Formation of wind-capture disc in Supergiant X-ray binaries

Consequences for Vela X-1 and Cygnus X-1

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ABSTRACT

Context. In Supergiant X-ray binaries (SgXB), a compact object captures a fraction of the intense wind from an O/B Sg companion star on a close orbit. Proxies exist to evaluate the efficiency of mass and angular momentum wind accretion but they depend so dramatically on the wind speed that within the uncertainty range, they only bring loose constrains. Furthermore, they often bypass the impact of orbital and dissipative effects on the flow structure.

Aims. We study the wind dynamics and in particular, the angular momentum it gains and carries as it is accreted. We aim at evaluating the conditions of the formation of a disc-like structure around the accretor and its observational consequences for SgXB.

Methods. We inject recent results on the wind launching mechanism into the three-dimensional frame of a binary system, accounting for the gravitational and radiative influence of the compact companion. Once it enters the Roche lobe of the accretor, we solve the hydrodynamics equations and evaluate the impact of different cooling prescriptions on the flow.

Results. A shocked region forms around the accretor as the flow is beamed. For wind speeds of the order of the orbital speed, the shock is highly asymmetric compared to the axisymmetric bow shock obtained for a purely planar homogeneous inflow. Provided we enable cooling within the shocked region, the flow always circularizes for wind speeds slow enough.

Conclusions. Although the donor star does not fill its Roche lobe, a realistic wind-launching representation can lead to a flow slow enough when it enters the Roche lobe of the accretor to be significantly beamed and bent by the orbital effects. The net angular momentum of the accreted flow is then large enough to form a persistent disc-like structure whose properties depend on the cooling mechanism.

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

1. Introduction

Most stars are found in multiple stellar systems, especially the high mass ones (**?**). Among them, a significant fraction will undergo a phase of mass transfer which can seriously alter their subsequent evolution. New observational insights on the long (**?**) and short term (**?**) evolution of High Mass X-ray Binaries (HMXB) has aroused the compelling need for a more comprehensive description of mass transfer via wind accretion.

In Supergiant X-ray binaries (SgXB), a supergiant O/B donor star is orbited by a compact object, generally a neutron star (NS), embedded in the stellar wind. O/B stars are known to loose mass at a rate up to several $10^{-6}\mathrm{M}_{\odot}\cdot\mathrm{yr}^{-1}$ through a wind whose launching mechanism was first determined by **?** and **?** : the resonant line absorption of UV photons by partly ionized metal ions provide the outer layers of the star with a net outwards momentum. As the flow accelerates, it keeps tapping previously untouched Doppler-shifted photons and can reach terminal speeds up to $2{,}000\mathrm{km}\cdot\mathrm{s}^{-1}$. It is the gravitational capture of a fraction of this abundant line-driven wind by the compact companion which produces the X-ray luminosity we observe in SgXB, of the order of $10^{35-37}\mathrm{erg}\cdot\mathrm{s}^{-1}$.

Until now, the mass and angular momentum accretion rates pertaining wind accretion have been evaluated based on the Bondi-Hoyle-Lyttleton model (BHL, see **?**, for a review) : a planar supersonic flow is gravitationally deflected by the gravitational field of an accretor and an overdense tail is formed in its wake. The mass accretion rate turned out to be so sensitive to the relative speed of the flow with respect to the accretor that within the uncertainties and local variations in a massive-star wind, any realistic SgXB mass accretion rate can be reproduced. Furthermore, the axisymmetry of the BHL problem circumvented any discussion on the accretion of angular momentum. This assumption was first relaxed by **?** and **?** to assess the possibility of the formation of a wind-capture disc around compact accretors : they concluded that it was likelier for close binaries, where the star gets close to fill its Roche lobe, but that it was also highly dependent on the relative wind speed. This dependency is made even more crippling when one notices that in SgXB, the accretor lies within the region of acceleration of the flow, which prevents us from simply relying on the terminal speed of the wind.

In consequence, a fully consistent treatment of both the wind acceleration and its accretion by the compact object is required to avoid being left with the wind speed as a convenient but not constraining degree of freedom. **?** computed the steady state wind stratification for a 1D radial non-local thermal equilibrium

⋆ The university of heaven temporarily does not accept e-mails
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atmosphere of a star representative of the donor star in Vela X-1. They accounted for a plethora of chemical elements and ionization levels susceptible to absorb the stellar UV photons, and for the X-ray ionizing feedback from the accretor on the wind ionization state. In this paper, we intend to use this computed 1D line-driven acceleration to see how the 3D structure of the flow departs from a spherical wind once the orbital effects are added. Rather than being set based on an empirical fitting formula, the static wind velocity and density are mere consequences of the stellar and orbital properties. In section **??**, we evaluate the systematic bending of the wind streamlines by the orbital effects, as the wind unfolds and enters the Roche lobe of the accretor with a non-zero net angular momentum. Within the latter, we run 3D HD simulations described in section 2 to capture the structure of the flow as it cools down downstream the shock and its capacity to form a disc-like structure. In section **??**, the implications of such a component are discussed in the context of the archetype of wind accreting NS-SgXB, Vela X-1, and of the SgXB Cygnus X-1 hosting a stellar-mass black hole candidate accreting the wind from a companion supergiant which does not fill its Roche lobe.

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Yet, we still miss a fully consistent frame to follow the flow from the stellar surface down to the X-ray emitting region, in the immediate vicinity of the accretor. Until now, the six orders-of-magnitude or so separating the two scales has precluded any bold numerical attempt to follow the flow all along its journey.

? first derived a critical impact parameter, the accretion radius, below which material is likely to be captured by the accretor.

brought a firm motivation

brought serious motivations to the field of accretion disks

The turbulent twilight of massive stellar binaries stars determines their final fate. In Supergiant X-ray binaries, mass transfer proceeds through the accretion of a fraction of the dense and fast wind from an evolved donor star by an orbiting compact object, generally a neutron star. The accretor both perturbs the stellar wind and provides a moving X-ray source to probe its internal structure : the characteristics of the flow constrain the X-ray emission and absorption along the line-of-sight, while the X-ray ionizing feedback alters the wind acceleration. In order to consistently monitor the flow from the stellar surface down to the accretor, we designed a multi-scale model which includes recent insights on the properties of massive star winds. We performed 3D numerical simulations to evaluate the mass and angular momentum accretion rates onto the compact object, depending on the wind to orbital speed ratio and to the cooling efficiency within the shocked region. We identified conditions favorable to the formation of a disc-like structure beyond the neutron star magnetosphere, in spite of the low angular momentum carried by the wind, and analyzed its properties. These conditions, compatible with the currently known parameters of the Supergiant X-ray binary Vela X-1 and to a certain extent with Cygnus X-1, indicate the possible presence of a limited disc-structure in the former case and account for an extended one in the latter case.

Our current theories of single-star evolution have proved consistent with the observational surveys carried on by contemporary missions. However, few stars are deprived of a gravitationally bound stellar companion, with more high mass stars showing a higher multiplicity frequency (**?**). Some of them undergo a phase of interaction with their companion tied enough to significantly alter their subsequent evolution. One of the stages important to provide a more complete evaluation of the impact of binarity on stellar evolution are high mass X-ray binaries (HMXB). They represent the turbulent twilight of the entangled evolution of two massive stars, one having already collapsed into a compact object. They are believed to be progenitors of compact object binaries whose final coalescence has been observed by the LIGO/VIRGO collaboration (**?**).

The main characteristic manifestation of binarity is through mass transfer between the two components. It can lead to chemical contamination (e.g. in the case of Barium and Carbon-enhanced metal-poor stars **??**) or to the stripping of the outer envelope of an evolved star, leaving a naked Helium-rich core (e.g. for some hot subdwarf stars **??**). The transfer of mass goes hand in hand with a transfer of angular momentum which can produce fast rotators like millisecond pulsars (**?**) or Be-stars (**?**).

Supergiant X-ray Binaries (SgXB) are systems where a compact object, generally a neutron star, orbits an O/B Supergiant (see **?**, for a recent review). Mass transfer proceeds through the capture of a fraction of the dense and fast line-driven stellar wind by the accreting body. This highly non-conservative mechanism, called wind accretion, has been put in opposition to the better understood Roche lobe overflow mechanism, although elements of both can co-exist in hybrid models (**??**). The central distinction lies in the presence of a large and permanent disc in the latter case, while the conditions for such a structure in the former case are still unclear. Our present knowledge on angular momentum wind accretion builds up on models of asymmetric Bondi-Hoyle-Lyttleton accretion (**??**) and on numerical investigations of the impact of transverse gradients of density (**??**) and velocity (**?**). Yet, we still miss a fully consistent frame to follow the flow from the stellar surface down to the X-ray emitting region, in the immediate vicinity of the accretor. Until now, the six orders-of-magnitude or so separating the two scales has precluded any bold numerical attempt to follow the flow all along its journey.

Wind accretion turns out to be extremely sensitive to the properties of the stellar wind. O/B supergiants display dense and fast outflows, with mass loss rates up to several solar masses per million year. The underlying mechanism, unveiled by **?** and **?**, is the resonant line absorption of UV photons by partly ionized metal ions in the outer layers of the star. As the flow accelerates, it keeps tapping previously untouched Doppler-shifted photons XXX FOR ANDREAS : INFLUENCE OF DETAILED IONIZATION STRUCTURE AND X-RAY IONIZING FEEDBACK XXX

key-ingredient

2. Orbital deviation of the wind

2.1. Model and numerical method

Sophisticated models and simulations of the launching of line-driven winds show that they become supersonic shortly above the stellar photosphere. It motivates a ballistic treatment of the wind bulk motion at the orbital scale similar to what was done in **?** : the trajectory of test-masses is integrated assuming the star and the accretor are on circular orbits and that stellar rotation is synchronized with the orbital period. The 3D equation of motion in the co-rotating frame is :

$$\boldsymbol{v}\frac{\mathrm{d}\boldsymbol{v}}{\mathrm{d}\boldsymbol{r}} = \boldsymbol{a}_{\star} + \boldsymbol{a}_{\mathrm{NS}} + \boldsymbol{a}_{\mathrm{ni}} \quad (1)$$

where $\boldsymbol{a}_{\mathrm{NS}}$ stands for the acceleration due to the NS gravitational field and $\boldsymbol{a}_{\mathrm{ni}}$ for the non-inertial acceleration (centrifugal and Coriolis). The effective acceleration linked to the donor star of mass M_1, once projected on the radial unity vector of the spher-

Table 1. Parameters and integrated quantities at the outer edge of the simulation space for the 2 models considered.

	LF	HS
M_1	$20.2M_\odot$	
R_1	$28.4R_\odot$	
P	8.964357 days	
$\dot{M}_1$	$6.3{\cdot}10^{-7}M_\odot{\cdot}yr^{-1}$	
M_2	$1.5M_\odot$	$2.5M_\odot$
Boosted	Yes	No
$\dot{M}_{out}/\dot{M}_1$	XXX	XXX
$\dot{j}_{out}/\dot{j}_{SL}$	XXX	XXX
R_{circ} / R_{mag}	XXX	XXX

ical frame of the star, is given by :

$$a_\star = -\frac{GM_1}{r_1^2} + a_{rad}(r_1) + a_{press}(r_1) \tag{2}$$

where a_{press} is the acceleration due to thermal and turbulence pressure. For describing the total radiative acceleration a_{rad}, containing both the line and total continuum contribution, we rely on the computation by **?** for Vela X-1. Using the stellar atmosphere code PoWR (**??**, e.g.), they calculate an atmosphere model for the donor star assuming a spherical, stationary wind situation. The radiative transfer is performed in the comoving frame, allowing to obtain the radiative acceleration without any further assumptions or parameterizations, i.e. :

$$a_{rad}(r_1) = \frac{4\pi}{c}\frac{1}{\rho(r_1)}\int_0^\infty \kappa_\nu H_\nu \mathrm{d}\nu \tag{3}$$

where the mass density ρ is deduced from the mass loss rate and the velocity using the conservation of mass. Using the technique described in **?**, the model provides 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 are balancing each other throughout the stellar atmosphere. The resulting velocity and density stratification shows notable deviations from the typically assumed β-law, especially within a couple of stellar radii, where the orbiting accretor lies and where the obtained wind velocity is lower. Notice that in spite of the non-spherical situation due to the presence of the NS, we adopt a_{rad} as a_{press} as functions of the distance r_1 to the donor star here for simplicity.

(and neglect Roche deformation of the star)

can be seen as a modified Roche potential which encapsulates the gravitational potential of the accretor, the centrifugal component and the effective gravitational potential of the star given by

Wind acceleration XXX ANDREAS : would you be able to summarize the principle of your calculation and the way we account for it here?XXX

we focus on the fraction of the wind susceptible to be eventually accreted, not on an accurate representation of the accretion tail in the wake of the accretor (for this component, see rather **?**)

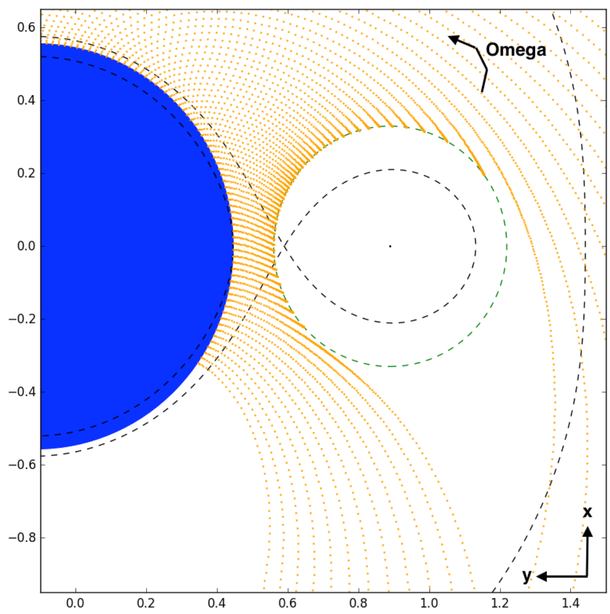

Fig. 1. Computed streamlines (orange dots) from the star (dark blue) to the Roche lobe of the accretor on the right (green dashed circle), in the orbital plane. The black dashed lines represent the critical Roche surface passing by the first Lagrangian point.

2.2. Inhomogeneity and asymmetry of the wind

3. Wind-capture discs

3.1. Hydrodynamics

3.1.1. Equations

1 refers to donor star 2 refers to accretor

normalization units

angular momentum preserving way

Using the finite volume code `MPI-AMRVAC` (**?**), we solve the equations of hydrodynamics under their conservative form :

$$\partial_t\rho + \boldsymbol{\nabla}\cdot(\rho\boldsymbol{v}) = 0 \tag{4}$$

$$\partial_t(\rho\boldsymbol{v}) + \boldsymbol{\nabla}\cdot(\rho\boldsymbol{v}\boldsymbol{v} + P\not{\mathbb{1}}) = \rho\boldsymbol{f} - 2\boldsymbol{\Omega}\wedge\boldsymbol{v} \tag{5}$$

$$\partial_t e + \boldsymbol{\nabla}\cdot[(e+P)\boldsymbol{v}] = -\rho\boldsymbol{v}\cdot\boldsymbol{f} \tag{6}$$

where ρ, $\boldsymbol{v}$, P and e are the mass density, velocity, pressure and total energy density respectively. $\boldsymbol{\Omega}$ is the orbital angular speed vector. $\boldsymbol{f}$ is the modified Roche force per mass unit given by :

$$\boldsymbol{f} = \alpha(r_1)\frac{q}{r_1^3}\boldsymbol{r_1} - \frac{1}{r_2^3}\boldsymbol{r_2} + \frac{1+q}{a^3}\boldsymbol{r_\perp} \tag{7}$$

with the mass ratio $q = M_1/M_2$ $\boldsymbol{r_1}$ $\boldsymbol{r_2}$ $\boldsymbol{r_\perp}$ α : see section **??**. Encapsulates wind acceleration process and stellar gravity. −1 with only gravity, leading to the usual Roche force per unit mass.

The energy equation 6 is adiabatic. See section 3.1.2 for way to account for cooling. EOS ideal gas monoatomic with an adiabatic index $\gamma = 5/3$ with a mean molecular weight set to 1.

3.1.2. Cooling

Cooling time scale (**?**) Polytropic index Γ (**?**). Physical meaning of Γ. Bypass the energy equation 6 where the cooling time scale is XXX times smaller than the dynamical time scale.

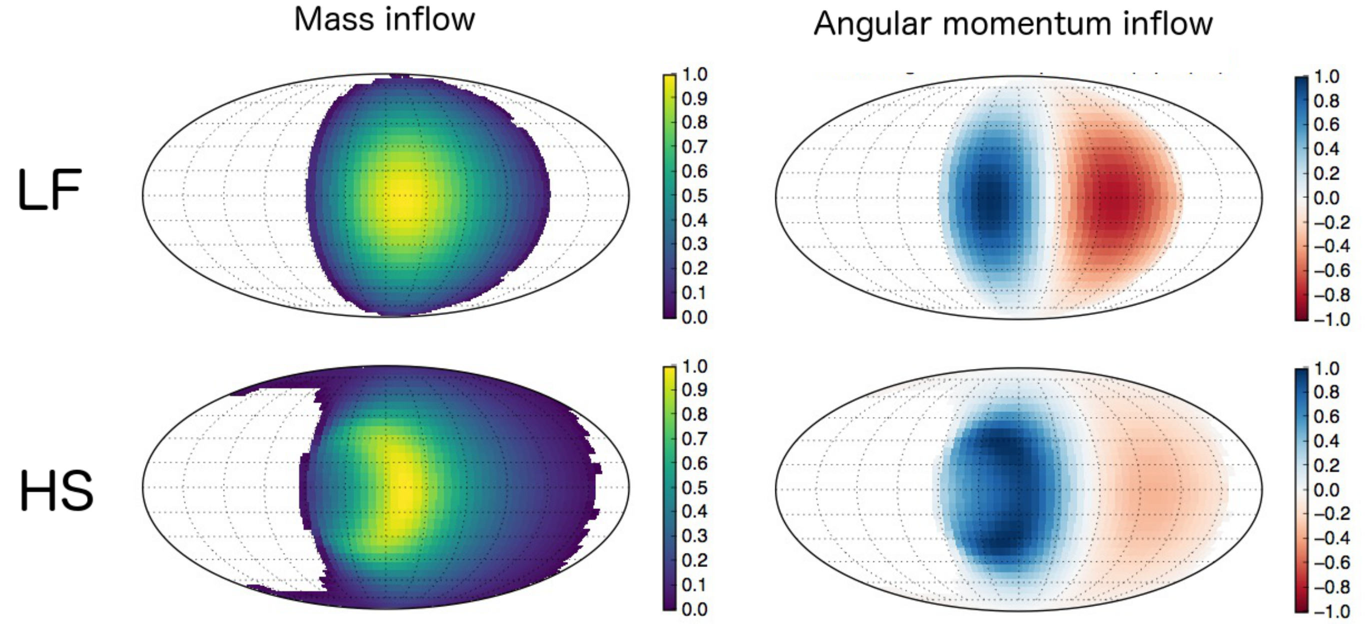

Fig. 2. Mollweide projections of local mass and angular momentum inflows within the simulation space centered on the accretor (dashed green sphere on Figure1). The upper row corresponds to the light fast (LF) case while the bottom row is for the heavy slow (HS) case. Each map is scaled to its maximum (absolute) value and centered on the axis from the accretor to the donor star. Positive (resp. negative) values of angular momentum stands for locally prograde (resp. retrograde) flow with respect to the orbital motion.

Provided the density is high enough, condensation of the hot shocked flow into a disc (**?**, and references therein) : underlying principle of two component accretion flows models.

3.2. Flow morphology

3.2.1. Without cooling

3.2.2. With cooling

FOR BLACK HOLES : Presence of a disc-like structure which does not extend as far as in RLOF-fed systems (LMXB) => no hysteresis in hardness-intensity diagram (for Cyg X-1, LMC X-1 or LMC X-3, the 3 wind-fed BH-HMXB). Indeed, the soft state might originate from : "A drop in the accretion rate affecting both flows would propagate through the halo immediately but might take up to several weeks to propagate through the disk.While the inner halo is thus temporarily depleted compared to the disk, a temporary soft state is expected." but if the disc has a much smaller outer radius (due to a much smaller angular momentum of the inflow), the viscous delay is expected to be so small that the dimming of the disc will be almost as fast as the one of the disc. (**?**). Explains also why no large outburst (ie a low contrast between the brightest and dimmest X-ray emission) in Cygnus X-1 (x3) (**?**) : without an outer cool disc, the thermal instability resulting from the ionization of Hydrogen cannot occur (REF?). No quiescent state in Cyg X-1 : it is an argument in favor of the existence of a cool disc in the hard state.

3.3. Mass and angular momentum accretion rates

If halted mass accretion, might be due to radiative heating from the X-ray source (**?**) : if circularization radius > 0.04 times the Bondi radius (for us, the accretion radius?), much lower accretion rate than Bondi (for us, BHL?). But their work depends also on isotropic or anisotropic X-ray source, alpha viscosity parameter, etc...

4. Observational consequences

4.1. Disc mass and morphology

5. Conclusion

In this paper, we connected the orbital scale, at which the wind unfolds, to the one of the accretion radius, at which the flow is significantly beamed by the gravitational field of the compact object and where HD shocks form, all the way down to the outer edge of the NS magnetosphere.

currently, lack of conclusive evidence in favor of the presence of a permanent disc in SgXB (**????**) : is it because it is could be truncated by the magnetosphere and not hot enough to contribute significantly compared to the accretion columns at the NS poles?

What about the impact of other orbital scale structures on the formation of wind capture disc? Impact of corotating (i.e. at the stellar rotation rate) interaction region (spiral-shaped density and velocity enhancements due to irregularities on the stellar surface such as local luminosity increase by 10%). Observed in single OB stars. In low luminosity SgXB and SFXT, proposed by **?** as a possible origin of the super-orbital modulation (between stellar and orbital period) observed, as the accretor crosses the CIR. Rq : since the super orbital period is usually of the order of a few times the orbital period only, it means that the stellar rotation period and the orbital period must be quite different (while I expected stars to be in synchronous rotation in HMXB...)

which connect the different scales

significant deviation from

bridge the gap between the / starts to resemble RLOF

The interest is twofold (**?**)

What about the micro-structure? Clumps small compared to accretion radius for such small wind speed.

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