Research summary

Most massive stars were born in multi-star systems but only a fraction ends up in a compact objects binary due to their agitated evolution. Binarity introduces new effects compared to the evolution of isolated stars such as mass and angular momentum transfer. I address these questions at a key stage in massive binary evolution, in High Mass X-ray Binaries (HMXB) where a neutron star (NS) or a black hole (BH) orbits a high mass donor star and captures part of its stellar wind. The aim of my investigations is to understand the accretion process onto wind-fed compact objects and to constrain the properties of the line-driven winds from the O/B supergiant donor stars.

I have used and developed state-of-the-art magneto-hydrodynamics codes to follow the flow through the 6 to 7 orders of magnitude from the stellar surface down to the accretor. I have laid the foundations of a consistent representation of the accretion process in Supergiant X-ray binary (SgXB) by isolating the appropriate physics at stake at each scale and accounting for the complexity of the flow geometry. My work does not only help to interpret observations in individual systems but bring new insights on the decisive effects which shape the secular evolution of massive binaries.

Time variability in Supergiant X-ray binaries

[1] ***Axisymmetric hydrodynamical Bondi-Hoyle accretion onto a compact object*, El Mellah & Casse, MNRAS 2015**
[2] ***Accretion from a clumpy massive-star wind in SgXB*, El Mellah, Sundqvist & Keppens, MNRAS 2017**
[3] ***The clumpy absorber in the HMXB Vela X-1*, Grinberg, Hell, El Mellah et al., A&A 2017**

Continuous monitoring of SgXB have revealed an incredible time variability (off-states, flares...) which could shed light on the micro-structure of the stellar wind. Using the orbiting X-ray source as a probe, we could evaluate its "clumpiness", provided we also appreciate the impact of these inhomogeneities on the time variability of the X-ray emission itself. Since clumpiness systematically alters the values of the mass loss rates we derive from observations, improved constrains would have important consequences on the predicted properties of the compact remnants massive stars eventually collapsed into, such as their mass distribution.

During my PhD, I developed a hydrodynamical (HD) representation of the ideal wind accretion configuration, where a compact object captures material from a planar homogeneous supersonic wind. Implementing a stretched grid to follow the flow over 4 orders of magnitude, I characterized the structure of the bow shock and the accretion tail which form as the flow is beamed towards the compact accretor, the actual mass accretion rate onto the compact object and the dependence on the Mach number of the incoming flow [1].

This setup served as a reference to study the effect of the clumps formed by internal shocks in the line-driven winds of hot stars. For long, it was proposed that the observed flares in a SgXB like Vela X-1 could be provoked by the serendipitous capture of a clump. However, we showed in [2] that realistic clumps computed from radiative-HD simulations do not undergo direct accretion (Figure 1). For the first time, we showed how material redistributes after the clumps dash the shock characterized in [1]. The induced flares do not directly relate to individual clumps but are rather triggered by instantaneous angular momentum cancellation within the buffer shocked region. Our results drove the community into exploring additional instabilities at the outer rim of the NS magnetosphere to reproduce the observed variability in SgXB.

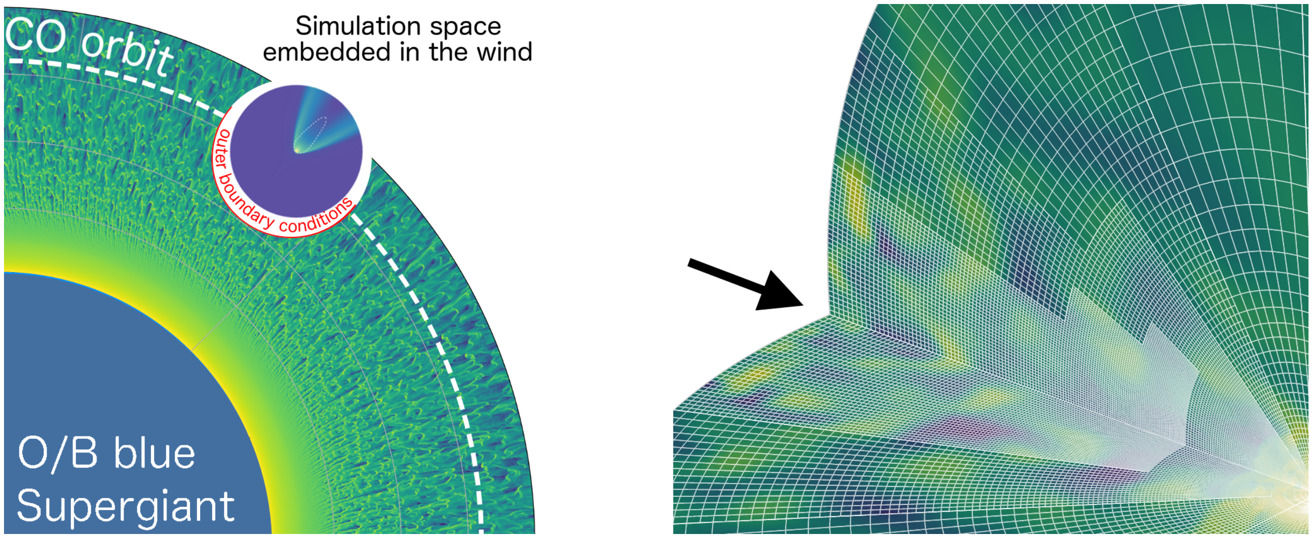

Figure 1: (*left*) Simulations of clumpy wind accretion : we inject into the simulation space a wind whose micro-structure was computed based on radiative HD simulations by Sundqvist, Owocki & Puls (2018). (*right*) Two-slices representation of the upstream hemisphere of the simulation space, with the wind flowing in from the upper left. The logarithmic density map shows the typical size of the clumps which can be resolved thanks to the coupling between a radially stretched grid and an adaptive mesh refinement algorithm. The accretor lies in the bottom right corner.

In [3], we reported coherent absorption events in Vela X-1. I showed that it could only be due to unaccreted clumps passing by the line-of-sight between the observer and the X-ray source provided the clumps were larger and the wind slower than expected. The latter result led me to evaluate how a slower wind would alter the geometry of the accretion flow and significantly enhance the mass transfer rate.

Enhanced accretion and wind-captured discs in High Mass X-ray binaries

[4] *A numerical investigation of wind accretion in persistent SgXB*, El Mellah & Casse, MNRAS 2016
[5] *Formation of wind-captured discs in SgXB : consequences for Vela X-1 and Cygnus X-1*
El Mellah, Sanders, Sundqvist & Keppens, submitted
[6] *Wind Roche lobe overflow in HMXB : a mass transfer mechanism for Ultraluminous X-ray sources*
El Mellah, Sundqvist & Keppens, submitted

In my last year of PhD, I designed a model to study how the coupling between stellar, wind, orbital and accretion parameters in HMXB could provide reliable estimates of the amount of angular momentum captured by the compact object [4]. I identified the configurations suitable to accrete enough angular momentum to form disc-like structures within the Roche lobe of the accretor. It seemed to require stringent conditions on the speed of the wind, which had to be very low compared to what was considered at that time in the literature. However, refined observations and stellar atmosphere computations later on suggested that line-driven acceleration might be more progressive than initially thought, leading to low speeds at the orbital separation. It drove me into performing full 3D HD simulations with the appropriate sets of parameters I had found in

[4]. In [5], I showed that, below a certain ratio of wind speed by the orbital speed and provided radiative cooling was accounted for, a centrifugally-maintained structure could form between the shock and the NS magnetosphere, below which the disc is truncated (see Figure 2).

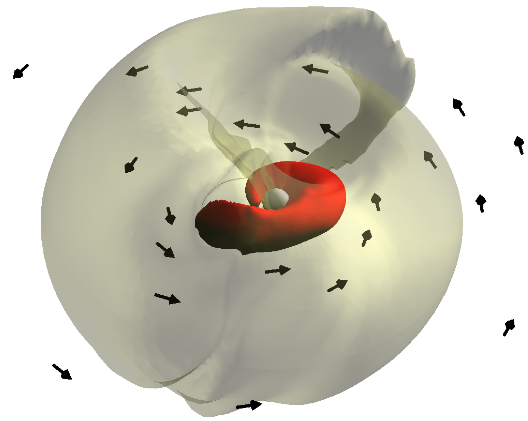

Figure 2: 3D contours of the mass density, where the arrows stand for the velocity field in the orbital plane. The central white sphere is the inner boundary of the simulation space which represents approximately the outer edge of the NS magnetosphere, a few 100 times smaller than the outer boundary of the simulation space.

This mass transfer regime known as wind - Roche lobe overflow is also associated to a surge of the rate at which mass is transferred thanks to the compression of the wind into the orbital plane. Along these lines, I proposed a new mechanism for mass transfer in Ultra-luminous X-ray sources which, because it does not require Roche lobe overflow, explains how a small donor star like in M101 ULX-1 can feed a super-Eddington accreting compact object [6].

Code development & Kepler data analysis

[7] ***MPI-AMRVAC 2.0 for Solar and Astrophysical Applications*, Xia, Teunissen, El Mellah et al., ApJS 2018**
[8] ***A study of the shortest-period planets found with Kepler*, Sanchis-Ojeda et al., ApJ 2014**
[9] ***Triple-star candidates among the Kepler binaries*, Rappaport et al., ApJ 2013**
[10] ***Possible disintegrating short-period super-Mercury orbiting KIC 12557548***
Rappaport, Levine, Chiang, El Mellah et al., ApJ 2012

For the last years, I have extensively developed the magneto-HD finite volume code `MPI-AMRVAC`. I implemented an angular momentum preserving scheme to guarantee the conservation of angular momentum to machine precision. I designed a radially stretched spherical grid and coupled it to an adaptive mesh refinement algorithm to monitor the accretion flow over several orders of magnitude at an affordable computational cost (see Figure 1, right panel). I made this new functionality public and validated it on the classic 1D Bondi spherical accretion in a paper describing new numerical techniques we developed for `MPI-AMRVAC 2.0` [7]. I also wrote a conservative scheme to handle viscosity as a flux term and apply the slope-limiting methods which enable us to combine high-order accuracy and stability in the solvers we use.

Finally, I volunteered to join the Kavli Institute for Astrophysics and Space Research (MIT) from September 2011 to July 2012 and take part in the Kepler satellite data analysis effort under the supervision of Saul Rappaport. I participated in the discovery and characterization of the first disintegrating exoplanet [10]. My involvement also contributed to the identification of 30 new triple star systems [9] and to a detailed analysis of the shortest-period exoplanets [8].