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New results on the study of transient X-rays binaries

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Abstract

X-ray transients (XTs) provide some of the strongest evidence for the existence of stellar mass black holes (BHs). In these systems, X-ray outbursts occur over timescales of weeks to months and are followed by years of quiescence when the optical light from the system is dominated by the companion star. Successful programs for determining the orbit of the companion star, and thus the orbital parameters of the binary – including the mass of the compact object – have been carried out for the last three decades. These mass measurements have been used to explore the distribution of the stellar BH masses, which has important implications for the population and evolution of massive stars, the energetics and dynamics of supernova explosions, and the critical mass dividing neutron stars and black holes. However, both the small number of BH candidates and the systematic uncertainties in the determination of their masses, prevent us from extracting completely compelling statistical conclusions. In this paper we review the recent attempts to improve our understanding of the mass spectrum of collapsed stars, i.e., to measure their masses more accurately and to enlarge the sample of known quiescent black holes.

1 Introduction

More than 50% of the stars in our galaxy are known to be in multiple systems. The analysis of binary systems has profound impact in several areas of Astrophysics. For instance, from simple Newtonian physics, one can obtain accurate stellar masses. Some systems, known as X-ray Binaries (XRBs), are formed by a compact object (neutron stars or black hole) accreting material from an apparently normal companion and they provide an ideal playground for exploring the physics of compact object yielding the confirmation of the existence of stellar mass black holes via dynamical mass estimates. On the other hand, although accretion discs are found in many different astrophysical environments (i.e. cataclysmic variables, AGNs with super massive black holes and young stellar objects), the favourable geometry of an accretion disc within a binary star combined with the short orbital periods makes these systems the prime targets for observational studies of the accretion disc structure.

The determination of the black hole mass in a binary requires the knowledge of the binary inclination angle and the mass ratio. The three essential observational constraints needed are: *(1)* The radial velocity study of the secondary star using optical spectroscopy yields the binary period (if this is not already known) and the companion's projected radial velocity semi-amplitude. Based on these quantities alone, an absolute minimum mass for the compact object can be calculated: the mass function or $f(M)$; *(2)* The rotational broadening of the secondary star's absorption lines is used to derive the mass ratio, $q = M_2/M_1$, where M_1 and M_2 are the masses of the compact object and the secondary star respectively; and *(3)* Finally, in the absence of eclipses, the binary inclination i can only be obtained from the ellipsoidal modulation of the gravitationally distorted secondary star due to its varying projected area as viewed around the orbit The amplitude of the light curve depends strongly on the binary inclination so this parameter can be determined using photometric observations coupled with models of the ellipsoidal modulation (see [1] for a review).

According the properties of the companion, XRBs can be classified as High mass X-ray Binaries (HMXBs), where the donor is a massive ($M > 10\,M_\odot$) star and accretion occurs via stellar winds; and Low mass X-ray Binaries (LMXBs), where the donor is a low mass star ($M < 1\,M_\odot$) and accretion occurs via Roche Lobe overflow. One of the main aims of optical observations of these systems has always been to find a signature of the donor star, and thereby constrain the masses of both components. This is most straightforward for the intrinsically luminous early-type companions of HMXBs, which provides the potential for a full solution of the binary parameters for those systems containing X-ray pulsars. However, when HMXBs are suspected of harbouring black holes, the mass measurement process runs into difficulties. First, the optical star is likely to be under massive for its spectral type; second, wind emission can contaminate the radial velocities of the donor star; and third, the donor does not fill its Roche lobe so mass ratios and inclinations derived from ellipsoidal models may be overestimated. LMXBs, on the other hand, do not offer better prospectives since their optical emission is dominated by the reprocessing of the X-rays in the outer accretion disc so the companion star is completely undetectable. There is, however, a few exceptional systems, the so called X-ray Transients (XTs), in which such a substantial X-ray activity occurs only during well-defined outburst. Between outbursts, the emission from the accretion flow fades to the point that the companion star is clearly visible and is nearly undisturbed by irradiation; hence it can be used to derive a dynamical mass for the compact object (e.g. [2]).

2 The case of XTE J1859+226

The X-ray transient XTE J1859+226 exemplifies the importance of X-ray Transients for several areas of the astrophysics. Discovered during its 1999 outburst [3], its X-ray properties promptly classified it as a black hole candidate. Observations during outburst (when large amounts of mass are suddenly accreted) and during the subsequent decay gave clues about the

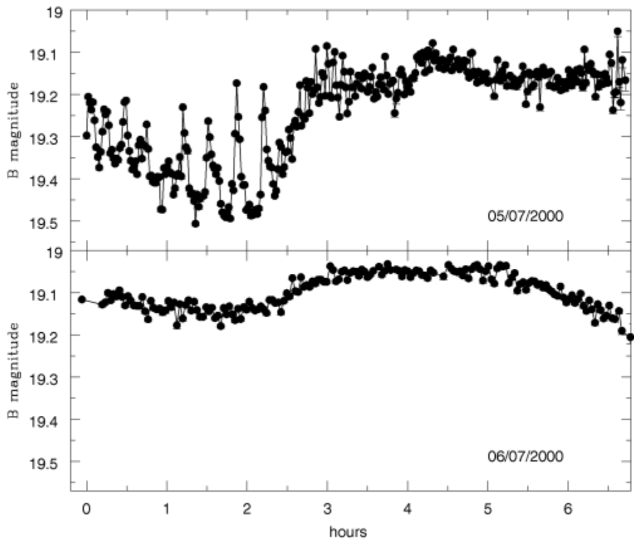

Figure 1: B-band light during the decay phase of J1859+226 on two different nights. From [4].

accretion disc structure. The change in the disc size after outburst could be calculated. Furthermore, the detection of rapid oscillations indicated inhomogeneities in the inner accretion disc (see Fig. 1). Different periodicities were proposed but none of then could be confirmed. By 2000 the system had reached quiescence with R= 22.48±0.07. The subsequent photometry exhibited a ∼0.2 mag semi-amplitude sinusoidal modulation consistent with a secondary star's ellipsoidal variation and periods in the range 6.6 − 11.2 h [4].

It took ten years until spectroscopic data of the source in quiescence could be obtained. Observations with the 10.4-m GTC revealed radial velocity variations of ∼500 $\mathrm{km\,s^{-1}}$ over 3 h. A simultaneous fit to the photometry and spectroscopy using sinusoids to represent the secondary star's ellipsoidal and radial velocity variations, yielded an orbital period of 6.58±0.05 h and a secondary star's radial velocity semi-amplitude of K2= 541±70 $\mathrm{km\,s^{-1}}$, implying a mass function of $f(M) = 4.5{\pm}0.6\,\mathrm{M_\odot}$, consistent with the presence of a black hole in XTE J1859+226 (see Fig. 2). The lack of eclipses sets an upper limit to the inclination of 70° which yields a lower limit to the black hole mass of $5.42\,\mathrm{M_\odot}$ [5]. This result is remarkable since the sample of black hole masses determinations is still very small.

3 The observational mass distribution of stellar black holes

The distribution of stellar mass black hole masses can only be determined from the study of X-ray binaries [2, 1] and it is intricately related to the population and evolution of massive stars, the energetics and dynamics of supernova explosions, and the critical mass dividing neutron stars and black holes. Although the sample of black holes is still very small and there

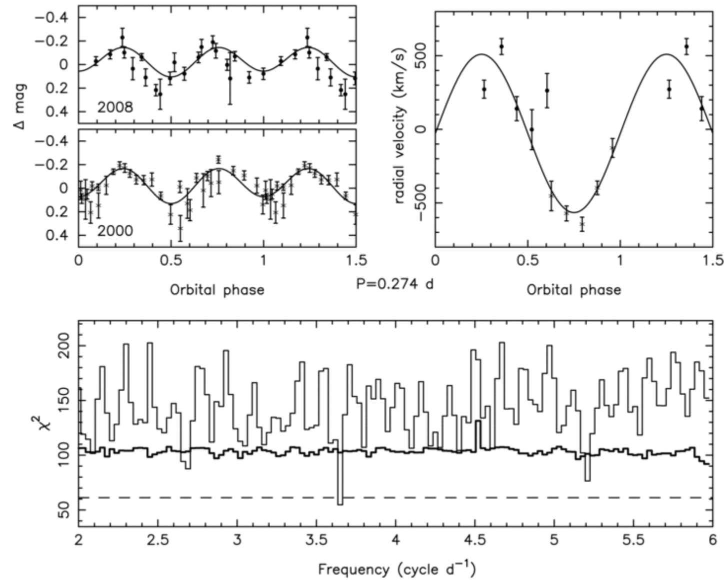

Figure 2: Top left and right: the optical photometric light curves and radial velocity curve of XTE J1859+226 phase folded on the best-fitting period, respectively. 1.5 orbital cycles are shown for clarity. Bottom: the χ^2 periodogram of the simultaneous fit to the photometry and spectroscopy. The dashed line shows the 99 per cent confidence level above the minimum χ^2 at a frequency of 3.65 cycles d^{-1} (=0.274 d). From [5].

remain large systematic uncertainties in the determination of their masses, several attempts to extract statistical conclusions have been made. The first study, in [6], examined a sample of only seven low-mass X-ray binaries thought to contain a black hole, and concluded that the mass function was strongly peaked around seven solar masses. They found evidence of a gap between the least massive black hole and the *safe* upper limit for neutron star masses of $3\,M_\odot$. More recently, [7] examined 16 low-mass binary systems containing black holes and found a strongly peaked distribution at $7.8\pm1.2\,M_\odot$ and a paucity of black holes with masses $\simeq$2–5 $M_\odot$. According to these authors, the low-mass gap cannot be accounted for by observational selection effects (it should be noted that the observing strategy has resulted in a flux limited sample and the mass measurement method requires a particular choice of targets). This result has been confirmed by the study of the largest sample to date. The analysis of 20 systems leads strong evidence for a mass gap between the most massive neutron stars and the least massive black holes, where the most favored model gives a black hole mass distribution whose 1% quartile lies above $4.5\,M_\odot$ with 90% confidence [8]. However, the mass gap identified in the previous works may be not real but the result of the systematic uncertainties in the determination of the BH masses [9].

Interestingly, theoretical distribution functions of black hole masses do not show evidence for a gap at low values, between 3 and 4–4.5 $M_\odot$ (e.g. [10]). A possible cause of such a gap is a step-like dependence of supernova energy on progenitor mass. Unfortunately, in addition to the scarce sample of black holes there are still large systematic uncertainties in the determination of their masses. The binary inclination is, by far, the most difficult parameter to determine because it depends on the relative contribution of other sources of light to the system. Note also that the mass of the compact object depends on $sin^3\, i$. There are only one system with mass of the compact object in the range 3–5 $M_\odot$: the XT GRO J0422+32 [11]. However, this low mass result has been questioned by [12] who estimated a lower limit to the compact object mass of $\sim$10 $M_\odot$. For some systems like GRO J0422+32 or GS 1354-64 [13] strong variability completely prevents determination of the inclination from the light curve; in these cases an upper limit on the inclination is often obtained from the lack of eclipses in the light curve. In summary, it becomes necessary to improve the determination of masses and increase the sample of black hole candidates.

4 Improving the determination of black hole masses

To obtain reliable inclination constraints is important to know and quantify the relatively strong and variable component of non-stellar light during quiescence. Several sources contribute to the ratio of nonstellar light to the total flux, some of which vary on short timescales compared to the orbital period. These sources can distort the shape of the photometric light curve in the following ways:

4.1 The fast flare-like variability

It is well known that the brightest, well studied XT, V404 Cyg, shows 0.1-0.2 mag flares superposed on the secondary star's double-humped ellipsoidal modulation (e.g. [14, 15]). This variability is indeed a common feature in quiescent XTs which had escaped previous detection (see Fig. 3). Both its timming properties and energetics pointed toward an origin associated to the accretion disc rather than the gas stream or chromospheric activity in the companion star [16]. The triggering mechanism of the flares is however less clear. In at least one case, that of V404 Cyg, optical line and continuum variability are well correlated [17, 18] and also are correlated with X-rays [19] and infrared flares [15]. Possible scenarios include magnetic reconnection events [16], X-rays reprocessing [19], and direct synchrotron emission from an advective dominated flow [20]. To determine the fraction of non-stellar light, one subtracts a template stellar spectrum from the observed spectrum, which reveals the continuum excess due to the nonstellar light (e.g., [21]). It is not necessarily the case, however, that such a measurement is valid for photometric observations taken at a different date from the spectroscopy. A high temporal resolution curve can allow us to disentangle and remove the non-stellar features by fitting the lower envelope instead the mean (blurred) light curve. However, because the curve shape changes over time, different observing runs will yield different inclination measurements, even if the same model is used to fit the light curve. Surprisingly, although infrared contamination had previously been thought to be minimal for quiescent XTs, infrared flickering has been also detected in the prototypical XT, A0620-00 [22] , in the short period system J0422+32 [12] and in the brightest of the class, V404 Cyg [15].

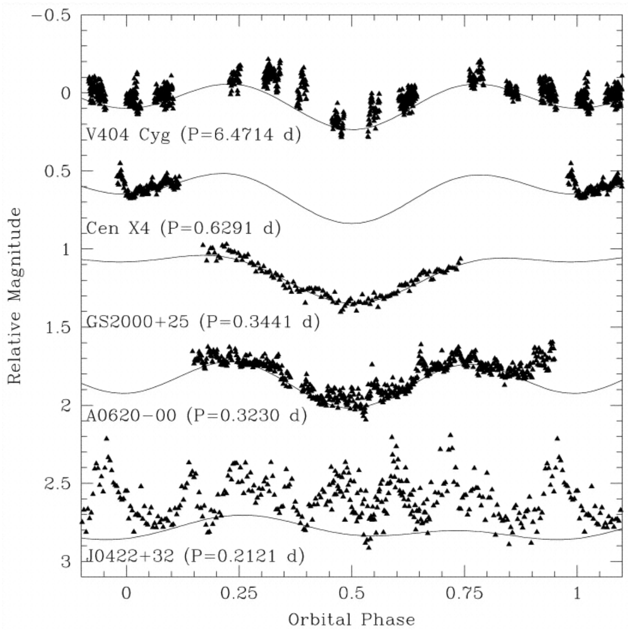

Figure 3: Light curves for five quiescent XTs: V404 Cyg, GS 2000+25, J0422+32, and A0620-00 showing fast optical variations superposed on the secondary star's double-humped ellipsoidal modulation. From [16].

4.2 Permanet superhumps in XTs

Superhumps are periodic variations in the luminosity of an accreting binary systems. With a period slightly longer than the orbital period, it was first discovered in the SU UMa class of dwarf novae. The most probable explanation for superhumps is that they are due to the effect of tidal stresses on a precessing, elliptical accretion disc. The changing shape and amplitude of the light curves can be explained by changes in the shape or size of the disc and resonance between the Keplerian orbits and the orbital motion of the companion. Since superhumps only occur in extreme mass-ratio systems, which can form elliptical accretion discs [23], they are also expected in XTs. In fact, superhumps have been observed in XTs in outburst [24] but also near quiescence although they are not expected after the outburst. This is the case of XTE J1118+480 ([25, 26]; see Fig. 4). Other key systems for the search of superhumps are the prototypical galactic black hole candidate, A0620-00, and the brightest of the class, V404 Cyg. Both systems have been extensively monitored since the onset of quiescence. All these studies have shown that the quiescent light curves are distorted from a purely ellipsoidal modulation and also vary on short timescales (days).

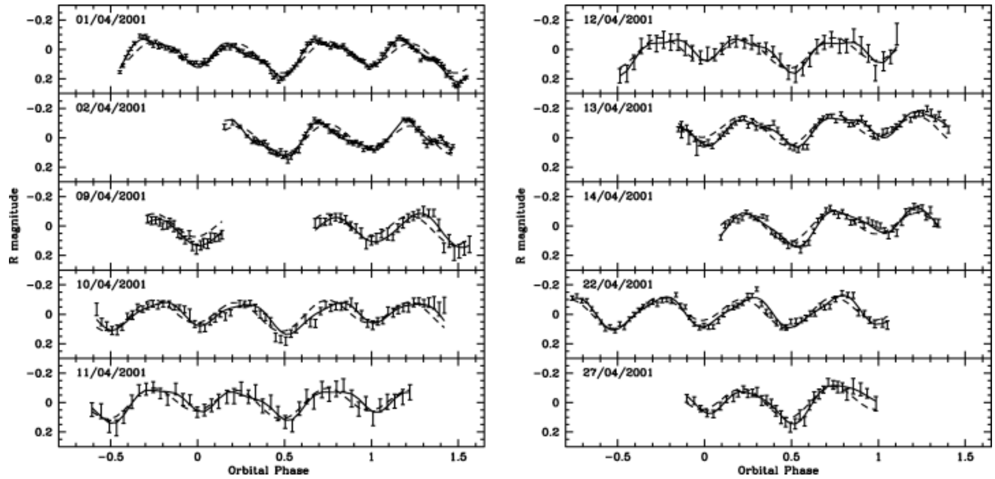

Figure 4: Sample of orbital light curves taken in 2002 for the X-ray Transient XTE J1118+480 near the quiescent state. Dashed line: ellipsoidal model. Continuous line: ellipsoidal model plus superhump wave. From [25]. A similar bahaviour was found when this system approachs quiescence after the 2005 outbursts [26].

5 Increasing the sample of black hole candidates

5.1 The Bowen fluorescence technique

It is usually not possible to find any signature of the donor star in persistent LMXBs because their optical emission is completely dominated by the accretion disc. For this reason, although a large number of persistent LMXBs have been known for many years, no strong constraints on their system parameters existed until recently. Fortunately, new prospects were opened by the discovery of sharp high excitation emission lines arising from the irradiated face of the companion star. The most prominent are found in the core of the Bowen feature, mainly NIII and CIII lines between 4630 and 4660Å, the former powered by fluorescence. These lines trace the motion of the companion star and provide the first constraints on their system parameters (see e.g. [27]).

The observation of GX339-4 is a good demonstration of the power of the Bowen fluorescence technique. Although it was one of the earliest proposed black hole candidates, its bright accretion disc still dominates the optical flux when the system is in quiescence. This has prevented a direct measurement of the system parameters and even its orbital period was uncertain. After applying the Bowen technique to GX339-4 a mass function of $5.8\,M_\odot$ was found, finally confirming the black hole nature of its compact object [28].

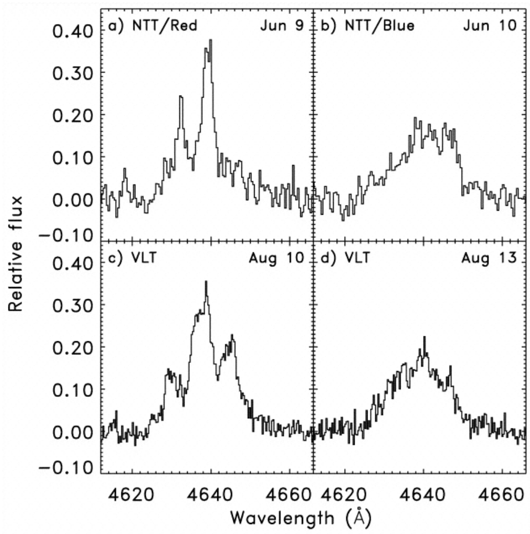

Figure 5: Examples of Bowen blend profiles from four different observations of GX 339-4. The left-hand two panels show profiles with sharp components; the right-hand panels lack them. The narrow components move at high radial velocity as due to the orbital motion of the companion star. From [28].

5.2 The search for new quiescent black holes in the IPHAS survey

About $\sim 10^9$ stellar–mass black holes are believed to exist in the Galaxy [29] and about $\sim 10^3$ are expected to be members of Transients Binaries [30, 31]. XTs are the best place to look for black holes, however, these systems are detected in outburst by X-ray all-sky monitors at a rate of one or two per year and, for the moment, we only know $\sim$20 black holes with dynamically measured masses. Hence, it appear necessary to search for the dormant population of X-ray Transients. Surveys like *IPHAS* (The INT Photometric Hα Survey of the Northern Galactic Plane) are useful tools for this purpose.

IPHAS maps the Northern Galactic Plane using the Wide Field Camera mounted on the Isaac Newton Telescope installed at the Observatorio del Roque de los Muchachos on La Palma. To unveil new members of the dormant population of quiescent XTs through its Hα excess, (r'-i') vs (r'-Hα) diagrams are being constructed (see [32]). To test the power of this technique we have tried to recover the quiescent counterpart of XTs already known. This was the case of KY TrA, a historical X-ray transient discovered on 1974. KY TrA was observed in quiescence with upper limit on the quiescent X-ray luminosity of $\sim$2–10$\times 10^{33}$erg s^{-1}. The ultrasoft X-ray spectrum seen by Ariel V and the hard tail observed by SIGMA [33] suggested that KY TrA is a black hole candidate. The optical counterpart was identified 12 days after the X-ray maximum at B=17.5 [34] but, surprisingly, nothing has been done since. We obtained optical photometry with FORS2+VLT in R, I and Hα [35] to build the (R-I)-(R-Hα) diagram (see Fig. 6) where the target into the circle shows a clear Hα excess above the main stellar locus, confirming this is the true quiescent counterpart of KY TrA.

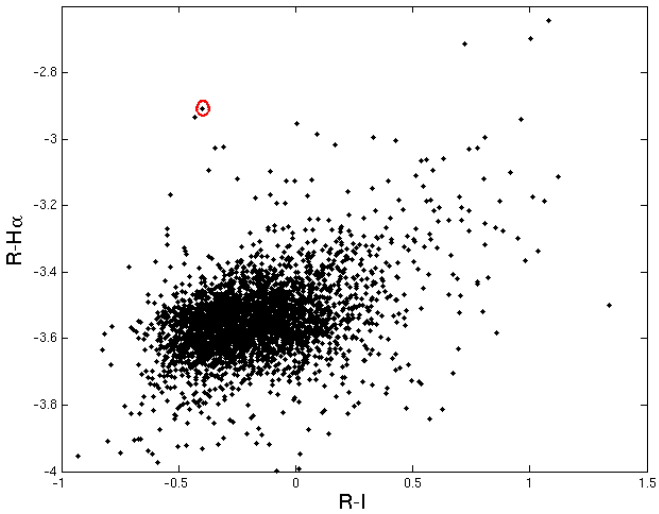

Figure 6: KY TrA uncalibrated (R-I)-(R-Hα) diagram. The object marked, with clear Hα excess, is the KY TrA counterpart proposed by [34].

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