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Spectroscopic Discovery of Binaries with Dormant Black Holes

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The goal of the Spectroscopic Discovery of Binaries with Dormant Black Holes survey is to spectroscopically follow up stars that might have dormant compact companions, either black holes or neutron stars. These stars have been identified as ellipsoidal binaries in the Magellanic Clouds by the Optical Gravitational Lensing Experiment (OGLE). A sample of more than 700 ellipsoidals with periods shorter than 10 days will be observed to obtain multi-epoch radial-velocity measurements. 4MOST radial velocities in conjunction with OGLE photometry will allow the determination of the secondary component mass and hence the identification of systems with compact companions.

Scientific context

Stellar black holes (BH) and neutron stars (NS) are the end products of massive stars that collapse after they have consumed their energy reservoirs. In NS, gravitational contraction breaks the protons of all atoms and creates one big nucleus of 10^{57} neutrons. BH are even more exotic objects — their entire mass is collapsed into one singular point, such that nothing, including electromagnetic waves, has enough energy to escape its event horizon. Because dormant BH do not emit any electromagnetic radiation, they are very difficult to discover. Only about 20 dynamically confirmed stellar BH are known to reside in X-ray binary systems with low-mass stellar companions. These are, along with Cyg X-1 and several other high-mass binary candidates, the only confirmed stellar-mass BH in the Galaxy (see, for example, BlackCAT; Corral-Santana et al., 2016). Most of the stellar-mass BH known so far have been discovered by their X-ray emission, which is due to either mass transfer from the low-mass (mostly F–K-type) companion overflowing its Roche lobe (BH low-mass X-ray binaries, BH-LMXBs), or accretion from the stellar wind coming from the high-mass (OB star) companion (BH high-mass X-ray binaries BH-HMXBs). The known masses of stellar X-ray BH as a function of their orbital periods (Tetarenko et al., 2016) are plotted in Figure 1. As can be seen, most of the known BH binaries have relatively short periods, with a median at about 0.5 days. The X-ray emission of the BH-LMXBs is characterised by luminous ($L_x \sim 10^{37}$ erg s^{-1}) outbursts, lasting for about a month, followed by decades-long periods of quiescence ($L_x \sim 10^{31-33}$ erg s^{-1}) (see Remillard and McClintock, 2006 for a review).

According to the commonly accepted model, outbursts from BH-LMXB systems are due to accretion disc instabilities that modulate the accretion rates onto the BH. Between eruptions, these systems are barely detectable, because a substantial part of the energy generated by the small mass flow is not radiated but stored as thermal energy in the accretion discs. Thus, many BH-LMXB remain undetected, because they have been in their quiescent state since X-ray surveys began.

A much larger fraction of BH with low-mass stellar companions are not yet detected because their optical counterparts are within their Roche lobes. In these systems, mass is not transferred, and X-rays are not generated, making these systems dormant BH. For example, Breivik, Chatterjee & Larson (2017) estimated that there should be 106 Galactic BH binary systems, most of which are still waiting to be discovered. One such system, Gaia-BH1, was discovered recently using astrometry (El-Badry et al., 2023).

All of the 19 confirmed short-period BH-LMXBs show periodic optical brightness modulations on the order of a few percent on the timescale of the orbital period (for example, XTE J1118+48 and A0620-00). This is mostly due to the ellipsoidal effect, induced by tidal forces exerted by the BH on its optical companion. For a general discussion of the ellipsoidal effect see, for example, Mazeh (2008).

The goal of the survey is to discover tens of those unknown dormant BH. The new discoveries will allow us to study the characteristics of the dormant objects in detail. We will be able to understand how frequent compact objects are, as well as the range and distribution of their masses. This will lead to a much better understanding of the astrophysics behind the formation of dormant compact systems.

Specific scientific goals

We plan to use ellipsoidal modulation (Faigler & Mazeh, 2011; Faigler et al., 2012) to discover tens of new unknown dormant BH binaries. Since BH binaries are rare, we have to search for these systems in large samples, on the order of 10^6 or more stars. Astronomy is now at a unique point in its history, where enough stellar light curves with adequate precision to measure ellipsoidal modulation are available for the first time.

The key step is identifying stars with photometric periodic ellipsoidal modulations that indicate the existence of companions more massive than the optical components. If the optical star is on the main sequence (MS), then the more massive unseen companion must be a compact object. To confirm our detection of a compact companion and identify false alarm cases, we will measure the radial velocity (RV) of the candidates and find the systems displaying ellipsoidal modulations with large amplitudes. The mass of the companion will be derived from the combination of the RVs and the ellipsoidal modulation. The companion can be either a white dwarf (very rare), or a NS, with a mass at around 1.4 $M_{\odot}$ or a BH (with a larger mass). We can discover only binaries for which the orbital separation is not too large, otherwise the ellipsoidal effect will be too small to detect. From the OGLE light curves available, we were able to detect tens of binaries with an ellipsoidal modulation of 1% or larger, corresponding to binaries with separations which are larger than the radius of the visible companion by up to a factor of 10.

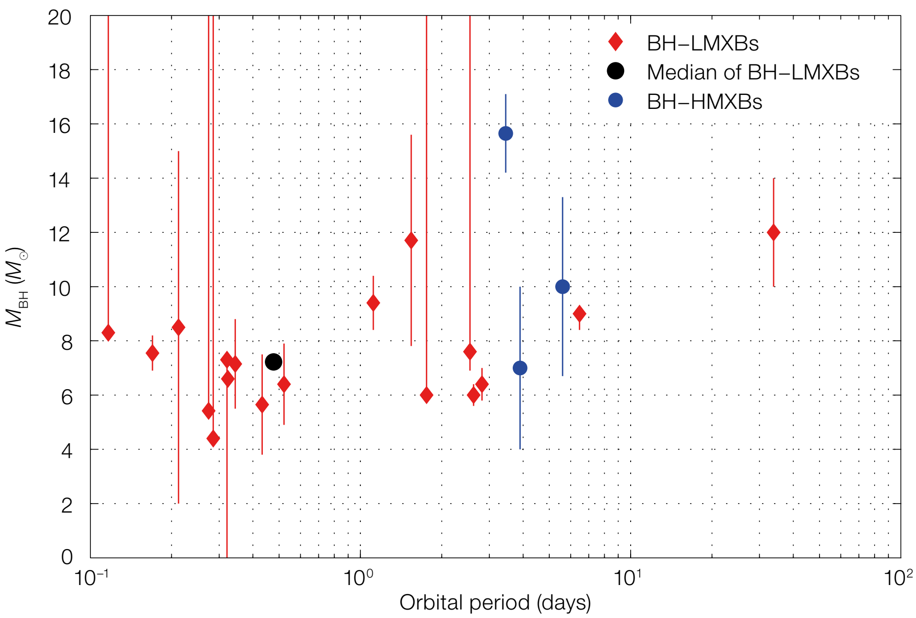

Figure 1. Known masses of stellar BH of the X-ray binaries as a function of their orbital periods. Blue circles represent BH-HMXBs and red diamonds BH-LMXBs. The black point represents the median mass and period of the known BH-LMXBs.

To measure our candidates' mass ratios, we will obtain six RV measurements per system and fit the RV points using the period and ephemeris known from the photometric data. For such short periods, we can safely assume that most of our candidates have a circular orbit. In such cases, the only two unknown parameters of the RV model are the center-of-mass velocity and the RV amplitude. We expect the RV modulation to be on the order of hundreds of km s^{-1}, so the expected accuracy of a few km s^{-1} per RV point will allow us to obtain an accurate solution for each system. This will allow us to identify the systems with a high mass ratio where the secondary component remains unseen, such as BH or NS-binaries.

As a by-product of our search, we will obtain the companion mass for all observed ellipsoidal variables, many of which have stellar companions. This will enable us to derive the mass-ratio distribution of the short-period MS binary population in the Magellanic Clouds.

Target selection and survey area

We use the OGLE-IV photometry (Udalski, Szymański & Szymański, 2015) of the LMC and SMC (80×10^6 stars) as our basis data. An extensive search for binary stars, including ellipsoidal binaries, has been carried out during both the OGLE-III and OGLE-IV projects and resulted in catalogues of 6581 binaries in the Magellanic Clouds (Pawlak et al., 2016). The sample spans the magnitude range from 13 to 18 mag. in the G band. The orbital periods for the ellipsoidal binaries with a MS primary are typically 0.2–10 days, while those with giants as primaries range from tens to hundreds of days.

Out of the entire sample of OGLE binaries, we selected more than 700 MS ellipsoidal binaries in the Magellanic Clouds with $P < 10$ days. This cutoff period allows us to separate the MS systems from the systems with giants. We decided to focus only on the MS stars as these are the only systems where we can unambiguously identify the compact companions based on the mass ratios. If we derive a mass ratio larger than one in a system with a MS primary, then there is a less luminous (likely invisible) but more massive secondary in the system, which means that the secondary is probably a compact object.

Apart from the ellipsoidal binary candidates, we will also monitor over 100 known Wolf–Rayet (WR) stars in the Large Magellanic Cloud. A non-negligible fraction (~ 3%) of O-type stars are expected to orbit black holes (Langer et al., 2020) with periods of the order of months to years. It can be shown from lifetime arguments that this fraction becomes even larger for the evolved descendants of O-type stars, the WR stars, reaching up to ~ 25% (Xu et al., in preparation). Hence, WR populations offer an attractive sample with which to uncover a population of dormant black holes. Previous low-resolution RV monitoring campaigns of the bulk of the WR populations in the Magellanic Clouds (for example, Foellmi, Moffat & Guerrero, 2003; Schnurr et al., 2008) did not attain the needed accuracy to probe the predicted period ranges of WR+BH binaries (~ 1 yr; Langer et al., 2020). In contrast, 4MOST monitoring of this population will enable us to probe binaries with periods up to a few years.

Furthermore, we plan to observe a small sample of known X-ray binaries, which will be used as science validation targets. We will also observe a number of faint X-ray sources in the field of the Magellanic Clouds to search for quiet X-ray binaries like VFTS 243 (Shenar et al., 2022).

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References

Breivik, K., Chatterjee, S. & Larson, S. L. 2017, ApJL, 850, L13
Corral-Santana, J. M. et al. 2016, A&A, 587, A61
El-Badry, K. et al. 2023, MNRAS, 518, 1057
Faigler, S. & Mazeh, T. 2011, MNRAS, 415, 3921
Faigler, S. et al. 2012, ApJ, 746, 185
Foellmi, C., Moffat, A. F. J. & Guerrero, M. A. 2003, MNRAS, 338, 1025
Langer, N. et al. 2020, A&A, 638, A39
Mazeh, T. 2008, EAS, 29, 1
Pawlak, M. et al. 2016, AcA, 66, 421
Remillard, R. A. & McClintock, J. E. 2006, ARA&A, 44, 49
Tetarenko, B. E. et al. 2016, ApJS, 222, 15
Shenar, T. et al. 2022, Nature Astronomy, 6, 1085
Schnurr, O. et al. 2008, MNRAS, 389, 806
Udalski, A., Szymański, M. K. & Szymański, G. 2015, AcA, 65, 1