Scientific description of the project

• Title of the project : **Numerical simulations of wind-accretion in high mass X-ray (HMBX) binary systems**

• DARI number : [Numéro de projet]

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• Laboratory : AstroParticule & Cosmologie (APC) - Paris 7

• Number of hours required (mono-process CPU) :
CINES BULL Occigen : 300 000 scalar hours

1 Abstract

Our team is asking for 300 000 h-CPU on the parallel CINES supercomputer 'Occigen' so as to investigate phenomenological statements concerning wind accretion in Supergiant High Mass X-ray Binaries (Sg-HMXB), either **hosting** a neutron star or a black hole. We developed a specific approach to described **both** the large scale ballistic behavior of the stellar wind and the accretion radius of the compact object (**whose ratio is typically of the order of 10**) and then, down to a few hundreds of gravitational radii of the compact object (**whose size ratio to the accretion radius 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 a stretched grid **centered** on the compact object. The former code **enables us** to grasp both 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 variabilities and the initial conditions from which close-in accretion discs ought to be modeled.

2 Scientific motivation

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 (e.g. LIU et al 2006). Once believed to be rare (ILLARIONOV & SUNYAEV 1975), those X-ray luminous wind-fed compact objects orbiting an evolved O/B star **did not fit into** the previously sketched categories. The characterization of the companion star is usually a **challenge** in itself because of the high obscuration **occurring** in those systems lying close from the galactic plane **several** kiloparsecs away from us. **Hopefully**, the recent **discovery ?** of HMXB **outside of the galactic plane** 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.

This hard radiation, **discovered** in 1962 (GIACCONI et al 1962), brought up so many questions that **it** 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 bf in order to go beyond toy-models, one needs to tackle the entire **dynamics** 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 of a black hole or the magnetosphere radius of 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. **In order to achieve such assessment**, one must first wonder how the orbital parameters (orbital period, mass of the compact object, masses ratio, eccentricity) and the properties of the stellar companion (wind velocity, **ejection** mass rate **and** clumpiness) **influence** the compact object environment **in order** 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 (AVNI et al 1975) Sg star (SHENAVRIN et al 2011) 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 (Walborn et al 2010) 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.

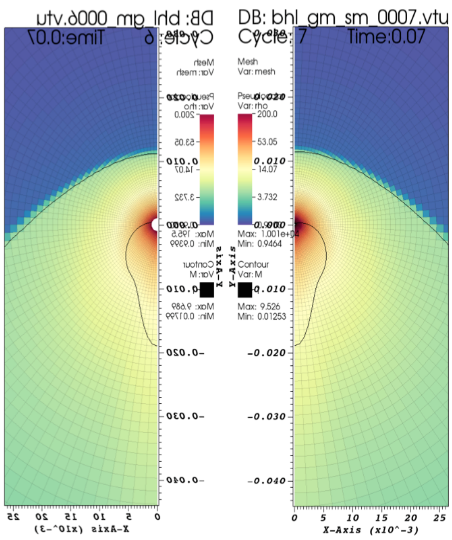

Figure 1 – Bow shock and sonic surfaces of an axisymmetric 2.5D accretion flow for two different accretion size.

Bondi, Hoyle and Lyttleton **laid** the foundations of an understanding of axisymmetric accretion flows (see a review by Edgar 2004) 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 (Horedt 2000), making the accretion line in the wake of the accreting body an accretion tail. In the end of the 1980's, two dimensional simulations of those flows (Matsuda 1987, Fryxell & Taam 1988) revealed an instability, coined **as** 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 (Foglizzo et al 2005) supported the possibility of an instability 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.

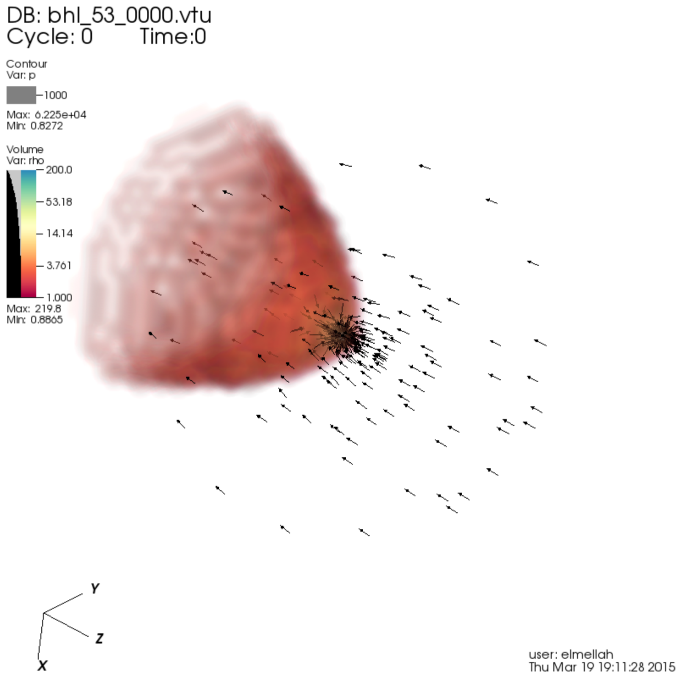

FIGURE 2 – 3D initial setup deduced from the relaxed 2.5D one

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 FOGLIZZO & RUFFERT (1997), especially **regarding** the topology of the sonic surface for a detached bow shock. **Nevertheless**, **in order to** enable non axisymmetric instabilities to develop, one needs to consider more realistic outer boundary conditions. We **then** need to **lift the 2.5D assumption** and go for a full 3D configuration. The required computational time motivates our application to the CINES facility.

It is noteworthy that our work also aims 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 regimes (e.g. the NOVAs project) 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 ?

Nom et prénom	Fonction	Etablissement
EL MELLAH Ileyk	Doctorant	APC
CASSE Fabien	Maître de conférences	APC
DODU Fabrice	Ingénieur de recherche	APC

TABLE 1 – Members of the collaboration

3 Presentation of the numerical tools

3.1 Numerical methods and setup

AMRVAC code

The code AMRVAC is an adaptative mesh refinement code parallelized with MPI. This code was created to be used in a wide variety of physical applications that can be described by a set of conservative equations, independently of their nature (and not only fluides). Among the pre-existing physics modules there are modules to see the hydrodynamical and MHD equations in the classical or special relativity case. Several types of solver are also implemented, for example TVD Lax-Friedrich or HLL solvers.
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 do not use the adaptative mesh refinement but instead we designed a non-regular grid fitting the geometry of the system and enabling us to reach outer radius to inner radius ratio up to 10^5 at a low computational cost. The grid is designed to maintain**

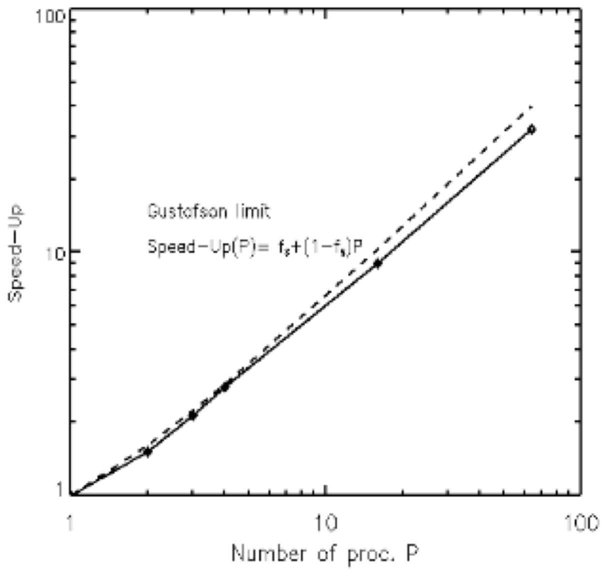

FIGURE 3 – Scaling of the MPI-AMRVAC code performed on the JADE super-computer.

the same radial to azimuthal cell size ratio constant for any radius of the simulation (Ileyk tu pourrais montrer un exempt de grille). The smallness of the cells close to the inner boundary sets CFL time step so small that several tens of millions of iterations are expected in order to describe the flow dynamics. Such computation can only be achieved using a large number of CPUs available on supercomputers.

The parallelization is done with MPI and the scalability test done on 'Jade'by Z. Meliani showed an efficiency of the order of 80% on 2000 processors. 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 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 Justification du temps

We ask for a relatively small quantity of computing time (100 000h) that will be shared between all the members of our groups since we are still in an early stage of our project and cannot foresee all issues that will have to be fixed during the GR-MHD development. This amount of computational time will allow us to perform about 30 runs on 128 processors, mainly devoted to the study of hydrodynamical accretion disks in the very close vicinity of black holes with various spin factors. We will also dedicated a part of these simulations to the study of the birth of Rossby Wave instability near the last stable orbit of the disk. The expected variability of the emission spectra (calculated with the GYOTO code) will be compared to observations from micro quasars where quasi-periodic oscillations are observed. If we make faster progress than anticipated we intend to resubmit a proposal in june 2014.

4 Bibliographie

Références