Accretion flows around compact objects: stellar wind and neutron stars in massive binaries

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Abstract.
Strong winds from massive stars are a topic of interest to a wide range of astrophysical fields, e.g., stellar evolution, X-ray binaries or the evolution of galaxies. Massive stars, as heavy as 10 to 20 solar masses, generate dense fast outflows that continuously supply their surroundings with metals, kinetic energy and ionizing radiation, triggering star formation and driving the chemical enrichment and evolution of Galaxies. The amount of mass lost through the emission of these winds dramatically affects the evolution of the star. Depending on the mass left at the end of its life, a massive star can explode as a supernova and/or produce a gamma-ray burst, which are among the most powerful probes of cosmic evolution. The study of massive star winds is thus a truly multidisciplinary field and has a wide impact on different areas of astronomy.

In High-Mass X-ray Binaries the presence of an accreting compact object on the one side allows to infer wind parameters from studies of the varying properties of the emitted X-rays; but on the other side the accretors gravity and ionizing radiation can strongly influence the wind flow. As the compact objects, either a neutron star or a black hole, moves through the dense stellar wind, it accretes material from its donor star and therefore emit X-rays. Subsequently these X-rays will affect (heat and photoionize) the stellar environment and alter the ionization structure of the wind. The wind will therefore be more unstable revealing a very rich phenomenology. Using an armada of space based observatories (e.g., XMM-Newton, swift, INTEGRAL, NuSTAR, etc) and data spanning more than 10 years allowed for probing the inner velocity field close to the massive donor as well as neutron star masses estimations. As a result, stellar winds and neutron stars can be now studied in situ, thanks to X-ray observatories and state-of-the-art hydrodynamic simulations for the very first time.

1. Introduction
The density and velocity of stellar winds in massive stars are poorly constrained close to the stellar surface. Eclipsing high-mass X-ray binaries with short orbital orbits allow the conditions of the inner stellar wind to be probed in situ. Thanks to its high X-ray flux, Vela X-1 is a perfect laboratory, with a pulsar accreting and photo-ionising the wind of its massive (B 0.5 Ib) companion.

In supergiant High Mass X-ray Binaries (sgHMXBs) neutron stars are orbiting at a close proximity, $\alpha \sim 1.5 - 2 \, R_\odot$, to their companion/donor stars [5]. The donors, in these systems, are OB supergiants with enormous mass loss rates of the order of $\sim 10^{-6} \, M_\odot \, yr^{-1}$ and wind terminal velocities ranging from 500 km s$^{-1}$ to $\sim 2000$ km s$^{-1}$. The neutron star accretes gas from the stellar wind and a fraction of the gravitational potential energy is converted into X-
rays, ionizing and heating the surroundings. The X-ray emission can be used to investigate the structure of the stellar wind in situ [12].

The interactions between the neutron star and the stellar wind in Vela X-1 revealed that the wind of the massive star is heavily disrupted by the gravity and photoionization of the neutron star [2]. On the other hand, the heavily obscured sgHMXBs share some of the characteristics of the classical sgHMXBs. The main difference between classical and obscured sgHMXBs is that the latter ones are much more absorbed in the X-rays ($N_H > 10^{23} \text{ cm}^{-2}$) on average, 10 times larger than in classical systems and well above the galactic absorption.

2. Simulations & Results

2.1. The simulations

The VH1 hydrodynamical code [2] has been employed in order to study the interplay between the stellar wind and the compact object and compare it with the observational features of two supergiant sgHMXB systems. Namely, to explain the origin of the X-ray off-states in the classical sgHMXB Vela X-1. In our simulations of Vela X-1 we account for: i) the gravity of the primary and of the neutron star, ii) the radiative acceleration of the stellar wind of the primary star, and iii) the suppression of the stellar wind acceleration in the Strömgren sphere of the neutron star. The simulations take place in the orbital plane, reducing the problem to two dimensions. In both cases we have assumed circular orbits ($e = 0$).

The code produces density and ionization ($\xi = L_X/nr_{ns}^2$, where $L_X$ is the average X-ray luminosity, $n$ is the number density at the distance $r_{ns}$ from the neutron star) maps that are stored. These allow to determine the simulated column density. As short time-scale variations occurs, we have calculated the time-averaged orbital phase resolved column density. The 3-D instantaneous mass accretion rate ($\dot{M}_{\text{acc}}$) onto the neutron star is also recorded. From the mass accretion rate, we can infer the instantaneous X-ray luminosity of the neutron star. The relaxation time is of the order of 0.5 orbits. The first couple of days of the simulations are therefore excluded from our analyses. In both simulations, the grid is centered on the center of mass. The boundary conditions are set in a way that matter is removed when it reached the cell including the neutron star. The boundary conditions at the radial outermost part of the mesh are characterized as outflow.

A critical ionization parameter, above which the radiative force is negligible is defined. For $\xi > 10^{2.5}$ erg cm sec$^{-1}$, most of the elements responsible for the wind acceleration are fully ionized and hence the radiative acceleration force vanishes. The main effects of the ionization is the reduction of the wind velocity in the vicinity of the neutron star and the enhancement of the mass accretion rate onto the compact object.

The winds of massive supergiant stars are radiatively driven by absorbing photons from the underlying photosphere, as described in CAK model [3]. However, regions in the stellar wind can differ from the predictions of the CAK/Sobolev approximation when instabilities are taken into account [10]. The velocity is described by the $\beta$-velocity law, $v = v_\infty(1 - R_*/r)^\beta$ where $v_\infty$ is the terminal velocity and $\beta$ is the gradient of the velocity field.

A computational mesh of 900 radial by 347 angular zones, extending from 1 to $\sim 25 R_*$ and in angle from $-\pi$ to $+\pi$, has been employed. The grid is built in a non-uniform way in order to allow for higher resolution of $\sim 5 \times 10^{-8}$ cm at the neutron star. An in-depth, more detailed, summary of the simulations and their outcome is given in [6, 8, 7].

2.2. The classical sgHMXB Vela X-1

Vela X-1 (4U 0900−40) is a classical eclipsing super-giant High Mass X-ray Binary (sgHMXB). The system consists of an evolved B 0.5 Ib supergiant (HD77581) and of a massive neutron star of $M_{NS} = 1.86 \, M_\odot$. The neutron star orbits its massive companion with a period of about 8.9 days, in a circular orbit with a radius of $\alpha = 1.76 \, R_*$. The stellar wind is characterized by...
a mass-loss rate of $\sim 4 \times 10^{-6} \text{ M}_\odot \text{ yr}^{-1}$ and a wind terminal velocity of $v_\infty \approx 1700 \text{ km s}^{-1}$, although recent studies proposed much slower wind velocity, see e.g., [4] and references there in. The X-ray luminosity is typically $\sim 4 \times 10^{36} \text{ erg s}^{-1}$, although high variability can be observed. Recent studies on the hard X-ray variability of Vela X-1 have revealed a rich phenomenology. Flaring activity and short off-states have been observed. Both flaring activity and off-states were interpreted as the effect of a strongly structured wind, characterizing the X-ray variability of Vela X-1 with a log-normal distribution, interpreted in the context of a clumpy stellar wind. The quasi-spherical subsonic accretion model (see e.g., [11] and reference therein) is an alternative, predicting that the repeatedly observed off-states in Vela X-1 are the result of a transition from the Compton cooling (higher luminosity) to radiative cooling (lower luminosity).

![Figure 1](image_url)

**Figure 1.** Density distribution (in gr cm$^{-3}$) during the off-state (left) and before (right). The overplotted contours shows the radial velocities. The position of the neutron star is indicated by the black arrow. The figure is adopted by [8].

Our simulations predicts the formation of low density bubbles behind the bow shock, around the neutron star, resulting in the X-ray off-states. These bubbles are $\sim 10$ times larger than the accretion radius. When a bow shock appears, it moves away from the neutron star up to a distance of $\sim 10^{11}$ cm (see fig. 1). A low density bubble forms behind and starts expanding. It then gradually fall back and a stream of gas eventually reaches the neutron star and produces a new rise of the X-ray flux. The accretion stream can either move left-handed or right-handed. This breathing behavior is quasi-periodic. The observed light-curves also show a quasi-periodic signal at $\sim 6800$ sec [7]. This modulation is related to the characteristic free-fall time of the low density bubble (radius of $\sim 10^{11}$ cm) much longer than the accretion or magnetospheric radii.

We have constructed histograms of the observed and simulated light-curves (see fig. 2; left panel). The histograms are normalized to an integral equals to unity. All three distribution can be fit with the log-normal distribution characterized by a standard deviation ($\sigma$) of 0.23 for INTEGRAL (blue) and 0.30 for RXTE (red), while the distribution is narrower for simulated lightcurve (black) having a standard deviations of 0.2. A minor excess can be seen at the lower end of the distribution at about $L_X \sim 10^{35}$ erg s$^{-1}$.

The hydrodynamic simulations of Vela X-1 are sufficient to explain the observed behavior without the need for clumpy stellar wind or high magnetic fields and gating mechanisms. Self-organized criticality [1] of the accretion stream is enough to describe the observed variability.
The aforementioned simulations provide a good match to the observed (hard) X-ray lightcurves of Vela X-1, utilizing a number of orbiting observatories. The parameter space, in this study, is summarized in Table 1. A particular set of parameters \( (v_\infty = 1400 \text{ km/s} \text{ and } \beta = 0.5) \) which is making a remarkable match to the observation. The outcome of all available models is illustrated in Figure 2 (right panel) The velocity law favoured by the BAT folded lightcurve is significantly steeper than what is though \( (\beta \approx 0.8) \). We have checked that these two velocity laws give very similar results for what concerns the variability of the accretion rate and, in particular, for the X-ray flux and off-state distributions. This is understandable because the latter are mostly driven by the conditions within about ten accretion radii. Our current best fit model \( (v1400b05) \) confirms the results [7] with small deviations. The dynamical range and the durations of the off-states are very similar as presented earlier, and the histogram of the simulated variability is characterized by a similar log-normal distribution.

The hydrodynamic simulations of the wind of Vela X-1 are still incomplete, however they already provide an excellent agreement with the observations for the smooth properties (this work) and the variability. High-mass X-ray Binaries provide information on the initial acceleration of the stellar wind. This is unique and requires testing models accurately.

Table 1. Simulation parameters space (wind terminal velocity, beta parameter)

| Model Name | \( v_\infty \) (km s\(^{-1}\)) | \( \beta \) |
|------------|----------------|--------|
| v1700b08   | 1700           | 0.8    |
| v1400b08   | 1400           | 0.8    |
| v1700b05   | 1700           | 0.5    |
| v1400b05   | 1400           | 0.5    |
3. Future perspectives

Despite the large amount of published work, a lot of details regarding Vela X-1 system are still to be determined. Tackling the problem, from a computational point, is rather challenging, given that it is a multi-scale, multi-physics problem. Stellar winds are coming from the donor star, at orbital scales, typically $\sim 10^{12}$ cm and ranging down to the magnetosphere of the neutron star, typically $\sim 10^8$ cm, spanning over 6 orders of magnitude. The physics at each different regime is rather challenging, from magneto-hydrodynamic simulation close to the base of the magnetic field, that should be anchored to the neutron star, to accretion physics, around the magnetosphere, up to early stellar wind acceleration around the surface of the star.

Each of this regime is a challenging project by itself, combining them together is even harder. Currently, we are still working on regions that are much smaller than the orbital scale, and resolution is enough to resolve structure and instabilities. A work in progress is to include a model for the magnetic gating mechanism at distances close to the magnetosphere (currently under development). Early results shows that the magnetic gating mechanism will match the observed behavior by making the log-normal distribution (see e.g., the left panel of Fig. 2) slightly wider, better matching the observed ones.

Other treatments are taking into account the wind instability, to produce clumpy wind, in the presence of a neutron star or a black hole [9]. The simulated mass accretion rate of a clumpy wind onto a neutron star matches our results, although a much simpler model is employed in our simulations. Once all of them are put together, we can get more information on the physics of accretion in such extreme environment.

4. Conclusion

In this study, we have used extensive Hydrodynamic simulation, in a parameter space suitable for the archetypal sgHMXB Vela X-1. This source is well observed, summarizing more than $\sim 20$ years of data in the X- and $\gamma$-ray domain. Based on our simulation and comparison with the observations we conclude that: (a) the off-states can be explained as voids in the accretion structure around the neutron star and (b) a steeper velocity field is favored at the early acceleration phase. Recent developments, e.g., inclusion of magnetic gating mechanism, clumpy winds, etc, are indicative of a better match to the observed behavior. In addition, development of multi-physics and multi-scale simulations are essential to better understand the elusive nature of these objects.

Acknowledgments

The author, being a member of the X-WIND collaboration, initially supported by the International Space Science Institute (ISSI), located in Bern, would like to thank all the member of the collaboration for fruitful and insightful discussions.

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