THE COMBINED EFFECTS OF MAGNETIC FIELDS AND ROTATION ON THE ACCELERATION OF JETS: A QUASI–ONE-DIMENSIONAL MHD MODEL

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Using a quasi–one-dimensional MHD model for narrow jets (which we develop by projecting the system of the ideal MHD equations onto the jet axis) we examine the relative importance of the combined effects of rotation and magnetic fields upon the acceleration of matter in jets. We also examine the relative importance of the gas pressure and the gravitational field of the source on the flow and the position of the three critical points (Alfvén, slow and fast magnetosonic). The model, being semi-analytic, allows us to easily extract the relevant physical parameters, explore extreme ranges of these parameters, find the parameter range over which outflows are possible, and identify the physical consequences of different assumptions.

The model allows both a "pressure confinement" and/or a "magnetically-assisted confinement", implying that the gas pressure ($P \propto \rho^{\gamma}$ with $1 \leq \gamma \leq 5/3$) and the centrifugal pressure (which is the result of the rotation of the flow) are balanced by an external medium and/or the tension of the "frozen-in" magnetic field lines. The case $\gamma = 3/2$ plays an important role in distinguishing between initially fast and initially slow rotating jets as to whether or not an initially subsonic flow is possible. The importance of this value of γ is also seen in the solar wind problem, where the wind can accelerate and reach large distances only if $1 < \gamma < 3/2$ (Parker (1963)). This similarity is not accidental, since our model can be also used for the solar wind problem; the particular form that the model takes for the case of jets with *constant* opening angle can be also used for the problem of a wind flowing *radially* outward from the source.

We used parameters appropriate to jets emanating from black holes (in active galactic nuclei), neutron stars, and protostars. For the black hole and neutron star cases, the combination of rotation and magnetic fields is a very important acceleration mechanism, producing relativistic velocities far away from the source. The distance of the acceleration region from the source, however, is still small enough that it cannot be resolved by current VLBI measurements. For a typical black hole case (where $\alpha = B_o^2/4\pi\rho_o v_o^2 \approx 6000$, and $\varpi = (\Omega_o R_o/v_o)^2 \approx 24$, where all parameters have their usual meaning and represent the conditions at the jet origin) this distance is a few 100 AU, and thus the minimum resolution needed to observe such effects is ~ 0.03 mas (for Cen A, the closest extragalactic source). However, the length of the acceleration region is proportional to $(\alpha/\sqrt{\varpi})^{1/3}$, and thus it is possible that, for some cases, the length of the acceleration region may be large enough to be observed. For this reason we interpret the VLBI measurements of Biretta, Moore, and Cohen (1986) — who have shown that component C_4, located about 0.4 mas from the

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core of 3C 345, is accelerating — as a possible direct probe of the acceleration process we are considering.

For the neutron star case the acceleration region is a few 0.01 AU away from the source, and for SS 443 (at 5 kpc from the Sun) the required resolution is $\sim 2 \times 10^{-3}$ mas. Since the velocity achieves relativistic values and our model does not include relativistic effects, our calculations must be taken as suggestive only, giving only an order-of-magnitude estimate for the velocity and the length of the acceleration region. These estimates, however, are consistent with observations of the motion of blobs in SS 433 (Vermeulen *et al.* (1987)), suggesting that the jet achieves its terminal velocity ($\sim 0.26c$) after traveling a distance of only ~ 0.1 AU.

For the protostar case we find that the velocity increases rapidly close to the source and reaches its asymptotic value of $\sim 300\,\mathrm{km\,s^{-1}}$ at a distance of $\sim 10^{-4}$ pc. This is consistent with the observed velocities of HH objects and the very small (if any) velocity gradient along jets from protostellar objects (Mundt, Brugel, and Bührke (1987)). The combination of rotation and magnetic fields is able to sustain a velocity slightly larger than the injection velocity ($v_o = 50\,\mathrm{km\,s^{-1}}$) along the entire length of the jet, assisting the gas pressure in accelerating the flow.

We find it extremely suggestive that our *a posteriori* deduction of the radial dependence of the density distribution in the jets yields $\rho \propto r^p$, where $p > 0$. Thus the narrow-jet equations lead naturally to a *hollow* jet. We also find that the angular velocity and the φ-component of the magnetic field, as well as ρ, increase outward in these models. This is consistent with recent observations suggesting that some jets (e.g., M87; Hardee, Owen, and Cornwell (1988)) appear to be hollow (i.e., the density increases outward), with most of the emission coming from a thin surface layer containing filaments twisted around the jet.

In summary, our results suggest that the combined effects of rotation and magnetic fields play a very important role in the acceleration process in jets. Even though our model is not in any sense a global model, its simplicity enables us to explore much wider ranges of the relevant physical parameters than are possible in numerical simulations. For this reason, we hope that the narrow-jet model will prove useful in interpreting the results of more detailed MHD calculations.

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