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Decelerating relativistic two-component jets and the Fanaroff-Riley dichotomy

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Abstract. Transversely stratified jets are observed in many classes of astrophysical objects, ranging from young stellar objects, μ-quasars, to active galactic nuclei and even in Gamma Ray Bursts. We study two-component jet dynamics for an inner fast low density jet, surrounded by a slower, denser, extended jet. We investigate for the first time this two-component jet evolution with very high resolution in 2.5D and 3D. We demonstrate that two-component jets with high kinetic energy flux contribution from the inner jet are subject to the development of a relativistically enhanced, rotation-induced Rayleigh-Taylor type instability. This instability induces strong mixing between both components, decelerating the inner jet and leading to overall jet decollimation. The 3D simulation confirms the dominance of the non-axisymmetric character of this novel explanation for sudden jet deceleration. We note that it can explain the radio source dichotomy as a direct consequence of the efficiency of the central engine in launching the inner jet component. We argue that the FRII/FRI transition, interpreted in our two-component jet scenario, occurs when the relative kinetic energy flux of the inner to the outer jet exceeds a critical ratio.

Key words. Stars: abundances – Stars: atmospheres – Stars: Population II – Galaxy: globular clusters – Galaxy: abundances – Cosmology: observations

1. Introduction

Transverse stratification seems to be a fundamental feature of astrophysical jets. This stratification is induced by changes in the jet launching mechanism from the accretion disk and its corona. In addition, this jet stratification affects the jet stability during the propagation phase. Therefore, the study of the transverse stratification effects on relativistic jets will in turn inform us about the properties of the accretion disk and the extraction of energy and matter from the accretion disk by the jet. It can determine the jet efficiency in carrying this energy and matter to the intergalactic medium and thus can influence the potential cosmological-feedback role of the jet.

In the present work, we aim to investigate the jet transverse stratification effects in 3D in extension to our previous result obtained in 2.5D (Meliani& Keppens 2009). Multiwavelength observations of astrophysical jets reveal that relativistic jets are structured, in a direction perpendicular to the jet axis, with clear indications for a fast spine and a slower outer flow. In AGNs, this structuring plays an important role when analyzing the jet high energy radiation as in the TeV radio galaxy 3C 66B (Tavecchio & Ghisellini 2009). In particular, high energy jets seen head-on like the

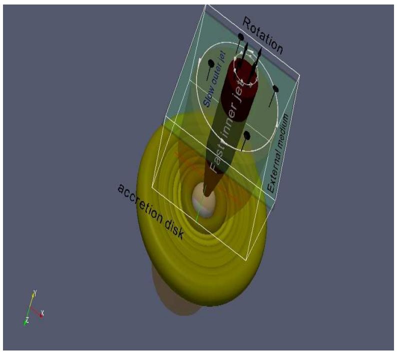

Fig. 1. 3D schematic view of the overall AGN disk-jet configuration (indicating the accretion disk and the two-component jet). Our 2.5D runs model the jet evolution in the transverse plane. The 3D run applies to a periodic section of the jet, where the suggested conical expansion near the source can be neglected.

TeV BL Lacertae objects show brightenings and rapid variability in TeV emission. This variation implies high Lorentz factor flows occuring at smaller scale, which point to ultra-relativistic inner jet components. At the same time, radio observations of the pc-scale jet structure indicate a broad, slower moving outflow. This has been interpreted to suggest the presence of a two component jet morphology (Ghisellini et al. 2005).

Our jet dynamics computations will assume AGN jet conditions, but it is noteworthy to recall that radially structured jet flows are now known to exist in virtually all astrophysical jet outflows. Indeed, recent observations of T Tauri jets (Gunther et al. 2009) suggest a fast inner outflow bounded by a slow outer outflow. Numerical models of two-component jets in classical T Tauri (Meliani et al. 2006) indicate that for such cases, the inner outflow is turbulent and pressure driven, associated with the young star wind. This jet/wind has a small opening angle, is collimated by the outer jet, which is in turn magneto-centrifugally driven from the surrounding disk.

To study the effects of jet transverse stratification, we adopt a two-component jet model with schematic configuration as in Fig. 1, as favored by jet formation scenarios (Blandford & Znajek 1977; Blandford & Payne 1982) and numerical simulations (Meliani et al. 2006). Specifically, we use the two-component model proposed in (Meliani & Keppens 2007) with an inner fast low density component with ultra-relativistic matter state (effective polytropic index $\Gamma_{\rm eff} \sim 4/3$) and dense, slower outer component with classical state of the matter (effective polytropic index $\Gamma_{\rm eff} \sim 5/3$). We assume differential rotation between inner and outer component, resulting from the differing properties of their launching region.

2. Jet transverse cross-section

We start with two-component jet model (A) with relatively high kinetic energy flux in the inner component, with an inner jet having initial Lorentz factor 30. It corresponds to a configuration of accretion-ejection structure with a relatively efficient mechanism to launch the jet in the inner region of the accretion disk-black hole system near the polar axis. The inner component carries 10% of the total kinetic energy flux of the jet. The effective inertia of the inner jet is then higher than in the outer jet with a ratio $\left(\gamma^2\rho h\right)_{\rm in} \sim 14.29\left(\gamma^2\rho h\right)_{\rm out}$, where γ is the Lorentz factor, ρ is the proper density and h is the specific enthalpy. As explained in detail in (Meliani& Keppens 2009), we can apply the criterium

$$\left(\gamma^2\,\rho h\right)_{\rm in} > \left(\gamma^2\,\rho h\right)_{\rm out}\,, \qquad (1)$$

to decide a priori whether this two-component jet is Rayleigh-Taylor unstable (with non-axisymmetric modes developing in the toroidal direction). During the initial phase, a toroidal Kelvin-Helmholtz instability develops at the interface $R = R_{\rm in}$ and reaches a non-linear phase. Spikes from the outer component with a relatively lower effective inertia then arise in the inner jet. The low effective inertia and high pressure of these spikes make the inward pressure force acting on the spikes larger than the centrifugal force acting outward (Fig. 2, top row). These spikes propagate then inward and sideways, since the pressure within it is higher than in the inner jet. As the overall outcome of all interacting instabilities, this two-component jet decollimates and the inner jet decelerates to $\gamma \sim 8$.

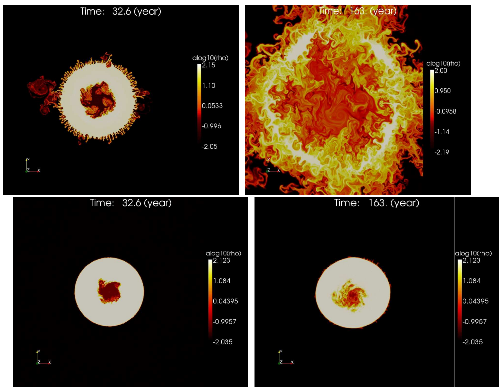

Fig. 2. Top row: Case (A), a purely hydrodynamical jet, showing logarithm of proper density at times (a) t = 32.6 year, (b) t = 163 year (one inner jet rotation is t = 20). Bottom: same for case (B), where the inner jet is magnetized.

We now describe the two-component jet evolution for a case with a magnetized inner component and relatively low kinetic energy flux in the inner component. The inner component carries 0.5% of the total kinetic energy flux of the jet, but is still initially at Lorentz factor 30. The parameters are altered such that the effective inertia in the inner jet is lower than in the outer jet with initial contrast $\left(\gamma^2 \rho\, h\right)_{\rm out} \approx 18 \left(\gamma^2 \rho\, h + B_z^2\right)_{\rm in}$ in this case (B), due to the initial lower pressure at the jet axis and the initial different distribution over thermal and magnetic energy in it. This case is then such that the inner interface is now stable against the dominating Rayleigh-Taylor type instability described above. During the evolution, some spikes develop at the interface, where the outer jet locally interchanges with the inner jet. These spikes are accelerated in the toroidal direction by the faster rotating inner jet. The centrifugal force acting on these slows down their inward expansion, and they then mainly propagate in the toroidal direction. Their interaction with the inner jet material induces Kelvin-Helmholtz body mode instability, with a spiral pattern forming, this time having 3 arms expanding inward (see Fig. 2, bottom row). However, these mainly Kelvin-Helmholtz type instabilities turn out to have lower efficiency in extracting angular momentum than the relativistic Rayleigh-Taylor instability encountered in case (A). At the end of the simulated time interval, the jet stratification evolves to a rather stable structure with still an inner fast, magnetized spine having a Lorentz factor of about 20.

3. Full 3D two-component jet

We followed the evolution of two-component jet model (A) from section 2 in full 3D with a jet length set to 1pc and using periodic boundary conditions along the jet axis. In Fig. 3 we show a volume rendering with transverse and poloidal cuts of the density (Fig. 3 left panel) and Lorentz factor (Fig. 3 right panel) of the jet after 49 years of evolution. The figures clearly indicate that the dominant instability is still the toroidal relativistic Rayleigh-Taylor instability described above. In fact, the inner and the outer outflow are relativistic and supersonic in the poloidal direction, making the growth of poloidally dominant Kelvin-Helmholtz instabilities slower. During the evolution, the Rayleigh-Taylor spikes propagate inward and form an extended shear shell that compresses the inner jet, which evolves to a helical structure. In the last phase simulated, the inner jet is destroyed and localized 'bubbles' with high Lorentz factor remains.

4. Conclusions

We investigated the stability of two-component jets beyond the launching region, where both components are rotating differently and a clear two-component structure exists. We initialized this model in accord with magneto-centrifugal models for jet generation, also using the observed analogy between radio source jets and two-component jets in young stellar objects, where the rotation within the jet can actually be observed. We performed various high resolution simulations of magnetized two-component jets with various magnetization and kinetic energy flux stratifications in 2.5D and full 3D. The two-component jets with a low inner kinetic energy flux contribution are

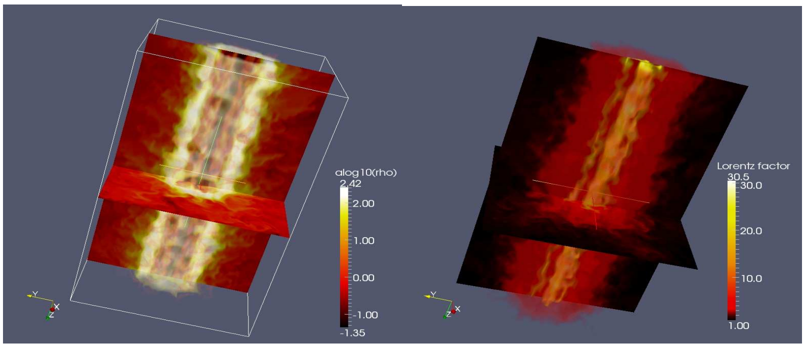

Fig. 3. 3D purely HD jet, showing at times $t = 49$ year logarithm of proper density (left) and Lorentz factor (right).

more stable and remain relativistic for long distances, whereas jets with a highly contributing inner jet to the total jet kinetic energy flux, are subject to a relativistic Rayleigh-Taylor type instability. Indeed for rotating relativistic two-component jets, the relativistically enhanced Rayleigh-Taylor instability may play a significant role in disturbing, mixing and decelerating the jet. The stability criterium is introduced and analyzed in more detail in (Meliani& Keppens 2009), and involves for purely poloidal field configurations the effective inertia contrast between both jet components. Here, we summarized from selected 2.5D cases the main findings, and presented a first 3D confirmation of this novel deceleration scenario. This instability turns out to be very efficient to decollimate and decelerate the (fast, inner) jet. Jets that are subject to this instability become turbulent after propagating for a distance of about 30pc. The results of this model and simulations suggest that the intrinsic properties of the inner engine (black hole and accretion disk) are the key-element which control the jet stability and its kinematics at the pc-scale. According to the contribution of various regions of the accretion disk-black hole to the total energy flux of the jet, the jet may remain stable and relativistic or become unstable and decelerate. The jets in radio sources are predicted to be more stable when the energy extracted by the jet is mainly from the external part of the inner emitting accretion disk-black hole. This might explain the radio source FRI-FRII dichotomy. The jets in FRII galaxies stay relativistic and narrow on all scales. This could correspond to two-component jet configurations with low energy flux contribution from the inner jet. The jets in FRI cases are brighter near the centre and fade out towards the edge, and decelerate from pc to kpc scales. This could match with two-component jet configurations with high energy flux contribution from the inner jet. In this case, the relativistic Rayleigh-Taylor type instability develops at the interface between the two components and expands inwards. This induces the deceleration of the inner component and the formation of a turbulent shear region. The shear region expands inwards and decollimates the jet as well, while the entire jet becomes more turbulent. Then the interaction of the jet with the external medium is significantly enhanced.

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