SESSION II

FORMATION, EQUILIBRIUM AND STABILITY OF JETS

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ABSTRACT

Consideration of the many observed types of jets on scales ranging from parsecs to megaparsecs seen in radio, optical, infrared and X-ray wavebands with a variety of morphologies both in galactic and extragalactic systems leads to some constraints on their fundamental nature. Jet formation is introduced with the concept of the Laval nozzle and related points include the problem of maintaining the nozzle, Mach disk effects due to under and over-expansion and the potential importance of magnetic confinement and focussing. Current ideas on jet formation at the black hole and accretion disk are given with emphasis on the plasma physics associated with black-hole electrodynamics, thermal and magnetically driven winds and thick disks. Stability of jet propagation is reviewed with emphasis on magnetised and unmagnetised Kelvin-Helmholtz instabilities and the various dominant modes. The particle acceleration physics of shocks, wave-particle interactions and turbulence is summarised while noting some outstanding plasma physics problems. Jet equilibrium associated with the non-linear saturation of instabilities, the formation of cocoons, shock stabilisation and magnetic fields is discussed. Detailed plasma physics studies that could significantly clarify jet physics are indicated.

I. INTRODUCTION

The range of scientific phenomena associated with the formation, stability and equilibrium of jets is extremely broad. Originally proposed to explain powerful double radio sources (Rees, 1971), the jet hypothesis has found widespread application to observations in all wavebands on both galactic and extragalactic scales. In this review I shall concentrate on exhibiting the important plasma astrophysics problems in the study of jets. I shall be posing more problems to this talented interdisciplinary group from many different fields of plasma physics, space physics and astronomy than I can answer, and I hope to stimulate a productive cross discipline interaction.

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It is very difficult to outline the well motivated plasma problems that can be directly inferred from the observations. We have nothing like a laboratory set-up such as Dr. Stenzel's or even satellite experiments such as Dr. Kennel's where the relevant microscopic processes can be isolated experimentally. It is a situation perhaps akin to early solar physics where our models are what motivates the interesting plasma problems. With this in mind the plasma astrophysicist is then challenged to solve some rather interesting physics problems concerning, for example, relativistic collisonless shock structure, energy flow in shearing turbulent fluids, particle acceleration, magnetic confinement mechanisms for jets and magnetic reconnection studies in turbulent jet flow. Specifically in the area of jet formation models one is faced with modelling, for example, black hole and accretion disk coronae and magnetospheres complete with general relativistic effects on electric circuit models of magnetospheres!

The definition of a jet is best obtained by inspecting some really excellent examples of various jet classes. This can be found in the proceedings of the recent IAU meeting No. 98 and the Turin Astrophysical Jets workshop. Here I shall merely state the examples of various classes of jet that I selected to illustrate the talk. Jets range from being quite straight over hundreds of kiloparsecs (HB 13) and highly collimated on all scales (NGC 236, NGC 6251), with occasionally an extreme widening or flaring at larger distances (IC 4296), to exhibiting considerable bending (NGC 449, NGC 326) with the classic head tail radio source NGC 1265 as an extreme case. VLBI jets such as 3C 236, 3C 303.1 and 3C 138 often show clear alignment with large scales. Severe bending is often seen in intermediate scale maps from the MERLIN array (3C 371, 3C 454.3) and small scale inner jets are seen in Seyfert and Markarian galaxies. Jets are also seen in the X-ray (Centaurus-A) and in the optical (3C 273, 3C 305 and Coma A). In our own Galaxy Coma A is a miniature, classic extragalactic double radio source, SS 433 has a well defined jet outflow, bipolar or collimated flows around protostars in molecular clouds are now often found (S 140, S 68, Mon R2) and there is even a potential jet candidate in the Galactic centre. The very high resolution numerical simulations produced by M. Norman and Winkler using the Garching Cray machine are now sufficiently detailed to provide us with excellent observational material to be assimilated with the real world. So much for the observations. Their direct interpretation is still rather controversial and the physical parameters are not particularly well constrained.

Extragalactic jets could still be either relativistic or non-relativistic. Superluminal motion observed in some radio cores seems compelling evidence for relativistic bulk motion (Blandford et al., 1977) although we should await the results of the new VLBI surveys of faint radio cores before being too definite. The large bending angles observed in extended radio jets seem most consistent with non-relativistic speeds (van Groningen et al., 1980). To slow a jet from relativistic in the galaxy core to non-relativistic further out requires the dissipation of most of the initial jet luminosity which would in general violate the observational limits, but energisation of the broad line region may be a real effect (Norman and Miley, 1983). Many jets look confined rather than free, for example HB 13. In a number of cases, for example 4C 32.69 (Potash and Wardle, 1980), extreme pressures are demanded for thermal confinement and magnetic confinement is most plausible. Whether jets could be generally magnetically, as opposed to thermally, confined is unclear. A related question is whether jets are heavy or light in terms of density contrast with their environment. Light jets will be buoyant and dense jets may develop knots and thermal instabilities. Knot structure in jets could well be due to cooling instabilities or alternatively to shock structures in a time variable jet flow. Convolved in with our basic jet model is the brightness function of jets associated with particle acceleration processes for the synchrotron radiating relativistic electrons. One-sided jets are seen with symmetrical hot spots and lobes on both sides of the parent galaxy. Therefore jets are either intrinsically invisible, glowing when triggered by a propagation instability, or always glowing, but rendered invisible by a physical process such as Doppler fading.

II. JET FORMATION

Why is the jet phenomena so ubiquitous? The most obvious concept of focussing a point explosion in an inhomogeneous atmosphere does not work. As shown by Sanders (1976), the focussing angle is only 25°-40° from the vertical direction for an exponential atmosphere where the explosion breaks free within a few scale heights. At break out, the cone angle is typically the inverse of the Mach number $\sim M^{-1}$ where M is the ratio of shock velocity to post shock sound speed. Only in the case where the density profile of a rifle barrel was used could any significant focussing be found and in no case would it account for jet collimation over a scale range of at least 10^6!

Continuous injection and outflow models can avoid at least some of these problems. The simplest and first version was the de Laval nozzle concept introduced by Blandford and Rees (1974) who noted that the transition from subsonic to supersonic in a preexisting one-dimensional flow involves a pinching or nozzling of the jet cross-section. A detailed numerical study of this process in an inhomogeneous atmosphere has been presented by Smith et al. (1981, 1983) who made several important clarifications. The nozzle point (at r_n) and the spherical shock between the injected fluid and the pre-nozzle cavity (at r_c) are rather close to each other; $r_n/r_c = 1.18$ and 1.05 for $\gamma = 5/3$ and $4/3$ respectively for strong shocks, so that the one-dimensional nozzle approximation may not be valid or alternatively the shocks may be weak. Interesting instability regions were isolated as a function of jet power. For a specified cavity sound speed, at low luminosity the nozzle becomes Kelvin-Helmholtz unstable resulting in "bubbling" at the nozzle, at higher luminosities the nozzle stabilises as the jet flow convection beats the instability and thus results in a stable flow regime. However, this regime has an upper luminosity limit where the cavity itself becomes Rayleigh-Tayler unstable creating clouds to be injected into the flow.

The pressures required to confine the nozzle for high luminosity jets are rather extreme (Blandford and Rees, 1978) and in the case of thermal confinement the gas would have to be dense X-ray emitting material which is not observed. Magnetic nozzling is a good candidate here but may be viewed as part of the class of direct jet formation models associated with black hole and accretion disk physics. Thick accretion disks develop very deep vortex funnels at their centres (Lynden-Bell, 1978). These are rifle barrels of the type referred to earlier. Abramowicz and Piran (1980) showed that a highly collimated radiation flux will flow up the funnel acting on matter injected from the funnel-disk surface. Very effective collimation occurs but the particles are so locked to the radiation flow that bulk Lorentz factors of at most only a few are produced which could lead to problems in certain models of superluminal sources.

While analysing accretion disk electrodynamics, Blandford (1976) found a similarity solution for the free-free magnetosphere above an accretion disk that could transport a sufficient flow of energy and angular momentum necessary for a steady flow in a Keplerian accretion disk. The poloidal field lines are paraboloidal with foci on the rotation axis and at larger distances the field becomes predominantly toroidal leading to focussed magnetically confined jets. Analogous self-similar solutions are given in Blandford and Payne (1982) for the magnetohydrodynamic field structure above a Keplerian disk. Similar flow patterns result. It is interesting to note here that both these models give quite a good qualitative understanding of the recent magnetic jet formation work of Uchida and Shibata (1983) who applied their numerical results mainly to the high beta to low beta transition for flux loops emerging into the solar corona and found that the emerging field evolves into a predominantly toroidal configuration focussed along the vertical axis, as in the above examples.

Black hole electrodynamics incorporates one of the most promising jet formation models (Blandford and Znajek, 1977, MacDonald and Thorne, 1982). A black hole is threaded by field lines that are due to currents flowing in a surrounding accretion disk or torus. The black hole has a surface resistance of 377 ohms and, as for any magnetospheric problem, an equivalent electric circuit can be drawn (Ionson, these proceedings). Incidentally, this is also true for the accretion disk electrodynamics problem. The maximum energy output from the hole occurs when the external impedance matches that of the hole. This seems to be related to the dissipative microphysical processes occurring in the far magnetosphere but there may be a more fundamental basis (Phinney, 1983). This question and the detailed examination of black holes magnetospheres seem a rich field of research for the current audience.

An interesting plasma physics problem arises when considering the ion-pressure supported torus model of galactic nuclei (Rees et al., 1982, Phinney, 1982). For very low accretion rates, thick disks or tori of hot ions will circulate a hole, their electrons having cooled via synchrotron or Compton losses, the ions remaining hot since they spiral into the hole before temperature equilibration due to Coulomb collisions occurs. Fields generated by currents in this torus thread the hole and extract energy from it. A two year old challenge is to prove this is instable. It is not obviously so. Characteristic scales are so large that current driven instabilities are unlikely to occur. Coupling between electrons and ions is unlikely due to the large frequency and wave number mismatch. As yet uncalculated anisotropic effects may do it, Dr. Coroniti may elaborate on these topics. Finally, it is important to mention the nearby jet-like systems in our own Galaxy and their formation mechanism. Particularly exciting is the possibility of observing jet flows form in real time over the next two decades using the Space Telescope on protostellar jets in the nearby Taurus-Aurigae association - a mere $10^{2.3}$ pc away!

III. JET INSTABILITY

Jet stability begins classically with the Klevin-Helmholtz instability (cf. Ferrari, these proceedings). For a cylindrical jet with shear flow, streaming through an ambient medium one applies a perturbation $\sim g(r)e^{i(kz+n\Theta-wt)}$ for jet radius r, Θ a polar coordinate on its circumference, the jet axis as the z-axis, t being time, and w, k and n are perturbation frequency, wave-number of the z coordinate and polar coordinate respectively. The standard ordinary mode classification calls $n = 0$ the Pinching mode, $n = 1$ the Helical or Kink mode and $n \geqslant 2$ the Flute mode. Effects due to the finite geometry are very important via the reflection models which can often dominate the physics of the jet instability.

Briefly summarising the instability behaviour (Hardee, 1982a,b; Ferrari et al., 1980, 1981, 1982; Cohn, 1983) of a jet with initial radius a, long wavelengths (with $ka \ll 1$) are always unstable if the propagation angle is large enough and here the helical and flute modes dominate. Short wavelength purely longitudinal modes ($ka \gg 1$) are stable for Mach numbers greater than $2\sqrt{2}$ but, for finite propagation angles ($\sim 90°$), they are always unstable. The reflection mode is always unstable for $ka \sim 1$ and Mach numbers $\gtrsim 2\frac{1}{2}$. Pinching dominates for large Mach numbers and in general the growth rates are faster than the ordinary mode.

Growth rates can be reduced by a density contrast for either heavy or light jets. For relativistic flows the ordinary modes have zero growth as the bulk Lorentz factor γ_b goes to infinity but for the reflection mode there is no real suppression except that ka tends to zero as γ_b goes to infinity. For strongly magnetised jets where the Alfven velocity v_A greatly exceeds the sound speed c_s all modes stabilise. The pinch can be stabilised for Mach numbers $\leqslant 2 \frac{v_A}{c_s}$ and all modes are stable for $M < 1$. Velocity profiles with a shear scale $\sim h$ stabilize the short wavelength modes for $k\,h \gtrsim 1$ and smoother profiles show growth for $ka \lesssim a/n$ which can be very important for reflection modes. Hardee (1983) incorporated jet expansion effects and showed that exponential growth rates become secular but remember how straight HB 13 is over most of its length.

Observable consequences of the instability calculation are that reflection modes may produce quasi periodic knot structures (Norman and Winkler, 1983) and that helical modes may produce twists and bends in, for example, M87 (Hardee, 1982) and flaring in NGC 236. The non-linear development of the Kelvin-Helmholtz instability is an important factor in considering jet equilibrium.

IV. NON-LINEAR EFFECTS AND EQUILIBRIUM

The actual jet equilibrium is related to the observations by a convolution with the relativistic electron and magnetic field dependent brightness function. What we see indeed looks turbulent and highly non-linear: an equilibrium only with a considerable coarse graining of the observations. The numerical work (Norman et al., 1981, 1983) shows the Kelvin-Helmholtz instability saturates in shocks, Mach disks, knot structures and back flowing cocoon around the jet.

The development of shocks during the Kelvin-Helmholtz instability occurs when the transverse expansion velocity of the perturbation exceeds the sound speed. Shocks then develop, making an angle ~ 1/M with the jet axis. Further growth of the instability is slowed from exponential to secular (Benford, 1981). Of particular interest for knots are the intersecting shock structures that develop from the reflection mode. Cocoons drive shock structures in the jets as the back flowing vortices pinch the jet in the axially symmetric case. Clearly three-dimensional work will be important here and the slender jet approximation may prove a useful first estimate (Smith and Norman, 1981a,b).

Thermally confined jets break free if the external pressure drops as $r^{-\alpha}$ where α exceeds 2 and consequently the transverse velocity becomes supersonic (Smith, 1982). Jets do not in general look free with a characteristic opening angle ~ 1/M. A solution is to reconfine the flow which, as shown by Sanders (1983) results in a series of Mach disks spaced roughly at the Prandtl wave length λ_p = Ma. Internal shocks could cause reheating and a quasi periodic free expansion and reconfinement process. Of particular observational relevance are the gaps in jets observed between VLBI scales and, say, the Holmberg radius of the parent galaxy. The jet may be switched on by the reconfinement shocks due to particle acceleration processes in shocks. Quasi-periodic knot structures may be found in the train of Mach disks created by overexpansion or reconfinement.

Magnetic confinement mechanisms are very plausible (Benford, 1978, 1981, 1983) and solar wind techniques have proved most useful (Chan and Henriksen, 1980; Achterberg et al., 1983). Making a self-similar hypothesis for the MHD flow variables an effective potential can be found for the behaviour of the jet radius where the effects of toroidal field, internal pressure, longitudinal field and toroidal flow are included. Motion in this effective potential is seen to be quasi-periodic and can be modelled to fit 3C 31 jet structure if the energy density in the toroidal field is roughly 1% (Bridle et al., 1980) of the bulk kinetic energy density.

In principle the Kelvin-Helmholtz instability can be saturated by particle acceleration (Lacombe, 1977; Benford et al., 1980; Henriksen et al., 1982; Bicknell and Melrose, 1983; Krautter et al., 1983). The reasoning is that the Kelvin-Helmholtz instability drives a turbulent cascade from wave numbers ka ~ 1 that is subsequently dominated either by hydrodynamic effects (Henriksen, these proceedings) or collisionless wave-wave interactions (Benford et al., 1980). At a particular wave number the cascade dissipates either by Fermi acceleration, resonant wave-particle interactions, weak shocks or heating. In practice one would expect that only some of the available free energy could be saturated in the particle acceleration process. The turbulence and particle acceleration regions must diffuse inward from the jet cocoon shear layer since limb brightening is not, in general, found (Eilek, 1982). No significant magentic field generation occurs as the Kelvin-Helmholtz does not generate helicity (de Young, 1980). A real weakness of both theory and data is that most of the above mentioned models can fit the observations!

Jet brightness is inconsistent with flux freezing and adiabatic expansion of the relativistic electrons. Magnetic field reconnection could provide the energy source for the particle acceleration but the reconnection process would have to be driven on very small scales since for typical jet parameters the Reynolds number is 10^{15}! Numerical simulations (cf. de Young, 1980) are one approach but possibly a minimum energy type variational principle could be constructed allowing an estimate of the available free energy in analogy to the solar corona (Norman and Heyvaerts, 1983, Heyvaerts and Priest, 1983).

A final word about shocks. That they develop in jet flow and can accelerate particles is unquestionable (cf. Blandford and Eichler, 1983). However, there is no real consensus yet on what limits the particle acceleration efficiency: shock precursor pressure of the accelerated particles, heating of the thermal component, escape of the highest energy particles or the limitations of the Alfven wave scattering centre amplitude to a value $\delta B/B \sim 1$ (McKenzie and Völk, 1981). Since it is electrons that radiate we require not only that the protons, but also electrons, are injected into the shock acceleration regime; possible mechanisms are preacceleration due to electrostatic processes in perpendicular shocks or Fermi acceleration. Note that whistlers as well as Alfven waves may become important scattering centers. Many shocks will not have time to develop into a stationary state, the upper energy cut-off to the accelerated particle distributions being given by equating the acceleration time to the shock age as is observed in the interplanetary medium.

These questions of non-linear self-consistent, self-regulating shock structures and particle injection seem one of the most precisely formulated challenges confronting the plasma astrophysicist. Considerable help is on the way from the study of quasi parallel shocks in the interplanetary medium (Kennel, these proceedings).

V. SUMMARY

Jet physics embraces many major plasma astrophysics problems including the magnetospheres and coronae of black holes and accretion disks, fully developed turbulence in magnetised, shearing jet flows, and the understanding of detailed shock structures and particle acceleration processes.

Emission line structures are now seen associated with jets and lobes and in these cases densities, temperatures and velocities can be constrained. This is the observational area that can allow much more detailed modelling to be done (cf. Norman and Miley, 1983). Much help can be gained from interdisciplinary collaboration in even just helping pose the correct question (cf. Kennel, these proceedings)! The problems are hard but involve extremely challenging and profound concepts at the frontiers of current astrophysics.

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DISCUSSION

Sturrock: What is the origin of the magnetic field in jets?

Norman: Probably entrainment, since the Kelvin-Helmholtz instability does not generate helicity and the expansion factors >> 10^6 in some cases made primordial fields generated at the jet origin unlikely as the dominant field in the jet at large distances.

Eichler: My impression of the axisymmetric simulations of Norman et al. is that they yield poor collimation. Is that the case?

Norman: Collimation is far better than for a point explosion in an inhomogeneous atmosphere, but for highly collimated flows from 10^{15}-10^{25} cm, some reconfinement and recollimation is necessary.

Vasyliunas: The term "jet" carries the connotation of flow along the observed structure. How strong is the evidence for such a flow, or is it simply that no one can think of another possibility?

Norman: Many other possibilities have been thought of in this context, including low frequency electromagnetic waves, compact objects, γ-rays and electron-position beams.

Chiuderi: Is it true that flow velocities deduced from optical emission lines are much smaller than those required by fluid models?

Norman: The emission line studies give velocities in the range 300-500 km s^{-1}, which is indeed at the lower end of the expected jet velocities. The interpretation of these observed emission line velocities as directly reflecting the jet's velocity is not yet certain.

Krishan: Has anyone tried to study the correlation between the velocity flows (from simulation) and magnetic fields from polarization data?

Norman: Not yet, but I hope this will be done soon.

Uchida: The importance of a large scale magnetic field in guiding the jet or in determining the initial direction of jets hasn't been mentioned. Shibata and myself recently worked on the formation of jets by a toroidal field relaxing into a low-β region along the external magnetic field (in these proceedings).

Norman: As noted in the text, your work can be quite nicely explained in terms of the physics of a magnetically confined jet shown by the simularity solutions.

Bratenahl: Regarding those beautiful numerical jets at the beginning, what were the boundary conditions? I saw no spreading. How was it confined?

Norman: The pictures I showed (due to Norman and Winkler) were taken in the comoving frame of the jet head in the simulation. The confinement is due to the external medium, as is probably the case in the real world.

Priest: What are the values of basic parameters such as the plasma beta and the ratio of the know separation to the mean free path or ion gyroradius?

Norman: The plasma's magnetic field is inferred using equipartition arguments and, therefore, beta is always of order unity. For typical parameters the proton gyroradius is many orders of magnitude less than the characteristic flow scales and, therefore, the fluid approximation is a good one.

Kundu: I have a question related to the physics of jets. I know from observational evidence that galaxies in the process of merging are more violently radio emissive than the interacting galaxies. Can you explain this in physical terms?

Norman: Merging can severely dynamically distort the surroundings of the central engines, repopulating stellar and gaseous orbits that can be used as fuel for the central black hole, say. Some of this has been ruled out in Norman and Silk (Ap.J. 266, 502, 1983) and Lake and Norman (Ap.J. 270, 51, 1983).