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Identifying Quiescent Compact Objects in Massive Galactic Single–lined Spectroscopic Binaries

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Abstract

It is now clearly established that massive stars are predominantly found in multiple systems. While their period and eccentricity distributions are now well established across different metallicity regimes, the mass-ratio distribution has been mostly limited to double-lined spectroscopic binaries. The mass-ratio distribution therefore remains subject to significant uncertainties and open questions encompass the shape and extend of the companion mass-function towards its low-mass end and the nature of undetected companions in single-lined spectroscopic binaries, i.e., low-mass main-sequence stars, binary interaction products, compact objects, etc. We have conducted a large and systematic analysis of a sample of more than 80 single-line O-type spectroscopic binaries in the Milky Way and in the Large Magellanic Cloud using a sophisticated multi-technique, and multi-wavelength approach. We report on the developed methodology, the constraints obtained on the nature of SB1 companions, the distribution of O star mass-ratios at LMC metallicity and the occurrence of quiescent OB+black hole binaries.

Keywords: spectroscopic binaries, massive binary evolution, black holes

1. Introduction

The most striking properties of massive stars ($M_{\rm ini} > 8\,M_\odot$) is that they are mainly found in binary or multiple systems (Sana et al., 2012). The presence of a nearby companion has the effect of significantly impacting the evolution of both stars. The strong binary interactions make the understanding of their evolution more complex such that many aspects are not yet completely understood. Of particular interest for the current projects is the detection and the characterisation of stellar-mass black holes (BHs) or neutron stars (NSs) orbiting around massive OB stars. As the end-of-life products of stars with $M_{\rm ini} > 20\,M_\odot$, over 100 millions of stellar-mass BHs are predicted to reside in the Galaxy (Agol and Kamionkowski, 2002; Breivik et al., 2017; Janssens et al., 2022, among others). Even more abundant should be NSs, which are the remnants of slightly less massive stars with $8\,M_\odot < M_{\rm ini} < 20\,M_\odot$.

So far, about 100 compact objects have been detected in X-ray binaries (e.g., Corral-Santana et al., 2016), accreting material from their stellar companions through Roche-lobe overflow or wind accretion. However, most of the known X-ray binaries involve a NS, and only a few are believed to harbour a stellar-mass BH. In most cases, the BH accretes material from a low-mass companion, only Cyg X-1 (Orosz et al., 2011; Miller-Jones et al., 2021), and, possibly, Cyg X-3 (e.g., Koljonen and Maccarone, 2017) are widely accepted as example of a BH accreting from a companion massive enough to end its life as yet another compact object. Such X-ray emission only arises in tight binary systems or when the secondary star starts filling its Roche lobe (e.g., Sen et al., 2022). In wider binaries or binaries with largely unevolved stellar companions, it is natural to expect a stellar-mass BH in a quiescent stage, i.e. without X-ray emission (see Langer et al., 2020).

One way to look for these OB+BH systems is to probe the population of single-lined spectroscopic binaries (SB1s), which are systems where only one component is visible, either because the companion is a low-mass star or because it is a compact companion. One must, however, be careful because some of these systems might be hidden double-lined spectroscopic binaries (SB2s), where the secondary is very diluted, or rotates very rapidly. Some could also simply be pulsating single stars, in which the line profile variability due to pulsations mimics a binary signature. This paper summarises the main results provided in Mahy et al. (2022), Sana et al. (2022), Shenar et al. (2022), and Banyard et al. (2023). We refer to those manuscripts for a complete description of the analysis.

2. Methodology

Our methodology to characterise the nature of the companions in SB1s is the following:

1. The radial velocities of the visible star were measured by applying a cross-correlation technique. Those that show a periodic variation, implying the presence of a binary companion were used to compute the orbital solution of the system, providing the period, eccentricity, longitude of the periastron, reference periastron time, and a first estimate of the semi-amplitude of the RV curve of the visible component (K_1) is obtained but does not need to be trusted, as even a small contamination of its spectral lines with that of a faint unidentified companion may bias the measurements, leading to an underestimation of K_1 (Sana et al., 2022).

2. A grid disentangling technique is then used, by fixing all the parameters with the exception of the semi-amplitudes of the visible and hidden objects. We tested both the Fourier disentangling (Hadrava, 1995) and the Shift-and-add methods (Marchenko et al., 1998; González and Levato, 2006; Mahy et al., 2010). By construction, the two-component spectral disentangling produces a spectrum for the primary visible and the secondary hidden components. If the companion is "dark", we expect a flat spectrum. For all the companions, we compare the output disentangled spectra with that of a stellar object.

3. For systems where the nature of the companion has not been characterised, we estimated the stellar parameters of the visible star. We applied the non-LTE atmosphere code CMFGEN (Hillier and Miller, 1998) to derive the effective temperature, surface gravity, stellar luminosity and projected rotational velocities. From these values, we computed the spectroscopic (obtained from the stellar radius and surface gravity) and evolutionary (obtained from the position of the star in the Hertzsprung-Russell diagram) masses of the visible component. We use these masses to deduce from the binary mass function a range of possible dynamical masses for the hidden object. We also deduce constraints on the orbital inclination of the system.

4. If no stellar companion is identified by spectral disentangling, we perform simulations to estimate the maximum mass at which the spectral signature of a non-degenerate companion would remain undetected through our disentangling analysis (Sana et al., 2022). We then compare this maximum threshold to the minimum mass of the hidden companion. When the minimum mass of the unseen companion is larger than 3–5 $M_{\odot}$, and that the spectral signature of the companion cannot be revealed by the spectral disentangling while our simulations do, we conclude that the system is likely an OB+BH binary. For our simulations we consider three different natures for the companion: 1) a main-sequence star, 2) a stripped helium star, and 3) an inner binary system (making the system a triple system). The reasons why these three cases were simulated are because 1) fast rotator main-sequence companions can have their spectral lines diluted due to their high rotation, which decreases their detectability, 2) stripped helium star companions have led to a number of false detections (e.g., Bodensteiner et al., 2020; El-Badry and Quataert, 2021; Frost et al., 2022) because of their significantly different mass-optical brightness relation compared to single main-sequence companions, and 3) an unseen component which is in fact a very short period near-equal mass binary more easily eludes detection compared to a main sequence star of the same total mass.

3. Sample

Our initial sample was constituted from a list of systems reported as SB1s by the Galactic O-Stars Spectroscopic Survey catalogues (GOSSS, Sota et al. (2011) and subsequent papers), dedicated monitorings of young open clusters and by the Southern Galactic O- and WN-type Stars (OWN) Survey (Barbá et al., 2017). We selected objects for which archival and/or new observed spectra exist to uniformly cover their orbital cycles, and to compute the orbital parameters with uncertainties close to 10% without further selection criteria. Our final sample contains 32 stars located in the Milky Way, including Cyg X-1, known to host a stellar-mass BH (Orosz et al., 2011; Miller-Jones et al., 2021), and HD 74194, a supergiant fast X-ray transient (i.e., a sub-class of high-mass X-ray binaries showing sporadic and bright X-ray flares) that hosts a NS (Gamen et al., 2015).

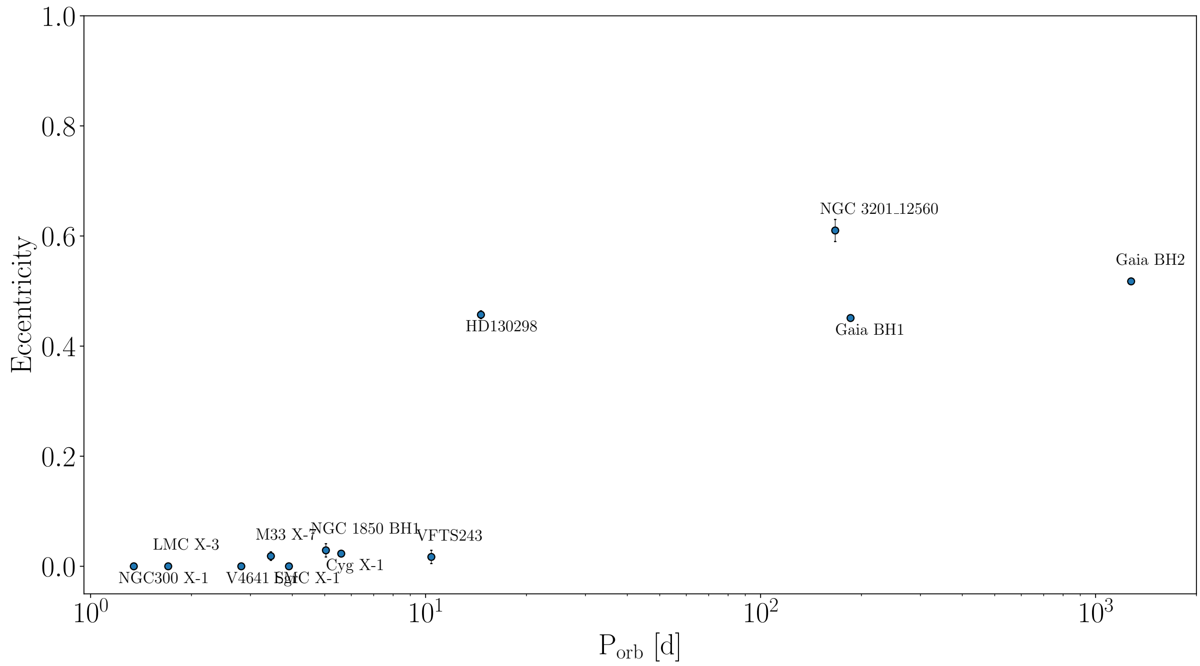

Figure 1: Period-eccentricity diagram of all the HMXBs with a stellar-mass BH.

4. Results and Conclusions

More details on the results obtained can be read in Mahy et al. (2022). The main result are summarised here. The spectral disentangling reveals the nature of the secondary star, for 17 systems out of 32. We rediscovered the OB+BH nature of Cyg X-1, which builds some confidence in the ability of our method to isolate good OB+BH candidates. In the Milky Way, we also detected another OB+BH system candidate: HD 130298. This system has an orbital period of 14.6 days, and an eccentricity of 0.46. The companion mass is larger than $7\,M_\odot$, and according to our simulation, such a companion should have been detected from the spectral disentangling. While the orbital period is in the same range as another OB+BH system recently detected in the Tarantula region (VFTS 243, Shenar et al. 2022, with an orbital period 10.4 days), its eccentricity is significantly different, as VFTS 243 has an eccentricity lower than 0.03. We show in Fig. 1 the period-eccentricity diagram of all the stellar-mass BHs detected around HMXBs or by Gaia (see http://mkenne15.github.io/BHCAT/index.html for a dormant BH catalogue and El-Badry et al. (2023a,b) for more information).

The negligible eccentricity in VFTS 243 suggests that the dying primary directly collapsed into a BH without losing much mass, and thus likely without an associated supernova (SN) explosion, while the formation scenario for HD 130298 is likely different since the system might have lost about 25% of its total mass prior to SN explosion, i.e., about $8\,M_\odot$. This suggests a significant mass loss and a possible BH formation through fallback.

Finally, we found nine systems where the mass estimates for the secondaries are in the same range as the predicted masses for NSs. However, optical data alone are not sufficient to confirm their compact nature.

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Further Information

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Conflicts of interest

The author declares no conflict of interest.

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