MHD EQUILIBRIUM AND INSTABILITIES IN EXTRAGALACTIC JETS

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ABSTRACT

Morphologies, energetics and nonthermal radiation emission of extragalactic radio sources can be explained in the framework of models based on the physics of supersonic jets interacting with the surrounding intergalactic medium. In this review current physical interpretation of acceleration, collimation, modulation and nonthermal radiation of these jets are discussed. We begin with an analysis of the equilibrium configurations of collimated flows; the propagation outside the galactic nuclei is shown to be modulated by fluid, MHD and resistive instabilities, which, at the same time, support charged particle acceleration by turbulent stochastic processes, and consequently nonthermal radiation emission from the radio to the X-ray range. Large scale morphologies (knots, wiggles and bendings) are considered from the point of view of their interpretation as global perturbations of the flow produced by fluid instabilities.

I. INTRODUCTION

The general scheme of our present knowledge about extragalactic jets has been summarized by Colin Norman in a previous review at this Symposium. Their most striking characteristic is that they emerge already collimated from the parent galactic nuclei ($\ll$ 0.1 pc) and afterwards maintain their perfect collimation over large distances until they reach the final lobes (up to a few Mpcs from the core, in some cases); all of this even though expansions, recollimations, wiggles, sharp bendings, etc., which clearly indicate a continuous interaction with the external medium. In Fig. 1 a few typical examples of this behavior are shown, namely NGC 6251 (perfect collimation and wiggles, Bridle and Perley 1983), 3C 129 (large bending, Burns 1983), 3C 418 (sharp helical structure in the nucleus, Browne *et al.* 1983). Fig. 2 gives the X-ray emissivity along the jet of Cyg A as measured by the Einstein Observatory (Feigelson 1982), which, when interpreted as bremsstrahlung emission, provides the density distribution of the gas around the jet (emissivity $\propto n^2$). More detailed observational data and theoretical arguments can be found in the Proceedings of the IAU Albuquerque Symposium on **Extragalactic Radio Sources** (Heeschen and Wade eds., 1982) and of the Torino International Workshop on **Astrophysical Jets** (Ferrari and Pacholczyck eds., 1983).

M. R. Kundu and G. D. Holman (eds.), Unstable Current Systems and Plasma Instabilities in Astrophysics, 393–412.

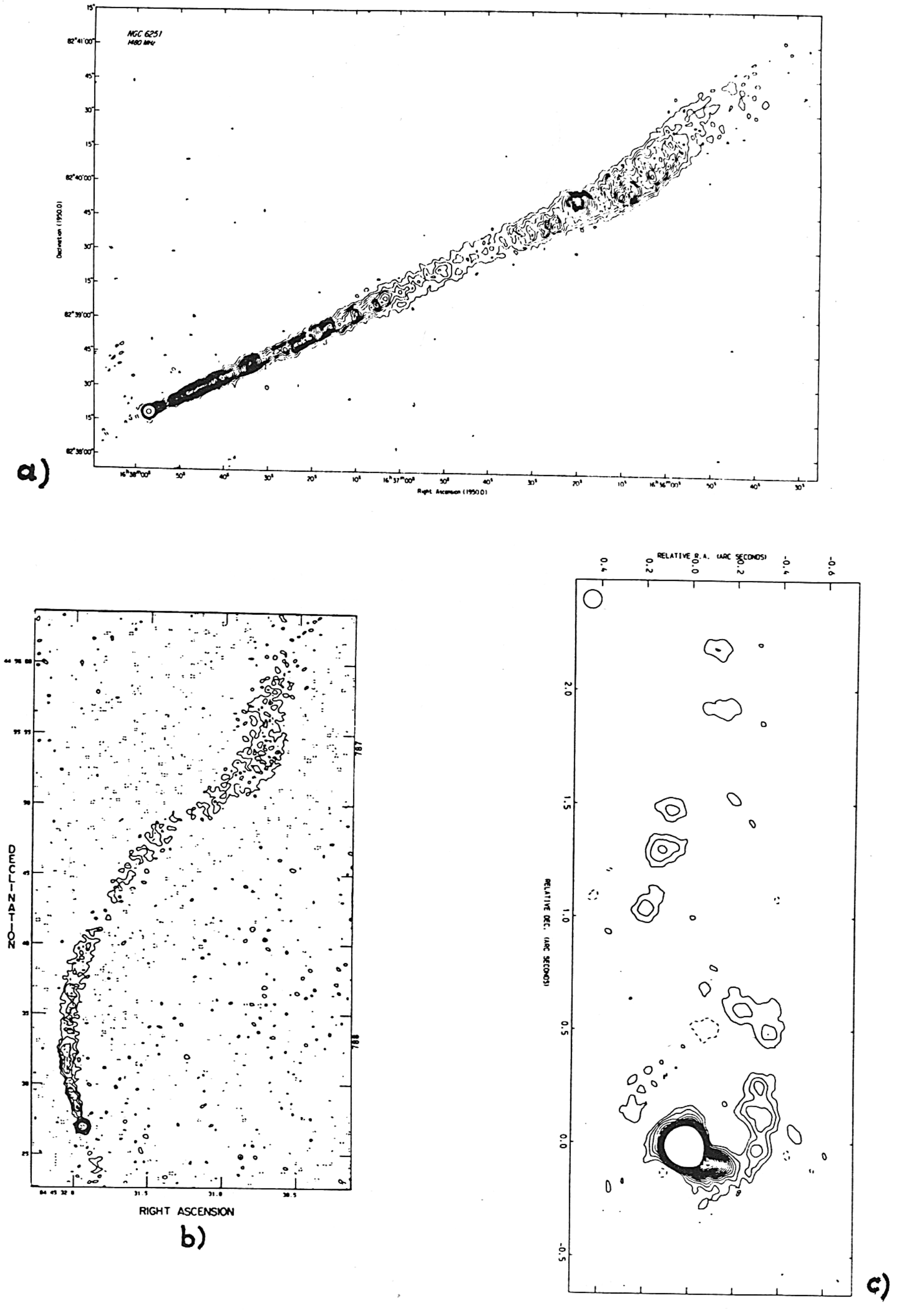

Fig. 1 - (a) VLA map of NGC 6251; (b) VLA map of 3C 129; (c) MERLIN map of 3C 418.

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In the framework of the existing scenario I present in this review some of the arguments which have been recently debated about the physical processes involved in the propagation and stability of extragalactic jets; these are typical plasma physics phenomena, which have been applied in similar contexts, as it appears from the papers presented at this Symposium: I must however warn the reader that, models for jets are at present underconstrained, and many of them can actually fit the data. We have still to find out which effects are actually more important.

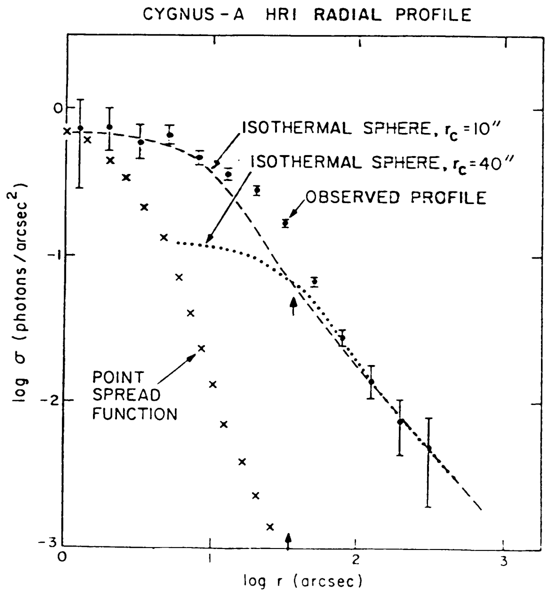

Fig. 2.
X-ray emissivity from regions surrounding the jet of Cyg A; distances are indicated from the core; arrows indicate the position of radio lobes (courtesy of E. Feigelson).

I shall devote the three following Sections to discuss collimation, stability and radiation of jets respectively; namely I shall try to emphasize which physical processes appear to be more relevant, and therefore deserve more detailed studies in the future.

In Table I the standard set of numerical values for the physical parameters of radio sources is presented: these values are derived using the incoherent synchrotron model for the radio emission from these sources, and the argument of energy equipartition between magnetic field and relativistic particles (Pacholczyk 1970). Table I illustrates the values for the four regions in which a radio source can be divided: core, jet, hot spot, extended lobe. In this respect one should keep in mind that our estimates are obviously obtained from the relativistic component of the plasma in the jet, as this is responsible for the observed nonthermal emission; the following discussion will be concerned instead with the bulk flow,

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and therefore with the thermal component of jets. How these different components are actually related is not clear at present, but the argument of equipartition appears to be valid also with thermal particles, at least as a constraint to estimates.

TABLE I

Average Physical Parameters in Jets

	Core	Jet	Hot-spot	Lobe-Halo
r(kpc)	<0.01	2÷1000	5	50÷1000
B_{eq}(G)	10^{-3}	10^{-5}	10^{-5}	$10^{-5.5}$
$n_{rel}(cm^{-3})$	$10^{-5.5}$	$10^{-10.5}$	$10^{-10.5}$	10^{-11}
$n_{th}(cm^{-3})$	-	$10^{-2} \div 10^{-5}$	$< 10^{-2}$	$> 10^{-5}$
% polariz.	< 2	0 ÷ 60	15	0 ÷ 60
V_b/c	< 1	$10^{-2} \div 10^{-1}$	10^{-3}	10^{-3}

Finally Table II shows a list of the measured lengths of small amplitude oscillatory perturbations (*wiggles*) in units of the observed jet radius (Bridle, private communication); they will be later confronted with the characteristics of the instabilities acting upon the flow. Note that all the jets in this list flare up after 2 - 3 oscillations of measurable amplitude.

TABLE II

Wiggle Wavelengths in Units of Jet Radius R
(R is taken as the mean HWHM of the jet
over the region of wiggling)

NGC 315 Base	1.3 kpc	6 R
M 87 Knots	0.6	22
3C 31 North	5	4
3C 449 South	17	14
NGC 6251 Outer	32	8
0326+396 West	36	12
4CT 74.17.1	56	7

II. EQUILIBRIUM CONFIGURATIONS OF JETS

The idea that extended extragalactic radio sources might indicate a continuous outflow of matter from active galactive nuclei was first proposed by Rees in 1971; until then, extended lobes had been actually considered the remnants of episodic ejections of single blobs of matter. The immediate advantage of the continuous outflow model was that the energy required from the associated galactic nuclei to support these structures could be diluted in time; but the idea was soon substantiated by high sensitivity observations which displayed bridges of emission connecting cores and lobes, and showed that the brightness distribution of these jets is actually continuous. Nevertheless direct measurements of jet velocity do not exist, if one excludes the detection of superluminal motions inside cores. Perhaps direct results will be soon available through optical line emission data, which are now being collected (Miley 1983). At present however we still rely solely upon the self-consistency of the idea.

II.1 Basic physical parameters and approximations

Originally, because of the low density suggested by observations, jets were studied in terms of the motion of test particles inside cavities plowed through the intergalactic medium by an original ejection of denser blobs of high-velocity matter (Longair *et al.* 1973); Rees (1971) also considered the possibility of jets powered by a low-frequency electromagnetic wave, as in pulsar models (with the appropriate scalings). Later it was realized that in fact collisionless beams of ejected particles might show collective aspects, due to the underlying action of magnetic fields, whose presence is implied by synchrotron models (Blandford and Rees 1974). I start therefore with a brief analysis of the arguments which allow to apply fluid considerations to a jet.

From the data of Table I it is easy to calculate that the collision mean-free-path is actually larger than the typical radius of a jet, while the thermal ($T > 10^7$ K) ion gyroradius is much smaller:

$$\ell_{coll} = \frac{(kT)^2}{n\, e^4 \ln \Lambda} \gtrsim R \gg r_g = \frac{m\, v\, c\gamma}{e B}. \qquad (1)$$

Typical values for ℓ_{coll} are larger than 10^4 pc and for r_g smaller than 10^{12} cm. This means that the plasma in a jet is essentially collisionless in terms of short-range interactions, but actually behaves collectively due to long-range interactions. Therefore we can assume, at least as a first approximation, that fluid equations can be used to describe the jet propagation. The plasma can be considered as quasi-neutral, since its Debye length λ_{De} is smaller than 10^7 cm; nevertheless a charge separation $|\,[n^- - n^+]/[n^- + n^+]\,| \sim 10^{-15}$ can be easily present, which is sufficient to generate magnetic fields of the order of equipartition fields.

The situation is more uncertain with viscosity and pressure anisotropy, as these are related with microscopic effects (undetectable directly). Deviations from pressure isotropy are likely to be negligible in the fluid approximation, as fast microscopic instabilities are ready to restore it; in addition we know that they do not modify substantially MHD stability calculations (Sen 1963). Much more delicate is the influence of viscosity, as we shall also discuss later in relation with numerical simulations. In accordance with some results valid for the case of the solar wind interacting with the Earth's magnetosphere (Eviatar and Wolf 1968), we may estimate that the value of the Reynolds number, Re, in terms of an *effective magnetic turbulent viscosity* is:

$$Re = \frac{R}{r_g} \gtrsim 10^{10}. \qquad (2)$$

As the formation of boundary layers and shears depends critically on the Reynolds number, their direct measurement would allow to put constraints to many of the models that we shall discuss in the following. However at present we can only say that the thickness of shear layers is certainly larger than r_g and probably of the order of R; this upper value is suggested by the study of instability (Sec. III).

II.2 Flow confinement

The next important question to answer before using a fluid model for jets, and for studying their stability, refers to the interaction with the external medium. A specific discussion on this point for the case of M87 jet is presented by Hardee (these Proceedings). Here I restrict myself to the general arguments.

The basic question is: are jets confined or free? Which is the evidence from observations? The internal and external pressures are both composite:

$$p_{int} = p_{th} + p_{rel} + \frac{B_{\parallel}^2 + B_{\perp}^2}{8\pi} \tag{3}$$

$$p_{ext} = p_{IGM} + \frac{B_{IGM}^2}{8\pi} + \frac{B_{\theta}^2}{8\pi}. \tag{4}$$

Namely the internal pressure is the sum of the pressures of thermal plasma, relativistic electrons and internal magnetic fields; the external pressure is due to the intergalactic medium thermal and magnetic pressures plus the confining pressure of azimuthal magnetic fields consistently generated by currents flowing along with the jet. Equipartition arguments on radio luminosities and spectra give lower limits for the value of the internal pressure (the relativistic and magnetic components only are included); X-ray emissivity of halos around jets allows to determine p_{IGM}, while the magnetic pressure of the IGM is considered negligible. No direct measurement of the azimuthal fields can be made, consistently with the fact that it has to be external to the jets, in regions of low effective emissivity.

The general trend of observational data is the following (see Miley 1980). Large scale structures and extended jets appear to be thermally confined; bright knots and hot spots are probably non-equilibrium, evolving features (e.g. shocks). Ram pressure confinement can also be important at the jet leading surface. However in at least three well-studied jets, M87 (Schreier *et al.* 1982), Cen A (Feigelson *et al.* 1981) and 4C 32.69 (Potash and Wardle 1980), p_{IGM} appear to be one or two order of magnitude below the lower limit for p_{int}. On the other hand, these jets appear to be very far from what one would expect in a free jet: namely, no regular opening angle is measured, but the flow in all cases goes through various phases of expansion; in addition the momentum flux that one derives for 4C 32.69 is so large, that it becomes impossible to explain the sharp bendings in terms of freely expanding flows. The obvious conclusion is that the azimuthal magnetic field is required for confinement (whether the above three cases are in fact exceptions cannot be decided at present). However one must keep in mind that magnetic confinement can be globally unstable if the external field required is substantially larger than the internal equipartition field (Parker 1979).

There are also indirect arguments which support the idea that jets are in some way confined. For instance Bridle (1982) has studied in some sources the extension of the beam radius against the distance from the nucleus, $R \propto z^{\alpha}$, finding that α is generally variable, in some cases even negative (recollimation), rarely close to 1, as it should be for free jets. This variable behaviour (from expansion to recollimation in a rather irregular way) indicates that jets do not simply expand at the diffusion speed (i.e. the speed of sound); on the contrary, they may go through different regimes in which they manage to reach equilibrium against some external confining agent, magnetic or thermal pressure. Clearly in these phases one expects the formation of boundary layers, with magnetic field amplification and development of viscous stresses. It will be interesting to detect observational evidences of the presence of these regions by using radio techniques with high angular resolution.

II.3 Hydrodynamic equilibrium models

Several authors have investigated the dynamics of jets, elaborating steady equilibrium models, based on different physical *ingredients*. I shall divide models in two main classes, depending on whether they include the effects of confining magnetic fields.

The pioneering paper of the first class is by Blandford and Rees (1974), who however included some pre-existent embrionic ideas (Gull and Northover 1973, Longair *et al*. 1973). An active galactic nucleus contains hot relativistic plasma buoyant with respect to the surrounding galactic matter; hot bubbles can then escape along the direction of least resistance, namely the rotation axis of the galaxy. The balance of hydrostatic and gravitational pressures external to the flow provides the conditions for the formation of two opposite nozzles, where the bulk flow velocity becomes supersonic at the expenses of the bubbles internal energy. Afterwards the flow remains supersonic, and the subsequent morphology is determined by the interaction with a light extragalactic medium; the extended radio lobes represent the head of this supersonic flow where a *working surface* dissipates most of the bulk kinetic energy.

In practice this model explain the acceleration by assuming a suitable shape for the confining plasma. Correspondingly, nozzles occur on galactic scale, and therefore relatively far from the core, as their position is essentially determined by the overall gravitational field; observations show instead that jets form well inside the cores. Numerical computations performed by Wiita (1978) have tried to overcome the difficulty, but still the position of the nozzle is an external input.

A new approach in the framework of fluid models has been recently devised by Ferrari *et al*. (1983a) and is discussed in more detail by Tsinganos in these Proceedings. The idea is to follow the acceleration and collimation of the jet from the accretion disk itself using the quasi 2-D theory of stellar winds (see for instance Kopp and Holzer 1976). The power of the method is based on reducing the problem to a single coordinate along the flow and transforming the lateral stresses in the form of geometrical effects. Obviously this means that one must assume independently the physical conditions for confinement, but from then on the flow is completely determined. It is then possible to write an equation for the flow velocity along the jet, where the forces acting on the plasma are the gravitational pull, the thermal pressure gradient and other forms of momentum deposition. In this scheme the acceleration can be produced either by the geometry of the confining medium, which determine the effective pressure gradients, or by the deposition of momentum through electromagnetic or plasma waves formed at the boundaries of the confining medium (the disk walls inside accretion funnels, or the interstellar medium outside the core). In particular one can follow the transition to supersonic velocity and define the conditions that this takes place well inside the disk funnel; also one can predict directly the formation of shocks when more critical solutions are allowed by the the parameters of the configuration. The momentum deposition needed to accelerate high-velocity beams is found to correspond to the Eddington limit; one can also predict morphologies created by the shocks induced by lateral perturbations, as for instance kink modes from Kelvin-Helmholtz instabilities.

The propagation of free jets has been calculated in some detail by Sanders (1983, preprint). What would be the appearance of a jet coming out from the galactic core into an underpressured region? Actually it will not be allowed to expand freely and smoothly, because its sudden expansion will produce lateral shocks, when the expansion velocity reaches the sonic velocity. Ultimately these shocks will provide a sort of self-collimation (see also Courant and Friedrichs 1948). This result means that, after all, a free jet cannot be very different from a confined jet because it must always be surrounded by a layer where pressure balances thermal expansion. Begelman (1982) has discussed how confined jets can simulate free jet expansion in terms of the effect of viscous stresses at the flow boundary.

II.4 MHD equilibrium models

The prototype of the class of models in which magnetic fields are taken into account consistently, is by Chan and Henriksen (1980), who have derived a self-similar solution for the dynamical MHD equations of an axially symmetric 2-D flow, including rotation around the symmetry axis. They were able to reproduce the observed morphologies and their various regimes of expansion, assuming reasonable distributions for the external pressure p_{ext} (z) along the flow and different values of the ratio

$$\epsilon_B = \frac{B_\theta^{\,2}}{4\pi\rho v_{z\infty}^{\,2}} , \qquad (5)$$

which measures the pinching effect of the azimuthal magnetic field (at the nozzle point) over the flow (asymptotic) longitudinal velocity; i.e. high-velocity jets require some large B_θ at the nozzle . Recently Krautter *et al.* (1983) have pushed the implications of this model further, taking into account specific equations of state for the jet plasma. They find good fit to observations for plasma actually dominated by the relativistic electron component, which is a rather interesting result. The magnetic fields required for pinching the flow in recollimation regions are always close to the equipartition fields.

In a similar framework Benford (1978) has discussed the origin of the azimuthal field in terms of a longitudinal current carried by the flow itself; to produce such a current a charge separation of the order of 10^{-15} is already sufficient. In support to this model one may hope to detect the azimuthal field. Observations so far are not favourable: strong jets have longitudinal fields, and jets with perpendicular fields have longitudinal structures at the edges. However in this model B_θ has to be external to the jet; then relativistic electrons are very few in regions where they could emit in the presence of B_θ. Therefore observations of weak background fields are necessary. A problem in this model is how to produce well ordered currents inside the jet, and the corresponding return currents outside it.

II.5 Numerical simulations

Sophisticated numerical simulations are now under study by several authors. The most detailed calculations published so far have been obtained by Norman *et al.* (1983) using a 2-D axially symmetric fluid code; this code allows the analysis of the rich morphology arising from the interaction of a supersonic flow with the surrounding medium *in conditions of pressure equilibrium.* The acceleration process is assumed to take place following the twin-jets model proposed by Blandford and Rees; collimation is provided by the external pressure at the nozzle and afterwards. The flow (see Fig. 3) develops perturbations at the contact discontinuity with the external medium, forming ripples and corrugations, and shedding its kinetic energy into a cocoon flowing backwards with respect to the leading edge. The cocoon is thicker for jets lighter than the external medium, corresponding to the formation of larger ripples. Internal shocks form along the jet, with spacing typically fixed by the fastest growing modes of the Kelvin-Helmholtz instability (see next Section). However the flow as a whole appears to be dynamically stable, since all perturbations moving backwards from the leading surface are progressively damped. No magnetic field effects are contemplated in this code and thus one cannot test other forms of confinement.

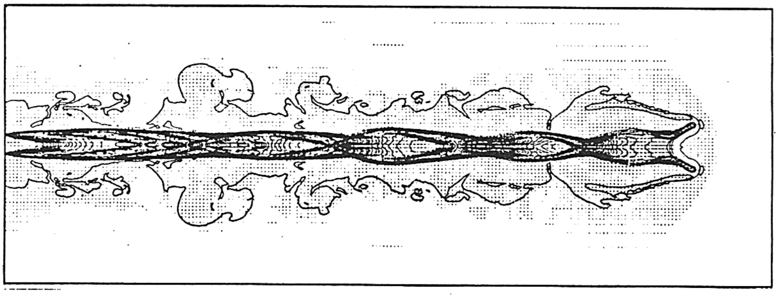

Fig. 3 - Numerical simulation of hydrodynamic jets (after M. Norman).

The numerical approach, though impressive, suffers from some fundamental inconsistencies (in addition to the fact that we are not able yet to describe the physics of the phenomena it displays).

1) The code does not allow non-axisymmetric perturbations, which on the other hand appear to be the most dangerous for the stability, if one refers to the data of laboratory experiments with collisional fluids.
2) In order to treat the formation of shocks the code has to include a numerical viscosity, which corresponds to Reynolds numbers much lower than those predicted by Eq. (2): this may excessively damp instabilities on short scales and thence stop the formation of turbulent diffusion.

Much more work is required on these points, which are in fact very critical for understanding the physics of these flows and to relate their morphology with the observed emission (I shall comment more on the second aspect in Sec. IV). However I note that several numerical works of interest in this context are

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already in progress. Wiita (1978) and Yokosawa *et al.* (1983) have addressed to the relativistic effects in the Rees and Blandford's scheme. Nepveu (1980) has directly discussed the effects of viscosity, finding results very similar to those of Norman *et al.*, but acknowledging the inconsistency of assuming high effective viscosity. Woodward (1983) is working on a 3-D code that will permit to represent non-axisymmetric effects. Finally I mention the numerical study of MHD flows presented at this Symposium by Uchida, which, if applicable to extragalactic jets, will enable us to evaluate some aspects of the physics of magnetically confined flows.

III. STABILITY OF DIRECTED FLOWS

A simple look at standard textbooxs on fluid dynamics (e.g. Goldstein 1965, Van Dyke 1982) must make anybody wonder how extragalactic jets manage to propagate over long distances without loosing collimation, while laboratory jets become soon turbulent and spread with large opening angles. The original idea to circumvent this objection was proposing that extragalactic jets are highly supersonic and free, and therefore do not loose their momentum to a surrounding medium, but expand at the speed of sound, which is much lower than the flow velocity. However I have discussed in the previous Section that observational data on morphologies do not support that idea: jets appear to *feel* the presence of an external confinement. Whether this is a thermal or magnetic pressure does not make much difference: jets seem to be very vulnerable to instabilities of all kinds.

III.1 Kelvin-Helmholtz instabilities

A large number of papers have been written on the linear stability analysis of collimated fluid jets in extragalactic radio sources (Blake 1972, Scheuer and Turland 1976, Blandford and Pringle 1976, Ferrari *et al.* 1978, Ferrari and Trussoni 1978, Hardee 1979, Benford 1981, Ray 1981, Cohn 1983).

The most obvious instability from which confined fluid flows are likely to suffer is Kelvin-Helmholtz instability, arising between fluids in relative motion. The classical literature, referring to the case of an infinite plane contact surface separating (incompressible or compressible) fluids (Chandrasekhar 1961, Gerwin 1968), shows that instability sets in for all perturbation scale lengths provided their wave vector is larger than the gradient scale of the physical quantities across the contact surface. At the same time, when considering compressible flows, an upper limit on unstable Mach numbers, M_{uc}, is found (for perfect gas is $M_{uc} = \sqrt{8}$). This limit arises from the obvious fact that, when the flow is largely supersonic, a perturbation cannot satisfy causality conditions across the contact surface, as it travels typically at the sonic speed. As a matter of fact the limit actually refers to the Mach number component along the wave vector of the mode considered. In fact, Kelvin-Helmholtz modes perpendicular to the flow, but still along the contact surface, can always grow fast enough to affect any flow.

Recent works (Ferrari *et al.* 1981) have explored the relativistic regime in the presumption that fast enough flows would lead consistently to a progressive decrease of the growth rates. This effect is however not so large to modify the fact that jets are unstable; the region of unstable Mach numbers presents in this case a lower cutoff also, $M_{lc} \gtrsim \sqrt{3}$, due to the finite ratio between the flow speed, $V = \beta c$, and the thermal speed, $V_s \lesssim c/\sqrt{3}$, in relativistic plasmas.

Quite essential in the astrophysical context is the presence of magnetic fields. Ferrari *et al.* (1981) have shown that a strong, aligned magnetic field, such that the Alfven velocity is larger than the sonic velocity by about an order of magnitude, $V_a \gtrsim 10\ V_s$, can stabilize modes parallel to the flow, while perpendicular modes always tend to remain unstable (at the same time the system becomes dynamically unstable). Similarly, fields perpendicular to the flow, but parallel to the surface discontinuity, fail to slow down the growth of the perpendicular modes. Neither an external magnetic field, aligned (Cohn 1983) or wrapped (Benford 1981) around the flow, of strength of the order of the internal pressure, can provide stability, although it may regulate the equilibrium structure (as discussed in the previous Section). Finally the growth rate of instability is typically proportional to the wavenumber component parallel to the flow; short wavelengths have faster growth rates, and parallel modes grow faster than perpendicular modes.

All these results apply to wavelength perturbations much smaller than the beam transverse size, so that one can consider the contact surface infinite and plane. On the other hand, if we study large scale perturbations of beams, we must look for wavelengths of the order of the beam radius. This motivation has led to study Kelvin-Helmholtz instability in cylindrical jets. Ferrari *et al.* (1978, 1981), Hardee (1979), Ray (1981) and Cohn (1983) have analyzed a large set of physical situation (compressible fluids with and without magnetic fields, thermally or magnetically confined, relativistic in flow velocity and/or temperature, contact discontinuity and shear layer for the surface boundary), using the following expression for the perturbations:

$$f(r, \theta, z, t) \propto g(r)\, e^{[i(kz + m\theta - \omega t)]}\,. \qquad (6)$$

Depending on the value of m, the azimuthal number, one can represent azimuthally symmetric perturbations or pinches (m = 0), kinks or helical modes (m = 1), fluting modes (m ≥ 2). The general outcome of these analyses is again that instability is always present for all cases, with even larger growth rates; more specifically:

1) The finite transverse dimension of the flow introduces a typical scale in the problem; thus one can estimate that the maximum growth rates correspond to modes with $kR \sim 1/M$ (k is the wavenumber, R the beam radius) (see typical examples in Fig. 4). Both subsonic and supersonic flows are unstable; however in subsonic flows pinching modes have growth rates lower than helical modes, while in supersonic flows they are similar, due to the intervention of a new branch of unstable modes, the so-called *reflected modes*. This branch arises from a destabilization of marginally stable modes in the case of plane geometry (Gill 1965).

2) Strong magnetic fields along the flow have a stabilizing effect; for $V_a/V_s \gg M$ ordinary mode instability is actually suppressed. Reflected modes are stabilized only at large wavelengths.

3) In shear layers all modes with wavelengths smaller than the thickness of the boundary layer are stable or have very small growth rates; this fact helps to concentrate the instability to modes with $kR \sim 1/M$.

4) Relativistic flows behave substantially like supersonic flows.

5) Very dense and very light beams have small growth rates.

6) Numerical values for the fastest growing modes are:

$$\text{oscillation frequency} \quad \omega_r \cong kR \frac{M}{\tau_c}, \quad \tau_c = \frac{2R}{V_s} \;,$$
$$\text{growth rate} \quad \omega_i \cong kR \frac{\Phi}{\tau_c} \;, \tag{7}$$

where τ_c is the beam crossing time for sonic perturbations and Φ is a factor obtained by integrating numerically the dispersion relation, typically $\approx 0.1 \div 2$. The typical growth time for the parameters of jets is $\tau_{inst} \ll \tau_{rs} \sim 10^6 \div 10^8$ years, the typical lifetime of radio sources.

7) The analysis of the radial structures of the perturbations indicates that they are not confined to the boundaries of the beam, but actually must be considered as affecting the whole flow pattern. In particular this means that they can actually be correlated with morphological patterns. A confirmation of this result can be found in the numerical simulations referenced above. It is rather obvious that the typical perturbations which grow along the flow satisfy the condition $kR \sim 1/M$; shocks also have a repetitive pattern which agrees with the specific case of pinching modes.

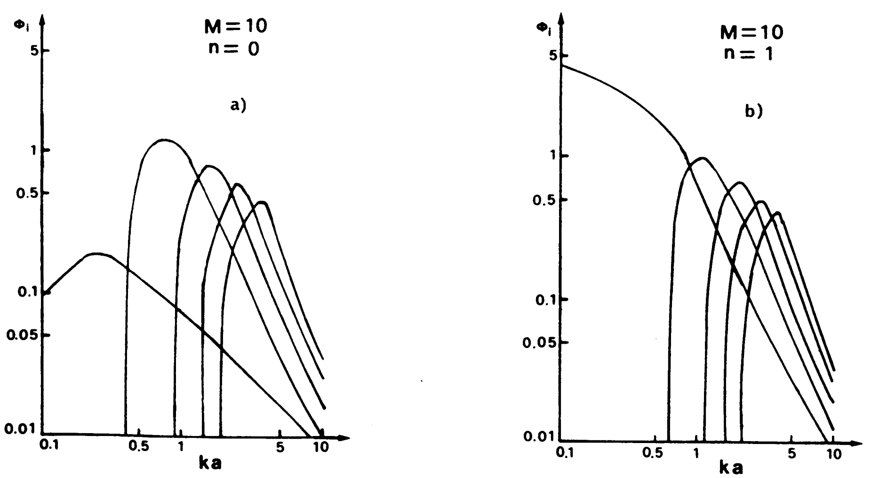

Fig. 4 - Typical growth rates, $\Phi_i = \omega_i/kV_b$, for Kelvin-Helmholtz instabilities in supersonic, cylindrical jets: a) pinching modes n = 0; b) helical modes n = 1.

There are other aspects of the study of linear instability that are now being studied. For instance Hardee (1983) has analyzed the case of conical jets for simulating a regular expansion in a medium with decreasing external pressure. The typical effect he finds is that growth rates tend to decrease in agreement with Eq. (7), which predicts $\omega_i \propto R$. It is also necessary to proceed in the study of cylindrical flows with spin around their symmetry axes; this should allow to apply the study of instability to jets in the deep core of accretion funnels, where rotation is likely to be an important effect.

Finally the effect of viscosity should also be taken into account: obviously not collisional viscosity, but what we may call an effective *magnetic turbulent* viscosity. Baan (1980) has addressed this problem for what concerns the general dynamical equations, and Nepveu (1980) has taken viscosity into account in his numerical simulations. However the effective viscosities used are too large in general for computational reasons and no specific attempt to derive a dispersion relation for Kelvin-Helmholtz modes has been completed. Furthermore we must proceed to the study of nonlinear effects, some of which are discussed below.

III.2 Resistive instabilities

Other instabilities relevant to magnetically confined jets are resistive instabilities. They are excited in the presence of electrical currents and neutral (or sheared) magnetic sheets. These conditions are verified in the magnetically-confined models, with an helicoidal field wrapped around the beam. The typical equilibrium field of such a configuration requires that the pitch-angle of the helicoidal field decreases from the axis outwards (Parker 1979). When a non-axisymmetric perturbation is created along the beam, its pitch-angle will match the equilibrium field pitch-angle at a well defined radius R_{crit}. The corresponding cylindrical surface will be a neutral sheet for the component of the magnetic field perpendicular to the perturbation wavevector, and therefore one envisage the formation of a helicoidal distribution of growing magnetic islands along this surface (the helix specifically chosen will depend on the boundary conditions). Perturbations with different pitch-angles will have different critical surfaces, according to the relation:

$$R_{crit} = \frac{m}{k} \frac{B_\theta}{B_\parallel} , \qquad (8)$$

where m is the same azymuthal number of Eq. (5). The surface also depends from the longitudinal wavelength, 1/k, which is determined by the boundary conditions at the origin of the jet. The growth time of reconnection in magnetic islands is typically related to the resistive time which is very large for the parameters of extragalactic jets ($\tau_{res} \sim 10^{10}$ years). However different islands grow out of the linear regime to reach a stage in which their transverse amplitude covers the gap between the surfaces. Merging regions become eventually stochastic (Rutherford 1980) and this phase can be explosive, with typical time scales not much longer than the MHD time $\tau_{MHD} \sim R/V_a$. In this sense reconnecting modes can modulate the magnetic field in beams on scales comparable with those of fluid MHD instabilties. The result of merging, as far as it can be predicted in terms of laboratory experiments, is to create regularly spaced pinches along helices wrapped around the flow pattern. This can be related with the jet morphological structures.

III.3 Instabilities and morphologies

In conclusion of this Section I want to justify in some quantitative way the argument that fluid instabilities can actually be related to observed morphologies. As recently discussed by Ferrari, Trussoni and Zaninetti (1983), one can derive the set of physical parameters for which the above comparison is acceptable. The idea is to compare the calculated most unstable wavelengths (see Eq.(7)) with the scales of observed features, namely knots and wiggles (see Table II); and correspondingly derive a theoretical value for the extension of the jet before disruption, as the distance after which the perturbation of pressure is so large to exceed p_{ext} by a large factor. This last part of the comparison is somewhat uncertain because it involves necessarily considerations on nonlinear stages of the instability. The theory shows that the wavelength and the growth rate of the most unstable modes depend on three parameters: the flow Mach number, M, the density contrast between internal and external plasma, n_{int}/n_{ext}, and the magnetic field strength, namely V_a/V_s. Actually the dependence on this last parameter is rather weak. Therefore we have substantially a two-parameter model, to be tested on two observational data. Applying this argument to the sources of Table II, one derives that the model can fit the data in almost all cases (M 87 is again an exception, as in several other respects); in particular wiggles should be connected with reflection modes $m = 1$, knots with reflections modes $m = 0$. The predicted flow velocities are supersonic $M \gtrsim 5$, and the density contrast is larger than unity; thus the model suggest that jets are heavier than the external medium. This last result, however, is very sensitive to the choice of the typical length on which nonlinear effects become large; in particular the density ratio can be easily reduced to ≈ 1. Furthermore the equivalence of the growth rates of different instabilities allows to extend these conclusions, although the study refers to the case of Kelvin-Helmholtz modes.

In conclusion the stability analysis confirms that jets are unstable in all possible situations, and actually the perturbed global modes appear to be responsible for some aspects of the morphology. These two statements are, in a sense, contradictory, because one would expect unstable jets to break and not simply wiggle; one has to envisage the possibility of saturation mechanisms, to keep perturbations to low amplitude. This problem is rather more complex, as nonlinear model of instabilities are mathematically awkward and cumbersome.

In addition I should mention that the instability analyses so far performed did not include the dissipation of modes into the external medium, where actually they can be coupled to local modes. This point will be partly discussed in the next Section, but still require more work.

IV. INSTABILITIES AND NONTHERMAL RADIATION

The problem of instability saturation is strictly connected with interpretation of observed morphological structures and radiation emission. We have discussed in the previous Section how the typical scales of unstable perturbations are equal to the measured wiggle and knot wavelengths. On the other hand nonthermal emission coming from jets (and more generally from extended radiosources) requires continuous generation of relativistic electrons *in situ*, as their synchrotron radiation lifetime is much smaller than the travel time from the central core. As the instability is dragging energy from the ordered flow, it appears straightforward to utilize unstable MHD modes to accelerate electrons. In fact several works have

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aimed to establish this connection and to generate a unified picture for radiation and morphology.

Henriksen has discussed in this Symposium the specific case of turbulent jets, in which fluid MHD modes, excited by internal stresses in sheared mixing layers, can diffuse particle (specifically electrons) in energy space to very high Lorentz factors. This process can take place all the way along jets and hence represents a local acceleration process.

Actually turbulence in jets can be directly connected with fluid MHD instabilities, as discussed by Benford *et al.* (1980). In fact, from the previous Section, we know that in a cylindrical jet the fastest growing modes are those with wavelength $\sim \lambda_o = 2\pi R$. These modes have typically the right scales for modulating the flow, but can also accelerate accelerate electrons trapped in their field. A Fermi-like acceleration process sets in, with acceleration time scale typically shorter than the confinement and/or crossing time in the region of acceleration (see also Bicknell and Melrose 1983).

Furthermore nonlinear mode interactions can start, in the limit of weak magnetic fields $V_a \lesssim V_s$, a turbulent cascade from long ($\lambda \sim \lambda_o \sim 10 \div 100$ pc) towards short ($\lambda << 10^{15}$ cm) wavelengths (Lacombe 1977, Eilek 1979, Benford *et al.* 1980), and provide the same type of physical situation invoked by Henriksen. The spectrum of turbulent MHD modes corresponds to the Kraichnan or Kolmogorov classical results, i.e. is represented by a power law, $W(k) \propto k^{-\nu}$, with $\nu \approx 1.5 \div 1.7$. Electron acceleration by small wavelength modes is now a resonant cyclotron process; electrons resonate with modes $k \approx 1/r_g$, where r_g is their (energy-dependent) gyroradius. In a stationary distribution we expect an electron spectrum with a power law $n(E) \propto E^{-\delta}$, where $\delta \approx 2.0 \div 3.0$ (typically 2.5 as consistent with emission spectra in the radio region).

It can be shown that a stochastic acceleration process can actually stop the cascade before the so-called dissipation limit; in fact, in the present situation, dissipation occurs at very large k only ($\gtrsim 10^{-13}$ cm^{-1}), when resonant interaction with thermal particles takes place. In fact, absorption of turbulent energy by relativistic electrons becomes dominant over nonlinear mode interactions at $k \sim 10^{-15}$ cm^{-1}, i.e. closer to the source of the cascade, $\sim 1/\lambda_o$. It is then possible to establish a stationary situation in which the energy released by the fluid instabilities at large wavelengths is transported to short wavelengths by nonlinear processes, where it is dissipated by particle acceleration. In particular the sequence of time scales of the different processes is such that they ultimately represent a way to saturate the instability (Benford *et al.* 1980).

If this saturation mechanism works, we can conclude that large amplitude modes are saturated close to the linear regime and, while non disrupting the beam, can provide both basic morphology and energetics of radiation emission. On the other hand it is also possible that the instability actually evolves beyond the linear regime, either because of different phyisical conditions or because the stationary energetic balance cannot be exactly satisfied. In this case we can easily predict that shocks will be formed, because the transverse perturbation of the collimated flow pattern cannot exceed an amplitude $\xi > \lambda/M$ (Ferrari *et al.* 1981): in fact, at this point the lateral velocity would exceed the velocity of sound in the external medium. Therefore shocks are likely to be, in such a context, the nonlinear mechanism which saturate instabilities; this point seems to be confirmed by the numerical simulations previously discussed. Shocks dissipate energy both heating thermal particles and accelerating superthermal electrons locally (Bell 1978, Blandford and Ostriker 1978). The problem of shock acceleration at highly relativistic energies has not been completely solved yet; Ferrari and Trussoni (1981) have shown that this process does not seem able to accelerate electrons emitting synchrotron X-rays, which are instead detected in M 87, Cen A and 3C 273. In this respect stochastic acceleration by MHD modes appears more promising.

A schematic summary of this unifying scenario is illustrated in Fig. 5 by means of a flow diagram. I have also indicated the other interesting fact that the small scale MHD turbulence can also affect the morphology directly by scattering the jet particles in real space. As shown by Benford *et al.* (1980), in such a model jet emissivity and morphological structures must be correlated: statistically significant observations to test this point would be interesting.

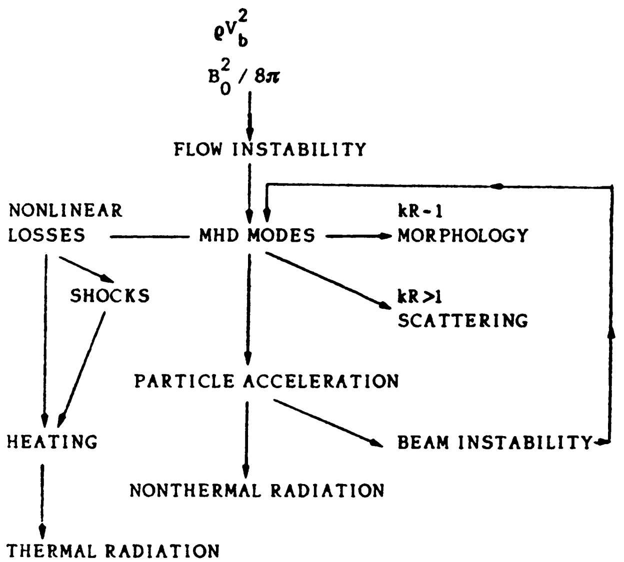

Fig. 5 - Flow diagram of the unified scheme for instability, morphology and radiation in jets.

Another possible instability saturation mechanisms in magnetically dominated flows ($V_a \gtrsim V_s$) is the coupling of surface modes with proper modes inside the jet plasma (the same idea could be applied to study the coupling of jet instabilities with modes in the surrounding medium) (Hasegawa and Chen 1976, Ionson 1978, Bodo and Ferrari 1982). In fact surface Kelvin-Helmholtz modes can be coupled resonantly with kinetic MHD waves inside the flowing plasma, whenever an inhomogeneous boundary layer is present in which density and velocity are increasing. The resonance takes place where the local frequency of Alfven waves, corrected by the Doppler effect of the flow, matches the frequency of the surface modes. These kinetic modes propagate transversally to the magnetic field towards the jet axis, where they provide local plasma heating and relativistic electron acceleration. An interesting aspect of this mechanism is that it leads to generate short wavelength MHD modes in the whole body of the jet, indipendently from any nonlinear cascade process.

V. CONCLUDING REMARKS

It is an obvious characteristic of all theoretical reviews to be a sort of personal interpretation of the achievements and failures of the models examined. I am sure that others would have approached this discussion in a different way; and I have probably left over aspects that others find crucial. Nevertheless I am convinced that the general scheme summarized in Fig. 5 can be accepted by everybody, although with different emphasis, as a starting point for future work.

I believe that the challenge put to us by the physics of jets is very stimulating. We must, in the next few years, reach a reasonable understanding of the following issues:

a) Acceleration of the flow in the inner cores of galactic nuclei: fluid acceleration or electromagnetic acceleration?

b) Collimation: does it occur at the same place where acceleration occurs, i.e. in the inner throat of accretion disks, or is it produced farther out, in nozzles shaped by the surrounding medium?

c) Confinement: is it due to the pressure of an external hot medium, or to the pressure of a self-consistent magnetic field?

d) Morphologies: are they actually related to the development of large scale instabilities, and therefore to the interaction with the external medium, or are they produced by the dynamics of the central powerhouse (precessing beams)?

e) Stability: how are large scale instabilities saturated? How important are the effects of boundary layers, dissipations, nonlinear mode interactions?

f) Nonthermal radiation: what accelerates electrons *in situ*? Turbulent modes or shocks?

Many of these questions have been already dealt with in other astrophysical situations. Some of them have also been solved, although in different ranges of parameters. But, above all, I stress that the new real element we have here to consider is the presence of supersonic, collimated flows which are able to provide all the energy needed. Of course, also in this case the ultimate energy source, deep in the core, is somewhat mysterious. However the real challenge is to explain how the ordered kinetic energy can be directly transformed into radiation, and create these incredible structures.

In the framework of this Symposium, the problem of jets is one of the latest subjects to which plasma astrophysicists have been asked to contribute. The main drawback is that the amount of data on these objects is still rather small, and also their reach is still instrumentally limited. After all we must keep in mind that the energy from extragalactic objects collected by all radiotelescopes, since Karl Jansky's first antenna, amounts to only a tiny fraction of the kinetic energy of a falling snow flake. For a real progress of our understanding of these jets we must urge for the definition of a statistically significant set of parameters of a *standard jet*. This will be achieved by the continuing operation of powerful radiotelescopes, as the Very Large Array and the Very Long Baseline Interferometry intercontinental network, and of orbiting observatories, as the Space Telescope and the Advanced X-ray Astronomy Facility.

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DISCUSSION

IONSON: Could you give me the following numbers for the physical parameters along jets: Alfven transit time, electron temperature, electron density, ion gyroradius ?

FERRARI: I can quote some typical values, which are all model dependent, as I have discussed before. The Alfven transit time is typically $\cong$ (10 ÷ 100)R/c, i.e. 100 to 100,000 years. Gyroradii for thermal particles are of the order of astronomical units; temperatures can be estimated below 10^8 K from X-ray data; electron density is $\lesssim 10^{-3}$, according to depolarization measurements (se also Table I).

STURROCK: Is it possible that a jet is really a stream of plasmoids, each of which could be confined by ram pressure ?

FERRARI: At present data cannot tell us the difference between a continuous fluid jet and a sequence of plasmoids, if these are really very small. If you mean by plasmoid something as large as the knots in M87, I am inclined to say that it cannot be the case, as we definitely see emission from the flow in between. From the theoretical point of view, ram pressure confinement requires large external densities (see Miley 1980).

BENFORD: When a jet moves to the side at an angle greater than M^{-1}, with M the Mach number, sidewise shocks develop. This means by the time you can see a wiggle it is in the nonlinear regime. Also, loading of external or confining B_θ field lines can alter the linear theory. How can you take this into account ? Won't this lead to lighter jets and lower M ?

FERRARI: I agree with you about these general statements. If one applies the linear theory of instabilities to interpret morphologies in jets, large densities and large Mach numbers are derived (Ferrari *et al.* 1983). The effects you indicate may change these results, if the perturbations grow to the nonlinear level. There are however processes that could saturate the growth of instabilities still in the linear regime, as I have discussed in Fig. 5.

RAY: Do you feel the observed wiggles are reflected modes ? You mentioned the coupling of short wavelength Kelvin-Helmholtz modes with kinetic Alfven waves as a source of transporting energy towards the center of the jet. Would the K-H waves not be damped by any reasonable velocity profile ?

FERRARI: As I mentioned in the answer to Greg Benford, I see the possibility that reflected modes generate wiggles, provided the concurrence of a sequence of physical processes. Concerning the coupling of surface K-H waves with Alfven waves, this actually represents a way to discuss how short wavelength modes are damped by physical gradients; in fact this coupling is studied deriving a dispersion relation for modes in the presence of density and velocity gradients. However the mechanism requires $V_a \gtrsim V_s$.

BIRN: Have you checked the possibility of a Jeans instability, i.e. a self-gravitational effect ?

FERRARI: Yes, but it can be excluded by the low densities and relatively high pressures of relativistic particles.

UCHIDA: Supplementing the question of numbers, could you say anything about the ratio of kinetic energy to magnetic energy ? In other words, whether the material stretches the field or the field guides the flow ?

FERRARI: The flow kinetic energy cannot be directly estimated, because we have no access to thermal matter. However the energy released in the whole radiosource extended lobes is several order of magnitudes larger than that required to support the emission of jets, and therefore its magnetic energy. I am inclined to believe that the kinetic energy in the collimated flow is actually dominating.

COPPI: I think that of all the assumptions that have to be made in order to develop a tractable theory the weakest is probably that the ions would have a Maxwellian distribution.

FERRARI: I agree that the fluid treatment is very approximate, as it neglects microscopic plasma effects, which are known to be very important in laboratory and space physics. However we are still at the initial stages of the theory, and look for large scale morphological and energetic effects. The sequence of processes indicated in Fig. 5 will certainly require appropriate consideration of those microscopic effects.