THEORY OF BIPOLAR FLOWS AND JETS FROM YOUNG STARS

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ABSTRACT. Current thinking on the origin, evolution and stability of stellar jets and bipolar flows is reviewed. Particular emphasis is given to the driving mechanisms of bipolar molecular and ionised gas outflows from young stellar objects. General constraints on both hydrodynamic and magnetohydrodynamic flows are presented. The interrelationship between the protostellar outflows and others such as those associated with powerful, highly collimated outflows in active galactic nuclei are discussed. Intimately connected phenomena such as maser sources and Herbig-Haro objects are briefly treated and finally, areas of potentially interesting future research are indicated.

I. INTRODUCTION

Observations of bipolar flows and jets have been made in an extraordinary variety of stellar and protostellar objects (c.f. Cohen, these proceedings) and, when discussed in the broader context of extragalactic radio jets, the range of luminosities, scales and densities attributable to this phenomenon are one of the more remarkable aspects of current astrophysics. While focussing here on flows from young stars I will draw considerably on work done over a longer time concerned with the extragalactic problem. My task is to review theories of these young stellar objects and to bring out the salient physical merits and demerits of various models to try to, at least, indicate where each model may be applicable and what can be learned from it. No single model explains the whole range of observations but I have selected to review those that are generally useful for reasonably large subsets.

The relatively close (10^2-10^3 pc) protostellar flows and jets are particularly fascinating to jet theorists because of the wealth of observational detail over many wave bands with consequently good physical constraints on the relevant parameters such as density, pressure, momentum and energy flow. In fact with the very high resolution and high astrometric accuracy data available with, say, the Hubble Space Telescope or the Very Long Baseline Array, it may be possible to make real time hydrodynamics observations of jet formation

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in protostellar objects and evolution over, say, a twenty year timescale for flows in the nearby Taurus-Aurigae association.

An additional, very general aspect of the models is the frequently invoked presence of an accretion disk. Although there is, as yet, very little direct evidence for these in protostellar systems it is obvious they must be there from angular momentum considerations and consequently may well strongly influence collimated flows. In fact, the evolution of bipolar flows and protostellar disks are inextricably related over the whole pre-main sequence phase from massive molecular outflows and protostellar disks to T-Tauri outflows and disks to the protoplanetary and planetary systems. When considering the Hertzprung Russell diagram for pre-main sequence evolutionary tracks both these additional effects of disks and bipolar flows should be incorporated in the track calculations.

I shall first discuss generally properties of the omni-present jets and bipolar flows (§II) and then review in more detail the facts concerning bipolar flows from young stellar objects. The origin, evolution and stability for both magnetised and unmagnetised flows are analyzed in the next two sections (§III and §IV). On small scales much can be learned by studying structures in the flow that give both OH and H_2O maser emission and emission-line objects such as Herbig-Haro objects (§V). The final section (§VI) is devoted to a summary and sketch of future work.

II. BIPOLAR FLOWS AND JETS

A quick mental run through of properties of the ubiquitous jet and bipolar flow phenomena shows an enormous dynamic range for the physical environment in which they are found. Large scale extragalactic radio jets have scales of ~100 kpc and luminosities of $\sim 10^{44}$ erg s^{-1}, intermediate scales are of order kiloparsecs with total powers of order 10^{43} erg s^{-1}, and compact jets resolved by VLBI techniques on scales of ~10 pc can have energy outputs of order 10^{45} erg s^{-1}. Closer to home in the Galaxy, sources such as SS433 and Sco X-1 seem very similar to the extragalactic sources. The Galactic Centre itself shows signs of a mildly collimated outflow possibly due to a starburst (Sofue 1984) and other recently discovered starburst driven extragalactic bipolar outflows have been found by deep CCD imaging in M82, Arp 220 and other IRAS selected sources (Heckman 1986, McCarthy et al. 1986). At the smallest end of the scale are the bipolar outflows from young stellar objects with scales of at most parsecs, velocities of order 10^2 km s^{-1} and central object mass of 1-10 $M_\odot$. This is a contrast of 10^6 in length, 10^4 in velocity and 10^8 in mass of central object between the powerful jets in active galactic nuclei and those in young stellar objects. The similarities in these outflows have been documented recently by Konigl (1986) to be high collimation and two sidedness, length extending over several decades, association with emission-line knots, origination in compact objects, termination in extended lobes, association with surface instabilities and entrainment, a possibly significant effect played by magnetic fields and quite generally an invocation of an origin associated with disks.

The specifically relevant physical parameters for molecular outflows and young stellar objects are; the high momentum input with $\dot{M}_w V_w \sim 10^2 - 10^3$ (L/c) (Lada 1985) where $\dot{M}_w$, V_w are the mass flow and velocity in the jet and L is the luminosity of the central object; the realization that the ionized central jets have insufficient momentum to drive the molecular outflow; characteristic velocities of order 10-100 km s^{-1}; Herbig-Haro and H_2O maser velocities of order 200-400 km s^{-1}; and other such details given in relevant reviews in this volume.

III. HYDRODYNAMIC FLOWS

The original Blandford and Rees (1974) application of the de Laval nozzle concept to jet collimation is applicable here if the dense molecular jets do not cool before they are nozzled (Konigl 1986). Nozzling occurs when the flow speed equals the sound speed in the flow and application of the formula for the ratio of cooling length, L, to characteristic flow scale, R_s,

$$\frac{l_{cool}}{R_s} = 10^{-5} \left[\frac{V_w}{10^2 \text{ km s}^{-1}}\right]^7 \left[\frac{L_{flow}}{L_\odot}\right]^{-1} \left[\frac{R_s}{10^{14} \text{ cm}}\right] \gtrsim 1$$

gives a required velocity in the case of L1551 of

$$V_w > 10^{2.5} \left(\frac{R_s}{10^{14} \text{ cm}}\right)^{-0.14} \text{km s}^{-1}.$$

Therefore one infers that typically the highest velocity jets could indeed feel this effect. For such flows, as indicated by Smith *et al.* (1983) bubbles, jets and clouds may form in the flow, depending on the mechanical luminosity in the jet and the sound speed on the cavity walls. Bubbles will form when the Kelvin-Helmhotz instability disrupts the surface of the cavity in which the jet is focussing. This effect is stabilised at higher flow velocities when the flow time across the cavity beats the Kelvin-Helmholtz growth rate. At higher luminosities the high pressure, low density jet will induce a Rayleigh-Taylor instability at the boundary with the cooler higher density external cavity medium. Such instabilities could possibly form structures that will eventually cool and form bullets and knots further along in the flow.

Bipolar flows are not highly collimated. Explosions in an inhomogeneous atmosphere were ruled out as a collimating mechanism for narrow extragalactic jets but in this protostellar context they may well be relevant. Calculations were made by Sanders (1976) and Mollenhof (1976) who concluded that for the exponential atmosphere, an initially point explosion will break out of the atmosphere in a few characteristic exponential scale heights, forming a mildly focussed cone with a break out angle of order the inverse Mach Number in the flow at the break out point. Focussing was found to give cone or bipolar flow opening angles of 25°-40°. In a similar spirit calculations of wind-driven flows in inhomogeneous atmospheres have been made by Sakashita and Hanami (1986), Konigl (1982), Okuda and Ikeuchi (1986) and Dyson (1984) for both the energy driven and momentum driven cases. Generally the thin-shell Laumbach-Probstein method, or variations thereon, was used. Here again after a few scale heights a mildly collimated outflow was formed. A careful analysis of existing data led Dyson to conclude that the energy driven calculations give the best agreement. Once again the absence of cooling is required, which can really only be satisfied for high jet velocities.

A completely different but powerful approach to the disk wind solution has been made by Bardeen and Berger (1978). They sought the stationary state for a massive self-gravitating disk with a wind by assuming the flow solutions would be self-similar. Such a viewpoint is potentially very powerful particularly for assessing focussing at large distances. Their self-similar solution needs internal heat sources in the flow to maintain the self-similarity but a modified version of this could be very relevant for molecular flows.

Expanding collimated flows can undergo reconfinement and even renozzling (Saunders 1983, Konigl 1982, Smith 1982). If the flow is in a region of low external pressure relative to that in the jet it will expand freely with an opening angle of order its internal Mach number. If it then propagates into a relatively higher pressure region (i.e., it hits a cloud or intercloud fragment) then pressure waves and shocks will travel back into the jet and it will reconfine, adjusting to the increased external pressure. Generally speaking if the external pressure falls as $p_{ext} \propto r^{-n}$, for $n > 2$ the jet will be free, for $n < 2$ there will be reconfinement and for $n = 2$ the jet will propagate in an unchanged manner. As discussed by Shu (these proceedings), self-similar collapse of isothermal clouds has an $n = 2$ solution. Both the reconfinement process and over-expansion process during the transition to confined or free jets can generate a train of Mach disks. In cooling flows, it has been suggested by a number of authors that the observed quasi-regularly spaced knots in jets may be a consequence of such a physical process (Mundt, this volume).

There are now quite rigorous calculations of essentially Kelvin-Helmholtz type instabilities in shearing, cylindrical jets with and without magnetic fields. The general form is that of a radially dependent function with a phase term $\sim e^{i(kz+n\theta-wt)}$. The standard nomenclature is that $n = 0$ is a pinching mode, $n = 1$ is a helical or kink mode, $n \geq 2$ are classified as flute modes. Ordinary modes exist even without the cylindrical boundary but reflection modes require one. It is now clear that these instabilities are hard to stablize. They can be slowed by increasing the density contrast between jet and environment for either light or heavy jets; velocity profiles with shear scale lengths, h, at, for example, the jet-environment boundary layer can stabilize short wavelength instabilities for wave numbers $kh \gtrsim 1$. Smooth profiles can show the growth for wavenumbers $ka \lesssim a/h$ which can be very significant for reflection modes; jet expansion corresponds to an expanding, comoving cylindrical radius $a = a\ (t)$ and allows secular rather than exponential growth to occur; magnetic fields can stabilize these modes if the Alfven speed greatly exceeds the sound speed, pinch stability is realized if $M \lesssim 2v_A/c_s$ and all modes stabilize if $M < 1$.

Observable consequences of these instabilities have been proposed to be that internal reflection modes shock and produce knots, helical modes produce twists and bends, and the general overall Kelvin-Helmholtz instability can produce flaring of jets. Saturation of this instability occurs when the perturbed flow trajectory diverges from the cylindrical one by an angle more than the inverse Mach number M^{-1}. In this case a shock will form. The final result of the Kelvin-Helmholtz saturated instability is probably to form an inner stable jet system with a much wider and turbulent, shearing, cocoon possibly found by the nor-linear evolution of cats eyes and shocks.

IV. HYDROMAGNETIC FLOWS

That magnetic fields are highly important in cloud structure, star forming regions and collimated outflows has long been suspected by theorists and is now becoming increasingly obvious from careful observational studies. Across the Taurus dark cloud complex the linear polarization measurements of Monetti et al. (1984) show a clear large scale alignment of clouds, subclouds and the overall magnetic field. The polarization data of Hodapp (1984) again indicates a strong correlation between polarization angle and flow direction in a number of sources including DG Tau, NGC 2071 and GL 961. Strom and Strom (1985) illustrate the remarkable alignment of four collimated structures in Orion across a large part of the entire complex which are also aligned with at least two other such systems in another region. While only circumstantial evidence for a general overall organizing mechanism, the cloud's magnetic field could obviously consistently explain this. A more quantitative study of the relationship between the projected directions of bipolar outflows and the interstellar magnetic field has been presented for 10 well studied bipolar sources (Cohen et al. 1984) and there is a clear alignment effect within of order ~30°. Therefore we feel confident the study of magnetized cloud structures is a very significant undertaking.

Anisotropic gravitational collapse naturally results in a pancake structure (Lin, Mestel and Shu 1985, see however Goodman and Binney 1983). The necessary small initial pressure anisotropy can easily be provided by the magnetic field when the cloud exceeds its magnetic Jeans' mass. A global field structure could, in this way, induce large scale pancake alignment in a cloud complex. More generally, collapse is expected to occur along field lines in a magnetically dominated system. When considering a wind or explosion in a medium dominated by a magnetic field the strongly anisotropic pressure will give rise to stationary flows preferentially elongated along the magnetic field.

The first paper to seriously suggest that hydromagnetic effects gave rise to bipolar flows was that of Draine (1983) who envisaged that one way or another a rapidly spinning, highly magnetized object was formed in the strongly non-equilibrium situation associated with the protostar formation process. Extremely strong toroidal fields, B_ϕ, are built up and there is strong pressure gradient $\nabla(B_\phi^2/8\pi)$ upwards and toward the axis that produces the collimated outflow. This mechanism certainly works but the credibility of these highly transient, non-equilibrium initial conditions has been questioned and will be discussed later.

In a seminal paper Blandford and Payne (1982) discovered and analysed the self-similar centrifugally driven outflow from a disk. The similarity assumption is that all velocities scale with disk rotation curves such that $v_A(r) \alpha\ c_S(r) \alpha\ v_{rot}(r)$. The case studied by these authors is the Keplerian one, but the flat rotation curve case seems also to be of relevance for massive self-gravitating protostellar disks. The wind is generated by particles heated at the surface of the disk in a corona that can move along corotating field lines on which the outward directed centrifugally driven 'sling shot' force exceeds the gravitational binding force at the disk. A smooth hydromagnetic flow develops and above the Alfvenic surface, as inertial forces become important, the field lines are swept back and strong toroidal fields develop with associated inwardly directed pinching forces, or hoop stresses, that tend to self confine the flow along its symmetry axis.

Uchida and Shibata (1985) have made remarkable axisymmetric magnetohydrodynamic calculations of a magnetically driven outflow where the principal driver is the strongly sheared and wound up toroidal magnetic field whose $\nabla(B_\phi^2/k\pi)$ force focusses the flow toward the axis. This is a fundamentally non-equilibrium, system and should be understood as a natural development of Uchida's work on the development and evolution of coronal transients. Its philosophical basis is quite similar to that of Draine (1983).

Pudritz and Norman (1983, 1986a, b) have considered in great detail the physics of a centrifugally driven wind from molecular disks surrounding the central protostar. The disk component is essential here since it is the huge angular momentum of the disk that is utilised in order to provide the basic driver of the outflow. The focussing is again that due to hoop stress. Typically, there is a central ionized gas flow at ~300 km s^{-1} with mass loss rate $\sim 10^{-6}\ M_\odot\ yr^{-1}$, a massive molecular wind $\dot{M}_{molec} \sim 10^{-4}\ M_\odot\ yr^{-1}$ with characteristic velocity ~50 km s^{-1}. The flow will corotate with rotation velocity roughly of order ~1 km s^{-1} up to the Alfven surface as has been found in LISS1 by Kaifu et al. (1984). At the termination surface of the flow there is a magnetohydrodynamic shock that could give characteristic shocked molecular lines such as H_2. In the flow itself there are Herbig-Hero objects and H_2O masses. The model can successfully account for the momentum and energy of the bipolar flow phenomenon and is a natural consequence of the standard magnetised collapse scenario for the star formation process. The magnetically driven bipolar flow transports angular momentum away from the disk thus acting as our effective source of viscosity. This in turn drives disk evolution further which drives the wind completing the feedback cycle. Clearly positive feedback driven outbursts can be generated in the feedback loop here. Corotation will occur out to the Alfven surface $R_A \sim (\Phi^2/\Omega\dot{M}_w)$, where Φ is the magnetic flux in the disk. Gradual acceleration of the flow will take place from the surface of the disk to the Alfven surface. The flow pattern is similar to that of a cone with some density profile increasing outwards i.e. a somewhat hollow cone. It is to be expected that once Uchida and Shibata run their code for long enough their initially transient state will with appropriate boundary conditions settle down to a steady state wind model as described in the Pudritz-Norman scenario. This is a model in which I have every confidence but because of the nature of this review it is only fair to give equal time to other alternatives. A major point here is that the theory does require substantial protostellar disks of which more should be observed in the near future.

In a most interesting paper Sakurai (1985) has solved numerically (not simulated) the difficult transfield equation for stationary axisymmetric magnetohydrodynamic flow. His boundary conditions were the simplest possible, that of a magnetic monopole. He finds that interior to the Alfven surface the toroidal field $\nabla(B_\phi^2/k\pi)$ initially focusses the flow and outside the Alfven surface hoop stress acts to focus this further. He is currently planning to calculate the complete wind-disk problem using this method.

There are a number of indications that axisymmetric magnetohydrodynamic flows may focus to the axis under quite a wide range of boundary conditions. Norman and Heyvaerts (1986, in preparation) have shown that; field line curvature is an invariant for open field lines above the Alfven surface for cold flows and consequently any slightly focussed field line at this inner region will remain so at infinity; a perturbation theory developed about the axis shows that focussing will always occur if the density fall off is $p \sim r^{-n}$ where n is less than or equal to 2; and finally all qualitative indications and numerical calculations lead to the conjecture that many, if not all, axisymmetric magnetohydrodynamic flows with only open field lines (i.e., no dead zone) will tend to focus along the axis of symmetry. With merely a conjecture this may give an underlying physical basis for the ubiquity of the jet phenomenon.

Another good way to approach our understanding of magnetic confinement of jets is to study sef-similar solution of cylindrical jets. Achterberg, Blandford and Goldreich (1983) adopted the scaling laws $B\phi \sim 1/r$, $v_A \sim$ constant, $B_r \sim r$, $v_\phi \sim r$, and $\partial p/\partial r \sim r$ and found a solution that for the jet transverse velocity that could be expressed as motion in an effective potential dependent only on the transverse radius. Quasi-periodic oscillations in the transverse cross section of the cylinder were found. The focussing was due to a balance of toroidal magnetic pinching, magnetic pressure, ram pressure, and internal thermal pressure. The solution matched roughly some extragalactic jet observational data and could be pursued further in the content of young stellar objects.

V. H_2O MASERS, HERBIG-HARO OBJECTS, AND OTHER RELEVANT OBSERVATIONS

Herbig-Haro objects are clearly associated with bipolar flows as are the high-velocity H_2O masers. This topic is discussed extensively elsewhere in this volume by Raga and analysed assuming that they are bullets (Norman and Silk 1979). Consequently all the beautiful recent data on this topic could well lead to a far better understanding of cooling processes, thermal instabilities, densities, temperature and processes in the flows themselves (Raga and Bohn 1986, Raga 1986, Raga, Bohm and Solf 1986).

H_2O masers are probably pumped in shock associated with bullets. These are C-shocks with broad magnetic precursors. The only viable models that pumps the strong masers as well as the lower luminosity ones is that in which hot electrons pump the maser up by collisions and cold neutrals pump it down by collisions. This two temperature system avoids the saturation problem (Kylafis and Norman 1986a, b). Here one can infer more accurately physical conditions in masers and their associated bipolar flow environment. H_2O masers can be used as excellent tracers of the proper motion of parts of the flow hydrodynamics particularly with the future VLBA.

Other simple questions concerning observations of bipolar flows include; the crucial question of whether all the flows corotate as indicated for L1551 by Kaifu *et al.* (1984); are bipolar flows associated with binaries, in particular those with S-shaped mirror symmetry; what are the further details of the correlations of these objects with magnetic fields; what are the physical parameters that can be determined by studying the molecular shocks, cavity boundaries and shells; is there an unambiquious association with molecular disks; what are statistical studies able to tell us--are these flows steady or integrated versions of a number of transient outbursts; can the Hubble Space Telescope really do real time hydrodynamics or will these be marred by phase effects where it is not in fact physical knots that seem to move.

VI. SUMMARY

I have only been able to briefly touch on some of the remarkably beautiful work that is being undertaken in this field. In assimilating our view of theories of the origin, evolution and stability of bipolar flows from young stellar objects and their relationship to other jets it seems obvious how highly interactive this field is between many fields including active galactic nuclei, and starbursts, star formation, numerical simulations and analytic hydrodynamics and magnetohydrodynamics. At this meeting the cross interaction has been excellent and I thank the organizers for their efforts in making this possible.

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