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Enhanced accretion and wind-captured discs in high mass X-ray binaries

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Abstract. The historical gravitational wave detections of last years ushered in a new era for the study of massive binaries evolution. In high mass X-ray binaries, a transient albeit decisive phase preceding compact binaries, a compact accretor orbits a massive star and captures part of its intense stellar wind. From the stellar photosphere down to the vicinity of the compact object, the flow undergoes successive phases. Our numerical simulations offer a comprehensive picture of the accretion process along this journey.
We report new results on the impact of the wind micro-structure on the X-ray time variability and how the revised downwards wind speed implies a significantly different flow geometry than the one previously considered. For wind speeds of the order of the orbital speed or lower, accretion is significantly enhanced and provided cooling is accounted for, transient disc-like structures form beyond the neutron star magnetosphere, with dramatic consequences on the torques applied to the compact object.
The recent observational reports on the limited extent of the accretion disc in Cygnus X-1 suggest that the disc is produced by this mechanism rather than a Roche lobe overflow of the companion star. In Vela X-1, such a structure remains to be observed but its indirect signatures through jets or the torques it applies on the neutron star could well be within our observational grasp.
This accretion regime could also account for large mass transfer rates, up to levels suitable for ultra-luminous X-ray sources, without Roche lobe overflow of the donor star, a situation observed in M101 ULX-1.

Key words. accretion, accretion discs – X-rays: binaries – stars: black holes, neutron, supergiants, winds – methods: numerical

1. Introduction

In Supergiant X-ray binaries (SgXBs), a subfamily of high mass X-ray binaries, a neutron star (NS) or sometimes a black hole orbits a supergiant O/B star and captures part of its stellar wind. SgXBs are thought to be the progenitors of the double compact object binaries whose final merger produces flares of gravitational waves similar to the ones first observed by the LIGO/Virgo collaboration in 2015. So as to make the most of the data from these merging compact objects, we need to study their evolution and understand how binarity has affected their properties.

In simulations of secular long-term evolution (eg Tauris & van den Heuvel 2006), proxies are used to deduce a mass and angular momentum transfer rate from elementary parameters such as the mass ratio, but the efficiency of accretion onto the compact companion and of the associated spin-up from mass transfer is still highly uncertain. This flaw hampers our capacity to interpret the gravitational wave observations and to predict accurate merging rates. On the other hand, the observing X-ray facilities in orbit tell us about the short term variability of SgXBs, within the reach of a mission lifetime (Fürst et al. 2018). Numerical models of the accretion flow provide the missing link between the two and have brought unprecedented insights on the geometry of these unresolved objects (Blondin et al. 1991).

Time variability of the emission in low mass X-ray binaries is generally attributed to instabilities in the large and permanent accretion disc formed around the accretor due to the Roche lobe overflow of the companion star. However, in SgXBs, the very existence of such a key-component is not obvious. In this case, stable mass transfer via Roche lobe overflow is unlikely, the star usually does not fill its Roche lobe but it displays spectacular winds with mass outflows up to a few $10^{-6} M_{\odot}\cdot\mathrm{yr}^{-1}$. A fraction of this radiatively driven wind can then be captured by the gravitational field of the companion. Since the flow has much less angular momentum than in the case of Roche lobe overflow, a disc is not necessarily formed.

We first take a closer look at the impact of overdense clumps of material in the stellar wind on the time variability of the mass accretion rate before discussing the conditions suitable for the formation of a wind capture disc, often associated to a mechanism of enhanced mass transfer.

2. Clumps in the wind

2.1. TIme variability of the emission

The launching of the wind in hot stars is made possible due to the resonant absorption of UV photons by metal ions partly ionized (Castor et al. 1975). As the flow accelerates, it keeps tapping previously untouched Doppler shifted photons. Due to the dependence of this line acceleration on the velocity gradient, these winds are the stage of a an intrinsic and remarkably strong instability, the line-deshadowing instability (Lucy & White 1980; Owocki & Rybicki 1984). Its development leads to internal shocks within the wind which forms overdense regions called clumps. Sundqvist et al. (2018) determined the transverse dimension of the clumps in unprecedented two-dimensional radiative-hydrodynamics simulations. The clumps appeared to be of the order of one hundred times denser than the interclump environment, with a typical clump size of the order of one hundredth of the stellar radius and a mass of approximately 10^{17}g. These results contrasted with dimensions and masses previously deduced from X-ray flares duration and intensity, orders of magnitude higher (Walter & Zurita-Heras 2007).

To solve this discrepancy between theoretical and observational conclusions, we carried out a numerical investigation to follow the clumps as they are accreted onto the compact object (El Mellah et al. 2018). We solve the classic equations of hydrodynamics using the parallelized finite volume code `MPI-AMRVAC` (Xia et al. 2018). The radially stretched spherical mesh, centered on the accretor and initially developed in El Mellah & Casse (2015), is here coupled to the adaptive mesh refinement feature which enables us to resolve the clumps and follow them as they are captured. Due to the cushioning role played by the hydrodynamical shock, the variability is lower than deduced from ballistic models of instantaneous clump capture based on a Bondi-Hoyle-Lyttleton framework (Hoyle & Lyttleton 1939; Bondi & Hoyle 1944). Furthermore, the clumps carry a non-negligible amount of angular momentum which precludes their immediate capture once they penetrate the shocked region. After some time, the angular momentum is either evacuated via spiral shocks or due to the capture of clumps with opposite angular momentum, triggering a sudden flare in mass accretion rate. However, the amount of material involved in such a flare is systematically larger than the mass of a clump since it has been mixed in the shocked region which acts as a buffer zone. It explains why clump masses directly deduced from flares have been overestimated.

2.2. TIme variability of the absorption

Unaccreted clumps passing by the line-of-sight also contribute to the dimming of the observed flux. Using Chandra spectroscopic archives, Grinberg et al. (2017) evaluated the variations of the column density in Vela X-1 and identified episodes of absorption enhancement. A model of stochastic absorption by clumps was developed to evaluate the amplitude and the duration of the enhanced absorption episodes produced by a wind whose micro-structure is set by the simulations from Sundqvist et al. (2018). In El Mellah et al. (2018), we assumed a constant opacity and traced the absorption using the column density of material along lines-of-sight representative of the inclination of Vela X-1, well constrained thanks to its eclipses. Based on a realistic stellar mass loss rate of $1.3{\cdot}10^{-6}M_{\odot}{\cdot}\mathrm{yr}^{-1}$ (Gimenez-Garcia et al. 2016), we could reproduce a median column density in agreement with what was observed by Grinberg et al. (2017), of the order of $2{\cdot}10^{22}\mathrm{cm}^{-2}$. However, the amplitude and duration of the stochastic variations produced by the small clumps from Sundqvist et al. (2018) was a few times too small to explain the observed episodes of enhanced absorption. This tension between theoretical predictions and observations can be partly alleviated once we consider that the wind speed might be much lower than initially considered, according to new theoretical and observational insights. By comparing a 1D radial velocity profile to a β-law (see e.g. Wen et al. 1999), Gimenez-Garcia et al. (2016) derived a terminal wind speed of $700^{+200}_{-100}\mathrm{km{\cdot}s^{-1}}$ and set the β exponent to 1, leading to a wind speed at the orbital separation of $\sim$300km$\cdot$s^{-1}. In parallel, Sander et al. (2017) identified a hydrodynamically consistent stratification, meaning that the mass loss rate and the velocity field were iteratively updated such that eventually, the outward and inward forces balance each other throughout the stellar atmosphere. It led them to derive a similar terminal wind speed but a higher β exponent which means a much more progressive acceleration such that the wind speed at the orbital separation could be as low as 100km$\cdot$s^{-1}. Since the Bondi-Hoyle-Lyttleton mass accretion rate depends dramatically on the flow speed, these uncertainties harm our capacity to predict the X-ray luminosity and constrain the stellar mass loss rate. However, these predictions bring up a common question : what is the role of the Roche potential and the Coriolis force in shaping the flow if the wind speed is lower than the orbital speed?

3. Orbital bending

3.1. Formation of wind-captured discs

In El Mellah & Casse (2017), we developed a ballistic model to identify the orbital, stellar and wind parameters susceptible to give birth to a wind-captured disc i.e. a disc formed without Roche lobe overflow of the donor star. This mass transfer mechanism was first described by Mohamed & Podsiadlowski (2007) and coined as "wind Roche lobe overflow". In this regime, the wind is slow enough compared to the orbital speed to be significantly deflected towards the accretor. It gains a significant amount of angular momentum and might form a disc, provided it radiates away energy and has a circularization radius large enough. The circularization radius is the radius of a Keplerian orbit with the same angular momentum per mass unit. If the accretor is a NS such as in Vela X-1, the dynamics of the flow is controlled by the magnetic field within a magnetosphere which extends up to a few hundred times the NS radius (Ghosh & Lamb 1979). At the outer edge of the NS magnetosphere, a possible disc is truncated by the magnetosphere so the flow should have a circularization radius larger than the magnetosphere radius to form a wind-captured disc. Focusing on these configurations suitable to lead to the formation of wind-captured discs identified in the first place, we solved the dynamics of the flow within the Roche lobe of the accretor in El Mellah et al. (2019a). The radiative acceleration was taken from Sander et al. (2017), accounting for the impact of the X-ray ionizing feedback on the acceleration efficiency. In order to differentiate

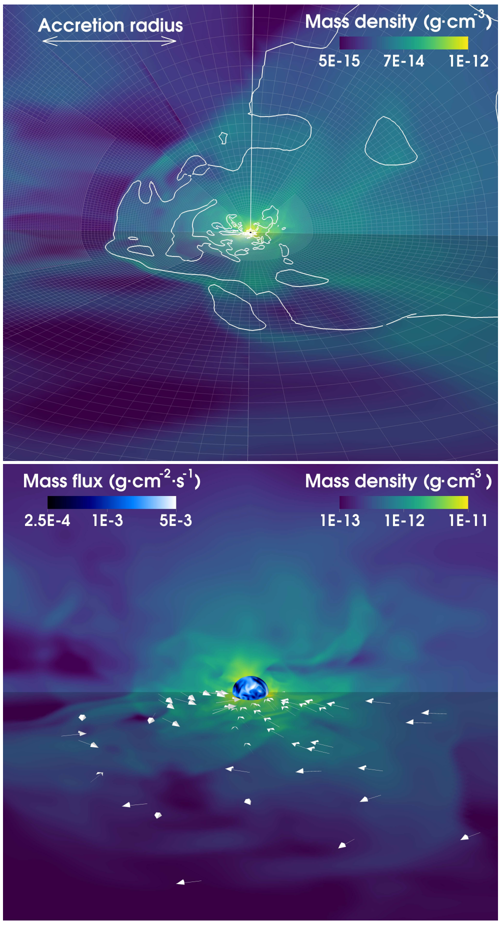

Fig. 1. Side view on slices of a mass density colormap. The supersonic flow comes from the left and the polar axis is vertical. In the left panel, the solid white line is the Mach-1 contour. The black frame stands for the dimensions of the right panel. In the right panel, we zoom and show the velocity field in the equatorial plane. The surface of the inner sphere, of radius $R_{acc}/100$, is colored with the absolute local radial mass flux.

the structure of the accretion flow produced for a wind with a speed lower or higher than the orbital speed, which is of $\sim$284km·s^{-1} in Vela X-1, we considered the two following cases:

– the heavy slow (HS): the accretor is heavy, with a mass of $2.5M_\odot$, lying on the upper edge of the expected maximum mass for a NS, and the radiative acceleration efficiency is not enhanced, leading to a relatively slow wind.
– the light fast (LF): the accretor has a mass of $1.5M_\odot$ and the radiative acceleration efficiency is enhanced by 50%.

First, we work with an adiabatic energy equation and discard any net heating or cooling. In the LF case, the morphology of the flow departs little from the planar Bondi-Hoyle-Lyttleton configuration. We do not observe any flip-flop instability and the shock remains essentially axisymmetric. The density increases by a factor of approximately 100. In the HS case, the situation is dramatically different (Figure 2, left panel). The net amount of angular momentum entering the simulation space is significant and a stream of matter, reminiscent of the Roche lobe overflow configuration, starts to appear. Material from higher latitudes on the star contributes to the accretion process, leading to a much more important density increase than in the LF setup, of the order of 1,000. The shocked region of the HS setup presents a characteristic spiral shape which delimits a narrow accretion channel along which matter flows in. In both LF and HS cases though, the increase in temperature is non realistic due to the adiabatic assumption we relied on. To account for the radiative cooling, we used three different prescriptions:

– Isentropic (or ”isoS”): cooling occurs only in a thin unresolved radiative layer immediately downstream the shock and is then negligible (for instance, because of intense X-ray heating).
– Isothermal hot (or ”hot”): above 10^6K, the net cooling is efficient enough to compensate any adiabatic compression as the flow accretes, which leads to an isothermal flow.
– Isothermal cool (or ”cool”): same as previous but with a temperature 10^5K.

Whatever cooling prescription invoked, the LF setup never leads to the formation of a disc-like structure around the accretor. On the contrary, in the HS configuration, a permanent disc forms within the shocked region, whatever the cooling prescription we rely on. It appears as a flattened structure essentially supported by the centrifugal force (Figure 2, right panel).

This work shows that a disc can form without Roche lobe overflow. In Cygnus X-1, it has been suggested recently that the absence of visible hysteresis in the hardness-intensity cycle is due to a hot and low angular momentum accretion flow (Taam et al. 2018). The orbital speed is larger than in Vela X-1, around 400km·s^{-1}, but since the donor star is an O Supergiant, its wind is also faster than the wind of the B Supergiant star in Vela X-1. All in all, the disc in Cygnus X-1 might be a wind-captured disc similar to what was derived in the aforementioned heavy slow configuration, much smaller than the Roche lobe of the accreting black hole.

3.2. Enhanced mass transfer in ultra-luminous X-ray sources

Ultra-luminous X-ray sources are spatially unresolved persistent sources with luminosities in excess of 10^{39}erg·s^{-1} (Kaaret et al. 2017). The accretor has been found to be a NS in several systems (Bachetti et al. 2014), which implies an X-ray luminosity above the limit above which isotropic accretion onto a body of this mass is thought to be self-regulated by the radiative field it produces, called the Eddington luminosity. Most ULX hosting a stellar mass accretor are now thought to be the high mass accretion rate end of SgXBs, which brings up the possibility that both types of objects belong to the same population and that the mass transfer mechanism at the orbital scale might be qualitatively the same.

In El Mellah et al. (2019b), we showed that stellar material could be transferred to the compact object at a rate high enough to reach the ULX. Since this mass transfer mechanism does not require Roche lobe overflow, it is not prone to the type of runaway mass transfer which leads to a common envelope phase when the mass of the donor is significantly larger than the mass of the accretor (see Quast et al. 2019, for recent developments on this question). Furthermore, it explains how a donor star like in M101 ULX-1, which has been shown by Liu et al. (2013) to not fill its Roche lobe,

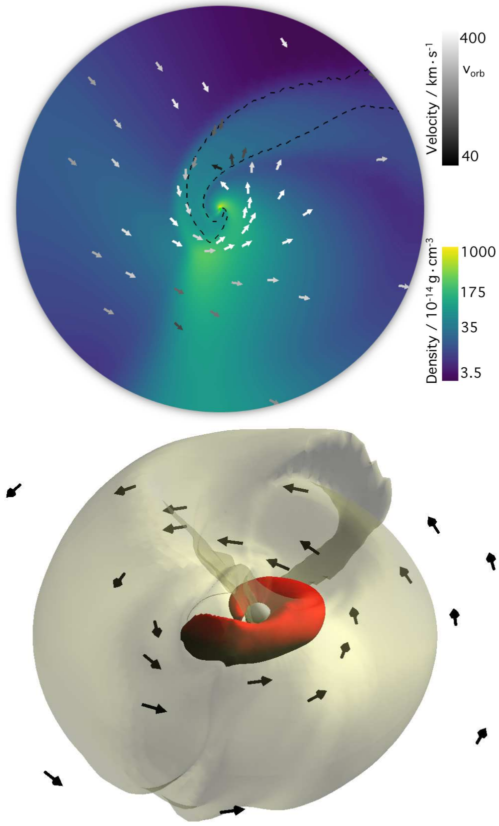

Fig. 2. (left) Color map of the mass density around the accretor (slice in the orbital plane). The arrows represent the velocity field and the dashed black line is the Mach-1 surface. The shock structure departs significantly from the planar case. (right) Isocontours of density of a centrifugally-maintained disc-like structure around the central NS. The central white sphere represents the NS magnetosphere while the arrows indicate the local orientations of the velocity field.

can feed a compact object accreting at a super-Eddington rate.

4. Conclusion

By connecting the different scales of the problem together, from the orbital scale down to the outer edge of the NS magnetosphere, we managed to follow the accretion flow over up to 5 orders of magnitude. We showed that the serendipitous capture of clumps is not enough to reproduce the 2 orders of magnitude peak-to-peak variability observed in a classic SgXB such as Vela X-1, and that flares could not be traced back to a single clump. This work highlights the role played by additional mechanisms at the magnetosphere of the accreting NS such as centrifugo-magnetic gating (Bozzo et al. 2008). Our work also indicates that if the wind speed is of the order of or lower than the orbital speed in a non Roche lobe overflowing X-ray binary, the flow will carry enough momentum to form a disc, even if the accretor is a NS with a magnetosphere extending up to a few hundreds of Schwarzschild radii. This regime is also associated to a significant enhancement of mass transfer which can lead to levels suitable to reproduce the super-Eddington mass accretion rates observed in ULXs.

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