Fundamental properties of High-Mass X-ray Binaries

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Abstract

The aim of this thesis is to characterise a representative sample of Supergiant X-ray Binaries, an important subgroup of the general group of High Mass X-ray Binaries (HMXBs). This sample is formed by four sources with different X-ray flux behaviours: IGR J00370+6122, XTE J1855-026, AX J1841.0-0535 and AX J1845.0-0433. These objects are composed of pulsars (rotating neutron stars) accreting material from the wind of their supergiant companions. The X-rays are produced in the interaction of the accreted material with the strong gravitational field of the neutron star that accelerates this material and heats it up to $\sim 10^7$ K.

The study of HMXBs has strong implications in several areas of Physics and Astrophysics. They contain neutron stars whose study is essential to constrain the equation of state of nuclear dense matter, and provides insights on the astrophysical models of core collapse and Supernova explosions. HMXBs considered as a population give information on the properties of the galaxy. In addition they are excellent test-beds to study accretion physics and outflows.

The X-ray behaviour of these systems determines the class of system (classical SGXBs, Supergiant Fast X-ray Transients, Be/X-ray Binaries). The differences in the X-ray emission are supposed to be due to the different properties of the binary systems, such as the orbital properties, the magnetic field of the neutron star or the spectral type of the donor star. HMXBs in this thesis are SGXBs, i.e. wind-fed systems, therefore, the properties of the wind (which depend on the spectral type) and the interaction of this wind with the gravitational field of the compact object are key elements to understand the X-ray emission.

Therefore, in this thesis an orbital solution for each target of study has been determined using optical spectra of the donor star. Moreover, to check if wind
variability is related to the orbit of the binary system, analysis of Hα variations have been carried out. Furthermore, in the case of IGR J00370+6122 and XTE J1855-026 we have obtained an atmosphere model for each of the donor stars allowing us to characterise the atmospheres of these stars, and consequently to determine physical parameters such as the effective temperature or the log g. Finally publicly available X-ray light curves have been analysed to study the X-ray emission of the different sources against their orbital periods. As a general conclusion, it seems there is a continuum of properties of these systems more than a strict classification. A combination of factors, of which some of them could be unknown, might be the cause of their different X-ray flux behaviours.

The outline of this thesis is as follows: the scientific context is given in Chapter 1; an overview of the analysis performed for each of the sources of study is presented in Chapter 2; Chapter 3 is dedicated to the description of a pipeline optimised for the reduction of FRODOSpec@LT spectra of obscured red sources (donor stars of the targets of study); Chapters (4, 5 and 6) present the characterisation of the four sources in this thesis, which are different kind of wind-fed systems; and finally general conclusions and future work are given in Chapter 7.
Conclusions & Future Work

Four wind-fed High Mass X-ray Binaries have been characterised during this thesis. The main results of each of them are given in the corresponding chapters. In this Section I summarise the main global conclusions.

Related to the X-ray flux behaviour and, therefore, classification (see Fig. 1.9 of Chapter 1) IGR J00370+6122 appears to be an intermediate system between Supergiant Fast X-ray Transients and typical wind-fed Supergiant X-ray Binaries, while XTE J1855-026 is a typical Supergiant X-ray Binarie and both, AX J1841.0-0535 and AX J1845.0-0433, are clearly Supergiant Fast X-ray Transients. Therefore, this sample should be good enough to deduce if any of the parameters studied during the thesis are able to explain the different X-ray flux detected behaviours.

BD +60° 73, the optical counterpart of the X-ray source IGR J00370+612, is a BN0.7 Ib. The binary system is the most eccentric ($e = 0.56 \pm 0.07$) HMXB with a supergiant donor known to date. This source has a measurable recoil velocity ($\gamma \sim 25\, \text{km s}^{-1}$) which is perfectly compatible with its high eccentricity. Probably this system will not circularise due to its relatively high orbital period. The integrated X-ray flux of IGR J00370+612 seems to be persistent with a constant luminosity value ($L_X \sim 10^{35}\, \text{erg s}^{-1}$) below that of typical SGXBs ($L_X \sim 10^{36}\, \text{erg s}^{-1}$). The eccentricity together with the possibility of an eclipse, could explain the X-ray flux overall variability shown in the averaged X-ray foldings. However, the X-ray flux is actually composed of continuous flares with lower intensities and lower amplitudes than that of SFXTs. Therefore, the clas-
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...sification of this HMXB within the established sub-classes is not plausible due to the infeasibility to fit its properties within any of these sub-classes.

The optical counterpart of the X-ray pulsar XTE J1855-026 is a BNo.2 Ia supergiant. This HMXB is also peculiar mainly because of the large distance of this source from the Galactic plane, contrary to the majority of HMXBs which are largely confined in a disc. This distance might be explained as a combination of the large recoil velocity detected during this work ($v \sim 60$ km s$^{-1}$), with the fact that this might have been ejected from a cluster not located in the Galactic plane. Despite the almost circular orbital solution found in the X-rays, which is perfectly compatible with the expected eccentricity of a persistent SGXB, we have found a measurable eccentricity ($e \sim 0.4$) in our optical orbital solution. This eccentricity might be associated with the mass loss reflected in the H$\alpha$ and H$\epsilon$ I P-Cygni profiles. This kind of profile causes a shift in the peak of the absorption lines, and might be interpreted as an extended mass loss from the supergiant to the neutron star. In spite of these shifts in the central peaks of the spectral lines, the orbital period found in the radial velocity values, is completely compatible with that of the X-ray orbital solution. Consequently, we were expecting variations of these profiles related to the orbital phase. Since we do not find such a correlation between P-Cygni profiles and orbital phase, it either is subtle, requiring higher quality spectra to detect it, or possibly non-existent.

Since both, AX J1841.0-0535 and AX J1845.0-0433, X-ray flux behaviour is typical of SFXTs, they are perfect candidates to confirm or discard completely whether the orbital parameters of this kind of binary systems play a key role in the X-ray flux transient phenomena observed. We have found that the eccentricity is perfectly compatible with a circular orbit in the case of AX J1841.0-0535 ($e = 0.16 \pm 0.11$), while it has a significant value in the case of AX J1845.0-0433 ($e = 0.34 \pm 0.11$), confirming the idea that eccentricity by itself cannot explain the X-ray flux behaviour.

In spite of their completely different X-ray flux behaviours, IGR J00370+612 and XTE J1855-026 are early-B supergiants, with similar masses, showing a high N/C ratio in their atmospheres and high rotational values compared to those of isolated stars of the same spectral type. Both, the N/C ratio and the high rotational values, might be a consequence of the binary evolution. The spectral classification of AX J1841.0-0535 and AX J1845.0-0433 is also similar, with a
late-O supergiant and an early-B "peculiar" supergiant respectively. Basically this confirms the fact that typical optical counterparts for this kind of system are mainly either late-O or early-B supergiants independently of their X-ray flux behaviour.

The highly variable winds of these HMXBs have been examined through the main wind indicator in the optical spectral range, i.e., Hα. All of the Hα profiles of the sources of study have emission features interpreted as a mass loss from the supergiant star. Variations of this line do not seem to be correlated with the orbital phase in any of the targets of study. Consequently, these variations might be due mainly to intrinsic variations of the wind. However, their moderate mass values would correspond to lower mass loss rates than those detected. Presumably these high mass loss rates are due to the binary interaction, that is plausibly responsible for the observed over-luminosity.

All these results together reinforce the idea of the existence of a continuum of properties in this kind of systems more than a strict classification into subclasses. In addition, they confirm there is not a unique simple factor determining the differences in the X-ray flux behaviour such as a higher eccentricity or wind clumping, or even a combination of both. The plausible explanation for these differences could be a complex combination of factors plus a "gating" mechanism that mediates the accretion processes.

Since blue spectra have metallic lines which are preferable to measure radial velocities we would like to obtain such spectra to better determine the orbits of XTE J1855-026, and the two SFXTs (AX J1841.0-0535 and AX J1845.0-0433) as future work. These blue spectra would also be useful to obtain a FASTWIND atmosphere model for AX J1841.0-0535 and AX J1845.0-0433 that will help to finally establish their spectral types and physical properties such as the effective temperature, the $\log g$ or the chemical abundances.

Red high quality spectral series will also help to be able to measure the variation of the P-Cyni profiles (in case of their existence) together with the Hα line profile variations. These measurements would finally disentangle whether or not there is a correlation between the wind variations reflected in these lines and the orbital phase.
Chapter 7. Conclusions & Future Work

We would also like to increase the sample of sources including, among others, the two peculiar SFXTs IGR J17544-2619 and XTE J1739-302. While XTE J1739-302 has a possible orbital period of \( \sim 50 \) days and shows orbital emission profiles that could be explained by the presence of a disc-like structure within the stellar wind of the supergiant companion; IGR J17544-2619 has a possible pulsation period of \( \sim 71 \) seconds, that combined with the \( \sim 5 \) days orbital period, locate the source close to the typical wind-fed SGXBs in the Corbet diagram in spite of their different X-ray flux behaviour.