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Grid-adaptive simulations of magnetized jet flows

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Abstract

We present high resolution numerical simulations of magnetized plasma jets, modeled by means of the compressible magnetohydrodynamic equations. The computations employ Adaptive Mesh Refinement [1], to investigate long-term jet dynamics where both large-scale and small-scale effects are at play. We first discuss recent findings for periodic jet segments at moderate Mach numbers (around unity) and large plasma beta values [2]. In such cases, a trend to large scales occurs by continuous pairing/merging between adjacent vortices, simultaneous with the introduction of small-scale features by magnetic reconnection events. The vortices form as a result of Kelvin-Helmholtz unstable shear flow layers, and their coalescence arises from the growth of subharmonic modes at multiple wavelengths of the fastest growing Kelvin-Helmholtz instability.

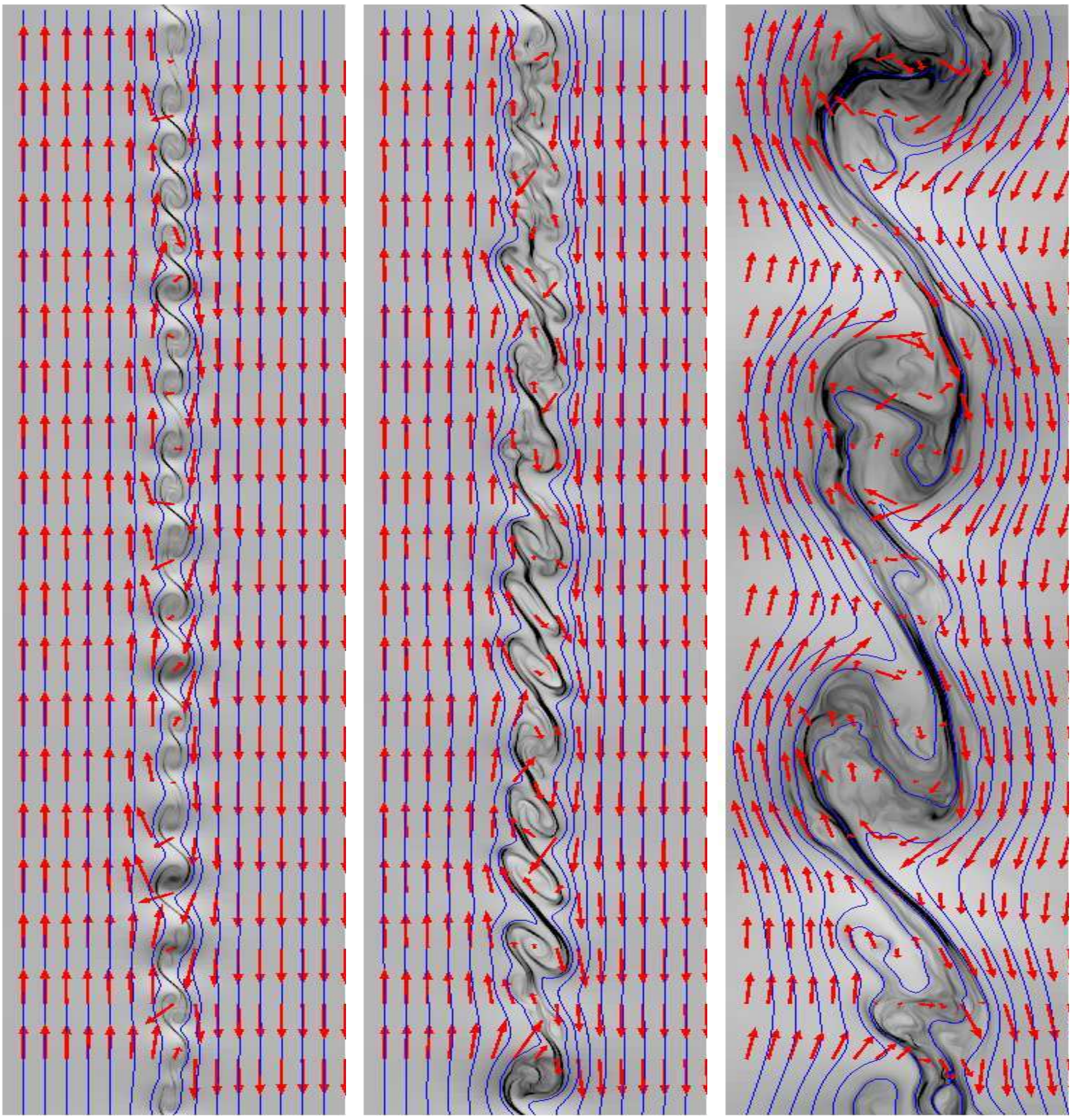
In addition to studies of periodic jet segments, we present shock dominated, magnetized jet simulations, impulsively injected at supersonic speeds (Mach $\mathcal{O}(10)$) to address jet propagation and stability issues in a fully temporal approach. In these simulations, the magnetic field is helical and confined to the jet interior, and characterized by a unit plasma beta. Commonalities between these two studies are highlighted, and their relevance in the context of magnetized astrophysical jet dynamics is discussed.

AMRVAC software

The AMRVAC software, described in detail in Ref. [1], allows to perform grid-adaptive simulations of three-dimensional magnetized plasma dynamics. Adopting a single fluid, magnetohydrodynamic (MHD) description for the macroscopic plasma behavior, the governing conservation laws are advanced on a continuously adjusted hierarchy of nested grid levels with finer and finer mesh spacing. In 2D and 3D simulations, a diffusive treatment to handle the $\nabla \cdot \mathbf{B} = 0$ constraint is combined with a level-dependent, shock-capturing spatial discretization. The computational efficiency achieved by the Adaptive Mesh Refinement makes it possible to perform parametric studies at unprecedented effective spatial resolution and physical duration.

2D magnetized shear layers

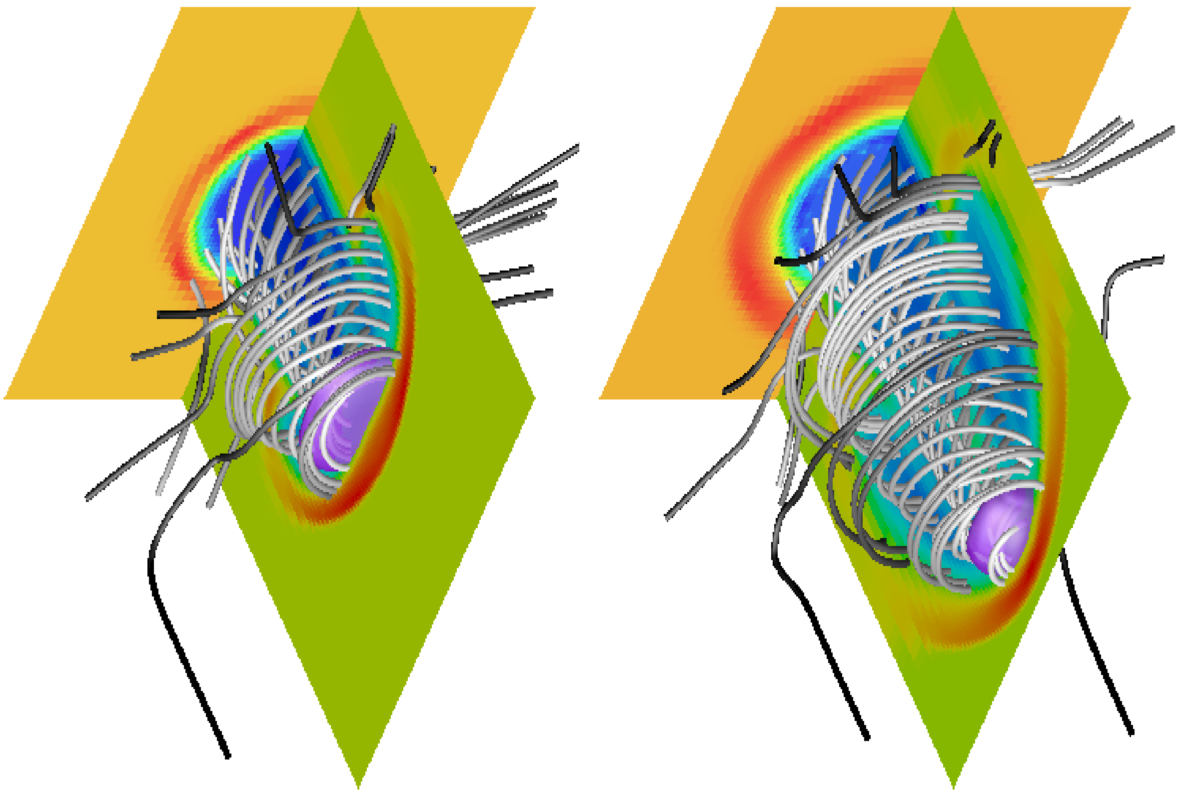
As a first step towards 3D magnetized jet studies, we performed a systematic study of an initially homogeneously magnetized, sheared flow layer. In pure hydrodynamic shear layers, vortex mergers drive the shear flow layer to a nearly minimum enstrophy state. In magnetized layers, two dimensionless parameters characterize the layer: the ratio of thermal to magnetic pressure β, and the sonic Mach number M quantifying the velocity jump across the shear layer. In Ref. [2], it was demonstrated that transonic layers where $M \simeq 1$ and $\beta > 19$, which have long been known to be susceptible to Kelvin-Helmholtz instabilities, show an additional trend to large-scale coalescence in their long term evolution. On a timescale spanning several tens of the typical growthtime of the fastest growing mode, the development of subharmonics with correspondingly larger lengthscales causes pairing/merging events of adjacent vortices up to the point where the largest structure covers the entire – periodic – domain simulated.



The figure shows three snapshots of the density evolution, with magnetic field lines and velocity vectors superimposed, for a simulation where $M = 1$ and $\beta = 58.8$. We used 5 grid levels, to cover a domain $[0,20] \times [-2,2]$ at an effective resolution of 1600×1600. The leftmost frame corresponds to the time when the most unstable linear mode has come close to saturation: this simulation includes more than 20 streamwise wavelengths of this Kelvin-Helmholtz mode. The middle frame, at $t = 7.5$ in our normalization, clearly shows subsequent mergers accompanied by vortex disruptions due to magnetic reconnection events. The rightmost frame, at $t = 17.5$ demonstrates that, despite the continuous process of vortex disruption, this trend to large scale coalescence prevails in the long term.

3D helical supersonic jets

Our latest simulations address the penetration of astrophysical jets into dense molecular clouds. Observational as well as theoretical arguments can be given in favor of helically magnetized jets: the hoop force aids in the collimation of the jet over its vast observed extension. Jets from Young Stellar Objects – typically surrounded by an accretion disk – are known to reach terminal velocities with Mach numbers of order 10 to 100. A plausible mechanism to explain the jet launch process involves a magnetocentrifugal acceleration from the inner equipartition accretion disk regions. Recent simulations [3] then show how a hot super(magneto)sonic jet, with equipartition between pressure and the internal helical field, is a natural outcome of such a magnetized accretion-ejection process. Therefore, our study looking at how astrophysical jets penetrate dense clouds takes the jet hotter (and more dilute) than the virtually unmagnetized cloud, with a magnetic field such that the jet axial $\beta \simeq 2$, and considers a Mach number $M \simeq 7.7$ (Alfvén Mach of about 10). The density contrast $\rho_{\mathrm{cloud}}/\rho_{\mathrm{jet}} = 10$, and the jet interior radial structure is one where the total pressure is essentially constant, and where rotation is set to balance magnetic tension centrifugally $v_\varphi = B_\varphi/\sqrt{\rho}$.



The figure shows two snapshots of a simulation using 3 grid levels reaching an effective resolution of $80 \times 80 \times 160$: due to the efficiency of the AMR strategy in computing resources, this 3D MHD run was simulated within 5 hours on a linux PC (1GB RAM, Pentium 4 processor 2.4Ghz). Shown is the logarithm of the density in two planes: the jet inlet plane, as well as in a cross-section. The latter clearly shows the bow shock formed, where compressed cloud material is separated from the jet cocoon by a contact discontinuity. The magnetic field lines, colored by the strength of the field (black indicates weak field) and helical within the jet interior, get compressed and pushed sideways just behind this contact discontinuity. At this location, a hot spot forms which marks the tip of the cocoon: the purple isosurface is one where temperature has risen roughly 8-fold compared to the jet interior. In an animation of this jet penetration model, one can clearly see how from this location, the cocoon is fed with strongly twisted field, which ends up filling the entire cocoon.

Outlook

MHD simulations of magnetized jet flows can directly address issues on laboratory, as well as astrophysical jet collimation, stability, internal variability and termination. With grid adaptivity, it is feasible to explore a much wider parameter space in 2D and 3D computations: for magnetized jets this implies minimally to vary the flow Mach number and its plasma beta. The results on single shear layers at unit Mach and high β will be extended to planar and fully three-dimensional jets where the jet width may significantly influence the vortex coalescence. For jets with a helical magnetic field configuration, current-driven modes can exist of equal importance than the Kelvin-Helmholtz type instabilities. Linear stability studies will be essential to guide and interpret the dynamics in realistic magnetized astrophysical jet simulations.

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