FORMULACIÓN DEL PROYECTO, MARCO TEÓRICO Y DISCUSIÓN BIBLIOGRÁFICA

Esta sección debe contener:

FORMULACIÓN DEL PROYECTO: la exposición general del problema, la novedad de la propuesta, hipótesis de trabajo, objetivos y metodología (incluir diseño experimental, si corresponde), así como los fundamentos teóricos, antecedentes bibliográficos u otros relevantes a la propuesta. Mantenga el formato, tamaño carta, fuente Verdana o equivalente tamaño 10. La extensión máxima para este apartado es de 6 páginas.

Eccentric high-mass X-ray binaries

The missing link to mergers

1. Context

1.1. The missing link between binary stars and merging neutron stars

Merging neutron stars (NSs) such as GW170817 (Abbott et al. 2017) are thought to be the last step of the co-evolution of two massive stars (Tauris et al. 2017). The gravitational wave signals, merger rates, electromagnetic counterparts and nature of the remnant depend on the past interaction between the two bodies which sets their properties (mass, spin period, magnetic field) at the moment of the merger (Chruslinska et al. 2018). In these evolutionary tracks to coalescence, **high-mass X-ray binaries (HMXBs) are thought to be the immediate progenitors** but they represent a stage so short and challenging to detect that we only know a few hundreds of systems.

1.2. Be X-ray binaries

In the majority of HMXBs, **a NS orbits around a Be star** (see artistic representation in Figure 1). Be stars are massive blue stars which were spun up close to critical rotation by a previous mass transfer episode from the progenitor of the NS (de Mink et al. 2013). These NSs capture, or "accrete", material from their Be companion star. Among BeXBs, we find a wide variety of configurations depending on **the mass, spin and magnetic field of the NS**, and on the properties of its surrounding environment (orbital parameters, mass and angular momentum accretion rates). In BeXBs, NSs are young so their magnetic field had no time to decay. As a consequence, these NSs are surrounded by **an extended magnetosphere** within which the accreted plasma is funneled along the magnetic field lines to the NS magnetic poles, where it emits most of the X-rays we observe. These accreting NSs thus manifest as **X-ray pulsars** which truly are goldmines for stellar evolution, high energy astrophysics and physics of ultracondensed matter.

Fig. 1 - *Artistic representation of a Be X-ray binary with the massive blue Be star (on the left) and the orbiting neutron star (on the right).*

Due to centrifugal support, the Be star is surrounded by **a decretion disk** in its equatorial plane and an isotropic stellar wind (Brown et al. 2019). At the moment of its formation, the NS got a natal velocity kick from the supernova explosion (Mandel et al. 2020). Consequently, in BeXBs, the orbits are **highly eccentric and misaligned** with respect to the decretion disk (Figure 2). Each time the NS crosses the denser decretion disk and/or at periastron, it accretes material and produces periodic X-ray outbursts which provide us with an accurate estimate of the orbital period, typically 10 to 300 days.

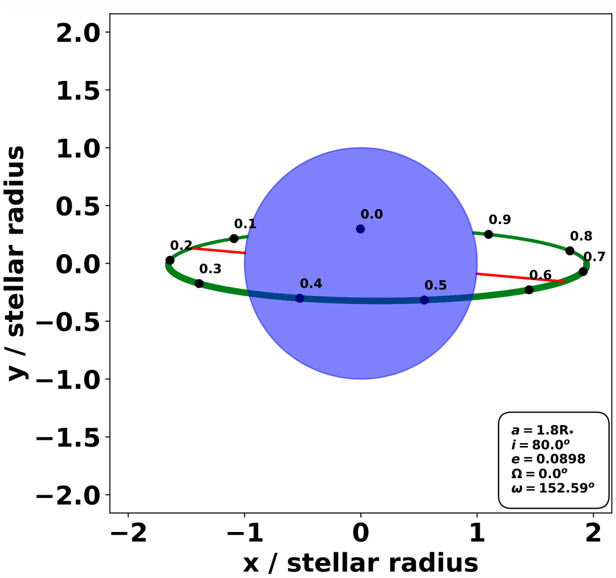
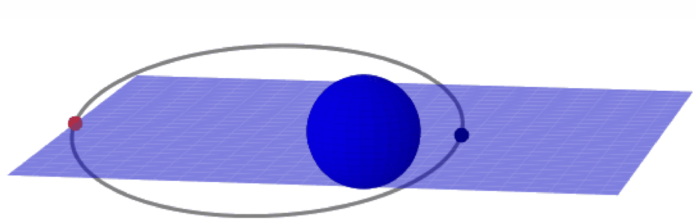


Fig. 2 - *(left) Slightly eccentric orbit (in green) of a NS around a Be star. The numbers indicate the orbital phase (with upper conjunction as a reference) and the red line is the main axis of the orbit. (bottom) Representation of an eccentric orbit misaligned with respect to the decretion disk (blue plane). The black dot (resp. the red dot) indicates periastron (resp. apoastron). From periastron to apoastron (resp. from apoastron to periastron), the NS is above (resp. below) the decretion disk.*



1.3. The neutron star, an unpredictable spinning top

We can measure and follow the evolution of the spin period of X-ray pulsars in BeXBs over the past decades (Malacaria et al. 2020). Although young and highly magnetized, they are slow rotators with spin periods ranging from 1 to 1,000 seconds. Interestingly, they show episodes of steady **spinning up and down**, separated by sudden torque reversals whose origin remains unknown (Figure 3 right panel). The torques do not correlate with the X-ray light curves, contrary to what would be expected from an accretion disk truncated at its inner edge by the magnetosphere of the NS (Ghosh & Lamb 1979). Yet, the loose correlation between the NS spin and the orbital period in BeXBs (Figure 3, left panel) suggests a **coupling between the two induced by mass transfer** but major uncertainties remain about its modalities (Langer et al. 2021).

New models of accretion-induced torques have been proposed, both for disk-like and quasi-spherical accretion flows at the outer rim of the magnetosphere (resp. Bozzo et al. 2009 and Shakura et al. 2014). Whether the accretion flow has enough angular momentum to form a disk or not depends on the **mass transfer mechanism which varies along an eccentric orbit** (El Mellah et al. 2019). Numerical simulations show that mass transfer can be mediated by stellar wind capture (Hirai & Mandel 2021), decretion disk crossing (Martin & Franchini 2021) and/or Roche lobe overflow at periastron (El Mellah et al. 2022). These mechanisms determine the geometry of the accretion flow, the evolution of the NS spin and whether the orbital separation shrinks fast enough for a merger to be, in fine, achievable within the age of the Universe.

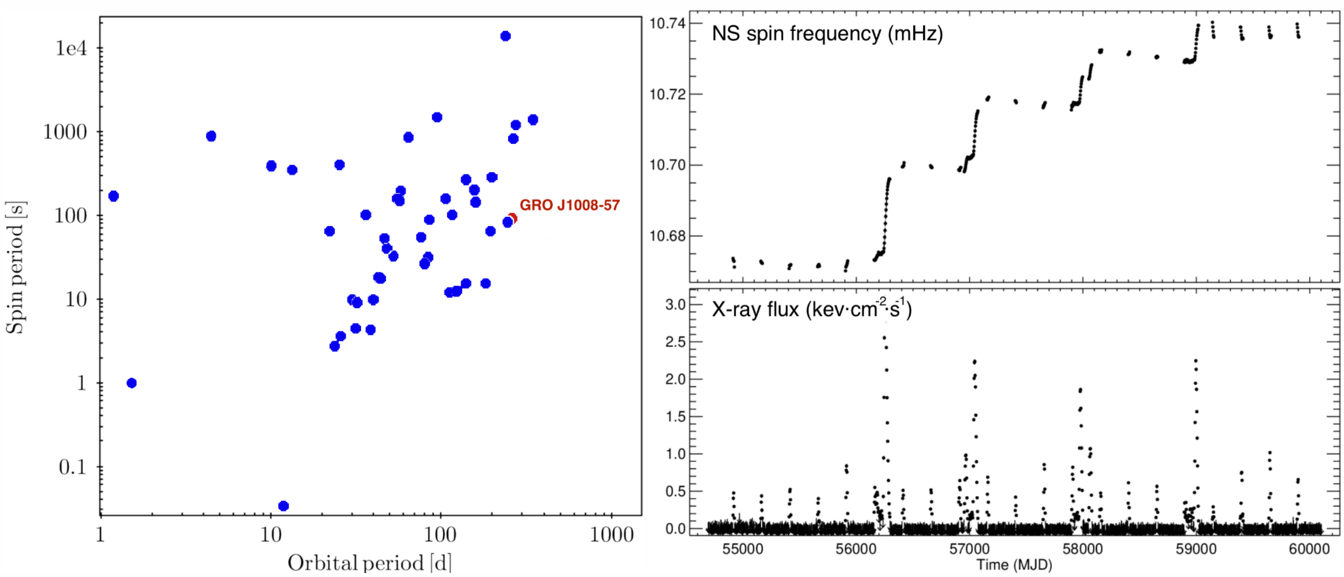


Fig. 3 - *(left) NS spin period as a function of the orbital period in BeXBs (adapted from Fortin et al. 2023). The red dot is the system corresponding to the observations on the right. (right) Evolution in time of the NS spin frequency in the BeXB GRO J1008-57 over the past 15 years (top panel), along with its Fermi/GBM X-ray light curve (bottom). X-ray flares occur at the orbital period each time the NS crosses the decretion disk surrounding the Be star near periastron.*

2. Project

Until now, our lack of parameters (for the orbit, the Be star, the NS, the decretion disk) was crippling our understanding of the alternating episodes of NS spinning up and down we observe. We want to build upon the new catalogs which were compiled by Malacaria et al. (2020), Neumann et al. (2023), Kim et al. (2023), Fortin et al. (2023) in the wake of the improved distance measurements made by the Gaia satellite (see Fig.3). Our main goal is **to analyze the publicly available data and verify the conjectures, assumptions and predictions made by different models of BeXBs**. It is a task particularly suitable for an *ayudante a la investigación* which will not only inspire the development of new BeXB models but will also be instrumental in the interpretation of the upcoming gravitational wave signals detected by the future gravitational wave interferometers.

Core hypothesis - I suspect that BeXBs differ essentially from one another due to their different ages since the formation of the NS. As the system gets older, the NS accretes material, taps the orbital angular momentum and spins up. The orbit subsequently circularizes and shrinks, and the orbital period decreases. Since the NS magnetic field is a good tracer of its age, we can verify this assumption by comparing the NS and orbital properties in multiple systems.

Motivation - With more than 40 entries for some 160 BeXB systems, these 4 new catalogs represent a unique chance to shed light on regular patterns which have gone unnoticed until now. Given how recent and massive the data release was, I need immediate support to seize this precious occasion to put the models to the test. It is why I request an *ayudante a la investigación* to perform this data analysis and publish the subsequent findings as soon as possible.

Questions - Is the evolution of BeXBs susceptible to lead to double NS mergers? Are BeXBs evolutionary linked to other families of high-mass X-ray binaries (e.g. gamma-ray binaries before and supergiant X-ray binaries after)? Is the spin period of the NS the result of the accretion process or does it retain information on its pristine value, at the birth of the NS?

Objectives - Our immediate objectives in order to address the questions above are the following.

1. **Gather catalog information -** The *ayudante* will gather the parameter estimates from the databases using web scraping tools (e.g. Python libraries like Selenium or Beautiful Soup).
2. **Harmonize databases -** We will harmonize the different databases by handling the conflicting, missing and/or redundant pieces of information.
3. **Clarify entries -** The meaning of each entry of the catalogs will be clarified to avoid any ambiguity and guarantee safe portability and legacy.
4. **Deliver a user-friendly platform -** We will provide the community with a major deliverable, an online platform where users will be able to plot the parameters for all BeXBs, similar to the one which exists for exoplanets for instance.
5. **Analyze the parameters -** The *ayudante* will analyze the BeXB parameters with classic data reduction tools (χ^2, covariance matrices, etc) to check expected properties and correlations.
6. **Identify phylogenies -** We will compute the Kendall's tau rank correlation coefficients for each pair of parameters in order to plot dendrograms showing the hierarchical relationships between the different parameters.
7. **Explore new correlations -** We will search the data for previously overlooked correlations with more advanced machine learning techniques (singular value decomposition, principal component analysis and clustering analyses, etc).
8. **Extrapolate to fainter systems -** We will explicit the observational biases and deduce the demographics of the population of BeXBs beyond the reach of the current instruments due to their low X-ray flux.

The timeline of each of these points is detailed in the next section *Plan de trabajo.*

PLAN DE TRABAJO: En relación con los objetivos planteados, señale las etapas y actividades para cada uno de los años de ejecución del proyecto. Utilice una carta Gantt. Extensión máxima para este apartado es de 1 página.

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Our work will follow, in order, the intermediate steps described above. The Gantt chart below illustrates the estimated time of completion for each task and the associated timeline of the project (1 year).

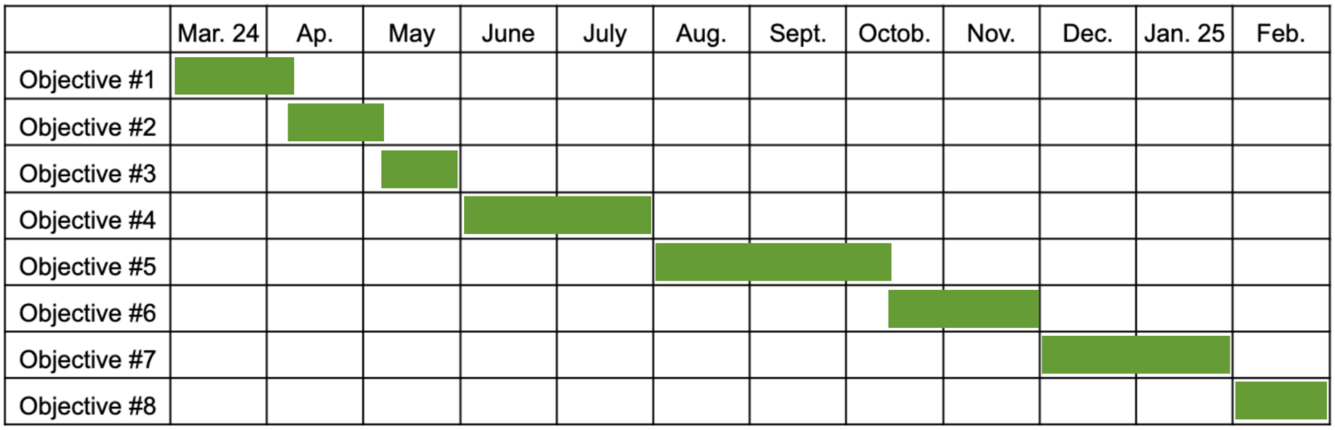

Fig. 4 - *Gantt chart describing the envisioned timeline for each of task, each being associated to one of the objectives described in the end of the previous section. The tasks will be performed in serial from March 2024 to February 2025.*

This work will lead to at least one paper involving the *ayudante* at the end of the project and that I will write in parallel of the two last objectives. Depending on her/his *grado* and level of avancement, the *ayudante* could lead a second method paper aimed at describing the usage and content of the online platform (objective #4).

TRABAJO ADELANTADO POR LAS AUTORAS Y/O LOS AUTORES DEL PROYECTO: Si corresponde, resuma los principales resultados de sus trabajos anteriores sobre el tema a investigar. Extensión máxima 1 página.

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I am the PI of an international team gathering approximately 20 observers, modelers and computational astrophysicists working on X-ray pulsars in high-mass X-ray binaries. During the 2 ISSI meetings I have organized in 2020 and 2022 in Bern (https://www.issibern.ch/teams/evolutionpulsars/), we have confronted the different models available and identified clear observational diagnostics in order to disentangle between the different scenarios. The goal was to investigate the phenomena responsible for the X-ray flares we observe in high-mass X-ray binaries in general and in BeXBs in particular (see bottom right panel in Figure 3). It has led to an ESO observational proposal that I am leading as a PI. In order to identify the best targets, I started to gather the information from the 4 aforementioned catalogs of high-mass X-ray binaries (Figure 5). We also developed a common theoretical framework to compare the key parameters each model relies on. Consequently, I am now in an ideal position to perform global analysis of BeXBs properties based on the available data.

1	Name	RAdeg	DEdeg	PosErr	Coord_Ref	ID_Flag	GLON	GLAT	Xray_Type	Porb	Ppulse	CRSF	Alt_Name
120	OAO 1657-415	255.203682	-41.65596	0.08485281185	2003yCat.2246..	0	344.3691632	0.3192390979	CL,EB,XP	10.4	37.03	35.6	AX J1700.7-413
121	AX J1714.1-391	258.432982	-39.201804	0.43716	2020A&A...641A	2	347.8072332	-0.1723806892					CXOU J171343.9-
122	XTE J1716-389	258.985248	-38.864929	0.1131370825	2010MNRAS.40	1	348.3311358	-0.3241875938		99.1			2CXO J171556.4-
123	IGR J17200-311	260.0246347	-31.28321065	1.72E-04	2022arXiv22080	0	355.0221244	3.347410151	BE		328.2		2MASS J1720059
124	IGR J17354-325	263.8649969	-32.93182312	4.21E-04	2022arXiv22080	0	355.4576076	-0.2730443291	SG,XT	8.45			2MASS J173527
125	IGR J17375-302	264.390595	-30.387358		2020MNRAS.49	2	357.8430121	0.7191522848	SG,XT				None
126	RX J1739.4-294	264.874958	-29.702723	0.4839	2020A&A...641A	2	358.6458156	0.7303809377	XT				Granat 1736-297
127	XTE J1743-363	265.7555147	-36.37284592	9.96E-05	2022arXiv22080	0	353.3700696	-3.420292155					2MASS J174301
128	1E 1740.7-2942	265.9785107	-29.7452874	1.004091599	2010ApJS..189..	2	359.1158834	-0.1058540833	BH,MQ	12.61			Great Annihilator
129	AX J1749.1-273	267.2787014	-27.5425132	1.012580848	2010ApJS..189..	2	1.590817881	0.06337468912	BE,XT	185.5	132		PBC J1748.6-27
130	AX J1749.2-272	267.3016669	-27.4272862	1.028137148	2010ApJS..189..	2	1.700093328	0.1052225261	XP,XT		220.38		INTREF 853
131	GRO J1750-27	267.3040333	-26.64414722		2019MNRAS.48	0	2.372650945	0.5064607228	CL,XP,XT	29.8	4.45	43	AX J1749.1-263
132	IGR J17503-263	267.575251	-26.604343	0.42312	2020A&A...641A	2	2.531355772	0.3188845219	SG,XT				None
133	IGR J17586-212	269.643971	-21.38933211	3.31E-04	2022arXiv22080	0	7.986221051	1.326593023					CXOU J175834.5-
134	IGR J18027-201	270.6747369	-20.2881668	1.37E-04	2006A&A...453..	0	9.420457672	1.036099924	BE,CL,EB,QPO,	4.57	139.6	24	IGR J18027-201
135	IGR J18048-145	271.162409	-14.94643364	3.04E-04	2022arXiv22080	0	14.30688405	3.251772793					2XMMi J180438.7
136	2MASS J180816	272.070386	-19.327656	0.155563491	2003yCat.2246..	0	10.90058878	0.3606433555	Gcas				TIC 174366572
137	Swift J1816.7-16	274.1780035	-16.2228343	1.08328755	2010ApJS..189..	2	14.58765338	0.0915019897		151.1	143.69		Swift J181642.3-
138	IGR J18179-162	274.467438	-16.358791	0.155563491	2012ApJ...757..	1	14.59988211	-0.2175532236	BE,CL,XP,XT		11.82	21	None
139	AX J1820.5-143	275.1253837	-14.5732045	1.033085161	2010ApJS..189..	2	16.47309911	0.06785749761	BE,XP	111	152.3		1FGL J1821.1-1
140	IGR J18214-131	275.3323425	-13.31089096	3.12E-04	2022arXiv22080	0	17.68123564	0.4852608671	SG	5.4246			2MASS J182119
141	IGR J18219-134	275.4783711	-13.7907374	1.041637646	2010ApJS..189..	2	17.32454669	0.1342861992	BE	72.44	52.46		Swift J1821.8-134
142	XTE J1824-141	276.1166667	-14.43833333		2010A&A...523A	2	17.04280978	-0.7161230223			120		IGR J18246-142
143	IGR J18256-103	276.433743	-10.58498	0.09999999776	2003yCat.2246..	0	20.59442988	0.8105921036					2MASS J1825440
144	XTE J1829-098	277.4332922	-9.8564536	1.035940617	2010ApJS..189..	2	21.69691951	0.278602807	BE,CL,XP,XT	246	7.85	15	1FGL J1829.6-1
145	HESS J1832-09	278.188173	-9.365154	0.08485281185	2003yCat.2246..	0	22.47683039	-0.1539191691	GP	86			XMMU J183245-0

Fig. 5 - *Extract from one of the databases I started to gather in order to cross the values given for many parameters and properties of the BeXBs.*