High-mass X-ray Binaries: Illuminating the Passage from Massive Binaries to Merging Compact Objects
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Clumpy wind accretion in Supergiant X-ray Binaries

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Abstract. Supergiant X-ray Binaries host a compact object, generally a neutron star, orbiting an evolved O/B star. Mass transfer proceeds through the intense radiatively-driven wind of the stellar donor, a fraction of which is captured by the gravitational field of the neutron star. The subsequent accretion process onto the neutron star is responsible for the abundant X-ray emission from those systems. They also display variations in time of the X-ray flux by a factor of a few 10, along with changes in the hardness ratios believed to be due to varying absorption along the line-of-sight. We used the most recent results on the inhomogeneities (aka clumps) in the non-stationary wind of massive hot stars to evaluate their impact on the time-variable accretion process. We ran three-dimensional simulations of the wind in the vicinity of the accretor to witness the formation of the bow shock and follow the inhomogeneous flow over several spatial orders of magnitude, down to the neutron star magnetosphere. In particular, we show that the impact of the clumps on the time-variability of the intrinsic mass accretion rate is severely damped by the crossing of the shock, compared to the purely ballistic Bondi-Hoyle-Lyttleton estimation. We also account for the variable absorption due to clumps passing by the line-of-sight and estimate the final effective variability of the mass accretion rate for different orbital separations. These results are confronted to recent analysis of Vela X-1 observations with Chandra by Grinberg *et al.* (2017). It shows that clumps account well for time-variability at low luminosity but can not generate, per se, the high luminosity activity observed.

Keywords. accretion, accretion disks, methods: numerical, hydrodynamics, stars: neutron, X-rays: binaries, stars: winds, outflows, stars: supergiants, plasmas, stars: early-type.

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1. Introduction

Supergiant X-ray binaries (SgXB) are thought to be the ideal stage to witness wind accretion. A SgXB hosts a Supergiant star which looses mass via a dense and fast line-driven wind, with a mass loss rate of the order of $10^{-6}\mathrm{M}_{\odot}\cdot\mathrm{yr}^{-1}$, while it is orbited by a compact companion, generally a neutron star (NS). The NS is deeply embedded in the wind, standing at approximately one stellar radius above the stellar photosphere. It captures a fraction of the wind and as it falls onto the compact object, the accreted flow emits a plethora of X-rays which account for the observed X-ray luminosity, ranging from 10^{35} to $10^{37}\mathrm{erg}\cdot\mathrm{s}^{-1}$ in SgXB. In this proceedings, I want to provide new insights about the possibility to study these systems through the coupling of multiple numerical simulations.

In SgXB, the main challenge we face when carrying out a numerical investigation is to bridge the scale gap between, at the lower end, where most of the X-rays we observe are emitted, the size of the compact object, and, at the upper end, the orbital separation, 6 orders of magnitude larger. Fortunately, the dominant physics at stake at each scale is different: if the immediate vicinity of the accretor requires a relativistic treatment, the NS magnetosphere needs to be handled in a magneto-hydrodynamical framework. While at the orbital scale, the bulk motion of the wind is essentially ballistic and a hydrodynamical (HD) bow shock forms within the Roche lobe of the compact object.

In this proceedings, I want to focus on what happens in-between: how is the flow carried from the bow shock down to the outer rim of the NS magnetosphere? And in particular :

• what is the impact of the overdense regions in the wind on the time variability of the mass accretion rate?

• does the flow gain enough angular momentum at the orbital scale and does it retain enough of it downstream the shock to form a disc-like structure before being truncated by the NS magnetosphere? Is there enough room for a disk between the shock and the NS magnetosphere?

2. Clumps in the wind

Wind launching for hot massive stars relies on the resonant line absorption of stellar UV photons by partly ionized metal ions in the outer layers of the star. As the flow accelerates, it keeps tapping Doppler-shifted previously untouched photons (Lucy & Solomon 1970, Castor, Abbott & Klein 1975). Due to the line-deshadowing instability Owocki & Rybicki (1984), we expect strong internal shocks to develop in the wind and lead to the formation of overdense regions a.k.a. "clumps". The shape, dimension and amount of mass contained in these clumps has been for long a matter of debate: the radiative-HD computation required to tackle this question are computationally expensive and only uni-dimensional radial simulations could be performed Feldmeier *et al.* (1997) but they would not tell us about the transverse extension of the clumps.

But last year, Sundqvist, Owocki & Puls (2017) performed two-dimensional simulations of the wind launching, resolved the micro-structure and derived a density contrast of the order of 100 in the wind. To evaluate the impact of this micro-structure on the wind accretion process, we plunge the orbiting compact object in the wind. We define a zone of gravitational and radiative influence around the accretor: within this zone, the X-ray ionizing feedback from the accreted flow onto the wind inhibit the line-driven acceleration (Hatchett & McCray 1977, Blondin *et al.* 1990, Stevens 1991, Manousakis & Walter 2015). The outer boundary conditions in the upstream hemisphere of the 3D spherical simulation space are entirely determined by the wind simulation of Sundqvist, Owocki & Puls (2017): we directly inject the clumps within the simulation space and monitor their HD evolution, using the new version of the `MPI-AMRVAC` code described in Xia *et al.* (2017).

The initial state of the simulations is a 3D extension of the axisymmetric planar uniform Bondi-Hoyle-Lyttleton problem (Hoyle & Lyttleton 1939; Bondi & Hoyle 1944) computed in El Mellah & Casse (2015). Upstream the shock, the clumps are ballistically advected in the supersonic flow. However, they do not preserve their structure when they cross the shock: the clumps are not zero-temperature bullets and do experience HD effects such as the sudden increase in entropy at the shock. Contrary to the uniform planar case, the instantaneous net amount of angular momentum is not zero since the captured clumps arriving with a non-zero impact parameter carry their own angular momentum and do not have a counterpart with opposite impact parameter to cancel out with. Consequently, the accretion of a clump can be delayed if it enhances the absolute value of the angular

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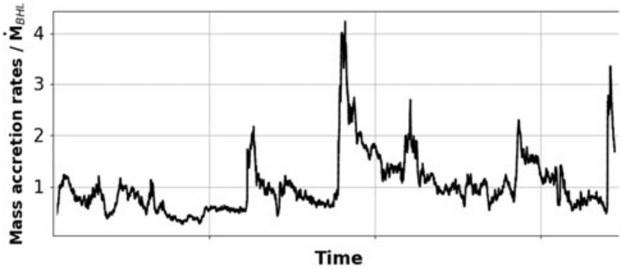

Figure 1. Mass accretion rate compared to the Bondi-Hoyle-Lyttleton proxy as a function of time (code units).

momentum already available in the shocked region while it can trigger the flush of a larger amount of matter if it lowers the absolute value of the angular momentum in the shocked region.

Because of this mixing of the clumps with the material already present downstream the shock, this region acts as a buffer where the clumps are restructured. It also means that the peak observed in mass accretion rate through the inner border of the simulation space (whose radius is a few times the NS magnetosphere radius) in Figure 1 do not correspond to one clump in particular but to the cumulative and contingent contribution of several of them: deriving the mass of the clump responsible for a given X-ray flare always leads to an overestimation compared to the actual mass of the clumps which participated in producing this flare.

The overall peak-to-peak variability in mass accretion rate reaches 20 for an orbital separation of 2 stellar radii and 10 for an orbital separation of 1.6 stellar radii. It is an order of magnitude lower than the observed time variability. The origin of this discrepancy might be numerical (e.g. an integration time too low compared to the characteristic time of occurrence of the extreme cases) but more likely, additional instabilities might occur within and at the edge of the NS magnetosphere which might amplify this time variability (see e.g. the propeller effect, Bozzo, Falanga & Stella, 2008) and account for the lack of high mass accretion rate regimes in our simulations.

The work presented in this section has been reported in more detail in El Mellah, Sundqvist & Keppens (2017).

3. Orbital bending and disc formation

The reader might also wonder about the contribution to time-variability of serendipitous absorption by unaccreted clumps passing by the line-of-sight. This question has been addressed in more detail in Grinberg *et al.* (2017) but the main conclusion is that with such a high wind speed, the duration of the coherent absorption events observed can not be reproduced.

But is the wind really that fast? In this preliminary model, we just cared about the clumps and assumed that outside of this limited simulation space the whole structure of the wind did not depart from the one of an isolated massive star, but it is only correct if the wind is too fast to see the Roche potential i.e. if the wind speed is large compared to the orbital speed. In a system such as Vela X-1, recent observations by Gimenez-Garcia *et al.* (2016) confirmed that the terminal wind speed was only twice the orbital speed and Sander *et al.* (2017) showed that the wind might accelerate slower than expected and consequently, upstream the accreting NS, the wind speed is not large compared to the orbital speed. It means that the dynamics of the wind will be dominated by orbital effects. From now on, I set aside the micro-structure of the wind, no more clumps, but I address the question of the systematic deviation of the wind from a purely radial wind

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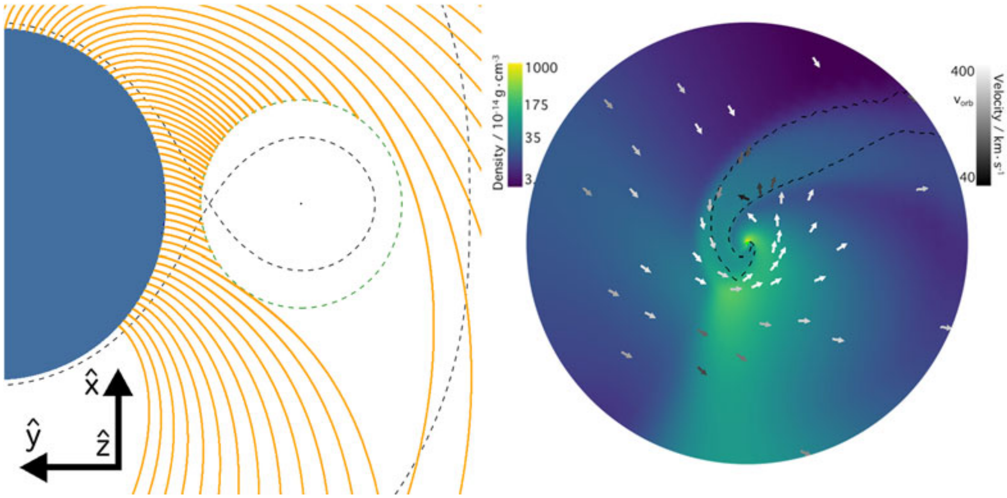

Figure 2. (left) Wind streamlines in orange in the orbital plane of the co-rotating frame, for the case Heavy Slow (HS). The black dashed line stands for the critical Roche potential curve passing by the first Lagrangian point while the green dashed line is the HD simulation space where we inject the wind. (right) Logarithmic colormap of the mass density in the orbital plane. The arrows stand for the velocity field and the black dashed line indicates a Mach-1 locus.

by the Roche potential and the Coriolis force. How much angular momentum does the accreted flow carry?

To evaluate the motion of the wind, we assimilate it to test-masses and compute in 3D in the co-rotating frame the steady streamlines using an integrator developed and validated in El Mellah & Casse (2016). The test-masses which reach an extended Roche lobe centered provide natural outer boundary conditions at the outer edge of the HD simulation space. The dynamics is set by the Roche potential, the Coriolis force and the line-driven acceleration taken from Sander *et al.* (2017). We consider two cases :

- Heavy slow (HS) : the line-driven acceleration is not altered and leads to wind speed of the order or smaller than the orbital speed upstream the accretor (of mass $2.5M_\odot$).
- Light fast (LF) : the line-driven acceleration is enhanced by 50%, leading to wind speeds 20% larger than the orbital speed. The accretor has now a mass of $1.5M_\odot$.

The result of this computation is illustrated for the HS case in Figure 2 (left) where the bending of the streamlines is significantly more important than in the LF case. The latter displays streamlines more radial while the former shows that a non negligible amount of angular momentum flows into the Roche potential of the accretor.

The consequences are dramatic. While the LF configuration leads to structures qualitatively similar to the classic fast wind Bondi-Hoyle-Lyttleton picture, the HS configuration produces a totally different geometry. In the LF case, the flow is still essentially planar and axisymmetric around the mean direction of arrival, which deviates from the line joining the 2 bodies by only ∼20 degrees. The bow shock is still present, along with the inner sonic surface. In the HS case (Figure 2, right), where the wind speed entering the simulation space is only a few 10% lower but enough to reach the orbital speed, the flow is highly compressed in the equatorial plane which leads to a more important density enhancement. It is also more beamed along a channel of matter reminiscent of the one observed in Roche lobe overflowing systems, although the star does not fill its Roche lobe. As explained in El Mellah, Sundqvist & Keppens (2018), it leads to a significant enhancement of the mass transfer rate and can lead to levels suitable for ultra-luminous X-ray sources. The shock is now totally misaligned and takes a spiral shape. It is the intermediate case coined as wind-RLOF by Mohamed & Podsiadlowski (2007) in the context of symbiotic binaries, where the donor is an Asymptotic Giant Branch star with a totally different wind-launching mechanism but where you retrieve a wind speed of the order of the orbital speed.

These HD simulations are adiabatic which means that matter does not radiate away any of the entropy it has been granted at the shock, leading to excessively high temperatures. We empirically represent the cooling relying on polytropic prescriptions: either isothermal or assuming a constant entropy in the shocked region lower than what a fully adiabatic simulation would yield. Whatever the cooling prescription we invoke, the HS always leads to the formation of a centrifugally supported structure in the innermost region while the LF never.

The work presented in this section has been submitted (El Mellah *et al.* 2018a)

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Discussion

KARINO: What about the subsonic quasi-spherical shell settling model by Shakura *et al.* (2013)? Is it compatible with the wind-capture disc you observe?

EL MELLAH: In the presence of a disc, we should rather resort on the Gosh and Lamb coupling with the NS magnetosphere. But keep in mind that for slightly (20%) faster winds, you go over the orbital speed and a disc does not form. Also, if the cooling is inefficient, a disc does not form neither. In these 2 cases, the quasi-spherical subsonic model remains valid.

POSTNOV: Did you characterize the statistical information/behavior of the mass accretion rate in your simulations and compared it to the observed ones?

EL MELLAH: In El Mellah, Sundqvist & Keppens (2017), I plotted the activity diagrams (see Figure 10), for different orbital separations and absorption, and compared it to the observed ones by Fürst *et al.* (2010) and Walter *et al.* (2015). The peak-to-peak variability is an order of magnitude lower but I retrieve approximately log-normal distributions.

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