

MASS AND ANGULAR MOMENTUM TRANSFER IN BE X-RAY BINARIES

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Abstract. The current uncertainties on the predicted merger rates of double compact objects highlight the pressing need for an accurate description of the mass and angular momentum transfer mechanism in Be X-ray binaries which are possible progenitors. The strong orbital modulation induced by the eccentric orbit provides us with an invaluable test-bed in order to confront accretion models to observations. While the correlation between the orbital and pulsar spin periods indicates an efficient angular momentum transfer, the exact amount of material accreted and the geometry of the accretion flow highly depend on the orbital parameters and on the properties of the decretion disk surrounding the Be star. With this work, I want to highlight how we can constrain mass transfer in Be X-ray binaries with numerical simulations covering a variety of configurations. Thanks to adaptive mesh refinement and neatly tailored 3D grids, we can follow the flow over several orders of magnitude and put to the test different accretion models. We find that type I outbursts reflect the amount of material captured from the decretion disk. The complex interplay between the replenishment of the decretion disk, truncated at its outer edge by the tidal interactions, and its periodic tapping by the neutron star leads to a multiplicity of accretion regimes.

Keywords: hydrodynamics - Be X-ray binaries - compact objects - decretion disks - methods: numerical

1 Introduction

Be X-ray binaries are systems where a young and highly magnetized neutron star (NS) orbits around a Be star. The latter is a rapidly rotating hot star surrounded by a decretion disk formed in its equatorial plane. When the NS crosses the decretion disk, it accretes material which can give rise to type I bursts (periodic) or type II bursts (aperiodic) in X-rays. Bright flares have recently been reported far from periastron in the Be X-ray binary A0538-66 (Ducci et al. 2021), which can partly be ascribed to the eccentricity of the orbit.

2 Models

We rely on a two-stages modeling approach with first, a simplified semi-analytic model to identify the main effects of the orbital parameters on the X-ray light curve (section 2.1) and second, a more realistic model that we implement as a numerical setup in order to carry hydrodynamic simulations (section 2.2).

2.1 Bondi-Hoyle-Lyttleton accretion

Due to its low computational cost, the first approach can be used to perform an exhaustive exploration of the parameter space. It also provides a tool to fit the X-ray light curve of Be X-ray binaries averaged over many orbits so as to find the most likely orbital parameters. The decretion disk around the Be-star is modeled as a steady structure with the following density profile (Kee et al. 2018):

$$\rho = \rho_0 \left(\frac{r \sin \theta}{R_*} \right)^\beta \exp \left[-\frac{GM_*}{c_s^2} \left(\frac{1}{r \sin \theta} - \frac{1}{r} \right) \right] \quad (2.1)$$

where ρ_0 is the density scale, R_* and M_* are the radius and mass of the Be-star, c_s is the sound speed at the photosphere of the Be-star, β is a dimensionless exponent, G is the gravitational constant and r and θ are the

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radial and longitudinal coordinates in the spherical frame aligned with the rotation axis of the Be-star. We set $\beta = 15/8$. The decretion disk is assumed to be in Keplerian rotation around the Be-star.

We work with fiducial orbital parameters with a mass ratio Be-star to NS set to 10, a Roche lobe filling factor of the Be-star reaching 1 at periastron, an orbital eccentricity and inclination of 0.5 and 20° and a longitude at periastron $\omega = 0^\circ$. We use the wind accretion formula from Bondi-Hoyle-Lyttleton to compute the mass accretion rate at each point on the orbit: the denser the environment and the lower the relative speed, the higher the mass accretion rate (see e.g. El Mellah et al. 2020a).

The main caveats of this simplified approach is that (i) we rely on an approximate formula which has been shown to be inaccurate when the donor star is close from filling its Roche lobe (El Mellah et al. 2019b) and/or when the relative speed is comparable to the orbital speed (El Mellah et al. 2019a), and (ii) we neglect the deformation of the decretion disk induced by the tidal interactions between the NS and the Be-star.

2.2 Numerical setup

Once we identified configurations susceptible to match a given Be X-ray binary, we perform numerical simulations with the GPU-accelerated magneto-hydrodynamic code Idefix based on the Kokkos library (Lesur et al., in prep). Thanks to neatly tailored 3D grids, with a higher resolution in the decretion disk and near the NS, we can follow the accretion process over many orbits and compute the averaged mass accretion rate as a function of the orbital phase.

3 Results

After a couple of orbital periods, the disk structure and the mass accretion rate onto the NS have relaxed in the sense that they depend essentially on the orbital phase. A snapshot of the flow structure at periastron is represented in Fig. 1. Due to the disrupted structure of the decretion disk, the mass accretion rate onto the NS does not necessarily peak at periastron but rather after, with a variable delay depending on the orbital parameters and properties of the decretion disk.

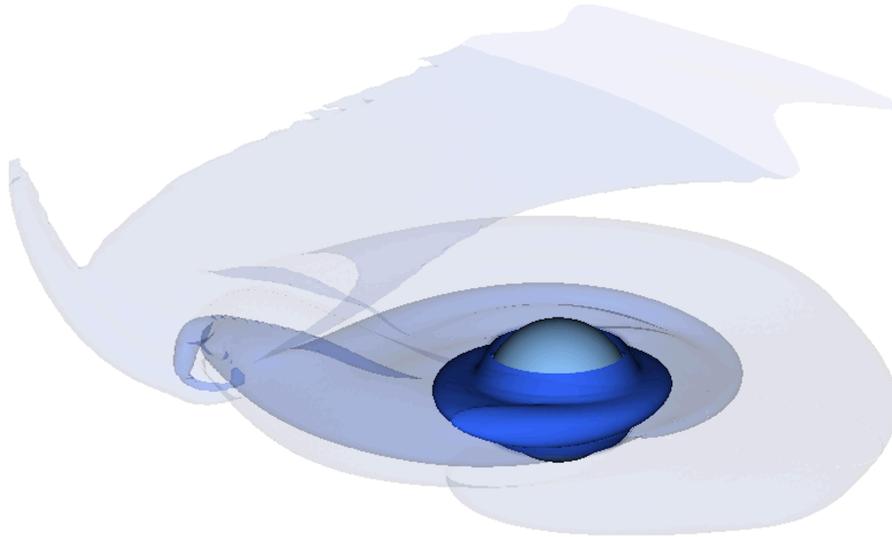


Fig. 1. Surfaces of iso-density around a Be-star (sphere in light blue on the right). The snapshot is taken at periastron, with the NS on the left.

4 Perspectives

In the future, we will carry systematic simulations to analyze the effect of different orbital and disk parameters and will pay particular attention to the possibility for the decretion disk to become significantly eccentric. The later feature was recently proposed to play a major role in the triggering of type I and type II outbursts in Be

X-ray binaries (Franchini & Martin 2019; Martin & Franchini 2019; Franchini & Martin 2021). We will also use the inputs from these simulations to perform magneto-hydrodynamics simulations of accretion within the NS magnetosphere similar to those carried by Romanova et al. (2004). The goal will be to monitor possible delays induced by instabilities and/or different accretion regimes, similar to what was done in supergiant X-ray binaries by Bozzo et al. (2020). The possibility to probe the disk structure based on the X-ray variability and absorption along the line-of-sight will also be studied, like in other types of high-mass X-ray binaries (El Mellah et al. 2020b).

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