NUMERICAL SIMULATIONS AND DIAGNOSTICS IN ASTROPHYSICS: A FEW MAGNETOHYDRODYNAMICS EXAMPLES

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We discuss some issues related to numerical simulations in Astrophysics and, in particular, to their use both as a theoretical tool and as a diagnostic tool, to gain insight into the physical phenomena at work.

We make our point presenting some examples of Magneto-hydro-dynamic (MHD) simulations of astrophysical plasmas and illustrating their use. In particular we show the need for appropriate tools to interpret, visualize and present results in an adequate form, and the importance of spectral synthesis for a direct comparison with observations.

Keywords: Magneto-Hydro-Dynamics; modeling; diagnostics; Astrophysics.

1. Introduction

The analysis of astronomical observations always rests on an interpretation of the phenomenon, sometimes even only a rather simple one as the assumption that the emitted spectrum originates from an isothermal plasma. On the other hand, given the impossibility to perform experiments under controlled conditions but, rather, to observe astrophysical phenomena and objects, plus the fact that most astrophysical objects are characterized by complex phenomena involving several physical effects at play simultaneously and interacting in complex ways, one is forced either to the risk of ignoring important effects by considering overismplified models or to the need of building up realistic but often complex models.

The need for models which involve several physical effects of comparable importance (e.g. thermal conduction, radiative losses, some heating agent, magnetic fields etc.) often cannot be treated analytically and typically leads to a numerical treatment of the model itself; sometimes even requiring high performance computing (HPC).

Such models are often used as a theoretical tool to understand the basic physics involved in phenomena, sometimes through parameters-space exploration or, more directly, through an appropriate switching on/off of the various terms in the equations and comparing the different solutions. Models can also be used in a less obvious way as tools to develop and tune-up new diagnostics, by identifying some important observable signature of a specific phenomenon or effect, or even as a diagnostic tool through a detailed comparison with observations.

However standard fitting procedures, e.g. through minimization of χ^2, are not viable with these models for several reasons: for instance each "point" in the parameter space may require a large amount of computing resources; on the other hand parameter derivation through inversion techniques in many cases has been proved mathematically unstable. The choice, thus, in many cases is forward modelling, i.e. compute (i.e. model) a set of cases guessing the mathematical domain of the right parameters of the model, obviously putting the guess for the best value at the center of your domain. Typically the comparison of the various (often computer demanding) calculations will bring a comprehension of the phenomenon and the related physics and probably show which case is closer to, or matches, observations.

However we have found that a comparison with models requires great care, given the complex nature and appearance of the phenomenona. First of all in order to understand the results of a model one requires powerful tools to organize, visualize and handle the model results, often in the form of large table of numerical results on, as is the case of MHD models, density, temperature and velocity plus magnetic fields at each point and time. The need for powerful "visualization tools" is common to all the area of HPC, and there is a general effort to develop and to provide them; some teams which develop powerful codes take care to provide a basic visualization tool along with their code, as it happens for the FLASH code (see next sections) which we use and have helped to develop.

Matching models to observations is an even more demanding feat: one has to match appearance, evolution (when possible), observed features including spectra as collected by instruments. The need to match the emission, and how it is detected by instruments, calls for powerful spectral synthesis codes, capable of producing the emission and spectrum from each part and from the globality of the modeled object or phenomenon. Over the years, along with the numerical models, our group has had to develop some visualization tools and complex tools for comparison with observations (e.g. in X-rays, in radio etc.).

In the following we will show two different examples pertaining to two fields of Astrophysics: the morphology and physical characteristics of one class of Supernovae Remnants and the X-ray emission recently detected in protostellar jets. This method, however, has been widely applied to many more cases, such as the study of solar magnetically confined plasma and the modeling of stellar flares.

2. Supernovae Remnants

The characteristics and the chemical abundances of the interstellar medium (ISM) are strongly influenced by supernovae (SN) and by supernovae remnants (SNRs). However, many features of the interaction between SNR shock fronts and ISM are influenced by several factors, among which the multi-phase characteristics of the medium, its density and temperature, the intensity and direction of the ambient magnetic field. These factors cannot be easily constrained, thus somehow limit our understanding of the ISM, of SNR dynamics and of their interaction.

In particular the bilateral supernova remnants (BSNR, also called "barrel-shaped," or "bipolar"), see [1], are benchmarks for the study of large scale SNR-ISM interactions, since small scale effects appear to be irrelevant. The BSNRs are characterized by two opposed radio-bright limbs separated by a region of low surface brightness; in general, these remnants appear asymmetric, distorted and elongated with respect to the shape and surface brightness of the two opposed limbs.

In spite of the interest around BSNRs, a satisfactory and complete model which explains the observed morphology and the origin of the asymmetries does not exist. The predictions of ad-hoc models have consisted so far of a qualitative estimate of the BSNRs morphology, with no real estimate of the ISM density interacting with the shock.

Orlando and collaborators [2], in order to explain BSNR at an adequate level, have used detailed physical modeling, high-level numerical implementations and extensive simulations. They investigated whether the morphology of BSNR observed in the radio band could be mainly determined by the propagation of the shock through a non-uniform ISM or, rather, across a non-uniform ambient magnetic field. To this end, they modeled the propagation of a shock generated by an SN explosion in the magnetized non-uniform ISM with detailed numerical MHD simulations, considering two complementary cases of shock propagation: 1) through a gradient of ambient density with a uniform ambient magnetic field; 2) through a homogeneous isothermal medium with a gradient of ambient magnetic field strength.

A proper use of modeling, synthetic "observations" derived from models and comparison of observations with models and derived for critical values of the parameters strongly constrained the models of the observed phenomenon.

The authors used FLASH, a very accurate and advanced multi-dimensional MHD code for astrophysical plasmas [3] designed to make efficient use of massively parallel computers with the message-passing interface (MPI) for interprocessor communications. The core of FLASH is based on a directionally split Piecewise Parabolic Method (PPM) solver to handle compressible flows with shocks and the code solves the MHD equations on a block-structured adaptive mesh. To this end, FLASH uses the PARAMESH package [4] for the parallelization and the adaptive mesh refinement portion of the code. FLASH has been developed mainly at the Center for Astrophysical Thermonuclear Flashes (the FLASH center) at the University of Chicago. Our group collaborates with the FLASH center to upgrade the code with new numerical modules and to test it. We have already adapted FLASH for applications to coronal plasmas, to supernova remnants, and to proto-stellar jets. In the simulations presented here and in the following section we have used FLASH with customized numerical modules that treat optically thin radiative losses and thermal conduction.

From the simulations, Orlando et al. [2] synthesized the synchrotron radio emission, making different assumptions about the details of acceleration and injection of relativistic electrons. The scope was to perform simulations for different plasma configurations and different magnetic fields orientations, to syntheze radio emission from the simulations postulating various electrons injection directions with respect to the magnetic field and the different orientations of the system with respect to the line of sight; and to compare the various "observations" synthesized from models with good observations to obtain constraints on the models and, anyhow, insight.

The authors found that asymmetric BSNRs are produced if the line-of-sight is not aligned with the gradient of ambient plasma density or with the gradient of ambient magnetic field strength; they also derived useful parameters to quantify the degree of asymmetry of the remnants that may provide a powerful diagnostic of the microphysics of strong shock waves through the comparison between models and observations. BSNRs with two radio limbs of different brightness can be explained if a gradient of ambient density or, most likely, of ambient magnetic field strength is perpendicular to the radio limbs. BSNRs with converging similar radio arcs can be explained if the gradient runs between the two arcs. Figure 1 shows good examples of simulations which yield two different apparent morphologies, along with the corresponding two examples of observed morphology well matched by simulations.

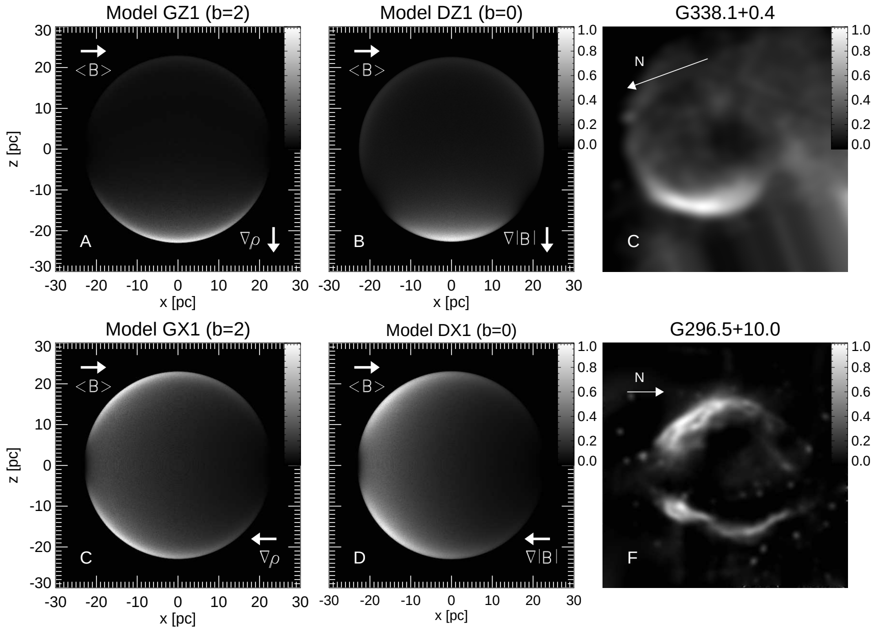

Fig. 1. Synchrotron radio emission (normalized to the maximum of each panel), at $t =$ 18 kyrs since the SN explosion, synthesized from models assuming a gradient of ambient plasma density (panels A and D) or of ambient magnetic field strength (panels B and E) when the LoS is aligned with the y axis. All the models assume quasi-perpendicular particle injection. The directions of the average unperturbed ambient magnetic field, and of the plasma density or magnetic field strength gradient, are shown in the upper left and lower right corners of each panel, respectively. The right panels show two examples of radio maps (data adapted from [5] and [1]); the arrows point in the north direction) collected for the SNRs G338.1+0.4 (panel C) and G296.5+10.0 (panel F). The color scale is linear and is given by the bar on the right. Adapted from [2]

3. Protostellar Jets

The early stages of the star birth manifest various mass ejection phenomena, including collimated jets which can travel through the interstellar medium at supersonic speed (at several hundreds of km/s or even at ≈ 1000 km/s), forming shock fronts at the interaction front between the jet and the unperturbed ambient medium. In the last 50 years these features have been studied in detail in the radio, infrared, optical and UV bands, and are known as Herbig-Haro (hereafter HH) objects.

Recently, see for instance [7], X-ray emission from HH objects has been detected with both the XMM-*Newton* and *Chandra* satellites in a few young stellar objects (YSO); the X-ray emission, given the relatively low temperature ($\approx 10^6$ K) derived from spectra and, in some cases, the evident misplacement with respect to the originating stars appears to be unrelated to the typical X-ray emission phenomena of stars, typically tied to coronae. Protostellar jets and the circum-proto-stars are usually low temperature (and low-energy) environments and X-ray emission, therefore, has been a surprise.

Thus understanding the X-ray emission from protostellar jets is important to understand which physical mechanism of star and planet formation leads to X-rays thermal emission. Furthermore, X-rays (and ionizing radiation in general) may affect the environment of young stellar objects and, in particular, the physics and chemistry of the accretion disk and its planet-forming environment. The ionization state of the accretion disk around young stellar objects will determine its coupling to the ambient and protostellar magnetic field, and thus, among other things, influence its turbulent transport. This, in turn, will affect the accretion rate and the formation of structures in the disk and, therefore, the formation of planets. X-rays also can act as catalysts of chemical reactions in the disk's ice and dust grains, thereby significantly affecting its chemistry and mineralogy. The ability of the forming star to ionize its environment will therefore significantly affect the outcome of the formation process.

Several models have been proposed to explain the X-ray emission from protostellar jets, but the emission mechanism is still unclear. In this perspective, we developed a detailed hydrodynamic model of the interaction between a supersonic protostellar jet and the ambient medium; our aim is to explain the detailed physics that may lead to the observed X-ray emission. Our model takes into account optically thin radiative losses and thermal conduction effects. We use the FLASH code also in this case.

A first paper [6], presented an exploratory study with a set of results concerning a jet less dense than the ambient medium, with a density contrast $\nu = n_{\rm a}/n_{\rm j} = 10$ (where $n_{\rm a}$ is the ambient density and $n_{\rm j}$ is the density of the jet); this model showed X-ray emission in good agreement with the observed X-ray emission from HH 154 [7]. Bonito and collaborators [6] have shown the validity of the physical principle on which our model is based: a supersonic jet traveling through the ambient medium produces a shock at the jet/ambient medium interaction front, leading to X-ray emission in good agreement with observations. A second paper studied the effects of varying the control parameters characterizing the jet dynamics, more specifically, the ambient-to-jet density ratio, $\nu = n_{\rm a}/n_{\rm j}$, and the Mach number, $M = v_{\rm j}/c_{\rm a}$ ($c_{\rm a}$ is the ambient sound speed). Through the exploration of a wide range of the control parameter space, [8] tried to determine the range of these parameters that can give rise to X-ray emission consistent with observations. The scope included:

- to constrain the jet/ambient medium interaction regimes leading to the X-ray emission observed in Herbig-Haro objects in terms of the emission by a shock forming at the interaction front between a continuous supersonic jet and the surrounding medium;
- to derive detailed predictions to be compared with optical and X-ray observations of protostellar jets;
- to get insight into the protostellar jet's physical conditions.

A wide set of two-dimensional hydrodynamic numerical simulations, in cylindrical coordinates, modeling supersonic jets ramming into a uniform ambient medium were performed. The model explains the observed X-ray emission from protostellar jets in a natural way and, in particular, shows that a protostellar jet less dense than the ambient medium well reproduces the observations of the nearest Herbig-Haro object, HH 154, and allows to make detailed predictions of a possible X-ray source proper motion ($v_{\rm sh} \approx$ 500 km s^{-1}) detectable with *Chandra.* The simulations of jets as dense as, or more dense than, the ambient cannot reproduce observations. ALso we found that a careful account of the interstellar and circum-jet absorption of X-rays leaves the X-ray emission of the tip of the jet, in excellent agreement with observations since it hides the very soft emission from the rest of the jet and surrounding region. Furthermore, our results suggest that the simulated protostellar jets which best reproduce the X-rays observations cannot drive molecular outflows.

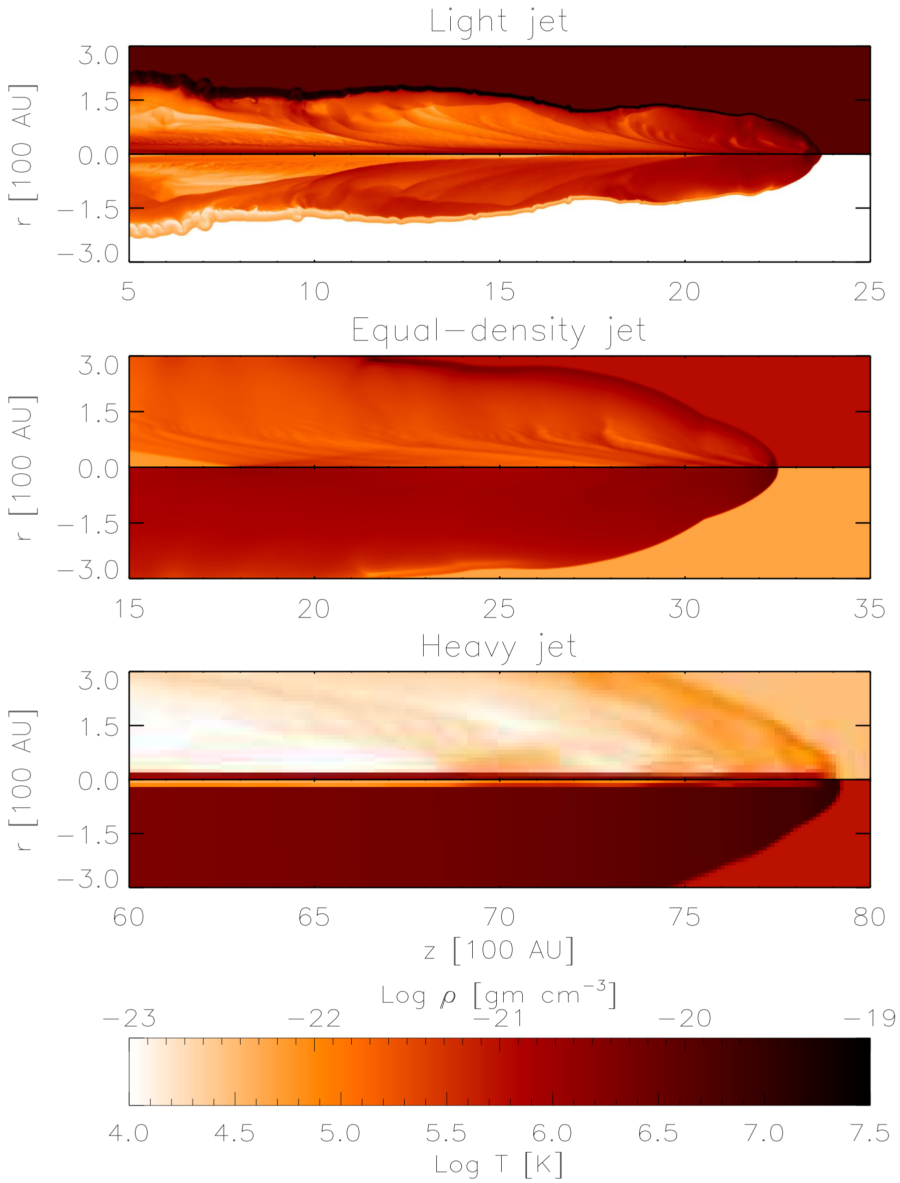

Fig. 2. Two-dimensional mass density (upper half-panels) and temperature (lower half-panels) cuts in the $r - z$ plane after 20 years since the beginning of the jet/ambient medium interaction for the best cases of light (upper panels), equal-density (middle panels) and heavy jets (lower panels). Adapted from [8].

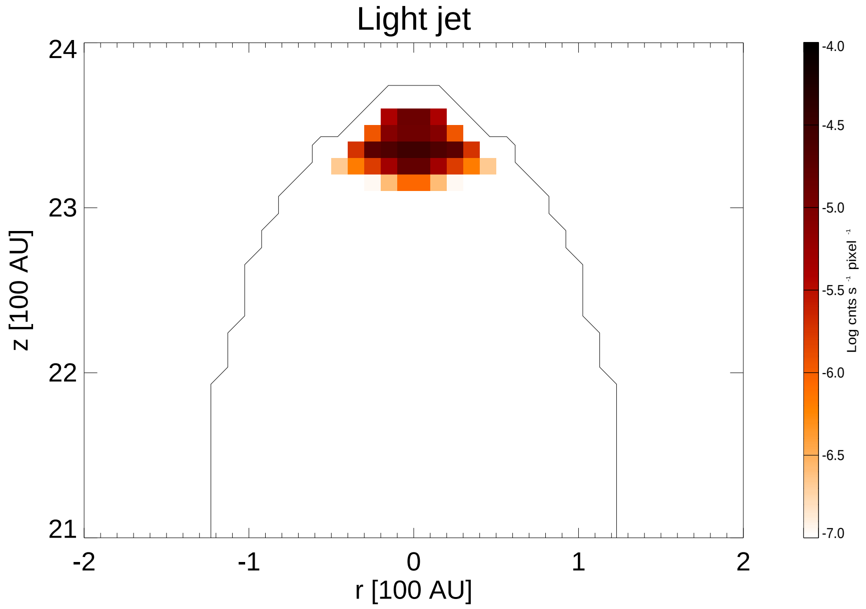

Fig. 3. Synthesized X-ray emission, in logarithmic scale, as predicted to be observed with ACIS-I, for the light jet simulation, 20 years since the beginning of the jet/ambient medium interaction. At a distance $D \approx 150$ pc, 100 AU corresponds to about 0.7 arcsec. Adapted from [8].

4. Conclusions

Models are fundamental to understand the physics of astrophysical objects because these objects are complex and controlled experiments on them are not possible. Models are not only important to provide physical insight but can give fundamental diagnostics of complex phenomena. It is very important, however, to supplement these models with appropriate tools to handle, present and interpret model results as well as tools for proper comparison with observations.

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References

1. Gaensler, B. M. *ApJ*, **493**, 781, (1998)
2. Orlando S., F. Bocchino, F. Reale, G. Peres, O. Petruk, On the Origin of Asymmetries in Bilateral Supernova Remnants, *A&A* in press (2007)
3. Fryxell et al. *ApJS* **131**, 273, (2000)
4. MacNeice et al. *Comp. Phys. Commun.*, **126**, 330, (2000)
5. Whiteoak, J. B. Z., Green, A. J., *A&AS* **118**, 329, (1996)
6. Bonito, R.; Orlando, S.; Peres, G.; Favata, F.; Rosner, R., *A&A* , 424, L1, (2004)
7. Favata, F., Fridlund, C. V. M., Micela, G., Sciortino, S., and Kaas, A. A. *A&A* , 386, 204, (2002)
8. Bonito, R.; Orlando, S.; Peres, G.; Favata, F.; Rosner, R., *A&A* **462**, 645, (2007)
9. $\mathcal{AMS}$-LaTeX Version 2 User's Guide (American Mathematical Society, Providence, 2004).
10. B. W. Bestbury, *J. Phys. A* **36**, 1947 (2003).