CONFERENCE SUMMARY

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1. INTRODUCTION

Astronomical phenomena are often grouped according to scale, distance or energy. Meetings designed to cut across such divisions, like this one, are risky undertakings. There is a great temptation for each sub-group to lapse into its own jargon, throwing the telephone numbers of its favorite objects around like the speaker at a comedian’s convention who gets a laugh by shouting the catalog number of a joke. Meanwhile, the members of the other sub-groups might be checking their e-mail or taking in the National Aquarium. The fact that this meeting resulted a very effective exchange of information and views among the investigators of jets in young stellar objects (YSOs), active galactic nuclei (AGNs), and Galactic compact remnants, is a tribute to both the organizers and the participants. We met and got to know each other. But do we have enough in common to go out on a second date?

2. INTERPRETING THE PHENOMENOLOGY OF JETS

2.1. YSO Jets

To paraphrase Robert Laing, the exquisite diagnostics which Reipurth, Ray and Stahler applied to YSO jets were enough to bring tears to an AGN observer’s eyes. YSO researchers are now able to map both radial velocities and proper motions in a number of spectral lines, while line ratio maps give spatial information on densities, temperatures, and ionization levels. Yet such fundamental quantities as the mass and energy fluxes in YSO outflows remain uncertain by as much as two orders of magnitude, mainly because we have little idea about the filling factor of the emitting gas. As Phinney warned, reliance upon emission diagnostics may give us a highly biased view of jets, since most emission processes pick out the localized regions where the density...
or temperature happens to be abnormally high (or, in the case of AGNs, where the relativistic velocity is closest to the line of sight).

Such a bias can be also very useful, since the emission can highlight interesting fluid interactions such as shocks. Overall, YSO diagnostics reinforce the simple fluid picture for jet propagation. In particular, the “working surface” where a YSO jet impacts on the ambient medium appears to exhibit both a bow shock and a Mach disk. The fact that the former shows higher excitation than the latter implies that YSO jets are denser than their surroundings, exactly opposite to the conclusion that is reached for jets in powerful radio galaxies. Patches of line emission are also observed where YSO jets appear to bend, as one would expect from the interaction of a gaseous flow with the ambient medium.

Herbig-Haro (III) objects are apparently internal shocks in YSO jets, but the trigger for shock formation is still controversial. Oblique shocks due to stationary obstacles or jet overpressure are ruled out by the large proper motions of III objects. The roughly periodic spacing of III objects along the jet suggests Kelvin-Helmholtz instability, a view which was somewhat favored by Ray. As supporting evidence, he cited a case in which the III objects appear to be moving more slowly than the jet. However, in the well-studied cases of III 111 and III 34, Reipurth and collaborators have found that the speed of the III objects is very close to that of the jet, so one would expect if the shocks were internal working surfaces in a “pulsed” jet. If this is the case, then the mean spacing of III objects implies that the central source undergoes an outburst roughly once every 10^5 years. Reipurth conjectured that these outbursts might account for the FU Orionis phenomenon.

YSO jets seem ripe for numerical simulation, particularly with the advent of useful 3-D codes. The array of posters on this subject shows that this opportunity is not being lost on the numericists. Whereas the manufacture of synthetic radio maps for AGN jets requires the adoption of an ad hoc scheme for “painting in” the radio emission (since we don’t know enough about particle acceleration), one can be more confident about the emission mechanisms operating in YSO jets. Norman reported on work he did with Stone (presented also in a poster) in which they are able to reproduce the spacing, kinematics, and emissivity of the III 34 knots fairly well in the context of the pulsed-jet model. According to their calculations, the Kelvin-Helmholtz model is incompatible with observations. Despite promising early results, much remains to be done on numerical modeling of YSO jets. None of the numerical models presented at this conference included magnetohydrodynamic effects. If YSO jets are magnetically driven, as many suspect (see §4 below), then the magnetic pressure could be much larger than the gas pressure in the jet. Magnetic fields of this magnitude would severely limit the compression in strong shocks and generally produce a cushioning effect. This, in turn, would affect the emission produced in the shock, as the work presented in a poster by Pudritz and Ouyed shows.

2.2. AGN Jets

Despite the fact that the diagnostics used to infer physical conditions in AGN jets are notoriously weak, the case for relativistic velocities in these jets is quite strong (Laing). The latest piece of evidence that apparently one-sided AGN jets are intrinsically symmetric is the optical hotspot which appears just where the counterjet in M87 is expected to be impacting on the ambient medium (Biretta). Most observed properties of AGN jets (especially one-sidedness and superluminal proper motions) can be
 accounted for with Lorentz factors not exceeding 2-10. However, the "intra-day" radio variability observed in some objects seems to require Lorentz factors as large as 100, if catastrophic Compton losses are to be avoided (Blandford). Marscher showed that this conclusion can be sidestepped if one is sufficiently clever about choosing the geometry of whatever is varying; it is not known how clever Nature has decided to be in this instance.

Morphologically, AGN jets show many features reminiscent of YSO jets (and vice versa); structures which appear similar to those found in fluid dynamical simulations are also seen. While certain aspects of the similarities are undoubtedly meaningful, one should be careful about carrying morphological analogies too far. Some YSO jets are beautifully one-sided, but obviously for different reasons than their AGN counterparts! As Phinney noted, the emission mechanisms which render YSO and AGN jets visible have little in common. In comparing AGN observations with numerical simulations, one should always remember that the regions of high synchrotron surface brightness may not have a simple mapping to features in the flow.

Nevertheless, there is reason to believe that AGN jets can also be described by fluid dynamical or magnetohydrodynamical models. Any of the three mechanisms advanced above, in connection with III objects, might be important in explaining the knots in AGN jets. Unlike the YSO case, however, the diagnostics available are not good enough to distinguish among the possibilities. There is also clear evidence for the fluid dynamical interaction of AGN jets with their environments, for example, the patches of line emission which bound the radio source in many objects (Wilson). In contrast to the YSO case, it seems clear that this gas is not material which has been carried out by the jet, but rather is interstellar medium which has been irradiated, shocked, entrained, or otherwise disturbed. The closest analogy in the YSO context may be the slow molecular outflows, which many investigators believe to be ambient material entrained by the faster atomic jets (see, e.g., the discussion by Stahler). AGN jets also exhibit additional, indirect evidence for interactions with their environments. Laing showed that the weaker, "Fanaroff-Riley Type I" jets emerge from the nucleus as one-sided, presumably relativistic flows. Only after traveling a few kiloparsecs do they revert to the plume-like morphology characteristic of weak sources. He suggested that this transition results from the deceleration of the jet due to entrainment of the surrounding gas. How this can happen slowly enough to avoid disrupting the flow remains a mystery (Phinney). In the more powerful (Fanaroff-Riley Type II) jets, the evidence for interaction consists of indications that most of the synchrotron emission is coming from a thin boundary layer on the jet surface. In both strong and weak jets, the magnetic field along the jet boundary is aligned with the jet direction, suggesting field-line stretching due to shear.

Some of the obvious differences between AGN jets and YSO jets can be understood in gas dynamical terms. YSO jets are highly radiative, cool rapidly, and tend to remain at high Mach number. AGN jets retain more of their internal energy, and perhaps are more susceptible to becoming turbulent as a result of entrainment. AGN jets are of lower density than their surroundings and tend to inflate large cocoons. YSO jets, being dense relative to the ambient medium, should not inflate cocoons, as indeed seems to be the case.

Recent observations of MS7 pose some tough challenges for models of jet emissivity (Biretta). The brightness of the jet in the optical band implies that particle acceleration is widespread, since electrons emitting optical synchrotron radiation are expected to cool very rapidly. The morphology suggests that dissipation occurs primarily near the
jet boundary. What is most surprising is that the radio emissivity follows the optical emissivity so closely. This suggests either that the optical synchrotron electrons survive longer than expected, or that the radio emission is confined to regions very close to the acceleration sites. Bireta and Phinney discussed a number of ways for achieving these effects, none of which is very compelling. Compounding the mystery is the fact that the "minimum pressure" inferred from the synchrotron surface brightness is considerably larger than the pressure in the region surrounding the M87 jet, suggesting that the synchrotron emitting regions are out of dynamical equilibrium. An obvious source of "free energy" for creating locally overpressured regions is the shear layer between the jet and the surrounding medium, or the internal shear in the jet. This energy could be tapped by magnetic stresses. Suppose the shear layer, of width $\Delta x$ and velocity difference $\Delta v$, were initially threaded by a field of strength $B_0$, as shown in Figure 1. The initial Alfén speed is $v_{A0} = B_0/(4\pi \rho)^{1/2}$. After a time $t$, both the field and the Alfén speed are amplified by a factor $(\Delta v/\Delta x)t$. If unchecked by reconnection, this process would saturate when the Alfén speed reached a value $v_{A1} \sim (\Delta v/\Delta x)^{1/2}$, corresponding to an enhancement in the magnetic energy density by a factor $\Delta v/\Delta x$. An overpressured synchrotron-emitting sheet could result if a fraction of the magnetic energy were dissipated via the acceleration of relativistic electrons. This mechanism has the added advantage that it naturally produces a field aligned with the jet in the synchrotron-emitting regions, as required by polarization measurements.

![Figure 1. Schematic illustration showing how local, transient regions of overpressure can be created by shearing the magnetic field at the boundary of a jet. See text for details.](image)

The regions of overpressure produced by shear would be highly localized and transient, nevertheless they could combine to yield a high volume-averaged synchrotron emissivity without violating volume-averaged pressure balance with the surroundings. An observer, measuring a mean synchrotron emissivity $\langle j \rangle$, would derive an apparent minimum pressure $p_{app} \propto \langle j \rangle^{1/7}$. However, if the emissivity were confined to unresolved regions with a filling factor of $f \ll 1$, the actual minimum pressure in the emitting regions would be $p_{min} = f^{-1/7}p_{app} \gg p_{app}$ while the volume averaged minimum pressure would be only $\langle p_{min} \rangle = f^{3/7}p_{app}$. To account for an apparent overpressure ratio $p_{app}/p \sim 20$ (as seems to be required by observations of M87 (Owen, Ilardec, & Cornwell 1989; Stiavelli, Maller, & Zarling 1991) without violating $\langle p_{min} \rangle > p$, would require $f \lesssim (p/p_{app})^{7/3} \sim 10^{-3}$ and a localized minimum pressure
\( p_{\text{min}} / p > (p/p_{\text{app}})^{-7/3} \sim 10^3 \). According to the simple model for shear amplification, this would require an Alfvén Mach number across the shear layer of 1000, which seems unlikely. However, the general idea of generating most of the synchrotron emission within localized regions of very high overpressure seems an attractive one, which has not been studied in detail. Note that such a model could also help to explain the close correspondence between optical and radio morphologies in M87, since all of the emission would occur very close to the acceleration sites.

One of the more intriguing morphological claims is that some jets are “braided” (e.g., Cecil, Wilson, & Tully 1992). I hope this simply reflects a misuse of terminology, and that the investigators simply mean “twisted.” A twisted jet can be constructed of two or more strands, can be undone by simple untwisting, and might reflect rotation, precession, or some kind of helical instability. A braid is topologically different from a twist (Fig. 2), requires at least three strands, and cannot be undone by untwisting or pulling apart the strands. A truly braided jet would be a surprising find indeed.

![Figure 2. A braided jet (a) is topologically different from a twisted jet (b).](image)

3. HOW COMMON ARE JETS?

Debate about the ubiquity of the jet phenomenon was sparse at this meeting, but this is probably more a reflection of ignorance than of negligence. It seems that the production of jets may be a universal feature in the early evolution of YSOs. The situation for AGNs is apparently more complicated. For reasons which are not understood, fewer than 10\% of all QSOs produce strong extended (\( \gtrsim 0.1 \) pc) jets, yet the optical, UV, and X-ray characteristics of radio-loud and radio-quiet QSOs are quite similar. Powerful radio galaxies are almost invariably ellipticals, whereas Seyfert nuclei, and possibly radio-quiet QSOs, lie in spirals. How the Hubble type of the galaxy can determine the physics of the active compact nucleus is a major mystery. Over the years it has been suggested that the effect has something to do with: 1) the angular momentum content and geometry of the accretion flow; 2) the amount of accreted magnetic flux; 3) the spin of the central black hole; 4) the ratio of accretion rate to black hole mass; and 5) the consequences of a galaxy merger (Wilson 1992). So far, none of the mechanisms
presented along with these explanations has been very convincing. Note that we are only able to detect powerful radio sources on scales larger than about $10^{-2}$ pc, because the radio emission is absorbed on smaller scales. Thus, it is possible that incipient jets form in most AGNs, but are quenched before reaching the scale on which they can be observed. The observational fact that broad absorption line QSOs (BALQSOs) are never radio-loud could be a very significant clue, which has been almost totally ignored by theorists. There are convincing statistical arguments that all radio-quiet QSOs appear as BALQSOs from certain viewing directions. Why are the production of broad absorption lines and the production of jets mutually exclusive?

Although Vermeulen paid homage to SS 433 in all its uniqueness, little can be said about the relationship of jets from Galactic compact objects to YSO or AGN jets. In addition to SS 433, a few examples are known of X-ray binaries or cataclysmic variables displaying bipolar or jet-like structure, but no systematic have emerged as yet. If jets are ubiquitous in YSOs and fairly common in AGNs, why do they seem to be so rare among accreting compact objects in the Galaxy? One possibility is that they are not all that rare, but that conditions in the circumstellar medium make them difficult to observe. Another is that their propagation is usually aborted by unfavorable conditions outside the formation region. A third possibility is that there is no tendency for them to form in the first place, unless very special conditions are satisfied. Fourth, they may persist for only a small fraction of the X-ray binary's lifetime.

Mirabel's announcement that the Galactic Center Annihilator may be producing a pair of jets is exciting news (Mirabel et al. 1992). If the connection between the double radio source and the Annihilator is confirmed, it would provide the first direct evidence for jets composed of electron/positron pairs. The temporal and spectral behavior of 1E1740.7-2942 in the hard X-rays is reminiscent of Cygnus X-1, leading to speculation that the object is a high mass X-ray binary, perhaps containing a black hole. Since, for a variety of theoretical reasons, it has been argued that the relativistic jets in AGNs might be composed of pairs, this discovery could strengthen the identification of accreting compact objects in X-ray binaries as "microquasars" (e.g., Rees 1981). The Annihilator would be unique among known X-ray binaries in that it is apparently embedded in a molecular cloud (Bally & Leventhal 1991). If the ambient medium density is $\sim 10^{5}$ cm$^{-3}$, then the radio lobes could have grown to their present size ($\sim 1$ pc) in $\lesssim 10^{5}$ years, assuming a total power of $\sim 4 \times 10^{37}$ ergs s$^{-1}$. The density disparity between the jets and the ambient medium would be so large that the source would grow by inflating a nearly spherical bubble rather than a highly elongated cocoon (Begelman & Cioffi 1989). The total pressure inside the bubble would be about $10^{-6}$ dyne cm$^{-2}$, 5-6 orders of magnitude higher than the minimum energy density (in relativistic electrons and magnetic field) necessary to produce the observed synchrotron radiation. A similar object, expanding into the interstellar medium ($n \sim 1$ cm$^{-3}$) or into the bubble blown by the wind of the massive star ($n \sim 10^{-2}$ cm$^{-3}$), would require $\lesssim 10^{5}$ years to expand to 1 pc, and would reach a size exceeding 10 pc in $10^{5}$ years. Even at this stage, the total internal pressure would be several orders of magnitude larger than the minimum pressure needed to make a detectable synchrotron source. Thus, if all massive X-ray binaries produce jets, the fact that they are not generally observable suggests either that the production of relativistic electrons is inefficient or that the magnetic field is weak.
4. HOW ARE JETS PRODUCED?

Studying the frequency of jet production in different types of objects leads one to more fundamental questions. What are the factors that lead to jet formation, how do jets form, and what factors inhibit the formation of jets?

Pringle and Blandford outlined the various suggested mechanisms for producing jets in different classes of objects. In YSOs, driving by radiation pressure seems to be ruled out by the lack of sufficient radiation. This may also be a problem for powerful radio galaxies (although it is hard to tell for sure because of the possible anisotropy of the radiation). Also, radiation drag would make it difficult or impossible to reach the large Lorentz factors which seem to be required in the latter, particularly if "intra-day variability" requires Lorentz factors much larger than 10. Acceleration by thermal pressure also seems difficult in YSOs, because the large mass flux implies a very short cooling time near the source. However, some investigators believe that all of the lines we see arise from material entrained by a fast stellar wind. A mechanism for driving such a powerful wind off the surface of the star, however, has not been found.

By the process of elimination, this leaves magnetic acceleration as the leading contender for driving jets in both AGNs and YSOs. There are really two effects which can contribute to the acceleration of material by a magnetic field anchored in a rotating medium, such as an accretion disk. At small distances, the magnetic field lines behave like rigid wires. Gas tied to the field is forced to corotate with it, and can be flung outward by centrifugal force. This mechanism is the basis for the self-similar model by Blandford & Payne (BP: 1982), which has led to further developments by many investigators including Pudritz and Norman, Lovelace and collaborators, Shu and collaborators, and Königl. The "centrifugal sling" mechanism works only until the magnetic tension can no longer resist the inertia of the accelerating gas. Beyond this so-called "Alfvén point" the magnetic field is swept into an ever-tightening spiral, and the "magnetic spring" becomes the main mechanism for further acceleration. The gas is accelerated by the pressure gradient of the coiled magnetic field.

Aside from the lack of plausible alternatives, magnetic acceleration possesses two important advantages over other mechanisms. First, magnetically accelerated flows can attain much higher Lorentz factors than flows accelerated by radiation or gas pressure. This is important for explaining the highly relativistic jets in AGNs, particularly if intraday variability requires Lorentz factors \( \gg 10 \). As radiation drag retards the acceleration of a flow near its source, it also increases the energy stored in the coiled magnetic field. The stored energy can be recovered once the flow reaches a region where the drag is small, giving back much of the acceleration that is initially robbed by the drag (Li, Begelman, & Chincin 1992). Second, the development of a predominantly toroidal field will lead to the self-collimation of a magnetized flow. Thus, it may not be necessary to invoke a "funnel" or external confining medium to explain the collimation of jets. (However, there are indications that the rate of collimation produced by magnetic stress alone is rather low. To obtain the degrees of collimation that are observed in jets, some external pressure may be necessary.)

Blandford spoke about the "disk-jet connection," but he might as well have spoken about the "jet dis-connection." We have very little idea about how jets are launched. Most "unified" disk-jet models take the BP self-similar solution as their starting point. If the "centrifugal sling" is to overcome gravity, the field lines must come off the disk at an angle greater than 30° from the vertical (Fig. 3a). In the BP model, the disk is treated as an infinitely thin current sheet, but this will not do for a more realistic
model. Instead, a poloidal flux tube must bend by a rather large angle while crossing the disk from one side to the other. A strongly curved flux tube is subject to a strong tension force, which will try to straighten it out. Königl and Lovelace and collaborators have ingeniously balanced the tension of the curved field by the drag due to field line slippage, either as a result of anomalous resistivity or ambipolar diffusion. They have shown that it is possible to construct self-similar models in which the interior structure of the disk is matched onto a BP-type wind (Fig. 3b). But I have heard no arguments which convince me that such a finely tuned balance will be established naturally. Time-dependent numerical simulations of these systems should be done as soon as possible.

I see two particular threats to the kinds of disk-jet models that have been proposed to date. I call the first one the "advected field problem." The power carried by AGN and YSO jets leads one to seek a model in which a large fraction of the energy released by accretion ends up in the jet. In BP-type models, the magnetically driven wind
removes all the accretion energy and dispenses all the excess angular momentum.
To do this in a self-similar model requires that the poloidal magnetic field scale with
radius as $B_p \propto R^{-5/4}$. But how does one obtain a field that increases so steeply with
decreasing $R$? If the magnetic field is frozen into the disk and is advected inward, then
one would expect $B_p \propto \sigma$, where $\sigma$ is the disk surface density. In a steady-state disk
with accretion rate $\dot{M}$, $\sigma$ is related to the inflow speed $v_R$ by $\dot{M} \sim \sigma v_R R$. To obtain
the BP scaling, the inflow speed would have to scale with $R$ as $R^{1/4}$. Note that the
standard $\alpha$-model for disk viscosity predicts $\sigma \propto \alpha^{-1} (H/R)^{-2} R^{-1/2}$ (where $H$

is the disk scale height), which falls far short of the BP scaling for simple assumptions about
$H$ and $\alpha$. The situation gets worse if one allows the field lines to slip.

Conceivably, the flux dragged inward by the accretion flow over a period of time
might accumulate in the central regions, and somehow redistribute itself to give the
BP scaling. But no one has come up with a mechanism that produces this scaling in a
natural way. Indeed, very little work has been done on the fate of magnetic flux advected
inward in an accretion disk. This flux cannot accumulate forever, since the pressure of
the confined field would eventually stop the flow. But it is not clear that a steady-state
solution in which outward slippage balances inward advection, as has been advocated
by Königl and Lovelace, can be established in general. Instead, one might imagine a
highly unsteady mode of field evolution, as illustrated in Figure 4. It is tempting to
identify the large-scale reconnection events, which would occur quasi-periodically, with
FU Orionis outbursts and the formation of III objects in YSOs (Reipurth), and with
superluminal knots in AGNs.

The second problem faced by disk-jet models is the “net flux problem.” It is likely
that the net magnetic flux advected inward by the disk contributes only a small fraction
of the total magnetic energy present close to the disk. The rest would reside in a
turbulent field with zero net flux, perhaps generated through instabilities inside the disk
such as that described by Balbus & Hawley (1991). While the rms value of the magnetic
field strength might satisfy the BP scaling, production of a magnetically collimated jet
would be impossible, since the toroidal field on neighboring flux surfaces would twist
in opposite directions. As a result, the pressure forces between flux surfaces would
overwhelm the tension force required to collimate the flow. Magnetic self-collimation
requires the net flux to dominate over the rms flux density. Emergence of a jet from the
messy dynamo field above the disk would require the reconnection and dissipation of
most of the dynamo field. This is not necessarily a bad thing for jet formation. Under
certain circumstances, part of the energy liberated by reconnection could be used to
launch the jet, by literally flinging blobs of gas onto open field lines. Since the gas would
then start out with substantial kinetic energy, one need not worry about the angle at
which the field lines join the disk.

5. CONCLUDING REMARKS

I could not help but be impressed by morphological similarities between jets from
YSOs and AGNs. They both seem to behave more or less as fluid flows should, exhibiting
shocks and entrainment, and generally interacting with their surroundings as they
strive to keep their channels open. But there are also fundamental differences in the
mechanisms that make them shine, their compositions, and their environments. I am
not sure that there is much in the propagation of jets that will make for a long-term
relationship among the sub-disciplines. It is in the origin of jets that the deeper similari-
ities may lie. Models relying on magnetic acceleration look very promising, but are
Figure 4. Advection of magnetic flux by an accretion disk may lead to an intrinsically unsteady model. (a) Flux is advected inward and deposited near the center of the disk. (b) Forces due to accumulating field crowd out the disk field. (c) Accumulated field reconnects across the disk, accreted flux is left behind in outer part of the disk. Process then repeats. Note that the cycle of accumulation and reconnection may occur on a variety of scales in the disk, leading to a hierarchical mechanism for removal of accreted flux.

in their infancy. There is no direct observational evidence for them as yet. But it may well be that future "interdisciplinary" jet meetings will focus on common formation mechanisms, if these can be put on a firmer footing.
But does this mean that magnetic acceleration and self-collimation are the "essence" of jet formation? Other ingredients that are commonly invoked are rotation and a disk. If magnetic fields are propelling the jets in YSOs and AGNs, does that imply that the jets in SS 433 are also magnetically driven? It is possible, but SS 433 is also the best case for acceleration by radiation pressure. Right now, the jets from Galactic compact objects are wild cards. They might be deuces, clinching the existence of a single universal mechanism for jet formation, or jokers, confirming that the production of jets is a very robust generic process that can occur in many different ways.

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