WIND-TYPE FLOWS IN QUASARS

Attilio FERRARI and Edoardo TRUSSONI
Istituto di Fisica Generale, Università di Torino
Istituto di Cosmo-geofisica del C.N.R., Torino, Italy

Jets are found in many astrophysical phenomena, from young stellar objects and collapsed stellar cores to quasar and radiogalaxies. Therefore they must represent a common dynamical phenomenon, while different morphological characteristics arise from the interaction with specific environments (Ferrari and Tsinganos 1985). In order to investigate the basic aspects of jet dynamics and morphologies, we have proposed a simple analytical treatment based on the fluid theory of stellar winds (Parker, 1963), which allows a direct test of different physical effects (Ferrari *et al.* 1985, 1986). We discuss here implications for the physical theories of quasars.

Quasar jets do not differ substantially from jets associated with radio galaxies (Bridle and Perley 1984). However a peculiar distinction in connection with the central core from which they emerge exists: while radiogalaxies have often weak cores, quasars are characterized by larger luminosities, both radio and optical, and this suggests a strong contribution of radiation pressure for jet acceleration.

An aspect of AGN, also relevant to the physics of collimated outflows, are the spatial distribution and width of optical emission lines. In some cases the spatial distribution is elongated and aligned with large scale radio jets, suggesting a direct connection between outflow hydrodynamics and cloud formation and/or excitation (Keel 1985). In addition line widths bear direct indication that AGN do in fact contain high-velocity clouds ($T \sim 10^4$ K) immersed in an optically-thin, hotter background, from sub-pc to kpc scales.

STEADY WIND EQUATIONS

Current AGN models assume that a galactic core consists of a compact massive body, $\gtrsim 10^8 M_\odot$, collapsed below its gravitational radius and surrounded by an accretion disk (*cfr.* reviews by Rees and Blandford in these Proceedings). The disk is heated via collisional dissipation of the inflow angular momentum and ionizes the surrounding optically emitting (coronal) plasma. Outflows are accelerated from the funnels along the spin axis; they also interact with the ionized plasma before escaping from the core.

The hydrodynamic equations for steady outflows in different physical and geometrical configurations have been presented in previous papers; for a general discussion we refer to the review by Ferrari and Tsinganos at the Toronto Conference on *Jets from Stars and Galaxies* (1985). We have adopted the wind theory to describe (i) the jet acceleration inside the accretion funnels and (ii) the jet propagation outside AGN with formation of various morphologies. The geometrical parameters of the funnels were assumed from standard models: the funnel length ranges from a few times up to a hundred times the

G. Swarup and V. K. Kapahi (eds.), Quasars, 399–403 .

gravitational radius of the central mass, and above this scale the cross-section of the channel undergoes a sudden expansion. As an example, the flow acceleration is taken from electromagnetic radiation fields generated by disk's walls and luminosities up to L_{Edd} are considered. Other mechanisms (acceleration by plasma waves, electrodynamic effects, etc.) do not produce qualitatively different results in the outflow dynamics. Similarly, although we refer to an optically thin proton/electron outflow, a positron/electron and/or optically thick plasma can be treated, as we shall discuss in the following.

The basic physical elements of the model are: (i) the gravitational force exerted on the outflow by the concentrated mass of the galactic core and by the extended potential well of the associated galaxy; (ii) the jet plasma thermal pressure force; (iii) the pressure force determined by the geometry of the confining channel; (iv) the non-thermal momentum deposition by external fields (*i.e.* radiation pressure from the accretion disk's walls). We have discussed separately all these effects in terms of which the various phases of the propagation of jets from AGN can be reasonably reproduced. We refer to Figs. 1 for discussing the results.

The relevant solutions are the so-called wind solutions, connecting a subsonic outflow close to the center (in the figure $Z = 1$ is the base of the flow) with a supersonic outflow at infinity, even when the thermal velocity at the base of the flow is well below the escape speed. The classical topology for isothermal flows is illustrated in Fig. 1a, where the sonic transition occurs through an X-type critical point. Figs. 1b and 1c illustrate the case of momentum addition upstream the Parker critical point. O-type critical points appear in the regions where momentum is deposited. Wind solutions do not cross these points, but their shape is modified. Multiple wind solutions are possible for the same physical parameters and boundary conditions: one solution is continuous, while one or more discontinuous wind solutions with shocks appear (vertical dashed lines).

Multiple wind solutions with shocks are again present where the channel's cross-section changes sharply. Fig. 1d shows the specific result of the divergence of the funnel above the disk ($L = 0$). Fig. 1e shows, for $L \sim 0.8L_{Edd}$, the occurrence of a focal point. Fig. 1f shows how a very strong radiation field ($L = L_{Edd}$) can produce a supersonic flow close to the base.

When the mass distribution around AGN is non-point-like, i.e. $M_{grav} = M_{grav,0} Z^n$, continuous outflow solutions are possible only for $n < n_1$, with $n_1 = (5 - 3\Gamma)/(\Gamma + 1)$, where Γ is the plasma polytropic index; in the opposite limit the flow cannot escape to infinity, because it does not have sufficient internal energy, nor receive sufficient energy from external sources to escape with supersonic speed at infinity: the corresponding solutions are called trapped solutions (Fig. 1g).

For the phase of propagation of the jet through the galaxy and its extended halo, the interaction of pressure-confined outflows with environment may excite fluid instabilities of Kelvin-Helmholtz type: perturbations modulate the cross-section of the propagation channel. In the case of a sinusoidal perturbation of wavelength $\lambda \gtrsim 2\pi R$, where R is the channel radius, which corresponds to the most unstable mode of the instability theory, the sequence of equally spaced compressions and rarefactions gives rise to a sequence of alternating O-type and X-type critical points (see Fig. 1h); the continuous wind solution Mach number oscillates due to the (equivalent) momentum additions and subtractions. For sufficiently large perturbation amplitude (but still in the linear limit), shock transitions may occur between the first upstream transonic solution and the downstream transonic solutions.

A time-dependent treatment is required to define which solution is actually adopted by the outflow. The complexity of the topologies discussed arises as soon as one modifies the standard Parker wind model; this agrees with the result of numerical simulations which display sequences of shocks and channel's walls perturbations. A time-dependent code is being used to discuss the evolution of solutions and shall be presented in a forthcoming paper. On the other hand we stress that the present discussion on static wind solutions allows a clear understanding of the physical elements which cause the various morphologies.

APPLICATIONS TO QUASARS

(a) Jets are accelerated and collimated well inside the quasar core. In fact outflows become supersonic very close to the disk. If only geometrical effects are considered, this transition occurs at the exit of the accretion disk; when momentum addition by radiation fields is included, the flow becomes supersonic inside the funnels. This agrees with VLBI radio data suggesting that jets are formed inside the parent AGN.

(b) Stationary shocks at the exit of the accretion funnel can be responsible for AGN short-period variability. The occurrence and position of shocks in discontinuous wind solutions depend critically upon the shape of the funnel and the radiation field distribution. Slight variations of the disk parameters can actually enhance or inhibit the dissipation of the outflow energy inside the core.

(c) Critical funnel luminosities ($L \sim L_{Edd}$) yield asymptotic outflow velocities $\beta_\infty \lesssim 0.28$; velocities close to the velocity of light can be reached for supercritical luminosities. The large luminosities required to produce high velocities are allowed in the case of quasars, if not for all radiogalaxies. Larger velocities ($\gamma \sim 5$) can be obtained for electron/positron jets. A detailed numerical study of the interaction of photons and particles inside thick disk radiation funnels yields $\beta_\infty \lesssim 0.7$ for the case of optically thick plasma (Nobili et al., 1985). In both cases a radiation-driven-wind theory appears inadequate to explain superluminal jets, if these actually imply $\gamma \sim 10$.

(d) The formation of jets is forbidden for certain disk and radiation field parameters. In certain configurations with focal points, no continuous wind solutions are allowed; and if the shock conditions cannot be satisfied, no supersonic wind is produced outside the galactic core. This situation, as well as those in which the shock at the exit of the funnel is very strong, suggests that the physical parameters of the core itself can actually forbid the formation of a collimated jet. The directional energy transported by the flow is randomized and gives rise to bright galactic nuclei with broad emission lines, but without extended jets.

(e) The distribution of matter in galaxies and extended galactic halos defines the length of large-scale jets. Diffused matter distributions around the central cores do not allow jets to escape from the gravitational well, because the flow topologies are trapped when $n < n_1$: this may correspond to AGN which show some indication of collimated outflow in their nuclei (spatial distribution of optically emitting regions), but are not associated with extended radio jets. In addition this process must occur at some distance from the core also for non-trapped solutions when heavy halos are present; a termination shock is formed where the jet dynamical pressure is balanced by the external pressure and represents a way to understand the formation of extended lobes in radiogalaxies. The Space Telescope will provide relevant informations about matter distribution in AGN and halos, allowing a test of this suggestion.

(f) Knots of enhanced brightness along jets at all scales correspond to compressions and transverse shocks in the flow generated by the flow's channel modulation by fluid instabilities. The oscillations of the Mach number correspond to plasma compressions where the flow expands under the effect of the instability; shocks are the nonlinear evolution of compressions. These dynamical phenomena can be associated with localized particle acceleration and non-thermal radiation emission (Ferrari *et al.* 1986).

(g) Thermal instabilities are responsible for cloud formation in galactic cores. In our framework it is possible to suggest that hot jets and their boundaries are unstable to thermal instabilities and break up into clouds which cool down to low temperatures in

agreement with the suggestions derived from optical lines observations (Bodo *et al.* 1985).

Support by Italian MPI and CNR is acknowledged.

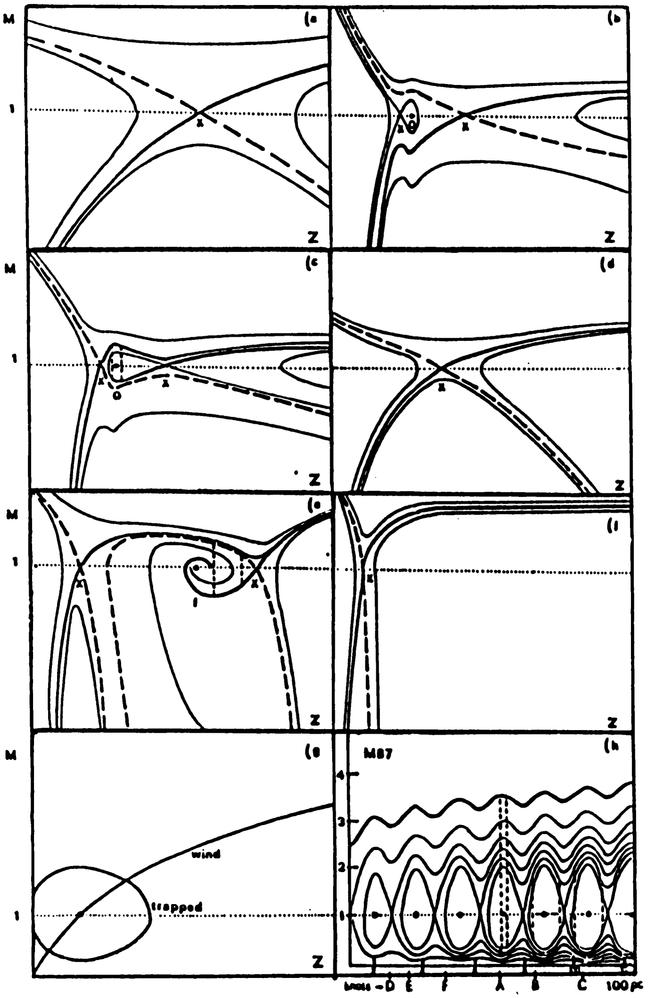


Figure 1. Typical topologies of wind-type flows (see the text for discussion)

Bodo, G., *et al.*, 1985, *Astron. Astrophys.* 149, 246.
Bridle A.H., and Perley, R.A., 1984, *Ann. Rev. Astr. Ap.* 22, 319.
Ferrari, A., and Tsinganos, K., 1985, in *Jets from Stars and Galaxies*, in press.
Ferrari, A., *et al.*, 1985, *Ap. J.* 294, 397.
Ferrari, A., *et al.*, 1986, *Ap. J.* in press, January 15.
Keel W., 1985, Nature, 318, 43.
Nobili, L., *et al.*, 1985, *M.N.R.A.S.*, 214, 161.
Parker, E.N., 1963, *Interplanetary Dynamical Processes*, Interscience.

DISCUSSION

Perry : Multiple and irregular sonic points in flows with radiation pressure and mass injection were found by Beltrametti (1980 A and A.86 181), and she also discussed shock transitions from sub to supersonic flows in that paper.

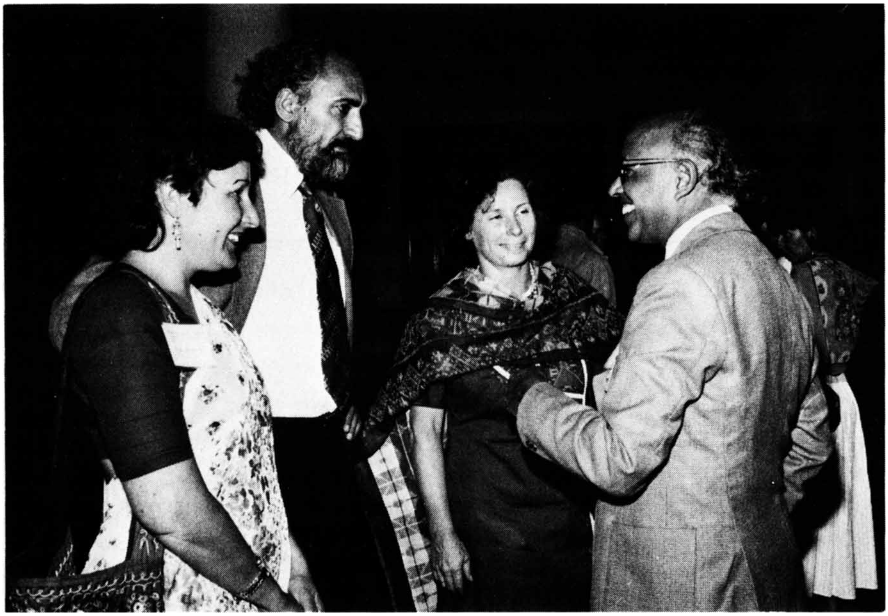
Ferrari : Beltrametti's paper does not contain a full description of flow topologies and therefore cannot really discuss the existence of shock transitions although she argues that they may occur but are actually unstable. For understanding shocks, one needs a time-dependent approach that we have now adopted. Preliminary results do infact confirm the existence and stability of stationary shocks connecting different transonic solutions.

Abramowicz : I would like to stress that the existence of more than one critical point is a very important general property of relativistic flows with angular momentum. We found this also in accretion flows (Abramowicz Zurek, Lu and Livio). However both in the case described by Dr. Ferrari and in our works the model of the flow is rather simple. It seems that complicated and more realistic numerical studies (e.g. Smarr and Co.). give far more complicated shock structure.

Ferrari : The significance of quasi-analytic approaches as the one I presented, is not in representation of all details of the outflow pattern, but in interpreting complicated features of numerical simulations - The topologies I have discussed allow to trace back morphological effects to specific physical processes and this is essential to interpret simulations.

Blandford : These interesting calculations demonstrate that a relatively modest (compared with what must actually be required) increase in the input physics of an outflow leads to a formidable increase in the complexity of the critical point structure. Now critical points are, in a sense, fossil relics of the initial conditions - the only places from where transients cannot propagate away. Isn't this then telling us that the correct way to understand these flows is not to seek stationary solutions but to carry out time - dependent numerical calculations ?

Ferrari : Thank you for stressing this aspect of the solutions - We have performed time-dependent calculations starting from a Parker-type outflow and adding momentum at a given rate or considering specific geometries of the outflow channel. In fact the rate of momentum addition and the cloud's expansion scale length define which solution is undertaken by the flow - one can follow the evolution of transient structures, and define in which cases they relax to stationary shocks. In this sense stationary solutions are useful to understand the asymptotic flow pattern.



D.Dultzin-Hacyan, V.Petrosian, J.Bergeron and G.Swarup