Research activity report

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In 2011-12, under the lead of Saul Rappaport at MIT, I was introduced to the problematics of stellar evolution in binary systems. Because most stars belong to a multiple stellar system, these questions are of prime importance to shed light both on the planets which orbit them and on the galaxies which host them. Stars do not only impact their surroundings when they perform thermonuclear fusion but also as stellar remnants, once the core has long shut down, especially when they are orbited by a close-by stellar companion. In this case, the interplay between the two bodies gives birth to spectacular phenomena which help us to understand the specificities of each body. It is why after my seminal research experience at MIT I turned to the turbulent twilight of binary systems, the X-ray binaries.

X-ray emitting binary systems host a compact object - a neutron star (NS) or a black hole (BH) - orbiting a stellar companion whose gas is accreted by the former. Since the discovery of the first extrasolar X-ray source in the early sixties (Giacconi et al. 1962), continuous observations of these systems have revealed a broad range of spectral and photometric behaviors with a special emphasis on their incredible time variability: flares, hysteresis loops in hardness-luminosity diagrams, off-states, quasi-periodic oscillations... The core of my research activity until now has been to explore the possible origins of this time variability.

PhD research activity

During my 3 years of PhD at the AstroParticule and Cosmology laboratory of Paris 7, under the supervision of Fabien Casse & Andrea Goldwurm, I focused on mass transfer in binaries via wind accretion, the low angular momentum counterpart of the more comprehensively understood Roche lobe overflow (RLOF) mechanism. Supergiant X-ray binaries (SgXB), where a compact object (generally a NS) orbits an evolved O/B supergiant, are the ideal stage for wind accretion to occur. Indeed, the latter displays intense outflows, a fraction of which being captured by the NS. The rapid increase since the late 2000's in the number of SgXB (Walter et al. 2015) and the ambiguous status of the newly discovered Supergiant Fast X-ray Transients (Negueruela et al. 2006) only increased the appeal of this burning topic.

In a first attempt to better understand the wind accretion process, I confronted the analytical prescriptions given by Bondi, Hoyle and Lyttleton (Hoyle & Lyttleton 1939, Bondi & Hoyle 1944) to a hydrodynamical (HD) representation of the flow. To do so, I used and developed the explicitely flux-conserving finite volume transport code `MPI-AMRVAC`, a code whose origins trace back to the mid 90's when Gábor Tóth and Rony Keppens first tackled the question (Tóth 1996, Tóth et al. 1998). The new version

I contributed to now addresses HD or magneto-HD problems, in Cartesian, cylindrical or spherical geometry, with or without polytropic prescriptions, source terms, etc (Xia et al. 2017). For wind speeds similar to the ones observed in SgXB ($\sim$1,000km$\cdot$s^{-1}), the main challenge is the contrast between the scale at which the gravitational beaming of the fast inflow by the accretor becomes significant (the accretion radius) and the size of the compact accretor, typically 4 to 5 orders of magnitude smaller. Since most of the emitted light comes from the immediate vicinity of the accretor, it is important to follow the flow through these scales. To uniformly resolve the incoming planar flow, I implemented a radially stretched grid in a 2D spherical geometry. With suitable boundary conditions, I reached a numerically relaxed state and spanned the 5 required orders of magnitude thanks to the computing time I was granted on the CINES Tier-1 cluster (see Figure 1). In El Mellah & Casse (2015), I characterized the structure of the flow, which forms a stable detached bow shocked as it is beamed towards the wake of the accretor, and the dependence of the mass accretion rate on the Mach number of the inflow. For the first time, we monitored the flow deep enough to also confirm the analytical prediction by Foglizzo & Ruffert (1997) concerning the topology of the inner sonic surface (where the shocked flow becomes supersonic again) which has to be anchored into the accretor.

In a realistic SgXB though, the incoming wind is not planar due to the orbital effects. It carries a non-zero angular momentum which could, in some cases, lead to the formation of a wind-capture disc. To identify the favorable configurations, I designed a model of supersonic line-driven wind propagation in SgXB, coupling the stellar, orbital, wind and accretion parameters (El Mellah & Casse 2016). I identified the minimal set of dimensionless degrees of freedom of the problem to optimally explore the space of parameters. This investigation showed how sheared and beamed the wind is when it enters the region around the accretor where the shock is expected to develop – i.e. where the ballistic assumption breaks up and where HD simulations similar to the ones above are required. The need to connect the orbital scale motion, essentially ballistic, and the accretion region, centered on the compact object, became apparent.

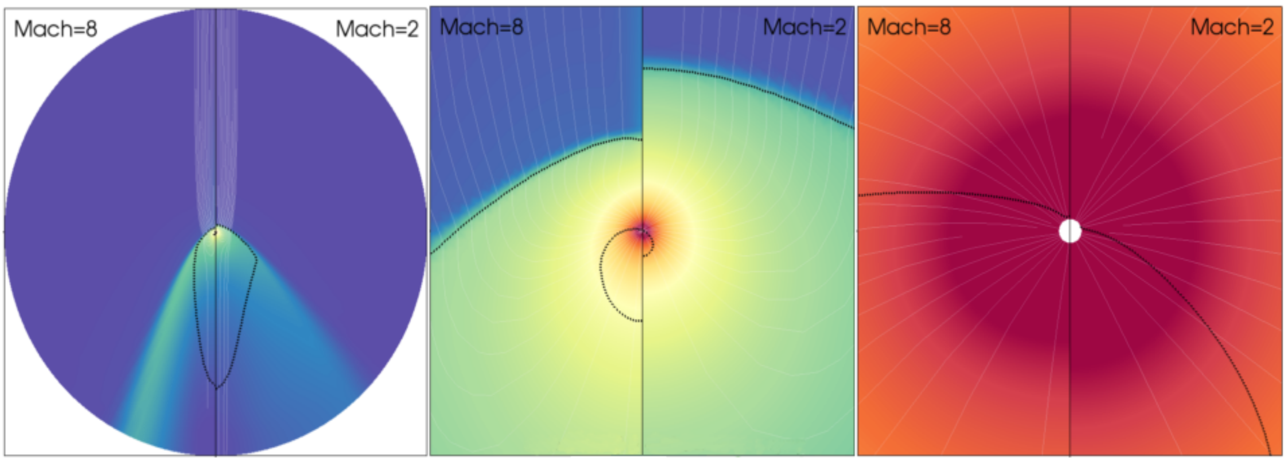

Figure 1: Successive zoom in on the innermost parts of a planar flow (coming from the top) being deflected by a central accretor for different Mach numbers at infinity. In white are represented the streamlines while the the dotted black lines represent the Mach-1 surfaces. The colormap is logarithmic mass density.

Postdoctoral research activity

Since the beginning of my postdoctoral activity one year ago, I started to consider more realistic internal structure for the incoming wind in SgXB than the uniform flow I had worked with during my PhD. Indeed, the line-driven winds of massive stars are notoriously inhomogeneous, due to the line-deshadowing instability (Owocki & Rybicki 1984) which leads to the formation of internal shocks. The serendipituous accretion of these overdense regions, or clumps, has been suggested as a possible explanation to the time variability of the X-ray luminosity in SgXB, of the order of 100 peak-to-peak. Using a two-dimensional pseudo-planar grid sampling a restricted angular region, Sundqvist et al. (2017) recently managed to compute the micro-structure of the wind and by then, the dimensions of the clumps, for an isolated massive stars. To evaluate the impact of clumps on the accretion process, I plunged a compact object in the wind ("CO" in the left panel in Figure 2), at different orbital separations, and injected the corresponding wind computed by Sundqvist et al. (2017) within the simulation space (right panel in Figure 2). By coupling the stretching of the mesh to the Adaptive Mesh Refinement (AMR) of `MPI-AMRVAC`, I could design 3D spherical setups spanning several orders of magnitude at an affordable computational cost and resolve small scale off-centered features like clumps injected from the upstream hemisphere. In El Mellah et al. (2017), we followed the clumps as they cross the shock and monitored the time variability at the inner border of the simulation space, corresponding approximately to the dimensions of the NS magnetosphere. With this work, we discovered how tempering the shock could be, which led to variations of the inner mass accretion rate an order of magnitude smaller than the observed variations of the X-ray luminosity in these systems. Thus, if the stochastic variations at low X-ray luminosity seem to match the variability induced by the clumps alone (see Figure 3), the high luminosity levels can only be reached due to other underlying mechanisms, possibly within the NS magnetosphere (e.g. the propeller effect,

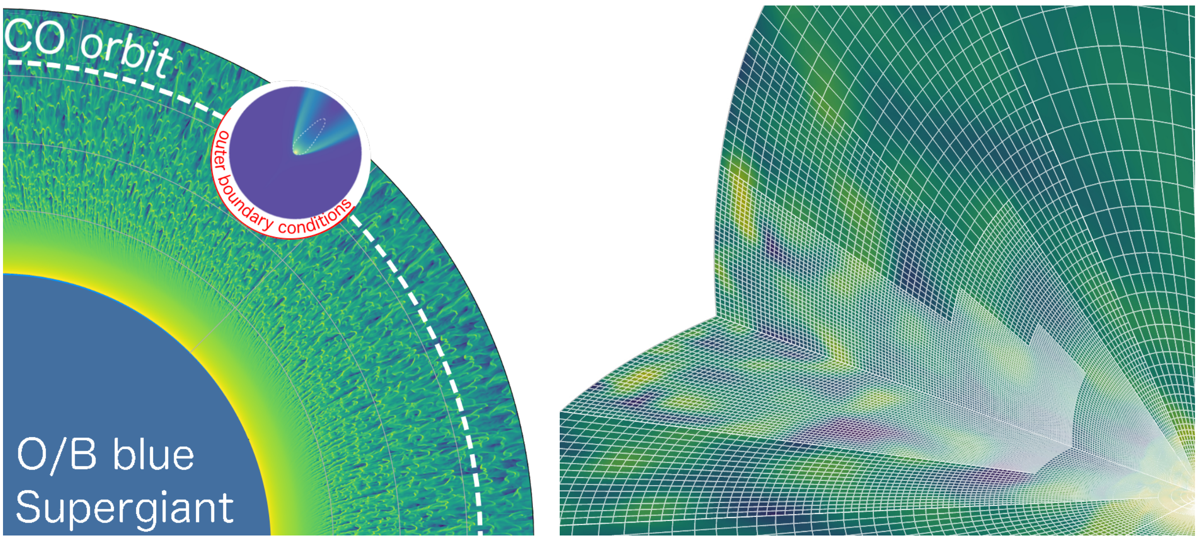

Figure 2: (*left*) Principle of the clumpy wind accretion simulations : we inject into the simulation space (upper right insert) a wind whose micro-structure has been computed out of radiative HD simulations by Sundqvist et al. (2017). (*right*) Two-slices representation of the upstream hemisphere of the simulation space, with the wind coming from the upper left. We overlaid a logarithmic density map to show the typical size of the inhomogeneities to resolve. The accretor lies in the bottom right corner.

Bozzo et al. 2016). Concerning the column density levels, we retrieve average values compatible with what has been observed recently in Vela X-1 by Grinberg et al. (2017).

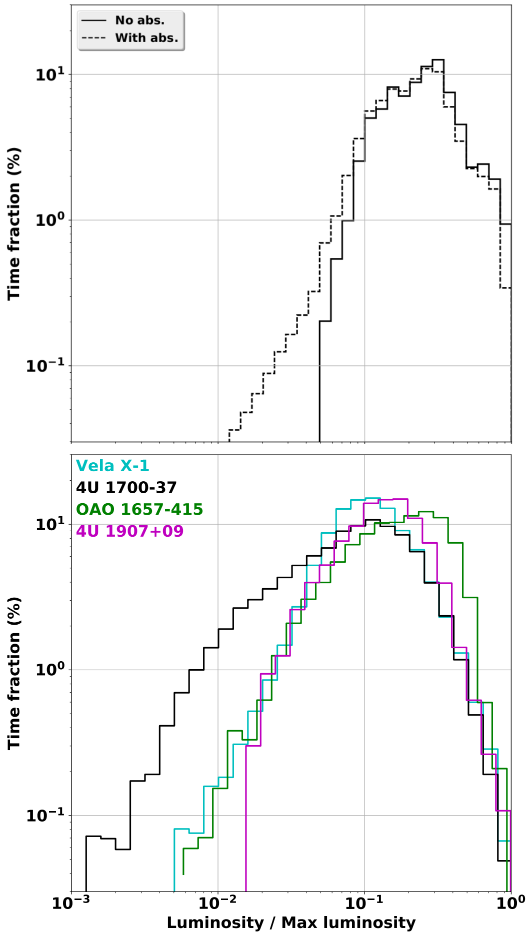

Figure 3: (upper panel) Simulated luminosity histograms, with and without accounting for absorption. (bottom panel) Observed luminosity histograms for 4 classic SgXB (from El Mellah et al. 2017).

I also participated to Grinberg et al. (2017) to evaluate the time variability associated to unaccreted clumps passing by the line-of-sight and concluded that this type of micro-structure within the wind can not explain by itself the variations in column density we observed. This contribution has been made possible thanks to the ISSI team I have been invited to join in February 2017, at the occasion of their second workshop in Bern. In November 2017, I gathered at ESAC (Madrid) with Peter Kretschmar, Silvia Martínez-Núñez, Victoria Grinberg and Felix Fürst to provide the theoretical expertise to the X-Wind collaboration which aims at developing further the work carried out by the ISSI team : providing a more comprehensive view of the stellar wind in Supergiant X-ray binaries thanks to a synergy between specialists in winds of isolated massive stars and specialists in high mass X-ray binaries.

Eventually, in Xia et al. (2017), I carried out a numerical validation of the stretched grid implementation I had made during my PhD by confronting quantitative simulation results of Bondi spherical accretion to the analytical expectations on the mass accretion rate and the location of the sonic point for different adiabatic indexes. We also studied the propagation of a trans-Alvénic wind from the solar surface to the Earth orbit to validate the compatibility of the stretched grid with the magneto-HD solver and Powell's method for the cleaning of the divergence of the magnetic field.

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