

Scientific description of the project

- Title of the project : **Numerical simulations of wind-accretion in high mass X-ray binary systems**
- DARI number : [Numéro de projet]
- Scientist in charge : EL MELLAH Ileyk
- Laboratory : AstroParticule & Cosmologie (APC) - Paris 7
- Number of hours required (mono-process CPU) :
CINES BULL Occigen : 300 000 scalar hours

1 Abstract

Our group is asking for 300 000 h CPU on the parallel CINES computer 'Occigen' so as to investigate phenomenological statements concerning wind accretion in Supergiant High Mass X-ray Binaries (Sg-HMXB), whether they host a neutron star or a black hole. We developed a specific approach to describe both the large scale ballistic behavior of the stellar companion wind to the accretion radius of the compact object (whom ratio is typically of the order of 10^{-1}) and then, down to a few hundreds of gravitational radii (whom relative size compare to the former ranges from 10^{-3} to 10^{-5}). The huge dynamical spatial scale is made possible thanks to both the highly parallelized MPI-AMRVAC software and to a stretched grid centered on the compact object. The former program makes it possible to grasp shocks and non axisymmetric instabilities likely to give birth to potentially transient accretion discs around the compact object. The three-dimensional characterization of such flows is a crucial prerequisite to better appreciate both the expected X-ray time variabilites and the initial conditions from which close-in accretion discs ought to be modeled.

2 General presentation

The number of detected Sg-HMXB has dramatically increased as the recent space missions stretched the limits of the high energy part of the light spectrum [9]. Once believed to be rare [8], those X-ray luminous wind-fed compact objects orbiting an evolved O/B star turned out to not fit well in the previously sketched categories. The characterization of the companion star is usually a challenge in itself because of the high obscuration of those systems, lying close from the Galactic plane and kiloparsecs away from us, but the recent inflation of the number of extragalactic HMXB partly lifted this difficulty. Still, the main information we get from those objects (some being microquasars whom study is believed to enrich our understanding of Active Galactic Nuclei) comes from the X-ray emission to which they owe their name.

Names	Status	Laboratory
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TABLE 1 – Members of the collaboration

This hard radiation, whose discovery in 1962 [6] brought up so many questions, remains puzzling when one attempts to explain the different "families" of behaviors observed - if that an agreement is found on the very classification. Those complex systems have been dissected (the launching of the stellar wind, its orbital trajectory, the shocks it can form, its subsequent accretion onto the compact objects, etc) but in order to go beyond toy-models which set the asymptotic separated behaviors, one needs to tackle the entire fate of the stellar material, from the clumpy wind scale down to the close vicinity of the compact object (being, in our study, around a hundred gravitational radii for a black hole and the magnetosphere scale for a neutron star). For instance, being able to corroborate the identity of the compact object deduced from orbital considerations would bring more scientific weight to the current observational constraints on the equation of state of matter in neutron stars. So as to achieve such assessment, one must first wonder how the orbital parameters (the orbital period, the mass of the compact object, the mass ratio, the eccentricity) and the properties of the stellar companion (its wind velocity and clumpiness, its mass ejection rate) prescribe the compact object environment to disentangle the contingent from the essential causes.

Independently from the accreting body nature, the systems we intend to model already differ a lot from each other :

- **Cyg X-1** : it hosts a highly ROCHE lobe deformed [1] Sg star [?] orbiting a compact object of comparable mass every 5.6 days. Although one of the most studied HMXB - if not the most - its genericity remains suspicious.
- **LMC X-1** : this extragalactic close X-ray binary presents a peculiar Onfp class [?] star whom rapid rotation might transfer an important amount of stellar angular momentum to the wind.
- **Vela X-1** : the archetype of the Sg-HMXB. Characterized by a larger mass ratio than the two previous ones, this eclipsing system feeds its compact object through the specially intense stellar wind of its B stellar companion, well embedded in its ROCHE lobe.
- **4U 1907+09** : in this high mass ratio eccentric X-ray binary, a hybrid accretion might proceed, mixing ROCHE lobe overflow and wind accretion. The torque accreted matter exerts on the compact object has been reported to potentially alternate between positive and negative values.

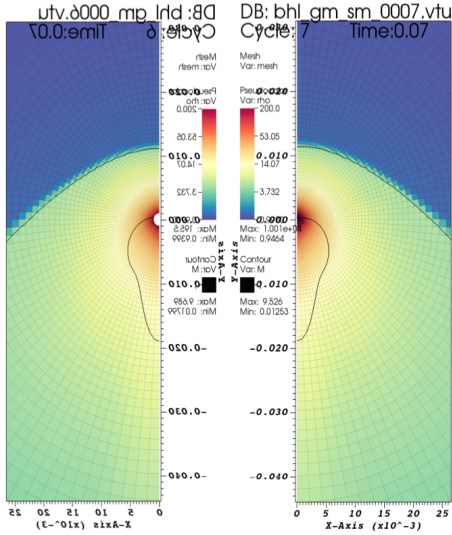


FIGURE 1 – Bow shock and sonic surfaces of an axisymmetric 2.5D accretion flow. Notice the stretched grid

BONDI, HOYLE and LYTTLETON laid the foundations of an understanding of axisymmetric accretion flows (see the review [2]) like the one we started from as a numerical sanity check (see next paragraph). Their ballistic approach has been improved to account for pressure effects [7], making the accretion line in the wake of the accreting body an accretion tail. In the end of the 80's, two dimensional simulations of those flows [?] revealed an instability, coined the flip-flop one; the two dimensional cylindrical geometry, the low resolution and the oversized inner boundary compare to the actual size of the accretor made this instability suspicious to the community, until theoretical models [3] supported the possibility of an insta-

bility growth important enough to account for the formation of tiny and transient discs around the accretor. The issue has remained polemical up to nowadays as the computational capabilities have proven insufficient to grasp the whole problem. That is why we developed a reliable upwind scheme on a logarithmic three dimensional grid centered on the accretor to jump from large to small scales at a cheaper computational cost. However, this numerical swindle would not have been enough to beat the dynamics barrier without the highly parallelized structure of the finite volumes program MPI-AMRVAC. Using the two together, we have now good hope to make the inner boundary small enough to be whether physical (for neutron star systems) or transparent (for black hole systems). The Figure 1 shows for instance a simulation where the structure of the flow and of the sonic surface is not altered by the unphysical inner boundary.

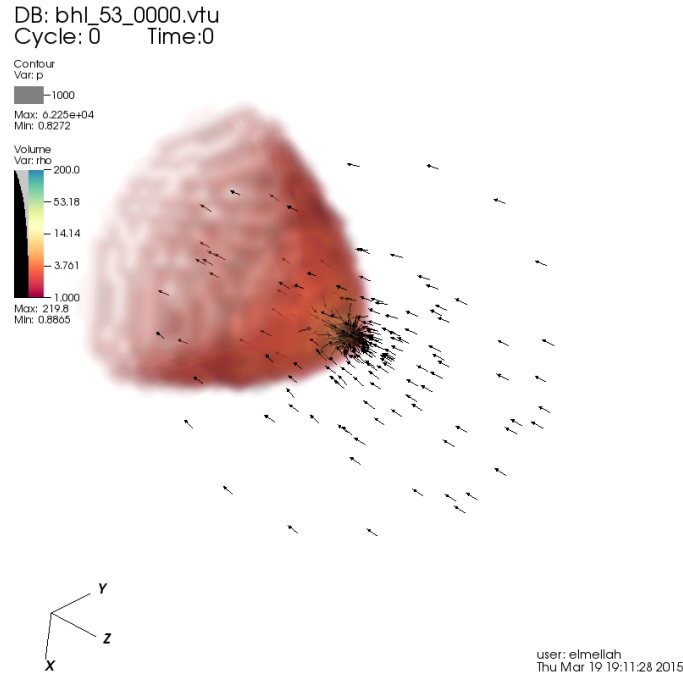


FIGURE 2 – 3D initial setup deduced from the relaxed 2.5D one

Concerning the numerical reliability of our setup, we already validated the behavior of the gas in 2.5D spherical geometry within the accretion radius by showing that the axisymmetric configuration is in agreement with semi-analytical results derived by [4], especially regarding the topology of the sonic surface for a detached bow shock. Nevertheless, in order to enable the possible non axisymmetric instabilities to develop and to consider more

realistic outer boundary conditions, we still need to free those 2.5D numerically relaxed simulations from their constraining geometry and go for the full 3D configuration. The computational time it requires motivates our application to the CINES facilities.

It is noteworthy that our work also aim to help constraining future and incoming observational mission ([ATHENA](#) & [ASTRO-H](#) eg) : which waveband should we look after ? Which time scale should we aim to characterize processes involved in the building up of an accretion disc ? Since the mass accretion rate determines the available power convertible into X-ray luminosity, such simulations would also set lower limits for the sensibility required to probe events taking place in the very neighborhood of the compact object. The related studies, led in parallel, of the instabilities in this strong gravitational field regims (the NOVAS project eg) might, one day, tell us more about the Physics at stake in those extreme environments : what kind of hitherto unseen events can take place in the wildness of a neutron star light cylinder or of a black hole ergosphere ?

3 Method

3.1 Numerical tools

The MPI-AMRVAC code

The code MPI-AMRVAC [?] (Message Passing Interface - Adaptative Mesh Refinement Versatile Advection Code) is an AMR code parallelized with OpenMPI. This code was developed to solve HD and MHD hyperbolic conservative equations, whether in a classical or a relativistic framework. The user-defined additional source termsⁱ entitle to explore a wide range of physical one or two-fluids configurations. Several types of RIEMANN solvers are implemented (ROE and HARTEN-LAX-VAN LEER ones eg), along with flux-limiter schemes as the Total Variation Diminishing (TVD) ones.

The AMR grid structure is based on the use of sub-grids (of a few tens of cells in every dimension) in a tree architecture (octree in 3D). At each iteration the code uses an internal LOHNER's method or user-supplied criteria to determine if a sub-grid needs to be refined, left as it is, or unrefined. The tree structure replaces each refined sub-grid by a 2^D sub-grid of the same cell-size but with the area of each cell less by a factor 2^D . For the present project, we will probably not use the AMR but instead, we designed a non-regular grid fitting the geometry of the system and enabling us to reach outer radius to

i. Radiative cooling (in optically thick or thin regims), gravity, viscosity...

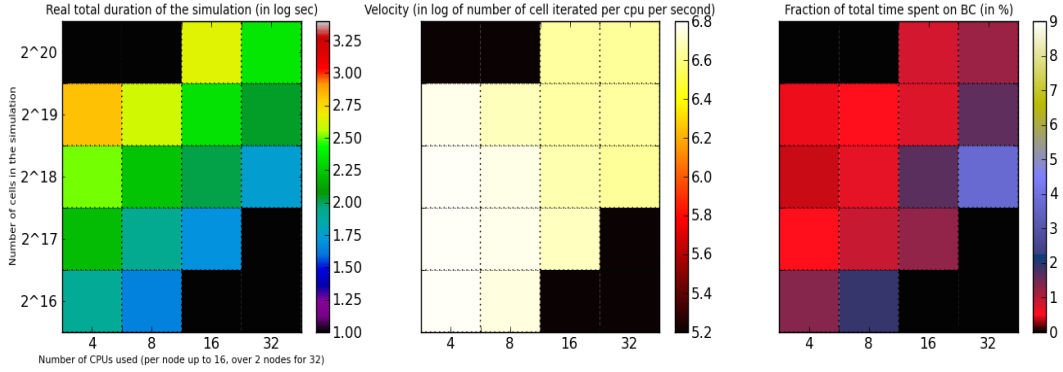


FIGURE 3 – General scaling of the MPI-AMRVAC code performed on the François Arago Center (FACe) cluster at Paris 7 Diderot

inner radius ratio up to 10^5 at a low computational cost. The grid is designed to maintain the same radial to azimuthal cell size ratio constant for any radius of the simulation. The smallness of the cells close to the inner boundary sets the COURANT-FRIEDRICHS-LEWY (CFL) time step to such small values that several tens of millions of iterations are expected in order to describe the flow dynamics both at large and small scales. Such computation can only be achieved using the large number of CPU available on supercomputers.

Parallelization and scaling

The parallelization relies on OpenMPI libraries and the scalability test done on ‘Jade’ by Zakaria MELIANI has showed an efficiency of the order of 80% on 2000 processors (see Figure 4). This value is very close to the theoretical limit when one takes into account the I/O of the code needed to write the data. Those results of the parallelization efficiency were obtained using a test case in relativistic hydrodynamics, taking into account the propagation of shocks with Lorentz factors between 100 and 1000. The main test was done in 2D with 10 levels of AMR with a refinement ratio of 2. This allowed us to locally increase the resolution of the simulation by a factor of 218. The MPI-AMRVAC code also includes two

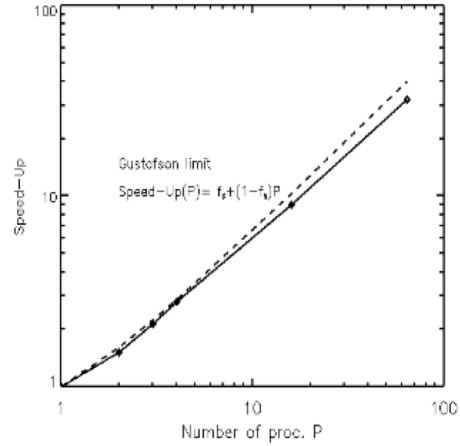


FIGURE 4 – Scaling of the MPI-AMRVAC code performed on the JADE super-computer

different methods to write the data allowing a better flexibility. Indeed, MPI-AMRVAC can either use the method MPI-II/IO or the method that consists of sending all the data from the slave node to the master node to minimise the number of processors taking part in the writing.

3.2 Time justification

If the logarithmically stretched grid we developed enables us to investigate this intrinsically multi-scale problem at an affordable cost, the huge time dynamics entailed precludes extended numerical simulations on local clusters as the [FACe](#) one (see Figure 3). The initial 2.5D relaxation step (cf Figure 2) partly lifts this caveat but for non axisymmetric outer boundary conditions, we still require the computational ability to monitor the flow over large scale time scales, which implies dozens of 10^6 iterations.

Here would be the main use of the 300 000 CPU hours :

- ★ **10 kh·CPU** to definitely confirm the observed trend of Figure 1 concerning the sonic surface shape of an axisymmetric flow, by making the inner boundary small enough to reach the physical size of the compact object. This simulation would firmly validate the theoretical approach suggested by [4] to semi-analytically study those flows.
- ★ **$30^i \times 300$ h·CPU \sim 10 kh·CPU** to explore the dependency of the stationary shock properties with the MACH number M_∞ and the mass of the accreting body M (attached/detached shocks, position of the forefront, opening angle of the tail, transverse density profile...).
- ★ **4 systems \times 7 possible configurationsⁱⁱ \times 10 kh·CPU \sim 280 kh·CPU** to decide between different observationally deduced system properties and retroactively, to shed light on the relevant large scale phenomenological description among all those which led observers to different conclusions.

Eventually, this numerical simulations set as a whole would bring fruitful answers to our core problematics : to what extent orbital parameters and properties of the stellar companion constrain the vicinity of the compact object in a wind-fed HMXB? Such answers would be robust starting points to inspire instability studies in those systems.

i. 30 points to explore the two dimensional (M_∞, M) space

ii. Depending on the wind velocity, its clumpiness, its temperature, the orbital parameters...

4 Bibliographie

Références

- [1] Y. Avni and J. N. Bahcall. Ellipsoidal light variations and masses of X-ray binaries. *Astrophys. J.*, 197 :675, May 1975. ISSN 0004-637X. doi : 10.1086/153558. URL <http://adsabs.harvard.edu/abs/1975ApJ...197..675A>.
- [2] Richard G Edgar. A review of Bondi–Hoyle–Lyttleton accretion. *New Astron. Rev.*, 48(10) :843–859, September 2004. ISSN 13876473. doi : 10.1016/j.newar.2004.06.001. URL <http://linkinghub.elsevier.com/retrieve/pii/S1387647304000739>.
- [3] T. Foglizzo, P. Galletti, and M. Ruffert. A fresh look at the unstable simulations of Bondi-Hoyle-Lyttleton accretion. *Astron. Astrophys.*, 2201(2201) :15, May 2005. ISSN 0004-6361. doi : 10.1051/0004-6361:20042201. URL <http://arxiv.org/abs/astro-ph/0502168>.
- [4] Thierry Foglizzo and Maximilian Ruffert. An analytical study of Bondi-Hoyle-Lyttleton accretion I. Stationary flows. 361 :22, April 1996. ISSN 00046361. URL <http://arxiv.org/abs/astro-ph/9905226><http://arxiv.org/abs/astro-ph/9604160>.
- [5] B. a. Fryxell and Ronald E. Taam. Numerical simulation of non-axisymmetric adiabatic accretion flow. *Astrophys. J.*, 335 :862, December 1988. ISSN 0004-637X. doi : 10.1086/166973. URL <http://adsabs.harvard.edu/abs/1988ApJ...335..862F>.
- [6] Riccardo Giacconi, Herbert Gursky, Frank R. Paolini, and Bruno B. Rossi. Evidence for x Rays From Sources Outside the Solar System. *Phys. Rev. Lett.*, 9(11) :439–443, December 1962. ISSN 0031-9007. doi : 10.1103/PhysRevLett.9.439. URL <http://adsabs.harvard.edu/abs/1962PhRvL...9..439G>.
- [7] G. P. Horedt. Pressure Effects in Line Accretion. *Astrophys. J.*, 541(2) : 821–830, October 2000. ISSN 0004-637X. doi : 10.1086/309443. URL <http://iopscience.iop.org/0004-637X/541/2/821/fulltext/>.
- [8] A. F. Illarionov and R. A. Sunyaev. Why the Number of Galactic X-ray Stars Is so Small? *Astron. Astrophys.*, 39, 1975. URL <http://adsabs.harvard.edu/abs/1975A%26A....39..185I>.

- [9] Q. Z. Liu, J. van Paradijs, and E. P. J. van den Heuvel. Catalogue of high-mass X-ray binaries in the Galaxy (4th edition). *Astron. Astrophys.*, 455(3) :1165–1168, September 2006. ISSN 0004-6361. doi : 10.1051/0004-6361:20064987. URL <http://adsabs.harvard.edu/abs/2006A%26A...455.1165L>.
- [] Matsuda, Takuya, Inoue, Minoru, Sawada, Keisuke, Takuya Matsuda, Minoru Inoue, and Keisuke Sawada. Spin-up and spin-down of an accreting compact object. *Mon. Not. R. Astron. Soc. (ISSN 0035-8711)*, 226 : 785–811, 1987. URL <http://adsabs.harvard.edu/abs/1987MNRAS.226..785M>.
- [] O. Porth, C. Xia, T. Hendrix, S. P. Moschou, and R. Keppens. MPI-AMRVAC for Solar and Astrophysics. *arXiv.org*, July 2014. URL <http://arxiv.org/abs/1407.2052><http://arxiv.org/abs/1407.2052v1>.
- [] V. I. Shenavrin, O. G. Taranova, and A. E. Nadzhip. Search for and study of hot circumstellar dust envelopes. *Astron. Reports*, 55(1) :31–81, January 2011. ISSN 1063-7729. doi : 10.1134/S1063772911010070. URL <http://cdsads.u-strasbg.fr/abs/2011ARep...55...31S>.
- [] Nolan R. Walborn, Ian D. Howarth, Christopher J. Evans, Paul A. Crowther, Anthony F. J. Moffat, Nicole St-Louis, Cecilia Fariña, Guillermo L. Bosch, Nidia I. Morrell, Rodolfo H. Barbá, Jacco Th. van Loon, Cecilia Farina, Guillermo L. Bosch, Nidia I. Morrell, Rodolfo H. Barba, and Jacco Th. van Loon. The Onfp Class in the Magellanic Clouds. *Astron. J.*, 139(1980) :27, March 2010. ISSN 0004-6256. doi : 10.1088/0004-6256/139/3/1283. URL <http://arxiv.org/abs/1001.4032><http://adsabs.harvard.edu/abs/2010AJ....139.1283W>.