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Black holes in dormant X-ray transients

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Abstract. Our calculations of stellar population synthesis indicate that the Galaxy contains at least 800 dormant X-ray transients with a black hole (BH) component. These objects do not emit X-rays, but their optical components should display ellipsoidal light variations, typical for Roche lobe filling components of close binaries. For a typical soft X-ray transient (mass of the optical component 0.5 to 2 $M_\odot$, mass of the compact component 5 to 10 $M_\odot$), the amplitudes of these variations (in V band) should be up to 0.5 magnitudes (depending on the inclination of the system). Similar variability (although with a smaller amplitude) should be displayed by so called pre-X-ray binaries (pre-XRBs) - the systems in which the optical component did not reach its Roche lobe yet, but fills it already in e.g. 80 or 90 %. One case of such pre-XRB harboring a BH was, possibly, already found by Rozyczka et al. (2010).

Key words. Stars: stellar population synthesis – Stars: binaries – Stars: X-ray binaries – Stars: X-ray transients – Stars: black holes

1. Introduction

First, we should define, what are dormant X-ray transients. These are systems that emit X-rays since time to time, but currently are not active. Probably, more than 90 % of X-ray binaries (XRBs) are dormant at any given time (and perhaps this fraction is much higher). At present, we know three major classes of X-ray transients (XRTs):

- **Hard XRTs (or Be XRBs)**

About 170 such systems are known. They contain a Be star as an optical component and, in almost all (or perhaps, even in all) cases, a young neutron star (NS) as a compact component. The name comes from relatively hard X-ray spectra (the compact components are usually seen as X-ray pulsars). These systems belong to high mass XRBs.

- **Soft XRTs (or X-Ray Novae (XRNs))**

About 65 such systems are known. Their X-ray spectra are much softer. About 85 % of them contain a black hole (BH) as a compact component. The optical components are usually low mass (0.5 to 1 $M_\odot$) stars and, so, these systems are counted into low mass XRBs, even if they harbor, sometimes, quite massive (up to $\sim 15\ M_\odot$) black holes.

- **Supergiant Fast XRTs (SFXRTs)**

About 20 such systems are known. Their X-ray spectra are relatively hard. The compact components are, again, in almost all (or perhaps, even in all) cases, young neutron stars, frequently seen as X-ray pulsars. The optical components are supergiants - hence the name.

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1.1. X-Ray Novae

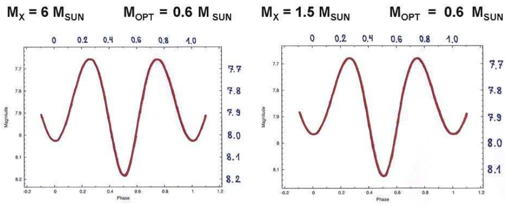

Fig. 1. The synthetic light curves showing the ellipsoidal variability (in *V* band) of dormant (no X-ray irradiation effects) X-ray binaries. The left panel shows the variability of a BH X-ray binary and the right panel the variability of a NS X-ray binary. The assumed masses of the components are given above the panels. The orbital periods were adjusted so that the optical components fill, in both cases, their Roche lobes. The pictures corresponds to the case of edge-on (i = 90°) orientation of the binary orbit. Both light curves were computed by Dymitrow (2006).

As one could notice XRNs (or SXRTs) are systems particularly favoured by BHs. In ~ 55 (out of ~ 65 known) XRNs, the compact component is a BH candidate (BHC). This compares with the total number of ~ 65 BHCs known in the XRBs. The XRNs are, usually, short period systems. Their orbital periods range from ~ 4 hours to ~ 33 days, but for great majority of the systems this range is narrower: from ~ 4 hours to ~ 2 days. The optical component is low mass (typically 0.5 to 1 $M_\odot$) dwarf or (in a few cases) subgiant, filling its Roche lobe. The accretion is supported by the Roche lobe overflow, but the mass transfer is not stationary. For more than 90 % of the time, XRNs are dormant sources. The active phases last, typically, few months, the intervals between them - few years or few decades. The typical relative length of the active phases may be much smaller than a few percent, since most of the long inactive intervals systems were not discovered yet.

The dormant systems do not emit X-rays. However, their optical components fill their Roche lobes all the time (also during the dormant phase). Therefore, they should display the ellipsoidal light variations, typical for tidally distorted stars. Synthetic light curves, calculated for typical XRN systems by Dymitrow (2006), indicate that the amplitudes of these variations (in *V* band) should be up to 0.5 magnitude (depending on the inclination of the system). The examples of such light curves, reflecting the ellipsoidal variability of a dormant (no X-ray irradiation effects) X-ray binary are shown in Fig. 1. The left panel shows the variability of a BH X-ray binary and the right panel the variability of a NS X-ray binary. The assumed masses were: 6 $M_\odot$ for a black hole, 1.5 $M_\odot$ for a neutron star and 0.6 $M_\odot$ for a lower main sequence optical component. The orbital periods were adjusted so that the optical components fill, in both cases, their Roche lobes. The pictures describe the case of edge-on (i = 90°) orientation of the binary orbit.

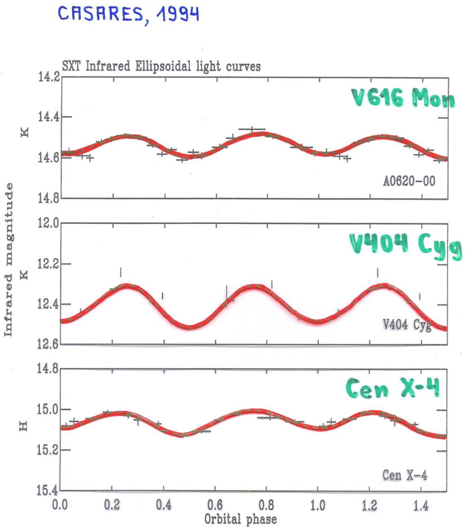

Fig. 2. The observed ellipsoidal light curves for three XRNs (after Casares, 1995). 2. Two upper panels describe the variability of BH XRNs, the lower one - the variability of a NS XRN.

The examples of the observed ellipsoidal light curves for three XRNs are shown in Fig. 2 (after Casares, 1995). Two upper panels describe the variability of BH XRNs, the lower one - the variability of a NS XRN.

The dormant XRBs are not the only objects that can be detected through their ellipsoidal variability. Also so called pre-XRBs - the systems in which the optical component did not reach its Roche lobe yet, but fills it already in, say, 80 or 90 %, could be detected in this way.

1.2. The expected number of BH XRNs

Few years ago we carried out the preliminary calculations of stellar population synthesis (SPS) in order to estimate the number of transient BH XRBs in the Galaxy. The aim of this estimate was to find what are the chances of detecting these ellipsoidal light variations in mass photometric surveys.

The calculations were carried out using the `StarTrack` code described by Belczyński, Kalogera & Bulik (2002) and Belczyński et al. (2008). We define BH X-ray binary as a system composed of a black hole and an optical star filling its Roche lobe (in all BH systems known, the optical component practically fills its Roche lobe, even if BH is accreting from the stellar wind). Such definition means that our statistics for the number of expected BH X-ray binaries include both transient and persistent systems. However, as it was pointed earlier, great majority of these systems must be transient sources.

The results of calculations of stellar population synthesis are sensitive to the values of different parameters entering the code and to the different assumptions made during the calculations. We found that, in the calculations carried out for our purposes, the most critical parameter was the assumed value of the critical mass of the final compact object $M_{\rm cr}$, below which it is a NS and above which it is a BH. Therefore, it is worth to discuss briefly the value of this parameter.

2. The upper mass limit for a NS

Until a few years ago, it was generally believed that there exists strong observational evidence (based on precise observations of radio pulsars in binary systems), indicating that all observed NSs have (for some unclear reasons) masses close to ~ 1.4 M$_\odot$ ("canonical mass" of a NS). This is no longer true. The radio pulsar PSR J0737−3039B, detected by Lyne et al. (2004) was found to be a companion of an earlier known millisecond pulsar PSR J0737−3039A. This discovery provided us with the first "true" binary pulsar (both components are pulsars). The masses of two pulsars are 1.337 ± 0.005 M$_\odot$ and 1.250 ± 0.005 M$_\odot$. The second value is the lowest, precisely determined, mass of a NS, found so far.

The situation improved also at the high end of the masses. Until quite recently, the determinations were based on X-ray pulsars in binary systems and were much less precise. The highest mass determined in this way belongs to 4U 1700-37 and is equal 2.44 ± 0.27 M$_\odot$ (Clark et al. 2002) but the NS nature of the compact object in this system is not well established. The best case, at present, for high mass NS in XRBs is Vela X-1. The most recent determination (Quaintrell et al. 2003) gives for its mass 2.27 ± 0.17 M$_\odot$ or 1.88 ± 0.13 M$_\odot$ (depending on the assumption about the inclination of the orbit and the Roche lobe filling factor). At the 95% confidence level, the lower limit is ~ 1.6 M$_\odot$.

Fortunately, recently, we found high values of masses also for some radio pulsars in binary systems (where the precision of the determinations is much higher than for binary X-ray pulsars). First, Champion et al. (2008) determined the mass of the radio pulsar PSR J1903+0327 as equal to 1.67 ± 0.01 M$_\odot$. Then, quite recently, Demorest et al. (2010) found (from the general relativistic Shapiro delay) that the mass of the radio pulsar PSR J1614-2230 is equal 1.97 ± 0.04 M$_\odot$. One should emphasize that this is a high precision determination. Therefore, at present, the precisely determined masses of the NSs are in the range 1.25 M$_\odot$ to 1.97 M$_\odot$.

That is not the end of the story. Three years ago, Freire et al. (2008) analyzed the radio pulsar NGC 6440B (in globular cluster NGC 6440). The mass estimate, as for radio pulsar, is still very imprecise (it is based on only one year of observations). However, it indicates the mass larger than 2 M$_\odot$, with probability greater than 99 %. The most likely value is 2.74 M$_\odot$!

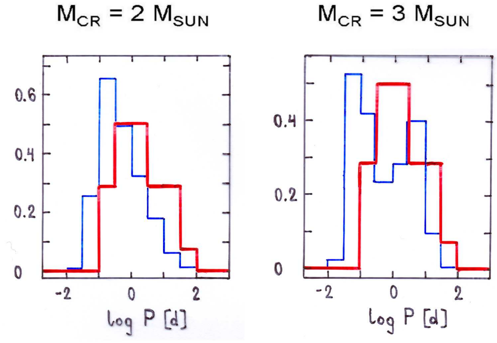

Fig. 3. Observed (red line) and expected (blue line) distributions of orbital periods of BH X-ray binaries for two values of the parameter $M_{\rm cr}$ (see the text). The observed distribution is based on catalogs of Liu et al. (2000, 2001). The expected one is the result of stellar population synthesis calculations with standard values of all parameters.

The precision of this determination will improve substantially after a few more years of observations. If the value in excess of 2.5 $M_\odot$ is confirmed, it would mean a disaster for most of the equations of state for dense matter, but it would also mean that the value of $M_{\rm cr}$ is substantially higher than we used to believe. It is a tantalizing situation and the outcome will be really very interesting.

To summarize, at present, the precisely determined masses of the NSs are in the range 1.25 $M_\odot$ to 1.97 $M_\odot$. Therefore, the undisputed statement about the value of $M_{\rm cr}$, is, at this moment, only to say that it must be larger than 2 $M_\odot$. However, it might be even larger than 2.7 $M_\odot$, and we might know the answer quite soon.

3. Calculations

From the discussion in the previous section, it is obvious that the value of $M_{\rm cr}$ must lie in the range between 2 $M_\odot$ and 3 $M_\odot$. However, it is not clear whether it is closer to the lower or to the upper limit. Therefore, we carried out all calculations for two values of $M_{\rm cr}$: 2 $M_\odot$ and 3 $M_\odot$. For each of these two values of $M_{\rm cr}$ mentioned above, we performed calculations, assuming relatively wide ranges for other parameters entering the numerical code. The resulting distributions of orbital periods of BH X-ray binaries were compared with the observed distribution to select the plausible values of these parameters.

4. Preliminary results

Fig. 3 shows the results of the calculations made with the standard values of the parameters and standard assumptions used in the `StarTrack` code. The red line shows the observed distribution of orbital periods of BH X-ray binaries based on catalogs of Liu et al. (2000, 2001).

One may notice that the value $M_{\rm cr} = 2\ M_\odot$ produces better fit to the observations than the value $M_{\rm cr} = 3\ M_\odot$.

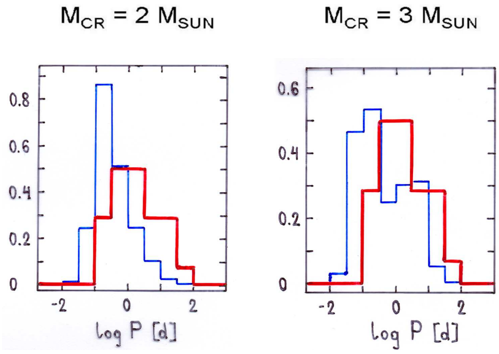

Fig. 4. The same as Fig.3 but for the value of the parameter describing the efficiency of the common envelope reduced by a factor of 10 (see the text).

Fig. 4 shows the results obtained when one changes the assumption concerning the efficiency of the process of the shedding of the envelope during the common envelope phase of the stellar evolution. One of the parameters used in the code describes how efficiently the gravitational energy released due to shrinking of the binary orbit (the orbit shrinks because both components experience drag force while moving in the common envelope) is used to unbind the common envelope.

Here the value of this parameter was decreased by a factor of 10 with respect to the standard value.

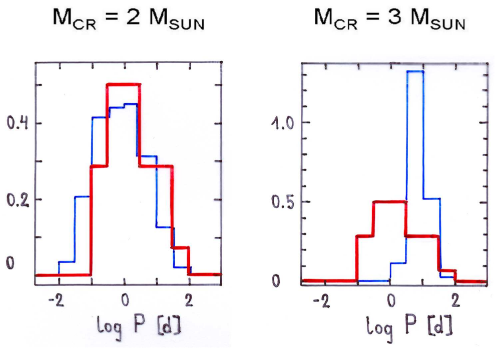

Fig. 5. The same as Fig.3 but for the assumption of no kick during the collapse event producing a black hole (see the text).

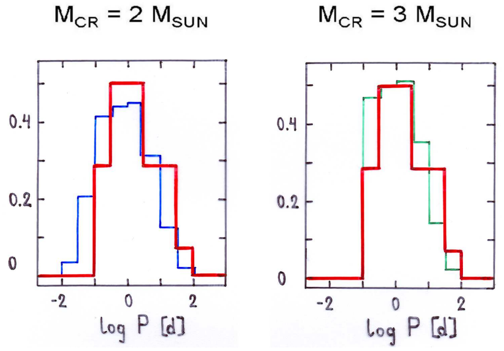

Fig. 6. The same as Fig.3 but for one value of $M_{\rm cr}$ parameter ($M_{\rm cr}$ = 2 $M_\odot$). The left panel is the same as in Fig. 3 (no kick case). The right panel is the same as the left panel, but with the black hole + white dwarf binaries arbitrarily removed from the expected population (the green line - see the text).

As one may see, the fit is now worse than in Fig. 3 (the fit for $M_{\rm cr}$ = 2 $M_\odot$ still being much better than the fit for $M_{\rm cr}$ = 3 $M_\odot$).

Fig. 5 shows the distribution expected if one assumes that black holes are produced with no kick during the collapse event. The standard approach assumes that the distribution of the kicks is the same as for the events producing neutron stars (this distribution is inferred from the space velocities of radio pulsars). There are, however, some observational arguments that many black holes may be produced with no substantial kicks (either through a dark collapse or with only small mass ejection, as demonstrated by Mirabel and Rodrigues (2003)).

This case produces the best fit so far for $M_{\rm cr}$ = 2 $M_\odot$ (for $M_{\rm cr}$ = 3 $M_\odot$ the fit is very poor).

Fig. 6 shows the same case as Fig. 5 (for $M_{\rm cr}$ = 2 $M_\odot$), but with the final systems composed of black hole and white dwarf being removed from the expected population. This removal is quite arbitrary. It is true that we do not observe such systems, but they are produced in the stellar population synthesis calculations and we do not understand what is the reason for this discrepancy.

As may be seen, the removal of black hole + white dwarf binaries improves the fit (the green line in Fig. 6).

5. Population of BH X-ray binaries

The expected numbers of galactic BH X-ray binaries depends mainly on the value of the parameter $M_{\rm cr}$. If this value is 2 $M_\odot$, then, according to our calculations, Galaxy contains some 15 000 to 40 000 of BH X-ray binaries (and some 30 000 to 250 000 of NS X-ray binaries). If this value is 3 $M_\odot$, then our Galaxy contains 800 to 6 000 of BH X-ray binaries (and some 70 000 to 250 000 of NS X-ray binaries). As we have seen (Section 3), the 2 $M_\odot$ value produces, systematically, better fits of the expected orbital period distributions to the observed one. However, this is not strong enough argument to disregard the rising recently evidence indicating that the value of $M_{\rm cr}$ may be substantially greater than 2 $M_\odot$, and, possibly, it might be even greater than 2.7 $M_\odot$. Therefore, the cautious summary of our preliminary SPS calculations would be to say that the number of BH X-ray binaries in the Galaxy is, probably, not smaller than ~ 800.

6. Photometric search for BHs in dormant X-ray transients

As discussed in the previous section, the Galaxy should contain, at least, 800 BH XRNs that, at present, are mostly dormant. These systems do not emit X-rays, but they could be

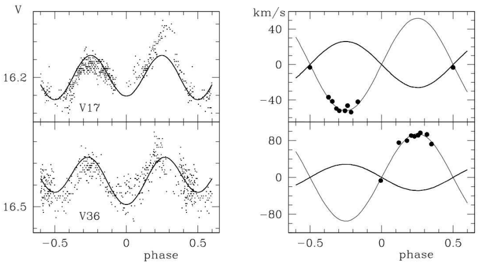

Fig. 7. Light and velocity curves of two systems at the main sequence turnoff in NGC 6397. Small ticks in light-curve plots are separated by 0.01 mag (after Rozyczka et al., 2010).

detected through ellipsoidal light variations of their optical components. As one can see from Fig. 1, the amplitude of the variability is so large ($\gtrsim$ 0.5 magnitudes) that, assuming random distribution of the orbital inclinations, the great majority of the systems should have amplitudes large enough to be detectable (even for $i = 10^{o}$, the amplitude should be still $\sim$ 0.1 magnitudes). Therefore, such systems should be easily detectable in mass photometric surveys.

We intended to start our search for such objects using catalogs of ASAS (All Sky Automated Survey) - a photometric survey carried out in the Astronomical Observatory of Warsaw University (Pojmański, 1997). The limiting *V* magnitude for ASAS survey is about 13, which for a typical system (mass of the optical component $\sim$ 1 $M_{\odot}$) translates into the limiting distance of about 0.5 kpc. Unfortunately, this distance translates our lower limit of $\sim$ 800 BH XRNs into only about 1 detectable BH transient. This is, certainly, not a very encouraging prospect. However, one should remember that this is only a conservative lower limit and that the calculations were done several years ago with a simple version of the `StarTrack` code. We are carrying now new calculations using the improved version of the code. The results should be available soon.

7. Successful photometric search for a BH in a pre-XRB?

At the end, I would like to notice that, perhaps, a successful photometric search for a BH in a pre-XRB took already a place. Namely, Rozyczka et al. (2010) investigated 11 objects in globular clusters ω Centauri and NGC 6397. These objects were selected photometrically, on the bases of their ellipsoidal type variability. The objects were, subsequently, observed spectroscopically in search for the radial velocities. As a result of these observations, ten of them were found to be binaries. Further analysis indicated that two of these binaries (both in NGC 6397) probably contain a degenerate component. The system named V17 contains probably a NS (mass of the compact component is in the range $1.1 \div 1.5$ $M_{\odot}$). The system named V36 might contain either a NS or a BH (mass of the compact component is in the range $2 \div 4$ $M_{\odot}$). The analysis indicates, that while V17 is probably a dormant XRB, the V36 is rather a pre-XRB (the optical component is smaller than its Roche lobe).

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