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Simulations of astrophysical relativistic plasmas

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Abstract. High-energy astrophysics is certainly one of the most fascinating topics in modern physics, since it deals with rather extreme objects such as neutron stars, black holes, and highly relativistic particles. During the last decade, great improvements in the theoretical modeling of astrophysical relativistic plasmas have been possible, thanks to the development and refinement of sophisticated numerical codes for special and general relativistic MHD. In this review I will discuss some of these progresses by focusing especially on the topics where Italian researchers are more actively involved.

Key words. Plasmas – *Magnetohydrodynamics* (MHD) – Relativity – Methods: numerical

1. Introduction

Most of the astrophysical sources of high-energy radiation and particles are believed to involve the presence of relativistic motions in *magnetized* plasmas. For example, the radio emission from extra galactic jets (especially from terminal radio lobes) or from plerionic supernova remnants (e.g. the Crab Nebula) is due to synchrotron radiation produced by relativistic electrons spiraling around magnetic field lines, thus indicating the presence of significant magnetic fields.

Strong magnetic fields are supposed to play an essential role in converting the energy of accreting material around super-massive black holes at the center of Active Galactic Nuclei (AGNs), into powerful relativistic jets escaping along open field lines. Similar phenomena may be at work in the galactic compact X-ray sources known as microquasars and even in Gamma Ray Burst (GRB) engines. These processes involve highly nonlinear interactions of relativistic gasdynamic flows and shocks with gravitational and magnetic fields. The fluid approximations employed to study the dynamics of relativistic plasmas are special relativistic MHD (SRMHD) and general relativistic MHD (GRMHD), when the curvature of space-time becomes significant in the vicinity of a compact object.

A strong impulse to the study of these complex phenomena has come from numerical simulations, especially in the last decade. Since relativistic magnetized flows are often associated with the formation of strong shocks and different kinds of discontinuities, it is thanks to the development of conservative shock-capturing, or Godunov-type, methods that this progress has been possible. After the first applications to special and general relativistic hydrodynamics (see Martí & Müller 2003, for a review), Komissarov (1999) first proposed a multi-dimensional shock-capturing code for SRMHD based on the so-called Roe-type methods, widely used in computational gas dynamics, in which the solution of the local

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Riemann problem at any cell interface is constructed by means of a full decomposition into characteristic waves (note that the SRMHD eigen-structure is not solvable analitically, contrary to classical MHD). Accurate and robust Riemann solvers for SRMHD requiring fewer eigen-modes have been also recently developed (Mignone & Bodo 2006; Mignone et al. 2009). Relying on the promising results obtained for classical MHD (Londrillo & Del Zanna 2000), Del Zanna & Bucciantini (2002); Del Zanna et al. (2003) first proposed a different approach for SRMHD: one or two-wave Riemann solvers are used component-wise in combination to higher-order spatial upwind reconstruction (third order at least). This latter scheme has also been extended to GRMHD (Del Zanna et al. 2007). Most of the codes available nowadays for SRMHD and GRMHD make use of a simplified Riemann solver (see Font 2008, for a review).

In this review I will briefly describe and discuss some astrophysical scenarios where numerical simulations of relativistic plasmas have been crucial to gain a deeper insight, focusing especially on the contributions by the (small but competitive!) Italian community, namely researchers from the groups in Torino and Firenze, homes of the *Pluto* (Mignone et al. 2007) and *ECHO* (Del Zanna et al. 2007) codes, respectively. Torino has a leading experience in numerical modeling of protostellar and AGN jets, while Firenze is more involved in the modeling of Pulsar Wind Nebulae and, recently, of winds and jets from proto-neutron stars and magnetars (in collaboration with UC Berkeley).

2. Simulations of relativistic jets

It is now commonly accepted that the physical origin of the collimated supersonic outflows observed in many astrophysical contexts ranging from Young Stellar Objects to X-ray binaries, GRB sources and Active Galactic Nuclei is related to the dynamical evolution of rotating magnetized material accreting onto a central object. In the case of X-ray binaries, GRBs or Active Galactic Nuclei, the central object is compact and the resulting outflow is relativistic.

The widely accepted magneto-centrifugal model has been studied in depth in the non-relativistic regime by looking for steady self-similar solutions starting from the seminal paper by Blandford & Payne (1982). More recently, this mechanism has been the subject of a series of numerical studies in which the disk is treated as a boundary condition, showing how a steady solution can be obtained in a few dynamical timescales and how the acceleration, collimation and stationarity of the outflow depend on the mass loading from the disk and on the magnetic field structure. Recent simulations (Casse & Keppens 2004; Zanni et al. 2007) have instead included the disk in the computational domain, having the possibility of determining in a consistent way the mass loading from the disk to the jet. In this last case one has to include a diffusive mechanism inside the disk to balance the inward advection of field lines and allow accretion to proceed. These last studies have pointed out the importance of minimizing the numerical dissipation in order to capture in a correct way the very delicate process of mass loading.

The introduction of relativistic effects may introduce qualitatively new behaviors and relativistic MHD does not naturally yields to a simple generalization of Newtonian results. While semi-analytic solutions have been useful in indicating the general properties of the flows, more general and time-dependent studies are needed in order to confirm the results and to obtain a full understanding of the generation of such outflows. GRMHD simulations of the full black hole plus disk scenario look promising (McKinney 2006; Hawley & Krolik 2006; Koide et al. 2006), though some crucial questions remain open: do disk outflows approach a stable steady state? How the properties of the accretion disk affect the dynamics of the jet acceleration and collimation? Is the magnetic mechanism able to attain the required Lorentz factors on an astrophysically relevant scale? Can these highly relativistic flows be collimated by purely magnetic stresses opposing the decollimation effect of electric stresses?

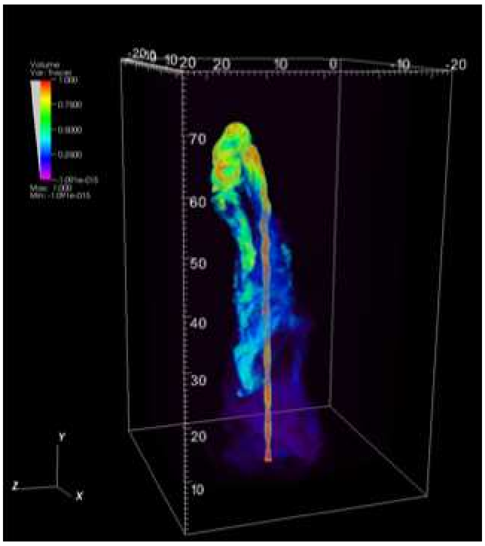

Fig. 1. Propagation of a simulated 3D SRMHD jet.

Alternative models based on the direct electromagnetic extraction of gravitational energy of the Kerr black hole leading to Poynting flux dominated jets, the so-called Blandford-Znajek effect (Blandford & Znajek 1977), basically the GR analogue of the physical mechanism at work on pulsars (Goldreich & Julian 1969), have also been successfully tested via numerical simulations, both in the force-free and GRMHD regimes (Komissarov 2004; McKinney & Gammie 2004; Komissarov 2005).

The dynamics of jet propagation and its interaction with the ambient medium is at the base of its morphological properties and of the energy dissipation leading to relativistic particle acceleration and ultimately to their non-thermal emission. Much work has been done on the propagation and stability of Newtonian jets. In the last years, some advancement has been performed in the understanding of reletivistic nonmagnetized jets. In particular, Marti et al. (1997) have performed a detailed analysis of the parameter space in 2D, Aloy et al. (1999) has performed the first 3D simulations and recently Rossi et al. (2008), by performing high resolution 3D simulations, have investigated the problem of the relativistic jet deceleration due to entrainment of the ambient medium, in the context of the FRI-FRII dichotomy of extragalactic radio sources. Much less work has been done in the RMHD case. In 2D Leismann et al. (2005) have analysed in detail the parameter space, while the first results in 3D are presented in (Mignone et al., *submitted*, see Fig. 1). Fully 3D studies are important because some instabilities, like the kink instability related to the toroidal field component, are inhibited in axisymmetry.

3. Simulations of Pulsar Wind Nebulae

When a supernova explosion leaves a compact remnant in the form of a highly magnetized and fast spinning young neutron star, whether or not detected as a pulsar, a magnetized and ultra-relativistic wind (the Pulsar Wind, PW) is believed to be accelerated via conversion of the neutron star's spin-down power. This relativistic outflow is supposed to be confined by a reverse shock (the so-called termination shock), receding from the slowly expanding ejecta, where the kinetic energy is converted to heat and acceleration of electrons and possibly other particles. When this conversion is efficient enough, a Pulsar Wind Nebula (PWN, or plerion), that is a hot bubble of magnetized plasma and ultra-relativistic particles shining through non-thermal radiation (synchrotron and Inverse Compton Scattering, from radio to the TeV band), is expected to be produced. The prototype of this class is the Crab Nebula (CN), the object for which data are most abundant and the most part of models has been elaborated. The CN is a relatively young object (1000 years old), still in free expansion inside the outer remnant, whereas several examples of older objects interacting with SNRs in the reverberation or Sedov phases, or even escaping from the outer envelopes due to the initial kick, producing bow-shock nebulae, are observed (Gaensler & Slane 2006).

The study of PWNe, and of the CN in particular, has been so far the primary source of information on the properties of pulsars' winds and magnetospheres. They have recently become even more fashionable due to evidence

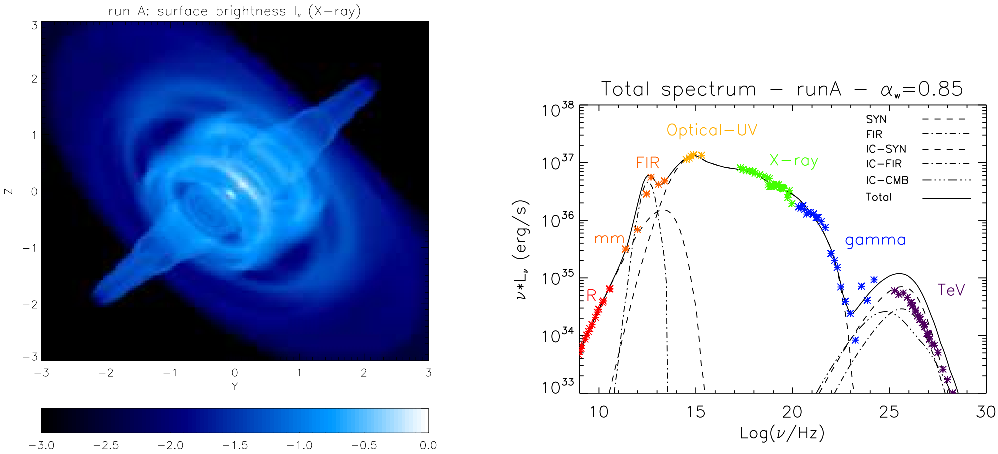

Fig. 2. Left panel: simulated surface brightness map in the X-rays. Right panel: the overall simulated SED compared to Crab Nebula data.

for the existence of relativistic jets (Weisskopf et al. 2000). These have long been studied in other classes of objects powered by a central compact source, like AGNs, or their galactic analogous, microquasars, and are thought to play a role also in the context of GRBs. Jets in PWNe are only mildly relativistic and from X-ray images they appear to be originated inside the PW itself, though magnetic collimation by hoop stresses is known to be not efficient in ultra-relativistic flows. Moreover, the interest in pulsars' electrodynamics and outflows has increased thanks to the observational proof of the existence of magnetars and to their possible role in GRB jets' acceleration as an alternative to Kerr black holes in the collapsar scenario (see next section), and to the recent discovery of the first double pulsar system, a unique laboratory for relativistic plasma physics other than General Relativity (Lyne et al. 2004).

The most recent advances in the modeling of PWNe have been possible thanks to the improvements in numerical methods for relativistic MHD. Axisymmetric simulations were able in particular to solve the puzzle of jet collimation and to reproduce the observed jet-torus structure, provided an anisotropic pulsar wind of sufficient magnetization is injected and inflates the PWN bubble (Komissarov & Lyubarsky 2004; Del Zanna et al. 2004). In these simulations the shock assumes an oblate profile, with the polar boundaries where the jet is launched closer to the pulsar, and since its collimation occurs downstream the termination shock, where the flow is only mildly relativistic, hoop stresses can operate efficiently. A most recent progress is related to the first attempt at taking to account the particles' energy evolution, with the aim of building realistic synchrotron emission maps on top of the flow structure (Del Zanna et al. 2006). The results are surprising for the detail in which X-ray observations of the inner structure of PWNe are reproduced (see Fig. 2): not only the torus and the jet, but also bright substructures like the CN's *knot* or *main arc*, which were thought to be due to complex non-ideal phenomena occurring in the wind, are now simply interpreted as a result of Doppler boosted emission associated to relativistic flows pointing at the observer.

This shows how a careful modeling of synchrotron emission coupled to MHD simulations provides us with a powerful diagnostic tool: in addition to surface brightness maps, also spectral index maps, polarization maps (Bucciantini et al. 2005) and integrated spectra can be used for comparison with data in

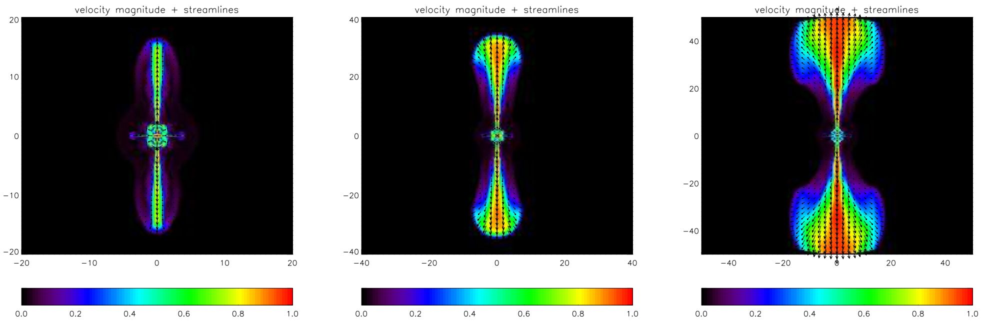

Fig. 3. The time evolution of the GRB jet (velocity maps) up to 10 s after core bounce, when the jet has finally left he stellar progenitor.

the different frequency bands. This comparison not only allows one to obtain more refined estimates of parameters such as the wind magnetization, but even to gather some insights on pieces of information that were thought to be not accessible, like the angular extent of the *striped wind* region, related to the inclination between the magnetic and rotation axis of the central star, or the efficiency of relativistic magnetic reconnection. Finally, the method has been extended to calculate the Inverse Compton emission by the same electrons responsible for synchrotron radiation scattering different target photons (Volpi et al. 2008), allowing us to produce the first gamma-ray maps (in the bands of the FERMI instruments and of ground-based Cherenkov detectors), and the complete CN spectrum from radio to TeV (see Fig. 2). Comparison with multi-wavelength data is important in order to disentangle the contributions to the emission by the magnetic field and by the particular shape of the energy distribution function of the emitting particles, and to investigate the possible role played by hadronic decay.

4. Simulations of GRB jets in the magnetar model

Observations of long-duration GRBs have demonstrated that they are associated with core-collapse supernovae and the death of massive stars (Woosley & Bloom 2006). As an alternative to the collapsar model, where the engine of the GRB jet is believed to be a Kerr black hole in analogy with AGNs and microquasars, a magnetized relativistic wind could be powered by a newly formed millisecond magnetar via the usual spin-down mechanism. The strong confinement of the ultra-relativistic wind provided by the stellar envelopes is supposed to form a kind of hot *magnetar wind nebula* where magnetic hoop stresses could operate in analogy to the lower energy case of PWNe and collimate bipolar jets. Recent numerical simulations seem to support this view (Komissarov & Barkov 2007; Bucciantini et al. 2008), while it is certainly needed to further investigate this promising scenario. The state of the art is currently provided by the first long-term (10 seconds after core bounce) simulation of the GRB jet, from its collimation in the hot post-shock bubble, to the final escape from the outer stellar surface (Bucciantini et al. 2009) (see Fig. 3). In this simulation the proto-magnetar's hot surface (due to the internal deleptonization) drives initially a thermal wind, and later, as the temperature cools down, it is the magnetar's magnetosphere (with a dipole field of 10^{15} G rotating with a period of 1 ms) that drives a relativistic magnetically dominated wind. When the hot bubble forms, the pinching effect by the toroidal field is able to collimate the wind into bipolar jets that make their way through the stellar envelopes and finally escape from the exploding star. However, for a realistic model of GRB jets forming inside a stellar progenitor, the core collapse and the launching of the relativistic wind should be followed self-consistently, while presently the former is modeled by prescribing density and temperature at the protomagnetar cooling surface as given functions of time. This is an extremely ambitious goal, since both fully general relativistic effects (i.e. evolving the space-time metric during the collapse) and complex microphysics, including neutrino transport and heating, should be taken into account.

5. Conclusions

Theoretical high-energy astrophysics has made substantial progress in the last decade thanks to the increasing power of supercomputers and to the refinement of numerical methods for relativistic MHD, allowing to simulate the complex interactions between electromagnetic fields and flows in relativistic plasmas. The Italian groups in Torino and Firenze have developed a great expertise in computational (classical and relativistic) MHD, and in this review I have summarized some of the most important contributions provided by the two groups in this fascinating field.

References

Aloy, M. A., Ibáñez, J. M., Martí, J. M., & Müller, E. 1999, ApJS, 122, 151
Blandford, R. D. & Payne, D. G. 1982, MNRAS, 199, 883
Blandford, R. D. & Znajek, R. L. 1977, MNRAS, 179, 433
Bucciantini, N., del Zanna, L., Amato, E., & Volpi, D. 2005, A&A, 443, 519
Bucciantini, N., Quataert, E., Arons, J., Metzger, B. D., & Thompson, T. A. 2008, MNRAS, 383, L25
Bucciantini, N., Quataert, E., Metzger, B. D., et al. 2009, MNRAS, 396, 2038
Casse, F. & Keppens, R. 2004, ApJ, 601, 90
Del Zanna, L., Amato, E., & Bucciantini, N. 2004, A&A, 421, 1063
Del Zanna, L. & Bucciantini, N. 2002, A&A, 390, 1177
Del Zanna, L., Bucciantini, N., & Londrillo, P. 2003, A&A, 400, 397
Del Zanna, L., Volpi, D., Amato, E., & Bucciantini, N. 2006, A&A, 453, 621
Del Zanna, L., Zanotti, O., Bucciantini, N., & Londrillo, P. 2007, A&A, 473, 11
Font, J. A. 2008, Living Reviews in Relativity, 11, 7
Gaensler, B. M. & Slane, P. O. 2006, ARA&A, 44, 17
Goldreich, P. & Julian, W. H. 1969, ApJ, 157, 869
Hawley, J. F. & Krolik, J. H. 2006, ApJ, 641, 103
Koide, S., Kudoh, T., & Shibata, K. 2006, Phys. Rev. D, 74, 044005
Komissarov, S. S. 1999, MNRAS, 303, 343
Komissarov, S. S. 2004, MNRAS, 350, 427
Komissarov, S. S. 2005, MNRAS, 359, 801
Komissarov, S. S. & Barkov, M. V. 2007, MNRAS, 382, 1029
Komissarov, S. S. & Lyubarsky, Y. E. 2004, MNRAS, 349, 779
Leismann, T., Antón, L., Aloy, M. A., et al. 2005, A&A, 436, 503
Londrillo, P. & Del Zanna, L. 2000, ApJ, 530, 508
Lyne, A. G., Burgay, M., Kramer, M., et al. 2004, Science, 303, 1153
Martí, J. M. & Müller, E. 2003, Living Reviews in Relativity, 6, 7
Marti, J. M. A., Mueller, E., Font, J. A., Ibanez, J. M. A., & Marquina, A. 1997, ApJ, 479, 151
McKinney, J. C. 2006, MNRAS, 368, 1561
McKinney, J. C. & Gammie, C. F. 2004, ApJ, 611, 977
Mignone, A. & Bodo, G. 2006, MNRAS, 368, 1040
Mignone, A., Bodo, G., Massaglia, S., et al. 2007, ApJS, 170, 228
Mignone, A., Ugliano, M., & Bodo, G. 2009, MNRAS, 393, 1141
Rossi, P., Mignone, A., Bodo, G., Massaglia, S., & Ferrari, A. 2008, A&A, 488, 795
Volpi, D., Del Zanna, L., Amato, E., & Bucciantini, N. 2008, A&A, 485, 337
Weisskopf, M. C., Hester, J. J., Tennant, A. F., et al. 2000, ApJ, 536, L81
Woosley, S. E. & Bloom, J. S. 2006, ARA&A, 44, 507
Zanni, C., Ferrari, A., Rosner, R., Bodo, G., & Massaglia, S. 2007, A&A, 469, 811