

longer enable us to consider the incoming flow as planar. Considering simple cooling and heating functions, we want to assess the possibility to form a disc in a wind accretion system, a question much less explored than the formation of an accretion disc by Roche lobe overflow : and if a disc forms, how different is it from the classical α -disc modeled by [9]? 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 General presentation

The number of wind accreting systems has dramatically increased as the recent space missions stretched the limits of the high energy part of the light spectrum [7; 11]. Once believed to be rare [6], those X-ray luminous objects where a compact object orbits an evolved O/B star (SgXB for Supergiant X-ray Binaries) did 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 occurring in those systems but the recent inflation of the number of extragalactic high mass X-ray binaries partly lifted this difficulty. Still, the main information we get from those objects 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, first discovered in 1962 [5], brought up so many questions which remain puzzling when one attempts to explain the different "families" of behaviours 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 only set the asymptotic separated behaviours, 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 for 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. 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 and possibly, the eccentricity) and the properties of the stellar companion (wind velocity, ejection mass rate, clumpiness) prescribe the compact object environment to disentangle the contingent from the essential causes.

A robust setup which revealed a previously unseen instability

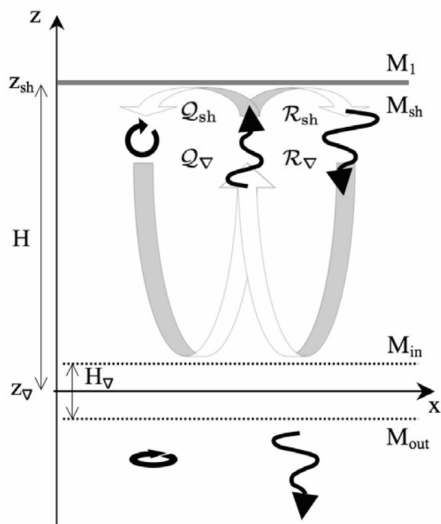


Figure 1: Sketch of the advective-acoustic cycle between the shock at z_{sh} and a subsonic zone of strong gradients, on the upper side of the sonic surface at z_v . See [3] for more details.

It is precisely what we undertook thanks to the first hoursCPU we were granted in July 2015. We tested the robustness of our 2.5D axisymmetric setup and managed to witness previously unseen qualitative and quantitative properties of the flow (its structure, the mass accretion rate, the topology of the sonic surface - see "rapport d'activité"). Those findings have been described in more details in a paper we published in October 2015 [2] and brought up an unexpected question concerning a recently analytically discovered instability, the "advective-acoustic" one [3]. Indeed, our simulations suggested that the flow had converged towards a steady-state we characterized ; although the results were resolution independent, there was a risk than the numerical solver we were using (the total variation diminishing Lax Friedrichs), known for being a diffusive one, could damp any resonance able to

make the instability grow at a sensible level. Then, we took the most of the CINES facilities to run very high resolution simulations with a much less diffusive solver (one relying on a monotonic upstream-centered scheme), starting from an interpolated version of the steady-state we had obtained.

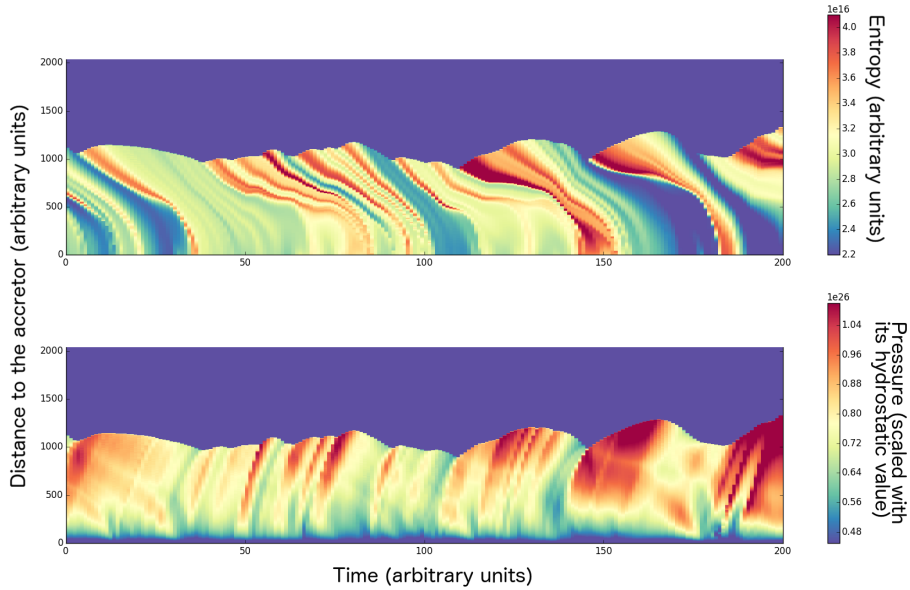


Figure 2: Colormaps of the entropy (upper panel) and of the deviation compared to hydrostatic equilibrium pressure (lower panel) as a function of time (horizontal axis) and of distance towards the accretor (vertical axis) which lies at the bottom. The waterline at the top stands for the position of the shock front, which is pushed upstream each time it is reached by a pressure wave. The flow is supersonic on the upper side of this border and subsonic just below. The very bottom blue part in the lower panel corresponds to the inner supersonic region, below the sonic surface, where the acoustic waves can no longer travel upstream.

As a result, the part of the region between the shock front and the sonic surface, ahead of the accretor, turned out to be a resonant cavity where entropic perturbations are advected by the inflow and excite, as they get closer from the sonic surface, acoustic waves which travel back upstream, towards the front shock. The shock is then moving back and forth as the acoustic waves reach it, exciting new entropic perturbations. The advective-acoustic cycle is illustrated on Figure 1, from [3].

If the growth of this instability has been thoroughly characterized the last decade, its saturation level remains totally unknown. Could this instability account for some of the many time variabilities observed in systems where a compact object undergoes wind accretion? Beyond the case of the X-ray binaries lie the runaway compact bodies which have been kicked at supersonic velocities with respect to the interstellar medium because of an

assymmetric explosion or in a close encounter - see eg [10]. Several neutron stars have been witnessed in this regime (eg IGR J11014-6103) and the question of shock cone vibrations is under investigation [8]. It has also been suggested that another instability, non-axisymmetric and coined as the "flip-flop instability", could be responsible for the quasi-periodic oscillations seen in some X-ray binaries [1]. If we are granted the requested hours on the Occigen BULL cluster, we intend to investigate the growth of this instability (to make sure it corresponds to the advective-acoustic one) and its saturation level. The interplay between inflowing entropic waves and outflowing acoustic ones we have glimpsed in our very first simulations is already very promising (see Figure 2).

Towards a comprehensive numerical setup for wind accreting XB

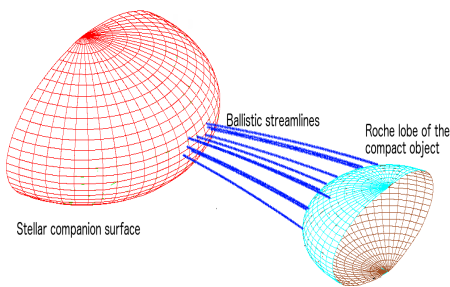


Figure 3: Sketch of some computed ballistic streamlines a supersonic wind would follow from the stellar surface (on the left) to the Roche lobe of the compact object (on the right)

It has been long known that the binary systems hosting a compact object can see the stellar companion fill its Roche lobe, which results in the formation of an accretion disc as matter is gently poured through the first Lagrangian point. If this picture holds for low-mass X-ray binaries, it does not do much to account for the X-ray luminosity of high-mass X-ray binary systems where, in much cases, the stellar companion is enclosed within its Roche lobe. The mass transfer occurs either when the compact companion, on an eccentric orbit, passes by the decretion disc surrounding a rapidly rotating star (BeHMXB) or through the intense stellar wind of a supergiant stellar companion (SgXB). In the latter case, the compact body undergoes a similar kind of accretion as the one previously described except that the wind arriving is not planar ; from the stellar surface to the Roche lobe of the compact object, it has been twisted by the Coriolis force and the Roche potential.

So as to apply the previously designed logarithmically stretched grid to this case, we decided to focus our simulations space on the compact object : it roughly fits the Roche lobe (the light blue sphere on the Figure 3.). Yet, to account for the non planar outer boundaries conditions, we wrote and used a ballistic integrator to draw the streamlines of a supersonic flow, from the

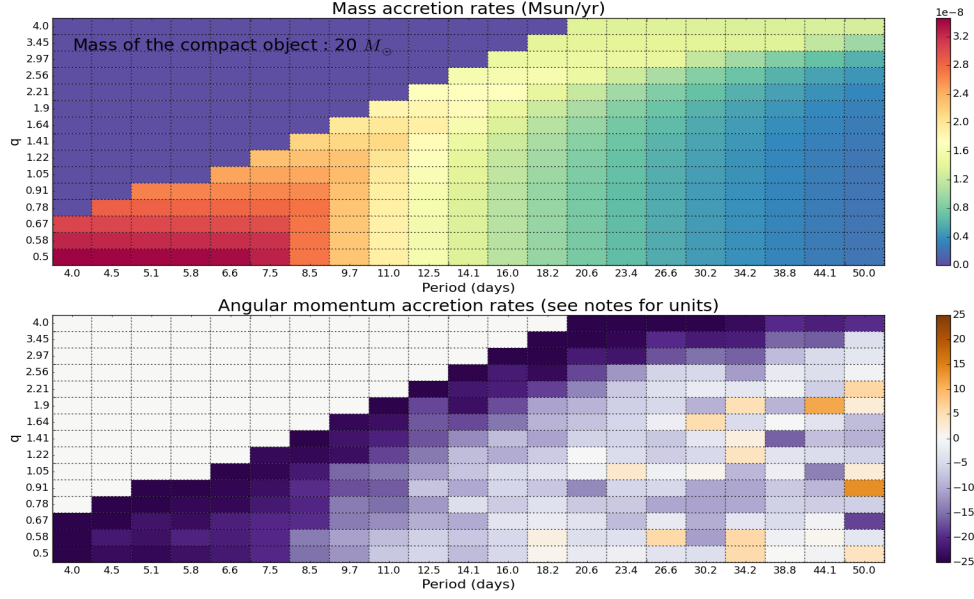


Figure 4: For a 20 solar masses compact object, colormaps of the mass and angular momentum inflowing within the Roche lobe as a function of the orbital period and of the mass ratio (given by the stellar mass divided by the mass of the compact object). The upper left corner corresponds to the Roche lobe overflow regime.

stellar surface to the Roche lobe of the compact object. In addition of giving us physically motivated outer boundary conditions, this code gave us the occasion to partly disentangle the orbital parameters (the mass ratio, the mass of the compact object and the orbital period) from the ones specific to the flow (its clumpiness, its temperature, etc). As a consequence, we could assess the fraction of the outflowing stellar wind passing within the Roche lobe of the compact object, which gives us an upper limit on the mass accretion rate (related to the X-ray luminosity) and on the angular momentum accretion rate (which evaluates the odds to get a disc instead of a direct impact system), see Figure 4. The mass accretion rates converted into X-ray luminosities are typically 2 orders of magnitude higher than the observed ones, suggesting that among the inflowing gas within the compact object Roche lobe, only a fraction will actually be accreted once dissipative effects come into play. We are now able to spot the orbital configurations likely to give birth to (i) luminous X-ray wind accreting systems (the SgXB are bright and persistent sources) and to (ii) accretion discs.

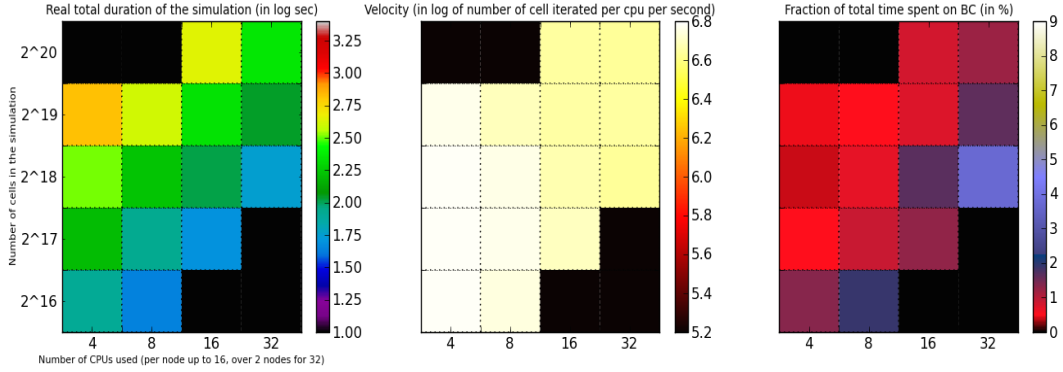


Figure 5: General scaling of the MPI-AMRVAC code performed on the François Arago Center (FAcE) cluster at Paris 7 Diderot

Finally, it is noteworthy that our work also aims at constraining future and incoming observational mission ([ATHENA](#) & [ASTRO-H](#) eg) : which wave-band should we look after? Which time scale should we aim to characterize processes involved in the building up of an accretion disc in a wind accreting configuration? 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

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

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 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 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 6). 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.

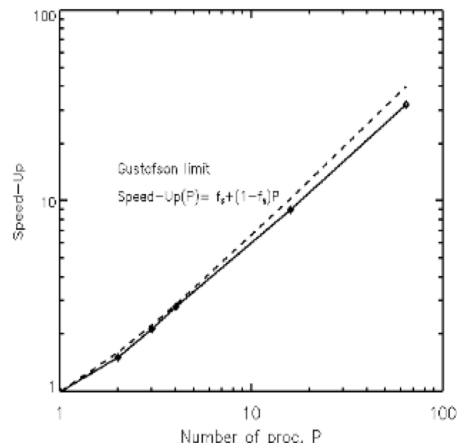


Figure 6: Scaling of the MPI-AMRVAC code performed on the JADE super-computer

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 5). For non axisymmetric outer boundary conditions, we still require the computational ability to monitor the full 3D flow over large scale time scales, which implies hundreds of 10^6 iterations.

We consider here the most demanding numerical simulations ie the full 3D one (the 2.5D ones will be launch depending on the remaining computing time available). To better assess the time needed for our 3D simulations, one can consider the following elements :

- in the nominal conditions of use with MPI-AMRVAC, the number of cells iterated per processor per second, v , is of the order of one million
- we intend to run full 3D simulations with spatial resolutions between $176 \times 32 \times 128 \sim 0.7$ million cells and $256 \times 64 \times 256 \sim 4$ millions cells
- to limit the communication time between CPUs, we will use subgrids of size $16 \times 16 \times 16$ (not smaller) and will set the number of subgrids per CPU to 4, which means that we can run simulations on 44 to 256 CPUs (depending on the resolution)

The real duration of a simulation (in seconds) is then given by $N_{it}/50$, where N_{it} is the number of time iterations we want to compute. Let us consider that we want to run those simulations over one orbital period. If we compare the orbital period P of an X-ray binary hosting a star of mass M_1 and a compact object of mass M_2 with a semi-major axis a , to the numerical time step Δt given by the gravitational oneⁱ, we have, for a wind with a velocity at infinity of v_∞ :

$$N_{it} = \frac{P}{\Delta t} = 300 \cdot 10^{\frac{3}{2}n} \left(\frac{v_\infty}{10^3 \text{km} \cdot \text{s}^{-1}} \right)^3 \left(\frac{a}{0.1 \text{AU}} \right) f(M_1/10M_\odot, M_2/10M_\odot) \quad (1)$$

f being given by :

$$f(x, y) = \sqrt{\frac{2}{y^2(x + y)}} \quad (2)$$

The aspect ratio of the cells has been set to 1 here. The n exponent stands for the relative size of the inner radius r_{in} compare to the accretion radius ζ_{HL} : $r_{in} = 10^{-n} \zeta_{\text{HL}}$. The numerical values considered here are the expected

ⁱUsually more constraining than the CFL one in this configuration.

figures for a wind accreting HMXB. Such as to approach the actual size of the accreting body, we want n to be as high as possibleⁱ (see also Figure 1 of the rapport d'activité, the vertical axis on the right). The table below is a summary of the computing cost and actual duration of those 3D simulations for different values of the n exponent and with a run on 256CPUs. If we did manage to go down to $n = 4$ in the 2.5D simulations previously

n	N_{it}	Duration	kh·CPU
2	$3 \cdot 10^5$	2 hours	0.5
3	10^7	2 days	12
4	$3 \cdot 10^8$	70 days	430

mentioned, it is clear that such a spatial and time dynamics will be difficult to reach in 3D but we still think we can get important results with inner boundaries given by $n = 3$ where the inner boundary would be of the order of 100 times the actual Schwarzschild radius of a 10 solar masses black hole. Each simulation would require 12 kh·CPU and we need to explore several sets of orbital parameters $(P, M_2, M_1/M_2)$, 5 for instance, each with different numerical processing or with different physical parameters for the incoming wind. Such an exploration would require a very minimum of $5 \times 6 \sim 30$ runs to indicate the first tendencies and direct our next studies, hence our request for 400,000 kh·CPU. If additional hours are necessary, we intend to apply in April for the procédure d'attribution complémentaire.

ⁱThe higher n the deeper into the gravitational potential those simulation go.

4 Bibliographie

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