R. D. Blandford

Hydromagnetic Outflow from Accretion Disks

ABSTRACT
Accretion disks are believed to be present with decreasing conviction in cataclysmic variables, X-ray binaries, protostars and active galactic nuclei. Collimated jets or bipolar outflows have been reported in examples of all four types of source. Magnetic extraction of disk angular momentum provides a generic method of launching and collimating these jets. A model for broad emission lines in quasars and Seyfert galaxies involving a disk- driven hydromagnetic outflow is outlined. This explanation may be appropriate to other classes of accretion disks.

INTRODUCTION

The interplay between gravitation, rotation and magnetic field, long studied in the classical theory of star formation, is notoriously subtle *e.g.*Parker (16). The initial concern that centrifugal force and magnetic pressure w ould prevent gravitational collapse has been replaced by the twin realisations that hydromagnetic torque provides a convenient means of extracting angular momentum and that magnetic flux can readily escape through buoyancy and ambipolar diffusion. Magnetic torques can be observed at work in the solar wind and have presumably slowed the sun's rotation over its lifetime just as appears to be the case for other F and G stars. Magnetic torques are also widely believed to establish the period distribution in cataclysmic variable stars longward of the period gap. The case for the dynamical importance of magnetic fields in stellar systems has been amply made.

Magnetic fields may also have a crucial role in the dynamics of two common astronomical structures, accretion disks and jets. Indeed, disks and jets (or bipolar outflows) are increasingly found in association, in active galactic nuclei (AGN), X-ray binaries, cataclysmic variables and protostars. It is reasonable to hypothesise that a magnetic field constitutes the mechanical link between these two types of flow.

In the standard theory of accretion disks, it is supposed that there exists a local viscosity responsible for angular momentum transport in the disk. This allows matter to sink slowly towards the central object, while its liberated angular momentum is removed to progressively larger radii. The viscous agent is generally supposed to be either turbulence or small scale magnetic field. It is my contention that, under many circumstances, much of the angular momentum is instead removed by surface magnetic stress and carried by a pair of jets.

These jets are probably launched centrifugally. To see how this might operate, consider an electrically conducting accretion disk threaded by magnetic field which is "frozen in" to moving gas. Plasma on the surface of the disk will also be constrained to move with the field line at the angular velocity of the disk, rather like a bead on a wire. Now if the field line leaves the disk vertically, the plasma will be bound stably and will simply undergo vertical epicyclic oscillation. However if the field direction is radially outward, then centrifugal force will dominate and the gas will be flung out. It turns out that for intermediate angles, the gas is unstable when the angle between the field and the disk vertical exceeds 30° (3). A modest radial variation of field strength with disk radius ensures that this condition will be satisfied.

Independent of these considerations, jets, most notably those associated with powerful radio sources and SS433, must be collimated by some form of external stress and observational arguments suggest that, in most instances, this is neither gas pressure nor radiation pressure. This leaves magnetic field. The simplest means of magnetic collimation operates when the jet carries a current so that a toroidal field is wrapped around it. There is magnetic tension associated with the field lines which, in association with the magnetic pressure, exerts a "hoop stress" on the jet. Although this magnetic field must itself be confined, presumably by thermal gas, the necessary pressure can be much smaller than the stress exerted on the jet walls. Loops of magnetic field can concentrate the stress onto a slender jet core. The origin of the toroidal magnetic field responsible for jet collimation is generally supposed to be gas orbiting a central compact object. A jet may therefore be a disk's way of shedding angular momentum.

I should relate my talk to the topic of this conference, particle acceleration in accreting compact objects. In a strict sense, the formation of jets by accretion disks is particle acceleration. However, our main concern here is with relativistic particles. I shall not discuss the direct acceleration of jets to flow speeds comparable with that of light as is observed to occur in compact extragalactic radio sources and SS433. This involves consideration of the central black hole, when present, and, necessarily, general relativity. However, relativistic electrons (and protons) can be accelerated by non-relativistic flows especially when the speeds are supersonic (*cf.*Achterberg's contribution). This is observed to occur in interplanetary shock waves and expanding supernova remnants. If real jets are formed in the manner outlined above, then they are unlikely to be as steady and axisymmetric as numerical and analytical simulations. Instead, they will be subject to a variety of instabilities and intermittency associated with activity in the disk which will create fast streams and internal shocks. It is hard to imagine that relativistic particle acceleration can be avoided under these circumstances, although it is not possible to quantify the fraction of the jet power that is likely to be dissipated in this manner.

I recently summarised the subject of hydromagnetic outflows from disks in a widely available conference proceedings Meyer *et al.*(1). Several articles in this book and the procedings edited by Belvedere (2) also cover this territory. I refer the reader to these references for general discussion. In this article, I shall therefore confine my attention to describing some work in progress on a model for the formation of AGN broad emission lines in a hydromagnetic outflow from an accretion disk.

BROAD EMISSION LINES FROM ACTIVE GALACTIC NUCLEI

One of the primary characteristics of quasars and Seyfert galaxies is broad emission lines. For a long while, these have been supposed to be formed by the photionisation of dense gas clouds by the central UV continuum source. Observations of the relative strengths of the lines have helped define the likely physical conditions in these clouds. Measurement of the line velocity profiles and, to a limited extent, their temporal variation, has stimulated a variety of kinematic proposals concerning the disposition of these clouds in phase space. However, some significant difficulties remain. Motivated by these problems, Robert Emmering, Isaac Shlossman and I are currently studying if these lines may be formed in a magnetically driven wind from a disk and I would like to report on our progress.

The permitted lines that are observed in most quasars and Seyfert 1 galaxies have velocity widths (HWZI) $\sim 10,000$km s^{-1} (15). The range of ionisation states observed is consistent with photoionisation by an extended UV and soft X-ray spectrum and the lines are sufficiently similar in profile that they are commonly characterised by a single ionisation parameter $n_{ion}/n_e \sim 10^{-2}$, where n_{ion} is the number density of (hydrogen) ionising photons and n_e is the electron density. The electron density is estimated from various spectral indicators, for example the presence of CIII]λ1909 and the absence of broad [OIII]λ5007to lie in the range 10^8cm$^{-3} \lesssim n_e \lesssim 10^{10}$cm^{-3} (Recent studies suggest that some denser gas may also contribute (18).) If the continuum radiation originates from a central source, the clouds must then be concentrated at a distance of $R \sim L_{UV46}^{1/2}$pc. Combining this distance estimate with the velocity width allows a virial mass of the central black hole to be estimated and values $\sim 10^{10}$M$_\odot$ are typically derived for quasars.

There are four problems with this standard interpretation.

(i) Emission lines are commonly observed to be cusped. The sharpness of the cusp is unclear, but it may often have a velocity width as small as $\sim$ 300km s^{-1}. The maximum velocity can be as large as 30,000km s^{-1} but is typically $\sim$ 10000km s^{-1}. If these velocities are representative of the local virial speed, then the gravitational potential must be dominated by the central black hole. A factor $\sim$ 30 in characteristic velocity then corresponds to a dynamic range $\sim 10^3$ in radius and a range $\sim 10^6$ in ionizing photon flux. This is inconsistent with the inferred approximate constancy of the ionization parameter and the limited range of allowed electron density.

(ii) The inferred black hole masses are surprisingly large, significantly larger than the upper limit central masses inferred in nearby galaxies. As more than $\sim$ one per cent of galaxies must once have been quasars, the nearest such mass should be $\sim$20Mpc away and it has not yet been identified (9).

(iii) Estimates of the size of Seyfert 1 broad line regions due to "reverberation mapping" in which the time delay between an observed variation in the strength of the continuum flux and the response of the emission lines is measured. In the best documented cases, these are inferred to be a factor $3-5$ smaller than sizes inferred from the ionization parameter (17).

(iv) The inferred pressures in the densest broad line clouds ($\sim$ 0.03dyne cm^{-2}), are too large to be confined by an inter-cloud medium, without invoking some extraneous heating mechanism. (The original suggestion that the intercloud medium is Compton-heated by a hard X-ray continuum, (10), fails because most AGN lack this hard component and their Compton temperatures are too low.)

There are some additional observational clues.

(i) The velocity profiles of the emission lines are not symmetric (22). Typically their peaks are blue-shifted by $\sim 500-1000$km s^{-1} with respect to the forbidden lines. Blue asymmetries in the line profile are also common.

(ii) The relationship between Seyfert 1 and Seyfert 2 galaxies has recently been clarified by polarisation observations (1). Seyfert 2 galaxies which do not exhibit broad wings in total intensity may do so in polarised light. This has been taken to imply that all Seyfert galaxies are essentially similar, but that the broad line region cannot be seen directly when viewed from an equatorial direction in Seyfert 2 galaxies. It can, however, be seen in light that is Thomson scattered by free electrons at high latitude.

(iii) It seems increasingly likely that broad absorption line quasars are normal emission line quasars viewed from special directions through a dense outflowing wind (21).

These factors motivated us to propose that the emission lines are formed by clouds of photoionised gas that are flung out from the surface of an accretion disk by magnetic stresses. (Although the gas in the disk may be originally neutral, it will almost certainly have sufficient ionisation for it to be tied to the magnetic field lines.) Let us consider our problems in turn.

The characteristic cusp profile can be reproduced if the outflow originates from several octaves of disk radius. The line profile associated with the outflow from a single ring of disk has a "twin peak" profile with a width that is a measure of the amplitude of the Keplerian velocity on the ring. Typically, the gas is accelerated to a velocity having both circular and poloidal components whose magnitude is several times the orbital speed in the disk. However what is observed is the projection of this velocity along the line of sight which is somewhat smaller. Only one hemisphere will be seen, and as there is net motion towards the observer, the centre of the profile will be blue-shifted. The total line profile is reproduced by the superposition of twin peaks from a range of radii, the net shape being a determined by the variation of emissivity with radius. We have computed total line profiles for a variety of emissivity prescriptions for an outflowing hydromagnetic wind. We find that the observed profiles can roughly be reproduced if the volume emissivity scales as the product of the magnetic pressure and the mean density in the outflow as we might expect. (At a fixed emission line gas temperature of $\sim 10^4$K, the emissivity per unit mass might scale as the recombination rate per unit mass, proportional to the pressure. The emissivity per unit volume is then formed by multiplying by the cloud density.)

However, this leaves the problem of explaining the large velocity range. To alleviate this problem, we propose that the broad wings may not be due to high bulk velocity of the emitting gas, but may instead be caused by electron scattering. To be more specific, we note that the outer parts of accretion disks are believed to be largely molecular and dusty (19). They can therefore re-radiate incident UV as infra red emission and most of the IR spectrum in normal quasars is thought to be produced in this manner. Now gas can only remain molecular as long as it can cool and this, in turn, requires that the dust remain cool enough ($T \lesssim 1500$K) not to sublime. By equating the radiation incident upon a grain to it emission, we find that the minimum radius for cool gas is ~ 0.1pc, where the Keplerian velocity is ~ 3000km s^{-1} for a powerful quasar.

The minimum velocity in the disk is unlikely to be less than the central velocity dispersion of a galaxy (~ 300km s^{-1}). (Indeed, it is an interesting observational project to see if observed line profiles are more cuspy than this.) In order to produce the full range of observed velocity width in the lines we propose that the lines are actually broadened by electron scattering. Roughly half the line photons emitted by outflowing clouds will illuminate the disk. Now, if the sun is any guide, it is quite likely that there be a hot corona above the surface of the accretion disk. If the coronal temperature is $T \sim 10^6$K, and the corona is optically thick to Thomson scattering, then the back-scattered radiation will be Doppler-shifted by the hot electrons to produce the observed broad wings (20). More detailed simulations verify that this does occur. (It might be thought that electron scattering will broaden the line profile. However, it turns out that the electron scattering redistribution function itself has a sharp gradient discontinuity at zero velocity shift and this preserves the cusp in the emission line profile.) By reducing the range of emission radius, we find that the range of ionisation parameter is also reduced.

Invoking electron scattering also alleviates our second problem above because the characteristic Keplerian velocity at the radius of the emission line clouds is reduced, thereby lowering the inferred central mass to $\sim 3 \times 10^8 M_\odot$ for a typical quasar.

We suspect that the third problem has a different solution. The cloud and gas density will be quite large close to the disk and this will render a large number of lines of sight partially opaque to the ionising UV radiation. The clouds will therefore be located closer to the central continuum source at a given photon density. An unrelated possibility, mentioned above, is that there may be a population of denser, optically thick clouds which would also be located closer to the continuum source.

The magnetic field is directly responsible for solving the final problem as it can confine clouds in the perpendicular direction. We envisage that cool clouds will be flung off the disk and, when they are exposed to the ionising flux, they will be heated to a higher pressure which will cause them to expand into the magnetic field until they achieve pressure balance. The clouds are free to expand along the direction of the magnetic field. However, this expansion will only be at the internal sound speed (as opposed to external fast mode speed for the transverse expansion). As the clouds move at high (sonic) Mach number, they will typically leave the emission region before they expand very much.

There is a second consequence of invoking magnetic pressure confinement and this involves the postulated electron scattering corona. One reason why electron scattering has not often been invoked in the past to broaden the emission line profiles is that gas at the required temperature of $\sim 2\times10^6$K is thermally unstable. Either it will heat to the Compton temperature $\sim 10^7$K or cool to 10^4K like the emision line clouds. However, the instability criterion must be modified if the confinement is by magnetic as opposed to thermal gas pressure. It turns out that gas at $\sim 10^6$K can be rendered thermally stable if magnetically confined.

What happens to the emission line gas after it leaves the disk? There is a substantial mass flux involved. Some of it may be decelerated by interaction with the ambient gas in the nucleus and may form the narrow line-emitting gas. It can also fall back onto the disk and be recycled several times.

Naturally, there are several predictions that follow from this interpretation. The most direct follow from our velocity field which is a superposition of axisymmetric rings that rotate, expand radially and translate vertically with respect to the disk. The line cores should be formed at greater distances than the gas at $\sim 1000 - 3000$km s^{-1}. This can be probed by comparing in detail the line profiles for different ions with different critical densities for collisional ionisation and by using "reverberation mapping". We also expect that the vertical velocity, measured by the blueshift, will be systematically larger for AGN observed at large angles to the disk. This effect may be detectable by comparing the velocity profiles of the different classes of Seyfert galaxy.

If electron scattering is responsible for the broad wings, then we expect that they should be linearly polarised and may show up in polarised light. As we have noted broad lines in polarised flux are observed from Seyfert 2 galaxies. However, we expect that the wings of Seyfert 1 galaxies should also be linearly polarised, although to a weaker degree on account of the different viewing angle. (Note that our explanation of the polarised wings seen in Seyfert 2 galaxies is subtly different from the standard explanation because the scattering electrons are located in a disk and seen along lines of sight where the optical depth is reduced. This is in contrast to invoking an otherwise very high density of free electrons.)

The Relationship to Jets

If this is the correct interpretation of the kinematics of emission line clouds, we must consider the connection between this outflow and that more directly observed in the form of extragalactic radio jets. Most AGN are radio quiet (though not silent). Nevertheless, observations of Seyfert galaxies suggest that they create weak, bipolar ouflows which produce biconical regions in which the narrow emission lines are often concentrated. (These lines may be excited directly by the outflow or may be photoionised by the central UV continuum which escapes preferentially along the directions evacuated by the outflow.)

Similarly, the majority of radio galaxies are relatively weak in emission lines and central bolometric luminosity. They are divided into two classes on the basis of their radio luminosities (4). Powerful radio galaxies appear to produce relativistic jets, which are responsible for beamed emission and apparent superluminal expansion when observed along their symmetry directions. The jets associated with lower power sources appear to move with speeds much less than that of light and are may not even be supersonic with respect to their internal sound speeds.

These observations can be interpreted in the following manner. Suppose that essentially all AGN contain accretion disks and associated bipolar outflows. Now the power liberated by the outer parts of the accretion disk is proportional to the mass accretion rate and is a relatively small fraction of the power that can be liberated when (and if) this gas reaches the innermost parts of the disk near the black hole. There is an additional source of power, the spin energy of the central black hole. If the central black hole is active, a powerful relativistic jet core will be produced and this will be collimated by the more slowly moving and essentially invisible outflow from the outer disk. If the central black hole is inactive, there will only be a weak and slow jet. The strength of the emission lines will be largely a reflection of the strength of the UV continuum produced by the inner disk and the relative importance of the broad components will be a measure of the orientation of our line of sight. On this interpretation, powerful jets will not be characterised by a single outflow speed, but will instead be cocooned in a slower moving sheath of denser gas.

The Galactic Centre

Although not "active" in the usual meaning of the word, our Galactic Centre may be the best environment in which to observe magnetically driven dynamical evolution of an accretion disk. Morris (12) has summarised observations on length scales of $\sim 10 - 100$pc of long, linear features variously called arcs filaments and threads, some of which exhibit linear polarisation consistent with synchrotron emission. Some of these features appear to pass straight through the plane of the Galactic disk. They have been widely interpreted as magnetic field bundles perhaps being illuminated by twisting in a fashion similar to that believed to occur in coronal loops and prominences. On a smaller scale ($\sim 1 - 10$pc), exists a molecular torus (6) in orbit about a central mass of a few million solar masses, possibly, though not necessarily, a black hole. 100μ polarisation observations (7) suggest that the magnetic field direction lies mainly in the disk rather than perpendicular to it. Furthermore, Zeeman splitting observations of the parallel component of the magnetic field, (*e.g.*Killeen, Lo and Crutcher 1990, preprint) indicate a strength ~1mG. slightly larger than the inferred equipartition magnetic field strengths. The simplest interpretation of these observations is that an open, poloidal field is convected inward by the disk gas and sheared by the differential rotation to become predominantly toroidal there. However, it may also be consistent with a model in which the disk magnetic field is more poloidal with a strength limited by the influence of ambipolar diffusion (Königl, 1990, preprint). Future observations should settle the matter.

Application to other Disk Systems

Broad emission lines have also been seen from other disk systems, notably protoplanetary disks (14), cataclysmic variables (13), SS433 (5) and the black hole candidate A 0620+00 (8). These may also originate, not in the accretion disk itself, but, instead, from a hydromagnetic bipolar outflow. This will increase the observed line widths. More detailed modelling is neccessary to determine of the salient features of the line profiles can be reproduced in this manner.

ACKNOWLEDGEMENTS

I am indebted to Bram Achterberg, Michiel van der Klis and Jan van Paradijs for the invitation to attend this meeting and travel support. I thank Robert Emmering and Isaac Shlossman for collaboration on some of the research described above. I also acknowledge financial support under NASA GRANT NAGW1301.

REFERENCES

(1) Antonnucci, R. J. J. and Miller, J. S., 1985. In: Astrophys. J., 297, 621.
(2) Belvedere, G. (ed.), 1989. *Accretion Disks and Magnetic Fields in Astrophysics* (Dordrecht: Kluwer).
(3) Blandford,R. D. and Payne, D. G., 1982. In: Mon. Not. R. astr. Soc., 199, 883.
(4) Bridle, A. H. and Perley, R. A., 1984. In: Ann. Rev. Astron. Astrophys., 22, 319.
(5) Filippenko, A. V., Romani, R. W., Sargent, W. L. W. and Blandford, R. D., 1988. In: Astronom. J., 96, 242.
(6) Genzel, R., (1989): In: *The Center of the Galaxy*, ed. by M. Morris (Dordrecht: Kluwer) p.393
(7) Hildebrand, R. *et al.*, 1990. In: Astrophys. J.. (in press)
(8) Johnston, H., Kulkarni, S. and Oke, J. B., 1989. In: Astrophys. J., 345, 492.
(9) Kormendy, J., 1988. In: Astrophys. J., 325, 128.
(10) Krolik, J., McKee, C. F. and Tarter, C. B., 1981. In: Astrophys. J., 249, 422.
(11) Meyer, P., Duschl, W., Frank, J. and Meyer-Hofmeister, E. (ed.), 1989. *Theory of Accretion Disks* (Dordrecht: Kluwer).
(12) Morris, M., 1990.: In: *Galactic and Intergalactic Magnetic Fields* ed. by R. Beck, P. Kronberg and R. Wielbinski (Dordrecht: Kluwer)(in press)
(13) Mauche, C. W. and Raymond, J. C., 1987. In: Astrophys. J., 323, 690.

(14) Mundt, R., (1985): In: *Protostars and Planets*, ed. by D. C. Black and M. S. Matthews (Tucson: University of Arizona Press) p.
(15) Osterbrock, D. E., 1989. *Astrophysics of Gaseous Nebulae and Active Galactic Nuclei* (Mill Valley: University Science Books).
(16) Parker, E. N., 1979. *Cosmical Magnetic Fields* (Oxford: Clarendon Press).
(17) Peterson, B. M., 1988. In: Publ. Astr. Soc. Pacific, 100, 18.
(18) Rees, M. J., Netzer, H. and Ferland, G. J., 1989. In: Astrophys. J., 347, 640.
(19) Sanders, D. B., Phinney, E. S., Neugebauer, G., Soifer, B. T. and Matthews, K., 1989. In: Astrophys. J., 347, 29.
(20) Shields, G. A. and McKee, C. F., 1981. In: Astrophys. J. Lett., 246, L57.
(21) Weymann, R. J., Turnshek, D. A. and Christiansen, W. A., (1985): In: *Astrophysics of Active Galaxies and Quasi-Stellar Objects*, ed. by J.Miller (Mill Valley: University Science Books) p.333
(22) Wilkes, B. J., 1986. In: Mon. Not. R. astr. Soc., 218, 331.

R. D. Blandford
Theoretical Astrophysics
130-33 Caltech
Pasadena
California 91125
U. S. A.