# Speeding up the spinning top

How accretion sets the pace in High Mass X-ray Binaries

Massive stars live a forceful life during which they shape galaxies with their mechanical, radiative and chemical feedback. Most of them evolve in a binary system where the two stars orbit close enough to strongly interact and sometimes merge during their evolution [1]. Last year, a gravitational wave detection granted us access to the very last moment this epic journey can lead to: the coalescence between two neutron stars (NS), which unveiled the final masses and spins they acquired during their turbulent lifetime [2]. An intermediate step between these two stages are High Mass X-ray Binaries (HMXB), systems where stellar material is transferred from an evolved massive star to an orbiting compact remnant. The conditions of this transfer determine whether a double NS with an orbital separation small enough to spiral-in and merge within a Hubble time will eventually be formed.

Loss and exchange of angular momentum during this phase is a key problem to address. NS are surrounded by an extended magnetosphere plays a major role in the accretion process: the spin of the NS in HMXB perturbs the accretion through magneto-centrifugal effects and episodic mass outflows [3]. Furthermore, the orbital separation has a direct impact on the mass transfer mechanism (Roche lobe overflow or wind accretion), on the geometry of the accretion flow and on the subsequent spiral-in time. Models are being developed to describe the formation of double NS systems [4] but thorough and repeated observations of individual HMXB remind us how uncertain the proxies we rely on to compute evolutionary tracks can be. The distinction between the limit disc and wind-fed regimes prevents us from treating the realistic intermediate case, with a stellar wind significantly beamed towards the accretor much before stellar evolution leads to stellar Roche lobe overflow. Within the current uncertainties on the properties of the winds of evolved massive star (mass loss rate, velocity profile, micro-structure), the geometry of the accretion flow when it reaches the magnetosphere fluctuates [5]. Since the instantaneous torques at stake depend on whether the material forms a thin disc (prograde or retrograde) or remains essentially spherical as it is accreted, it has dramatic consequences on the spinning up or down of the accretor [6, 7].

A good illustration of our incomplete understanding is given by the distribution and evolution of the NS spin in Supergiant X-ray binaries (SgXB, a sub-class of HMXB, see Figure 1). While some sub-classes of HMXB show common angular momentum trends, wind accreting NS in SgXB still defy theoretical expectations. They can display distinct long term phases of spinning up or down, which prove that the torque does not obey a random walk, and torque reversals are not necessarily associated to spectral or flux variations [8].

The aim of this project is to gather these torque mechanisms into a consistent frame to evaluate the loss and transfer of angular momentum in the complex environment of NS-hosting SgXB following these core questions:

**Q1.** How does the flow connect to the magnetosphere and what are the short and long term consequences for the spin of the NS?

**Q2.** How does radiative heating/cooling influence the flow geometry at the magnetosphere?

**Q3.** How does the partial capture of stellar material by the NS alter the orbital separation and how does it retroactively impact the stellar mass loss?

Until now, the several orders of magnitude which separate the orbital scale from the X-ray emitting region, in the immediate vicinity of the compact object, have precluded any

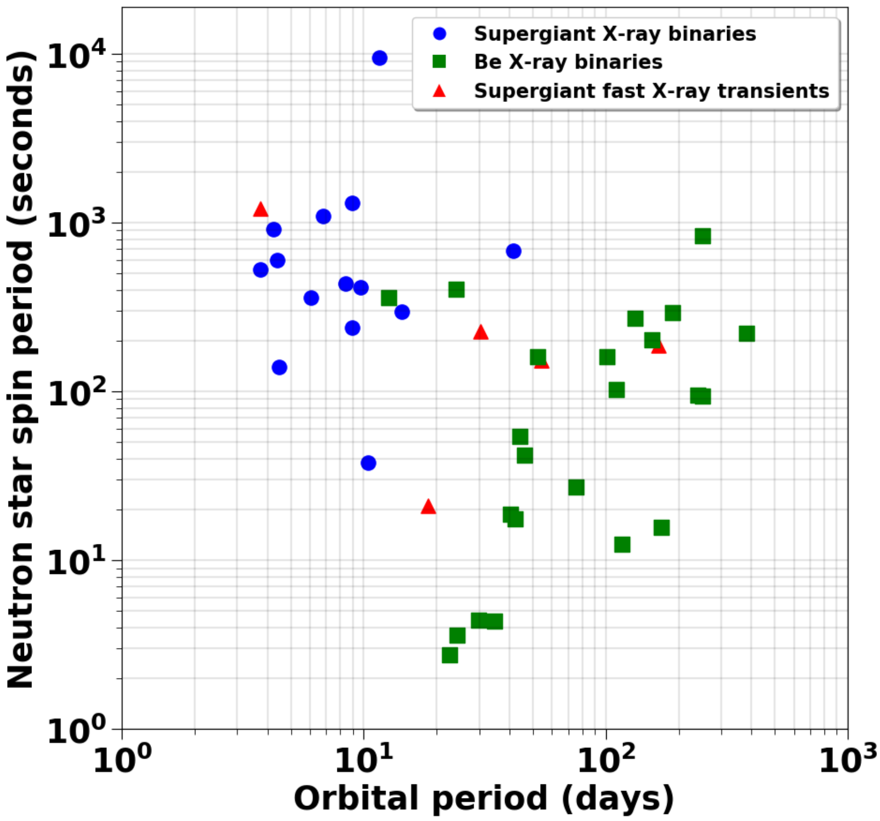


Figure 1: NS-hosting Galactic HMXB with known orbital and NS spin periods. While a correlation exists between the spin and the orbital period in X-ray binaries where the donor star is a massive Be star (a fast rotator surrounded by a decretion disc), it is not the case in SgXB or in Supergiant fast X-ray transients.

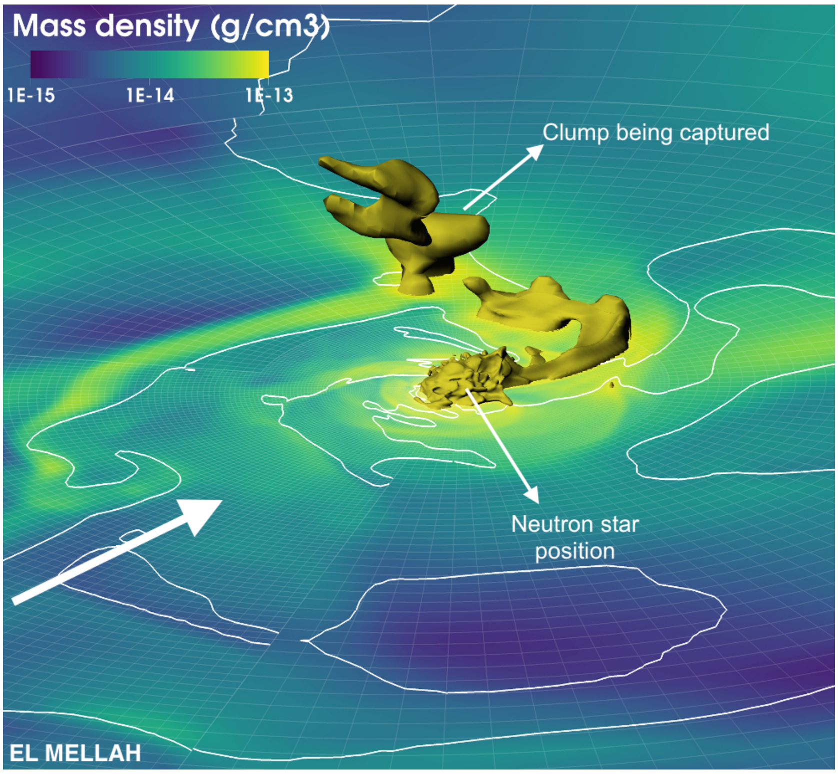


Figure 2: Color map slice of the density in the equatorial plane and 3D iso-density surface. The accretor lies in the center and the wind comes from the bottom left. The capture of an overdense "clump" of matter is visible. The solid white line delimits the envelope of the shocked region, perturbed by clumps. The clump carries enough angular momentum to form a transient disc-like structure around the NS magnetosphere, engulfed in the flow.

bold numerical attempt to follow the accreted flow all along its journey. We were condemned to compute the torques applied by ad-hoc accretion geometries, presupposing an idealized behavior of the scales out of the scope of the simulation. Within an active collaboration which gathered 20 to 30 observers and theoreticians of winds of massive stars and X-ray binaries over the last years, I have developed and validated a numerical framework which connects these scales and offer the first comprehensive view of mass transfer via line-driven winds to compact accretors in binaries. I am now in a position to step forward and investigate the torques associated.

## Methodology

As a computational astrophysicist, the underlying tools of my research are models based on observations and detailed numerical simulations. I have gained ample experience over the last five years with cutting-edge massively parallel codes to solve the 3D magneto-hydrodynamics equations in non-Cartesian geometries and I have performed computationally-intensive simulations on Tier-1 supercomputers. On the other hand, I also embraced the diversity of structures and environments highlighted by observers in the numerical setups I designed: I treat, within the same simulation space, zones of enhanced ionization or density [9] and the accretion tail [10] identified by orbital-phase resolved spectroscopy of the classic SgXB Vela X-1 with the NASA Chandra satellite [11] and the ESA XMM-Newton satellite [12] respectively. I can now address the entry of the accretion flow in the NS magnetosphere and its consequences on the transfer of angular momentum through the following steps. Notice that although they would profit from each other, these steps are autonomous enough to be performed separately, may one of them not unfold as planned.

- ↳ **Step 1: Flow-magnetosphere boundary layer** I could first make use of the representative flow geometries I identified in [5] (spherical, thin or thick disc, prograde or retrograde) to study the encounter between the inflowing material and the NS magnetosphere. The net spinning up or down associated to each regime would be computed in a full 3D time-dependent environment. I would measure the capacity of the flow to penetrate the magnetosphere via magnetic reconnection, relying on observational parameters (e.g. the magnetic moment deduced from observations of cyclotron resonance scattering features with the NASA NuSTAR satellite [13]). This step would also serve to refine the numerical setup (identification of appropriate adaptive mesh refinement criteria to reach numerical convergence, validation of the magnetic divergence cleaning tools already available in `MPI-AMRVAC`...). The torques measured in these simulations depending on the geometry and their comparison to reported values in SgXB would be reported in a first publication addressing **Q1**.

- ↳ **Step 2: Radiative feedback** *This step is subdivided in an implementation step (a) and two physical applications steps which would lead to a paper each (b linked to **Q2** and b' linked to **Q3**). (a)* The formation of a disc depends on the capacity of the flow to radiate away its internal energy and compress. I implemented a first cooling prescription and used cooling modules suitable for radiatively thin environments, but I now intend to rely on the more realistic treatment of radiative effects available in the `FLASH` or the `HARMRAD` codes used by several teams in the US [14]. A side application, suitable for a one-year graduate project, would be the extraction of photometric and spectroscopic synthetic observations from the simulations to be confronted to the observations. *(b)*

For a spherical accretion flow, the rate of plasma entering into the magnetosphere is determined by the interchange instability [7]. The latter is triggered by Compton cooling of the hot plasma as it interacts with the X-rays from the accretor. *(b')* An inspiralling NS could in theory eject the envelope of its massive star companion [15]. With the proper radiative treatment developed in *(a)*, 3D radiative-hydrodynamics simulations of common envelope ejection including regions where the luminosity reaches the Eddington luminosity could be performed. It would be an unprecedented computation of the efficiency of the envelope unbinding, a key parameter to evaluate the fraction of mergers of compact binaries susceptible to be detected [16].

↳ **Step 3: Transitions and duty cycle** making use of the multi-scale setup I developed, I could investigate how the micro-structure of the wind provoke stochastic variations of the geometry (e.g. in Figure 2) susceptible to make the accretion regime transit from a stage to another (e.g. activation of the propeller effect or inversion of the disc rotation). Longer simulations would estimate the duty cycle of the torques and the net spinning up or down of the NS. In a publication addressing **Q1** from a complementary point of view, I could confront the first synthetic curves of the evolution of the NS spin as a function of time to the observed ones (e.g. in the wind-fed NS Ultra-luminous X-ray source, P13 ULX-1, whose pulse period derivative remains to be explained, [17]). Perspectives to extend the present project would naturally arise, with the possibility to investigate the impact of these new results on the secular evolution of these systems.

## Relevance to NASA's Cosmic Origins questions & host institution

**"How did we get here?"** Serious uncertainties persist on the efficiency of angular momentum transfer in HMXB and need to be overcome to appreciate the tumultuous history of massive binaries, a family of stars which shaped the Universe.

**"How does the universe work?"** With the incoming LIGO/Virgo O3 observing run, we might witness hundreds of mergers of double NS each year whose properties could be more accurately interpreted if the aims of this project are fulfilled. This proposal is a unique occasion to put the newly born field of gravitational wave astronomy into perspective.

I wish to undertake this project within Pr. A. Tchekhovskoy's team at Northwestern University in Chicago. His expertise in modeling the immediate environment of NS and black holes would be extremely valuable to achieve these scientific goals, along with his broad experience of large scale simulations. The coupling between my knowledge with `MPI-AMRVAC` and the high performance techniques he co-developed (e.g. GPU-parallelization, [18]) would be highly profitable to the completion of this project. I also intend to interact with Pr. R. Taam's who has extensively worked on HMXB and recently published important results on the extent of the accretion disc in Cygnus X-1 [19]. The vicinity to the University of Chicago has two additional assets: the presence of the Flash Center for Computational Science which will be of tremendous importance to include the radiative feedback in my simulations, and the leading role research institutes of the city play in the LIGO collaboration, e.g. with Pr D. E. Holz in the University of Chicago and Pr. V. Kalogera at Northwestern University.

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