which are fairly convincing. (i) The iron $K\alpha$ line in MCG-6-30-15, which is consistent with emission from a disk, between 1.3 and 10 gravitational radii from the central black hole (Tanaka *et al.* 1995; Fabian *et al.* 1995; Iwasawa *et al.* 1996) and a similar line from NCG-5-23-16 (Weaver *et al.* 1996). (ii) The fact that the fit to the double peaked Balmer lines in 3C 390.3 with an accretion disk, and the superluminal motion observed in the same source, give an inclination angle for the disk and the jet which shows that the jet is exactly perpendicular to the disk (Eracleous, Halpern, & Livio 1996). (iii) The dust torus observed in NGC 4261 (Ferrarese, Ford, & Jaffe 1996), which is remarkably consistent with AGN unification schemes containing an accretion disk (*e.g.* Urry & Padovani 1995).

Incidentally, for some time there has been a question whether the double-peaked emission lines observed in some (mostly radio-loud) AGN (Eracleous & Halpern 1994) originate in an accretion disk, or in two line emitting cones (formed by two-sided jets; Veilleux & Zheng 1991). Recently, Livio & Pringle (1996) suggested that long-term monitoring of the variability of double-peaked lines, can distinguish between these two possibilities. The idea is that if the lines come from a circular disk, originating as a consequence of the photoionizing flux from a central source (George & Fabian 1991), then the red shifted and blue shifted peaks should respond together (with a delay between the wings and the central line core, due to the larger distance from the center of the former). If, on the other hand, the two peaks come from the jets, then: (i) if changes in the profiles are due to intrinsic variations in the jets, then the blue and red peaks would in general vary independently. (ii) If the changes are caused by variations in the central source, then we expect the variability in the blue shifted peak to always lead that in the red. Since the accretion disk may be optically thick up to radii of $R \sim 10^{18}\mathrm{cm}(M_{BH}/10^8 M_\odot)$ (*e.g.* Colling-Souffrin & Dumont 1990), this means that the time delay between the blue and red wings may be as long as $\sim$ 2 yrs. The fact that the red wing of a line produced in a two-sided jet may be obscured from view by the accretion disk is well known from YSOs (see *e.g.* [*OI*] $\lambda$ 6300 profiles for T Tauri stars; Edwards *et al.* 1987).

In the case of PNe, until recently, only theoretical arguments for the presence of disks in these systems existed (Soker & Livio 1994; Livio & Pringle 1996). These relied on the fact that following a common envelope phase (which is required, to form the observed close binary nuclei; see *e.g.* Livio 1996 for a review), the somewhat bloated secondary companion is likely to fill its Roche lobe. A recent spectacular image of the Egg Nebula (CRL 2688; Sahai & Trauger 1996), however, revealed a clear dust disk, with an ionization cone perpendicular to it.

A word of caution is needed in relation to YSOs. While the presence of accretion disks in these systems is unquestionable, some models for the formation of jets in these systems (and indeed in PNe), suggest that refraction through oblique shocks is sufficient to produce highly collimated jets, without an active role for the accretion process (*e.g.* Canto *et al.* 1988; Frank, Balick, & Livio 1996 and references therein). In these models, a fast and dilute wind interacts with a slowly moving or stationary torus in the equatorial plane, and collimation is achieved via refraction through the oblique shocks in the interaction region. Further work on these models will be required, to establish whether they can indeed produce long-living jets. Here, however, I will not discuss such models further, since, as explained in the introduction, I am interested in a universal model for all the classes of objects.

To conclude this section therefore, my answer to the question: do jets *require* an accretion disk? is: yes!

### 2.3. Do Accretion Disks *Require* Jets or Outflows?

What I mean by this question is: are outflows/jets the *main* mechanism for transport/removal of angular momentum? The suggestion that this may be the case has been made by many authors (*e.g.* Blandford & Payne 1982; Pudritz & Norman 1986; Königl 1989). The idea here is very simple, the angular momentum carried away by a disk wind is

$$\dot{J}_W = \dot{M}_W \, \Omega \, r_A^2 \quad , \tag{1}$$

where $\dot{M}_W$ is the mass loss rate in the wind, $\Omega$ is the local angular velocity and $r_A$ is the local Alfven radius (§ 3). At the same time, the rate at which angular momentum needs to be removed from the disk for accretion to occur is

$$\dot{J}_{acc} = \frac{1}{2} \, \Omega \, r^2 \, \dot{M}_{acc} \quad , \tag{2}$$

where $\dot{M}_{acc}$ is the accretion rate through the disk. If we require that all the angular momentum is removed by the wind, we obtain

$$\frac{\dot{M}_W}{\dot{M}_{acc}} = \frac{1}{2}\left(\frac{r}{r_A}\right)^2 \quad , \tag{3}$$

from which it is clear that if $r_A \sim 10r$, then only less than 1% of the accreted mass needs to be lost in the wind. Such mass loss rates are indeed observed in CVs and YSOs (*e.g.* Drew 1995; Knigge, Woods, & Drew 1995; Lizano *et al.* 1988), so from this point of view, winds could in principle provide the main mechanism for removal of angular momentum.

One signature of potential removal of angular momentum by the outflow would be the detection of rotation in the wind or jet. Most models of hydromagnetic acceleration (§ 3) predict that the ratio $V_\varphi/\Omega r_o$ (where $V_\varphi$ is the angular velocity in the wind and $(\Omega r_o)$ is the rotational velocity at the base of the outflow) should increase approximately linearly with distance till the Alfven radius (because the magnetic field enforces rigid corotation), and then decline, while more or less conserving specific angular momentum. Indications for rotation in the disk winds in CVs have been observed in OY Car (Naylor *et al.* 1988), and more recently in V347 Pup (Shlosman, Vitello, & Mauche 1996). In V347 Pup in particular, it was found that during eclipse, the fastest rotating wind is eclipsed. Evidence for rotation in jets has also been found in AGN (*e.g.* in NGC 4258; Cecil, Wilson, & Tully 1992; or M87, Biretta 1993). However, it is not easy to distinguish between rotation in the jet material and precession of the jet, which may occur as a result of a radiation-induced warping of the accretion disk (Pringle 1996; Maloney, Begelman, & Pringle 1996).

It should be noted, however, that Shlosman *et al.* (1996) and Knigge (1995), were able to fit successfully the observed wind lines in CVs by simply assuming that the wind rotates with the rotational velocity at the *base* of the flow $(\Omega \, r_o)$. Thus, at present, there is no clear observational evidence for the type of extraction of angular momentum that is predicted for hydromagnetically driven winds.

Furthermore, at least in the case of CVs, there exists clear observational evidence which suggests that winds *are not* the main mechanism of removal of angular momentum. This is related to the behavior of the *disk radius*, during dwarf nova outbursts. The point is the following, if angular momentum is transported outwards in the disk through viscous processes (rather than being removed by the wind), then at outburst, since matter diffuses inwards, the angular momentum of that matter has to be transferred to the outer parts of the

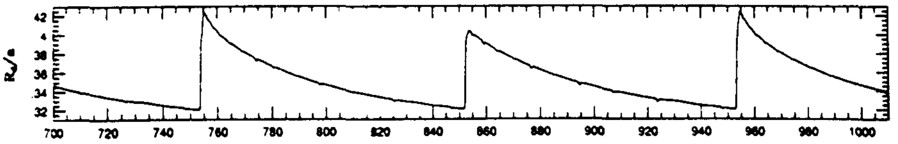

Figure 2a. The theoretical expectation for the behavior of the disk radius during a dwarf nova eruption (from Ichikawa & Osaki 1992).

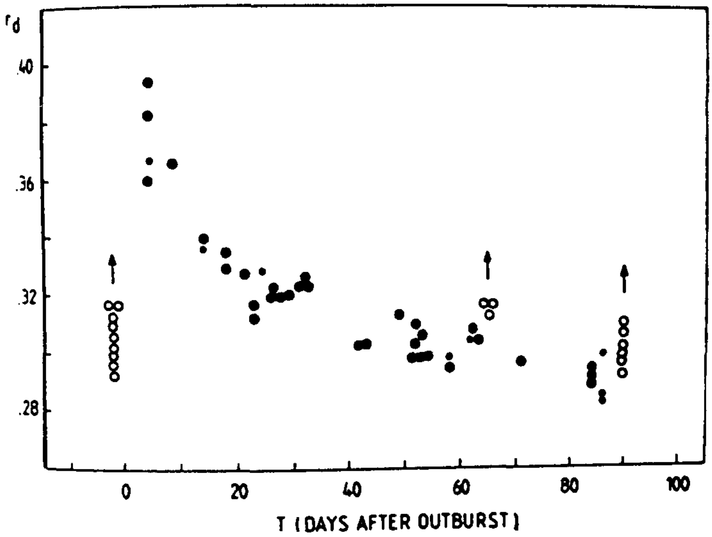

Figure 2b. The observed behavior of the disk radius during a dwarf nova eruption in U Gem (from Smak 1984).

disk, and the radius is expected to expand (Livio & Verbunt 1988; Ichikawa & Osaki 1992). The theoretical expectation for the behavior of the disk radius is shown in Fig. 2a. Observations of the dwarf novae *U* Gem and *Z* Cha in outburst (Smak 1984; O'Donoghue 1986), show that the radius behaves exactly as expected (Fig. 2b). Furthermore, Harrop-Allin & Warner (1996) have shown that the disks in OY Car, HT Car, and Z Cha are all *larger* in outburst than in quiescence, which is again consistent with viscous transport of angular momentum (rather than removal by the wind). Coming back, therefore, to the question posed at the beginning of this section: Do accretion disks *require* jets or outflows, as their *main* mechanism for angular momentum transport/removal? On the basis of observations of CVs, the answer appears to be: no!. More observations of rotation in jets and bipolar outflows (including velocity gradients across the outflow) are needed, in order to settle this question definitively.

**TABLE 2: The Ratio of Jet Velocity to the Escape Velocity from the Central Object**

| Object | $V_{jet}/V_{escape}$ | Example |
|---|---|---|
| Young Stellar Objects | $\sim 1$ | HH30, HH34<br>$V_{jet} \sim 100 - 350$ km s$^{-1}$ |
| Active Galactic Nuclei | $\sim 1$ | Radio sources, $\gamma \lesssim 10$<br>M87, $\gamma \gtrsim 3$ |
| X-Ray Binaries | $\sim 1$ | SS 433, Cyg X-3<br>$V_{jet} \sim 0.26c$ |
| Black Hole X-Ray Transients | $\sim 1$ | GRO 1655-40, GRS 1915+105<br>$V_{jet} \gtrsim 0.9c$ |
| Planetary Nebulae | $\sim 1$ | FLIERS, Ansae, hot winds<br>$V \sim 200 - 1000$ km s$^{-1}$ |
| Supersoft X-Ray Sources | $\sim 1$ | RX J0513.9-6951<br>$V_{jet} \sim 3800$ km s$^{-1}$ |

## 3. OTHER CLUES ON THE FORMATION OF JETS

Since we have determined that the formation of jets most probably *requires* the presence of an accretion disk, we can now examine some of the properties of jets, in an attempt to determine which basic ingredients must be associated with the accretion disk, for the acceleration and collimation mechanisms to operate.

### 3.1. The Jet Origin

An important conclusion can be drawn from the observed jet velocities. In Table 2, I give examples for the ratio $V_{jet}/V_{escape}$ (where $V_{escape}$ is the escape velocity from the central object) for the different classes of objects. It is immediately clear that in *all* cases the jet velocity is of the order of the escape velocity from the central object (this has recently been shown to be true for the new class of SSS; Southwell *et al.* 1996). This immediately indicates that the jets originate from the *center of the accretion disk*, from the vicinity of the central object (see also Pringle 1993). This general conclusion has received impressive confirmation by the HST image of HH 30 (Burrows *et al.* 1996), which shows clearly the jet emanating from the center of the accretion disk.

### 3.2. Ingredients Which May *Not* Be Essential for the Formation of Jets

In Table 3, I list a few properties which are probably not absolutely necessary for the formation of jets (I include CVs for completeness, even though collimated jets have not been observed from CVs). It should be remembered that we are considering mechanisms which can operate in all the classes of objects, and therefore, any ingredient which has "NO" for any of the classes is considered

**TABLE 3. Ingredients Which May *Not* be Absolutely Necessary for the Formation of Jets**

| | YSOs | AGN | XRBs | SSS | PNe | CVs |
|---|---|---|---|---|---|---|
| Central object near break-up rotation | NO | NO | NO | ? | NO | ? |
| Relativistic central object | NO | YES | YES | NO | NO | NO |
| "Funnel" | NO(?) | NO(?) | NO(?) | NO | YES(?) | NO |
| $L \gtrsim L_{edd}$ (Radiation pressure driven) | NO | NO | NO | YES | YES | NO |
| Extensive hot atmosphere (Gas pressure) | YES(?) | YES | NO | NO | YES(?) | NO |
| Boundary Layer | YES(?) | NO | YES(?) | YES(?) | YES(?) | YES(?) |

unnecessary, unless it can be shown that an equivalent ingredient is present for that class. A few words of explanation are in order. There is no question that the central object does not need to be near break-up rotation, although models relying on this property have been suggested for YSOs (*e.g.* Shu *et al.* 1988; Shu 1991). Similarly, it is quite clear that the central object does not need to be relativistic. The question of funnels is somewhat more ambiguous, since one may argue that an ion torus in AGN (*e.g.* Rees *et al.* 1982) or a torus formed by a slowly moving wind in PNe and YSOs (*e.g.* Frank and Mellema 1996) can provide for a form of inertial collimation (see also model for SS 433 by Begelman & Rees 1984). At present, however, there is no reason to suspect that a funnel is present in the SSS. Furthermore, some of these structures are believed to be either globally unstable to non-axisymmetric modes (*e.g.* Papaloizou & Pringle 1984) or to generate too much radiation drag to be able to produce the observed superluminal motions (*e.g.* Blandford 1993). I therefore do not regard funnels as a necessary ingredient, but more work on this mechanism is needed. It is very clear that the source luminosity does not exceed the Eddington luminosity in a number of classes of objects, and therefore it is very unlikely that jets are driven by radiation pressure, as a universal mechanism.

The surrounding gas pressure of the extensive hot atmosphere in elliptical galaxies has been suggested to be an essential ingredient in the production of jets in radio loud AGN (Fabian & Rees 1995). However, such an environment certainly does not exist in some of the classes of objects in Table 3.

The situation with the boundary layer is somewhat more problematic. A boundary layer between the accretion disk and the central object *may* exist in all of the objects, with the exception of those containing a black hole (AGN and black hole x-ray transients). Pringle (1989), suggested in fact that the origin of the energetic winds in YSOs is the boundary layer (the driving being due to shear-generated toroidal magnetic fields). In view of the fact, however, that the black hole sources do not contain a boundary layer, we have to conclude at this point that a boundary layer is not an essential ingredient in the formation of jets, *unless* some physical entity can be found in the black hole sources, which plays a similar role to that of the boundary layer (§ 5).

As a consequence of all of the above, we are now led to examine the formation of jets in the context of what has come to be accepted as the most promising model for jet acceleration and collimation: *an accretion disk threaded by a reasonably ordered, perpendicular, large scale magnetic field.*

## 3.3. Magneto-Centrifugal Jet Acceleration and Collimation

The suggestion that accretion disks could generate a magnetically driven outflow was first made about 20 years ago (*e.g.* Blandford 1976; Lovelace 1976; Bisnovatyi-Kogan & Ruzmaikin 1976; see also Michel 1973). Much of the work done presently (*e.g.* Königl; Ostriker; Matsumoto, these proceedings) relies on the seminal model of Blandford & Payne (1982). Significant progress has also been achieved in numerical simulations (*e.g.* Kudoh & Shibata 1996a,b). The basic idea is that at least some fraction of the magnetic flux is in open field lines, which form some angle with the disk surface (Fig. 3a). The magnetic energy density is larger (above the disk) than the thermal and kinetic energy densities, and hence the outflowing (ionized) material is forced to follow field lines. Since these lines are corotating with their foot points in the disk, material is accelerated by the centrifugal force like a bead on a wire (Fig. 3a). It turns out that the acceleration is optimal around an inclination (of the field lines to the disk) of 60° (Blandford & Payne 1982). For angles larger then 60° there is an effective potential barrier, while for angles much less than 60° large mass fluxes can be obtained, leading to a failure of corotation and a wound-up magnetic field (*e.g.* Königl 1989; Spruit 1996).

In this model, the acceleration stops at the Alfven surface, where the kinetic energy density becomes comparable to the magnetic energy density. The collimation however, occurs in this picture, outside the Alfven surface. Since the gas is no longer attached to the field lines, the field gets wound up by the rotation, generating loops which are carried by the outflow to form a spiral field (Fig. 3b). The curvature force exerted by the toroidal magnetic field on the outflowing material acts in the direction of the rotation axis, and thus collimation of the flow by these "hoop stresses" can in principle be obtained (*e.g.* Sakurai 1985; Begelman, & Li 1994; Heyvaerts & Norman 1996). However, magnetic fields which are wound up to the point at which the toroidal component dominates, are known to be unstable to kink instabilities (*e.g.* Parker 1979), similar in nature to those of a twisted rubber band. Once the instability sets in, collimation by hoop stresses is strongly reduced. Since the effects of kink instabilities have not yet been properly incorporated in numerical simulations, and therefore, it is not clear how effective collimation by hoop stresses really is, it is important to examine other possible collimation mechanisms.

## 3.4. Poloidal Collimation and Its Consequences

A poloidal magnetic field can also act as a collimator, if the radius of the disk is large compared to the radius of the central object, and if the magnetic *flux*

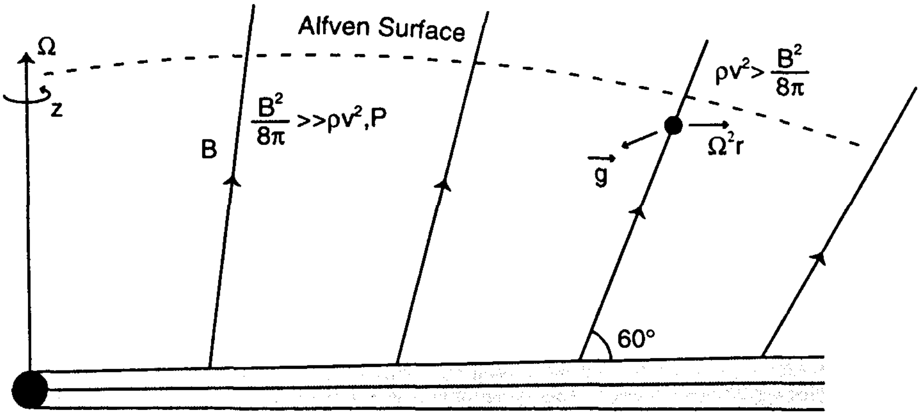

Figure 3a. A schematic representation of magneto-centrifugal acceleration (see text).

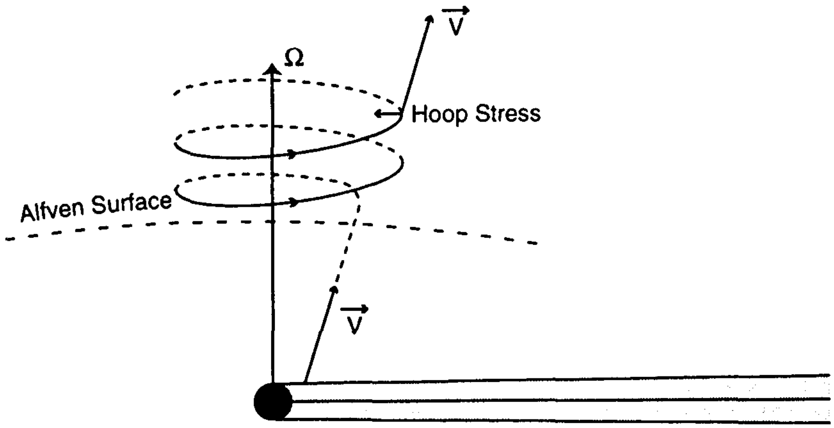

Figure 3b. A schematic representation of collimation by "hoop stresses"

is the largest at the outer disk (Blandford 1993; Spruit 1994; and see Ostriker, these proceedings). For example, for a vertical field of the form $B_Z \sim (r/R_{in})^{-1}$ (where $R_{in}$ is the radius at the inner edge of the disk), good collimation is obtained for $R_{Alfven} \sim R_{disk}$ (*e.g.* Spruit 1996; Königl & Kartje 1994; Ostriker these proceedings).

One of the important consequences of poloidal collimation is that the minimum opening angle of the jet can be estimated. For a vertical field of the above form, and assuming that all the collimation occurs before the Alfven surface (due, for example, to kink instabilities after the Alfven surface), the minimum jet opening angle is given by (*e.g.* Spruit 1996)

$$\Theta_{min} \simeq (R_{in}/R_{out})^{\frac{1}{2}} \quad . \tag{4}$$

Here, $R_{in}$ and $R_{out}$ are the inner and outer radii of the disk, respectively. In Table 4, I give the expected values of $\Theta_{min}$ for all the classes of objects which produce jets. An examination of Table 4 reveals something extremely interesting. For YSOs, HMXBs, the black hole x-ray transients, AGN, and $R$ Aqr, the opening angle is indeed very small, which is consistent with the observation of powerful jets in these systems. In CVs, the opening angle is quite large, which is consistent with the fact that no highly collimated outflows have been observed from CVs. However, *in the two new classes of objects which were found to produce jets, SSS and PNe, the opening angle is as large as in CVs!* This suggests either that poloidal collimation as described above is not the real collimation mechanism, or that *there exists another necessary ingredient in the production of powerful jets.*

I would also like to point out that the images of the disk and jet in HH 30 (Burrows *et al.* 1996) are also in mild conflict with the simple poloidal collimation picture. These images show that the jet is collimated to probably much better than 20 AU in diameter, already at 70 AU from the source (while the disk radius is $\sim$ 250 AU), and there may also be evidence for recollimation taking place.

## 4. THE ORIGIN OF THE LARGE SCALE MAGNETIC FIELD

One of the important questions in relation to the model for acceleration and collimation described in the previous sections is what is the origin of the large-scale magnetic field that is assumed to thread the disk (*e.g.* Begelman 1993). Two main possibilities exist: (i) the field is *advected inwards* by the accreting matter in the disk (*e.g.* Blandford & Payne 1982; Königl 1989; Lovelace, Romanova & Newman 1994; Pelletier & Pudritz 1992), or (ii) the field is *generated locally* by the same disk dynamo (Tout & Pringle 1996) which is responsible for the disk viscosity (*e.g.* Balbus & Hawley 1991; Hawley & Balbus 1991; Stone *et al.* 1996; Brandenburg *et al.* 1995).

In the first case one might expect a field distribution in which the vertical field is proportional to the surface density, $B_Z \sim \Sigma$, (*e.g.* Spruit 1994; Begelman 1993). If the disk is standard, then $\Sigma \sim \alpha^{-1} R^{-1/2} (H/R)^{-2}$, where $\alpha$ is the Shakura & Sunyaev (1973) viscosity parameter and $H$ is the disk half-thickness. If in addition $\alpha \sim (H/R)^{1.5}$, as was found necessary in order to produce the observed exponential decays in the outbursts of black hole transients (Cannizzo,

**TABLE 4: Minimum opening Angle of the Jet in Poloidal Collimation (see text)**

| Object | $R_{in}$ (cm) | $R_{out}$ (cm) | $\Theta_{min}$ |
|---|---|---|---|
| YSOs | $10^{11}$ | $10^{15}$ | 0.01 |
| XRBs, XRTs | $10^{6}$ | $10^{11}$ | $< 0.01$ |
| AGN | $10^{14}$ | $> 10^{17}$ | $\sim 0.01$ |
| R Aqr | $10^{9}$ | $10^{13}$ | 0.01 |
| CVs | $10^{9}$ | $10^{11}$ | 0.1 |
| PNe | $\lesssim 10^{10}$ | $\gtrsim 10^{11}$ | 0.2 |
| SSS | $10^{9}$ | $10^{11}$ | 0.1 |

Chen, & Livio 1995), then we obtain (for a standard disk) $B_Z \sim R^{-81/92}$, which is very close to the $B_Z \sim R^{-1}$ used in several models (*e.g.* Ostriker, these proceedings). Under different assumptions (*e.g.* that motions in the $r - \varphi$ plane generate a magnetic diffusivity $\eta_{mag}$), one can obtain $B_Z \sim R^{-\gamma}$ with $\gamma = 3/2\ \nu/\eta_{mag}$ (where $\nu$ is the kinematic viscosity; *e.g.* Spruit 1994).

The question whether a stable global field configuration, generated by advection, and capable of launching a wind can really exist, is a matter of debate (*e.g.* Lubow, Papaloizou, & Pringle 1994a,b; Königl 1989; Spruit, Stehle, & Papaloizou 1995).

My personal feeling is that it will eventually be shown that angular momentum transport in disks does result from a dynamo generated viscosity, with the dynamo process itself being driven by the type of MHD turbulence described by Balbus, Hawley, Stone, and Torkelsson in these proceedings. I therefore favor the second possibility above (locally generated field).

If the field is generated locally, then one still needs to explain the origin of the *large scale* (length scale of order $R$) field (which is required for the collimation of the hydromagnetic wind). This is required, since the dynamo generated fields have a length scale only of order $H$ (*e.g.* Hawley, Gammie, & Balbus 1995; Matsumoto & Tajima 1995). It has been suggested by Tout & Pringle (1996), that through reconnection of magnetic loops, an inverse cascade process results, which leads to the generation of large scale fields. Here I will adopt a strictly phenomenological approach, in an attempt to place constraints on the required model. First, it is easy to show (*e.g.* Pringle 1993) that if: viscosity is generated by a dynamo (and hence $\alpha \sim B_D^2/4\pi\rho_D C_S^2$, where $B_D$ is the magnetic field in the disk, $\rho_D$ is the density and $C_S$ the speed of sound), $B_Z \sim B_\varphi$ and the jet velocity is of the order of the Keplerian velocity then

$$\frac{B_Z}{B_D} \sim \left[\frac{\dot{M}_j}{\dot{M}_{acc}}\frac{H}{R}\right]^{\frac{1}{2}} \quad . \tag{5}$$

Here $\dot{M}_j$ is the mass loss rate in the jet. If we now assume that the large scale field is generated by reconnection of magnetic loops with a length distribution $n(l) \sim l^{-\delta}$, then (since the length scale of $B_D$ is $H$ and of $B_Z$ is $R$; Tout &

Pringle 1996)

$$\frac{B_Z}{B_D} \sim \left(\frac{H}{R}\right)^{\delta-1} \quad . \tag{6}$$

Combining eqs. (5) and (6) we obtain

$$\frac{\dot{M}_j}{\dot{M}_{acc}} \sim \left(\frac{H}{R}\right)^{2\delta-3} \quad . \tag{7}$$

Now, from observations we know that $H/R$ is in the range 0.03–0.3, while $\dot{M}_j/\dot{M}_{\rm acc}$ is in the range 0.01–0.3 (*e.g.* Pringle 1993 and references therein). Therefore, if reconnection of magnetic loops is indeed the process through which the large scale field is generated, then irrespective of how the process works, the length distribution of loops must satisfy

$$1.7 \lesssim \delta \lesssim 3.4 \quad . \tag{8}$$

In the particular model of Tout & Pringle (1996), they obtained $\delta = 2$, which satisfies condition (8).

## 5. ARE THERE ADDITIONAL INGREDIENTS?

At this point it is appropriate to ask whether there are additional ingredients (other than the accretion disk, threaded by a magnetic field) which are necessary, in order to produce *powerful* jets. This question is, in my opinion, inevitable, because of the following three puzzles (the first two of which have been known for quite some time): (i) why are there radio-loud and radio-quiet AGN? (ii) What is the difference between SS 433 and other neutron star LMXBs (of which only Cir X-1 has perhaps a jet)? (iii) Why CVs appear not to produce jets, while SSS and PN nuclei which are very similar systems do produce jets?

In view of these questions, I am going to make the following, admittedly speculative, suggestion: *Powerful jets are produced by systems in which in addition to an accretion disk threaded by a vertical field, there is an energy/wind source associated with the central object.*

First of all, let me identify this energy/wind source in the Galactic objects which produce jets; this is done in Table 5.

I can now (tentatively) explain why powerful jets are not observed in CVs. In these systems there is no wind source from the accreting WD: there is no steady nuclear burning, accretion is very sub-critical, and very probably the boundary layer is missing. The latter is a consequence of either a weak WD magnetic field (Livio & Pringle 1992), or of syphon evaporation of the inner disk (Meyer & Meyer-Hofmeister 1994), or of the fact that the WD is near break-up rotation (Popham & Narayan 1995). Consequently, the additional basic ingredient for the formation of powerful jets, according to my new suggestion, is missing in CVs, resulting in no jets from these systems. It should be remembered, however, that jets are normally observed through their interaction with the environment. It is thus not impossible that CVs do produce weaker jets, which are difficult to observe, due to the absence of such an interaction. A comment should also be made about x-ray binaries with neutron star accretors. In

**TABLE 5. The Energy/Wind Source that is Associated with the Central Object in Jet Producing Galactic Sources**

| Object | Energy/Wind Source |
|---|---|
| Young Stellar Objects | Boundary Layer |
| SS 433 | Supercritical accretion onto central object |
| Supersoft X-Ray Sources | Hot central star (due to steady nuclear burning) |
| Planetary Nebula Nuclei | Hot central star (due to nuclear burning) |

these systems, typically, the inner disk is radiation pressure dominated. Since the magnetic pressure cannot normally exceed the gas pressure, these systems will normally have $P_{mag} \lesssim P_{gas} << P_{rad}$. Consequently, jets will not be routinely produced by these systems, and a strong energy/wind source associated with the central object is probably absolutely necessary. This may be the reason why only SS 433, which has supercritical accretion, produces unambiguous powerful jets among the neutron star x-ray binaries.

I now turn to the extragalactic sources and the long standing question of what are the differences between radio-loud and radio-quiet AGN. This problem has been recently reviewed by Wilson (1996) and discussed by Blandford & Levinson (1995) and Fabian & Rees (1995). Generally, there are two classes of explanations for the fact that powerful jets are found in radio-loud AGN and not in radio-quiet ones: (i) the central engines in radio-louds and radio-quiets are the same, but either the formation and/or the propagation of the jets is prohibited by some external circumstances in the radio-quiets. (ii) Only the central engines in the radio-louds are capable of producing powerful jets.

Examples of possibility (i) include the suggestion by Blandford & Levinson (1995), that mass losing stars in spiral galaxies prevent the hydromagnetic wind from self collimating (by never becoming super-Alfvenic), and the suggestion by Fabian & Rees (1995) that the gas pressure of the hot atmosphere in ellipticals is essential for the production of jets. It is impossible to rule out such possibilities. I should note however, that while the central environments of S0 galaxies are generally similar to those in ellipticals, no S0 galaxy is a powerful radio source. At any rate, since my basic assumption has been that the formation and collimation of jets *is the same* in all classes of objects, while these types of scenarios are specific to AGN only, I will proceed under the assumption that only the central engines in radio louds are capable of producing powerful jets (see also Wilson 1996, for a discussion).

Figure 4 (taken from Rawlings (1994); see also Baum & Heckman 1989), shows the radio luminosity (which is related to $\dot{M}_j$) as a function of the [O III] $\lambda$5007 luminosity (which is probably related to $\dot{M}_{acc}$; *e.g.* Falcke, Malkan, & Biermann 1995). The figure shows a clear separation between radio-louds and radio-quiets, with a correlation between the radio and [O III] $\lambda$5007 luminosities existing in each of the groups. It is important to note that the *range* in the [O III] luminosity (and hence, presumably the range in $\dot{M}_{acc}$) in the two groups is similar. We may now attempt to interpret Fig. 4, in the context of the ideas presented in the present paper. First, the existence of a correlation be-

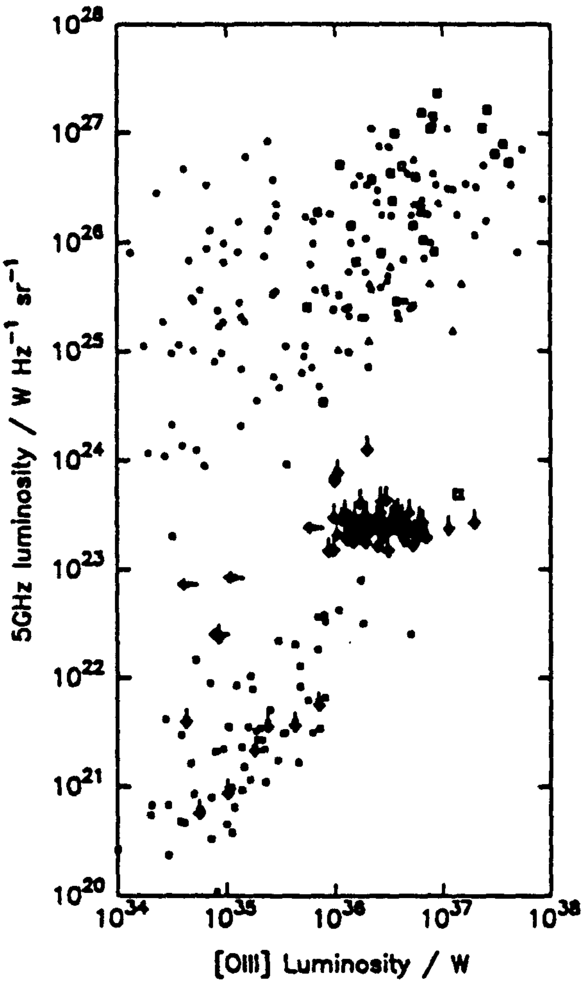

Figure 4. The radio luminosity vs. [OIII] luminosity for AGN (from Rawlings 1994).

tween the power in the jet and the accretion luminosity is a direct consequence of hydromagnetic jets driven by accretion (see eq. (7)). Second, the mass of the central black hole determines the Eddington luminosity, and therefore, the *maximum* $\dot{M}_{acc}$ which an object can have (how far to the right, on the [O III] axis, the object can be found). Hence, only the most massive black holes can occupy the upper right portion of the correlation for each group. We now come to the most difficult question, namely, which parameter distinguishes the upper group (radio-louds) from the lower one (radio-quiets). In the context of the new suggestion made in the present work, *an additional energy/wind source must be identified with the central object.* A natural such source can be provided by the black hole *spin*, since the rotational energy can be extracted from the spinning black hole by the Blandford & Znajek (1977) mechanism (essentially equivalent to a resistor rotating in a magnetic field). In fact, the suggestion that the spin of the black hole is what distinguishes radio-louds from radio-quiets has already been made in the past (*e.g.* Blandford 1993). I feel that the new suggestion made in the present work, *on the basis of a universal mechanism for all the classes of objects*, makes the central black hole's spin an even more attractive possibility. I should note, however, that at some level, the suggestion of Fabian & Rees (1995), of an extensive hot atmosphere around the nucleus being essential, can perhaps also be regarded as the additional energy source.

It is beyond the scope of the present work to attempt to explain why the spin of the central black holes should be different in powerful radio sources (Fanaroff-Riley class II, FR II's) than in spirals (if the black hole spin is indeed the distinguishing factor), but major galaxy mergers are certainly an attractive possibility (Wilson 1996).

At this point it is fair to ask whether what has been presented is supposed to represent the entire picture of jet formation. The answer is, unfortunately, that this is almost certainly not the case. Two examples will suffice to demonstrate that the situation is more complicated, at least in the detailed behavior. In the Galactic source GRO 1655-40, radio jets have been observed to be associated with some x-ray outbursts, but the source has been shown to be radio quiet during some equally strong x-ray outbursts (Hjellming & Rupen 1995; Tavani *et al.* 1996; and see Hjellming, these proceedings). Clearly, there are two types of x-ray outbursts, one associated with jets and one not. Similarly, in the AGN 3C 390.3, while the x-ray and optical light curves are nicely correlated (although rather sparsely sampled), the ejection of radio blobs seems to occur sometimes in high (x-ray) states and sometimes in low states (Eracleous, Halpern, & Livio 1996). Clearly we are still a long way from an understanding of the formation of jets in detail.

## 6. CRITICAL OBSERVATIONS

Since tentative conclusions have been presented already in the different sections; I will end by listing some critical observations which can help test the ideas presented in this work. These have been divided into observations which test the general picture and those which test more specifically the new suggestion (that an energy/wind source associated with the central object is a necessary ingredient for the production of powerful jets).

### 6.1. Critical Observations for the General Picture

1. Reliable determinations of the ratio $\dot{M}_{jet}/\dot{M}_{acc}$ are badly needed (§ 2 and § 4).

2. Determinations of the collimation length scale are needed, in all classes of objects (§ 3 and § 4).

3. Long-term monitoring for variability patterns in double-peaked emission lines in AGN can help distinguish between models for the formation of these lines (§ 2).

4. It is necessary to detect and measure rotation and toroidal magnetic fields in jets and bipolar outflows (§ 2 – § 4).

### 6.2. Critical Observations for the New Suggestion

1. It is extremely important to determine whether CVs indeed do not produce jets. Extensive searches should be conducted for shifted emission features (like those observed in the SSS RX J0513.9- 6951). The best candidates are the recurrent novae, since they are characterized by very high accretion rates.

2. Searches for jets in other supersoft x-ray sources, in other planetary nebulae, other symbiotic systems, and in other x-ray transients (especially during flares, *e.g.* in A0620-00, GS 2023+338, GS 1124-683, Cen X-4, Aql X-1) are strongly encouraged (§ 1).

3. Determination of black hole masses in AGN are badly needed (§ 5). The first results in this direction are starting to appear (*e.g.* Ford, these proceedings).

4. Determination of black hole spins in AGN are badly needed (§ 5). This may become possible in the not too distant future, through Fe $K\alpha$ line profiles (Ross, these proceeding and Wehrse, these proceedings).

5. It is important to determine whether non accreting pulsars can generate highly collimated, powerful jets (§ 1).

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