Simulating magnetized jets

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Abstract. A suitable model for the macroscopic behavior of accretion disk-jet systems is provided by the equations of MagnetoHydroDynamics (MHD). These equations allow us to perform scale-encompassing numerical simulations of multi-dimensional non-linear magnetized plasma flows. For that purpose, we continue the development and exploitation of the Versatile Advection Code – VAC – along with its recent extension which employs dynamically controlled grid adaptation. In the adaptive mesh refinement AMRVAC code, modules for simulating any-dimensional special relativistic hydro- and magnetohydrodynamic problems are currently operational.

Here, we review recent 3D MHD simulations of fundamental plasma instabilities, relevant when dealing with cospatial shear flow and twisted magnetic fields. Such magnetized jet flows can be susceptible to a wide variety of hydro- (e.g. Kelvin-Helmholtz) or magnetohydrodynamic (e.g. current driven kink) instabilities. Recent MHD computations of 3D jet flows have revealed how such mutually interacting instabilities can in fact aid in maintaining jet coherency. Another breakthrough from computational magneto-fluid modeling is the demonstration of continuous, collimated, transmagnetosonic jet launching from magnetized accretion disks.

Summarizing, MHD simulations are rapidly gaining realism and significantly advance our understanding of non-linear astrophysical magneto-fluid dynamics.

Keywords: Jets – MHD – numerical

1. Versatile Advection Code and AMRVAC

The ideal MagnetoHydroDynamic (MHD) equations form a set of 8 nonlinear partial differential equations which can be written in conservation form. They express the basic laws of mass, momentum, energy, and magnetic flux conservation for a perfectly conducting plasma. Since in many astrophysical phenomena involving magnetized plasma dynamics, compressibility and nonlinearity effects give rise to complex, shock-dominated behavior, appropriate numerical tools for handling conservation laws are a necessity. This is particularly evident for simulations of magnetized astrophysical jets and MHD processes occuring in accretion disks about forming stars, or more exotic astrophysical objects.

1.1. Numerical details

To that end, the Versatile Advection Code – initiated by Tóth (1996) [see `http://www.phys.uu.nl/~toth`] – has now evolved to a mature software package for integrating sets of (near)-conservation laws in any dimensionality. VAC offers various choices for the equations, including Euler, Navier-Stokes, isothermal MHD, visco-resistive MHD, ..., and many options for the shock-capturing spatial and temporal discretizations employed, and the geometry of the computational domain. In all cases, VAC uses a finite volume discretization on a structured grid.

Its most recent extension is the possibility for grid-adaptive, time-explicit computations on nested Cartesian grids in 1D, 2D or 3D settings. AMRVAC (Keppens et al., 2003) uses a patch-based Adaptive Mesh Refinement (AMR) strategy to dynamically create and destruct hierarchically nested patches. It offers an efficient means to capture both global and local magneto-fluid dynamics in multi-dimensional simulations.

1.2. Grid-adaptive relativistic simulations

In a national collaboration including computational scientists, plasma- and astrophysicists, the AMRVAC software has been extended with modules for simulating special relativistic hydro- and magnetohydrodynamics (Bergmans et al., 2004). This is of particular interest for simulating astrophysical jets, especially those associated with Active Galactic Nuclei which are observed or inferred to reach speeds with Lorentz factors of order 10 (Vermeulen and Cohen, 1994). The indirect evidence for the existence of near-equipartition magnetic fields in these jets (Tavecchio et al., 2000) calls for relativistic MHD models.

The numerical challenge posed by the RHD and RMHD equations is in essence due to the coupling between the conservative variables, needed to perform the time evolution in a fully conservative fashion, and the primitive variables, such as pressure and velocities that appear in the flux expressions. Various powers of the Lorentz factor $\Gamma = 1/\sqrt{1 - v^2/c^2}$ couple these two sets of variables. In RMHD, just as in non-relativistic MHD, we need to take care about the solenoidal constraint on the magnetic field in multi-dimensional problems.

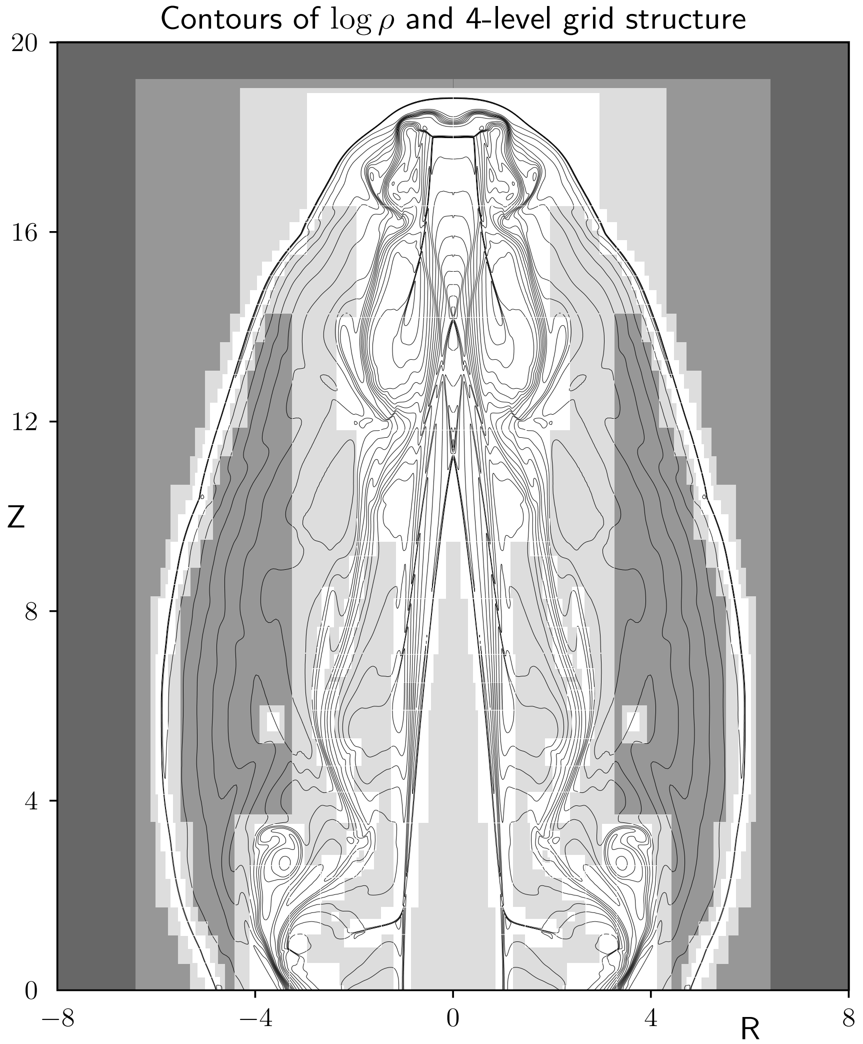

Figure 1. Logarithmic density contours and the AMR grid structure for a special relativistic hydro jet injected at the bottom at a Lorentz factor $\Gamma = 7$ (0.99c).

An example taken from Bergmans et al. (2004) is shown in Fig. 1. An axisymmetric 2D RHD relativistic jet, injected at the bottom of the figure develops internal shocks, shear flow related instabilities within the cocoon, and a pronounced bow shock. This jet is heavier than its surroundings, pressure-matched and has a Lorentz factor of $\Gamma = 7$. The AMR scheme succeeds to trace all details in the jet dynamics, and reaches an effective resolution of 640×1600. Future applications will include magnetized relativistic jet flows, to be compared with similar simulations obtained with fully independent solvers.

2. 3D magnetized jet simulations

The presence of a structured global magnetic field configuration in accretion disk-jet systems is important in all three aspects of the astrophysical jet phenomenon: it plays a role in realizing a magneto-centrifugal jet launching, provides a natural way for jet collimation by magnetic tension, and modifies the jet linear and nonlinear stability properties against perturbations. In what follows, highly idealized examples of all three aspects will be shortly reviewed.

2.1. Kelvin-Helmholtz unstable jets

As an example of the role of magnetic fields in jet stability issues, we recapitulate findings from Keppens and Tóth (1999). In a periodic segment of a cylindrical jet flow at sonic Mach number $M_s = 0.5$, an initially weak, uniform magnetic field is aligned with the flow at time $t = 0$. As a result of the shear flow at the jet boundary, Kelvin-Helmholtz modes develop. The ratio of thermal to magnetic pressure denoted by the plasma beta $\beta(t = 0) = 120$ indicates that the initial, linear dynamics will hardly differ from a pure hydrodynamic simulation. This is true up to and including the entire quasilinear regime, where analytic reasoning predicts the excitation of specific azimuthal and axial mode number perturbations under a given initial 3D excitation. In Figure 2, two cases are shown which differ only in their initial perturbation: the leftmost panels show the response of the jet in terms of thermal pressure on the jet surface after about two sound crossing times. They agree with the analytic results assuming pure hydrodynamic evolution. However, the magnetic field subsequently becomes locally amplified in fibril and sheet-like structures. It then controls the jet deformation entirely at roughly 4 sound crossings (middle panels). This is then followed by an abrupt transition to jet disruption, as evident in the rightmost snapshots of Fig. 2 at 6 time units. Hence, even in weakly magnetized astrophysical jets, where the occuring flow is at much higher speed than considered here, it is questionable whether pure hydro simulations can be interpreted as virtual astrophysical jets.

2.2. Mode-mode interactions

As far as jet collimation is concerned, the presence of a helical magnetic field provides hoop stresses which can confine the jet proper. Unfortunately, more twisted magnetic field configurations render the issue of jet stability even more problematic: linear stability analysis of helically magnetized jets predict the existence of current-driven kink modes, on top of the Kelvin-Helmholtz (KH) instabilities. As the twist increases,

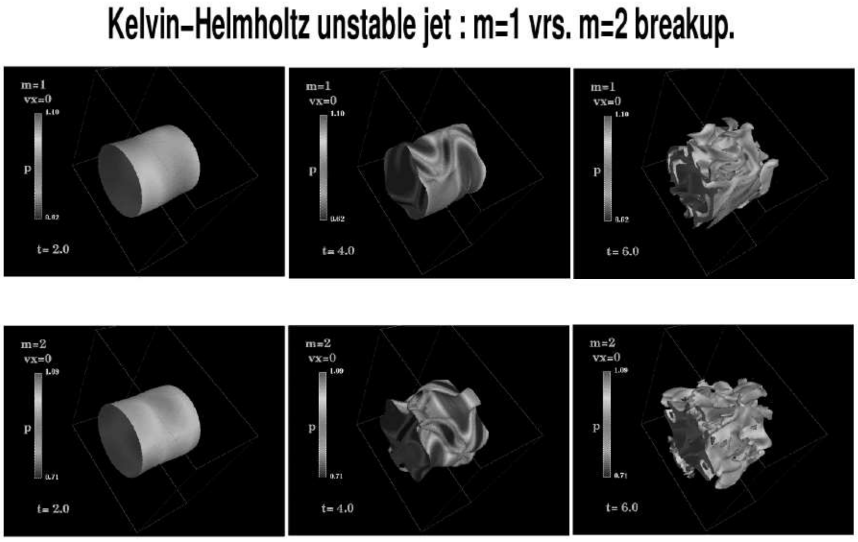

Figure 2. Magnetized jet evolutions, as seen in the deformation and breakup of the jet surface, colored by thermal pressure. The top row is for an initial perturbation with azimuthal mode number $m = 1$, the bottom for $m = 2$. In the nonlinear stage ($t = 4$ middle panels), the detailed flow dynamics can be understood completely as a result of locally amplified magnetic fields, controlling the jet deformation.

these magnetic modes can have growth rates larger than the shear-flow induced instabilities. A study by Baty and Keppens (2002) [see also the contribution by Baty et al., these proceedings] demonstrated how their mutual nonlinear interaction can still be favorable to jet coherency. As the current-driven mode linearly develops within the jet core, while the surface KH modes perturb the jet boundary, both modes initially behave independently. However, the nonlinear evolution of the current-driven mode expels magnetic twist from the central region outwards. As the azimuthal field is then enhanced at the location where the KH vortices develop, this saturates their evolution as quantified in perturbed energy levels. As an illustration, a cross-cut of the density distribution in the jet is compared for 3 cases in Fig. 3. Again, the initial jet configuration is still weakly magnetized ($\beta = 32$), but now slightly supersonic on axis ($M_s = 1.26$). The three panels in Fig. 3 are all after 14 sound crossing times, and started with a uniform field for the left case, versus increasingly twisted helical field configurations in the middle and right panel. The most twisted configuration was characterized by the simultaneous development of current-driven and KH modes, and the development of fine structure is clearly suppressed

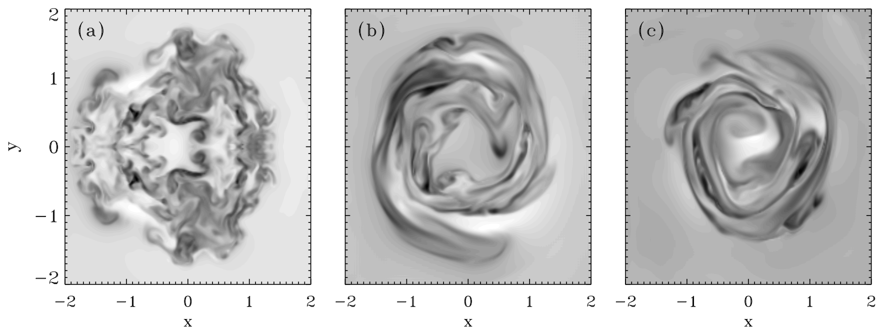

Figure 3. Cross-section of the density structure in 3 different 3D jet simulations, after 14 sound crossing times. At left, the initial weak magnetic field is uniform (a), while it has increasing twist for cases (b) and (c). Case (c) is characterized by the additional development of an internal current-driven mode, interacting with the surface Kelvin-Helmholtz modes.

for more twisted configurations. At the same time, the jet coherency is also maintained. Again, these idealized simulations would need to be repeated for more realistic jet parameters, but they demonstrate how helical fields are interlinking collimation with stability aspects in a manner which is only partially understood at present.

2.3. Launching self-collimated magnetized jets

Finally, a third application from Casse and Keppens (2002, 2004) [see also Casse, these proceedings], touches upon the role of magnetic fields in the launch and self-collimation mechanism of jets from accretion disks. To make the problem computationally tractable, these simulations are performed in a 2.5D framework, where the flow and magnetic field is fully three-dimensional, under the restriction of axisymmetry about the jet axis. Note that this in effect already eliminates the kink-mode dynamics studied in the previous section. It also precludes the development of potentially disruptive non-axisymmetric perturbations in the magnetized accretion disk.

The challenge in simulating magnetized accretion-ejection structures (Ferreira, 1996), is to reach an almost stationary configuration which can explain the long-term, persistent launching of transmagnetosonic jets from disks. In equipartition thin accretion disks ($\beta \simeq 1$), it is possible to realize sufficiently bent magnetic field configurations in the inner disk regions needed for magneto-centrifugal acceleration of jet material. To reach a stationary configuration in the simulations, it is needed to model the disk internal regions in a resistive MHD framework, as material should be allowed to accrete without dragging in magnetic field lines. At the same time, the jet regions and the

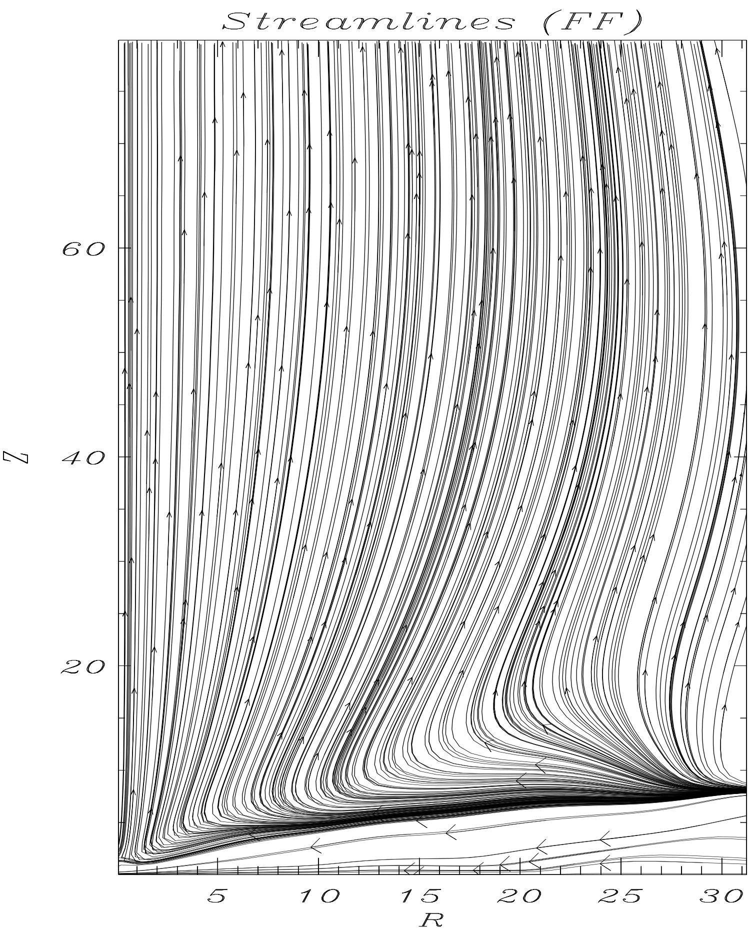

Figure 4. Poloidal streamlines in a simulation of an accretion disk-jet system. Zooming in on the jet launch area, one clearly sees how a fraction of the accreted material is lifted by the thermal pressure gradient at the disk surface, and subsequently accelerated magneto-centrifugally to form a collimated transmagnetosonic jet.

surrounding medium is adequately modeled in ideal MHD. Figure 4 shows the streamlines in the inner jet launching region as obtained by Casse and Keppens (2004) after several tens of disk revolutions as measured at the inner disk radius. The dominant part of disk matter is effectively accreted (a numerical sink region is implemented near the origin). A constant fraction reaches the inner disk surface while it accretes, where the pressure gradient lifts the matter to be propelled in the jet. Jet material is then accelerated to reach super-fastmagnetosonic speeds. Note how the collimation is already complete near the top of the simulated domain.

3. Conclusions and outlook

Magnetized jet simulations are an important means to study (virtual) astrophysical jets. As the presence of magnetic fields significantly enriches both the linear and nonlinear dynamics of the jet, while at the same time complicates the numerical treatment of supersonic MHD flows, advances in algorithmic issues and physical insight will continue to be closely connected. Several code efforts already incorporate grid-adaptation, the possibility to run on massively parallel supercomputers, and a variety of physical models that can be expanded or modified for specific applications. VAC and AMRVAC are a promising example of one such efforts. The simulations discussed here form the initial steps to reach the goal of simulating accretion disk-jet systems in 3D, where launch, collimation and stability issues are coming together. Grid adaptation is required to make this goal realizable. Ultimately, additional 'refinement' in terms of the physical model solved locally can be envisaged: treating non-relativistic to relativistic, hydro- and MHD models in a coupled fashion.

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