THE MASS SPECTRUM OF X-RAY BINARIES

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Abstract

This review summarizes the observational constraints on the mass spectrum of compact objects in X-ray binaries. We currently have 20 X-ray binaries with confirmed black holes, based on dynamical information (i.e. mass in excess of 3 M\(_{\odot}\)). In two cases, V404 Cyg and GRS 1915+105, the black hole mass exceeds the maximum predicted by current Type Ib supernovae models and challenges black hole formation scenarios. The great majority of black hole binaries are members of the class of X-ray Transients, where long periods of quiescence enable spectroscopic studies of the faint donor stars. On the other hand, neutron star binaries are mostly found in persistent binaries, where reprocessed light from the accretion disc overwhelms the companion star and precludes mass estimates. New results, based on the detection of optical fluorescent lines from the donor star and X-ray burst oscillations, provide the best prospects for mass constraints of neutron stars in persistent X-ray binaries.

Keywords: binaries: close - X-rays: binaries,- stars: neutron, black holes

Introduction

Building the mass distribution of compact objects is a fundamental experiment in modern Astrophysics which can only be done in X-ray binaries. The interest of this research is two-fold: set constraints on the equation of state of nuclear matter (hereafter EOS) and test models of supernovae explosions and close binary evolution. X-ray binaries are interacting binaries where a normal star transfers matter onto a compact object, a black hole (BH) or neutron star (NS). Matter is accelerated in the strong gravitational field of the compact star and heated up to \(~ 10^7\) K before being accreted. This is the canonical model, first proposed by Shklovskii (1967) to explain the new X-ray sources detected in the 60’s and 70’s by X-ray satellites such as UHURU or Einstein. In the 80’s and 90’s, a new generation of higher sensitivity satellites, such as Ginga, Rosat and XTE, revealed a population of several hundred X-ray binaries in the Galaxy with X-ray luminosities in the range \(10^{36} \text{ to } 10^{39}\) ergs s\(^{-1}\) and displaying rapid variability, down to the kilohertz regime. And nowadays, the
large collecting area and high angular resolution of satellites such as Chandra and XMM-Newton allow us to resolve the X-ray binary population in nearby galaxies, obtaining the X-ray luminosity function and proving that they are responsible for typically a third of the galaxy’s total X-ray emission.

X-ray binaries are classically divided into two populations, based on the nature of the optical (companion) stars: high mass X-ray binaries (HMXBs) and low mass X-ray binaries (LMXBs). In HMXBs the companion is a hot luminous O-B supergiant whose bolometric luminosity completely dominates the energy spectrum. These binaries are relatively young (short lived) with estimated ages in the range $10^7 - 10^8 \text{ yrs}$. There are about $\sim 100$ such binaries in the Galaxy, strongly concentrated towards the spiral arms and, hence, they are considered as good tracers of the star formation rate (Grimm, Gilfanov & Sunyaev 2002). Neutron stars in HMXBs are recognized by the presence of regular X-ray pulsations as a consequence of their strong magnetic fields.

On the other hand, LMXBs contain low-mass companion stars of spectral types (mainly) K-M. These binaries are very compact, with orbital periods clustering around 4-8 hours and concentrated in location towards the galactic bulge. They are associated with the old stellar population and show a large spread in galactic latitude, interpreted as a signature of kick velocities received when the supernova explosion formed the compact star. Neutron stars in LMXBs are also revealed by the exhibition of sporadic X-ray bursts i.e. thermonuclear eruptions of matter slowly accreted over the surface. There are $\sim 200$ X-ray active or "persistent" sources in the Galaxy, and about $10^3$ "transients", which only show X-ray activity occasionally. The reason for this transient behaviour is the mass transfer rate from the donor star $\dot{M}_2$, which is driven by the binary/donor evolution. In X-ray transients, $\dot{M}_2$ is lower than a critical value $\sim 10^{-9} \text{ M}_\odot \text{yr}^{-1}$ and this triggers thermal-viscous instabilities in the accretion disc. This causes enhanced mass transfer episodes onto the compact object, the so-called "outbursts", with recurrence times of a few decades (King 1999). In the interim, these systems remain in the "quiescent" state, with typical X-ray luminosities below $\sim 10^{32} \text{ ergs s}^{-1}$. It is during these periods when we can attempt to detect the faint low-mass star and extract dynamical information. The many studies performed on quiescent X-ray transients have demonstrated that BHs outnumber NS by more than 70%, and hence the transients provide excellent hunting grounds for BHs. More details about the optical and X-ray properties of galactic X-ray binaries can be found in Charles & Coe (2004), McClintock & Remillard (2004) and Psaltis (2004).

1. Establishing Black Holes

As opposed to NS, which often show X-ray bursts or pulses, the best observational evidence for a BH is still its mass function $f(M_\text{x})$. This equation
relates the masses of the compact object $M_x$, the companion star $M_c$ (or alternatively the binary mass ratio $q = M_c/M_x$) and the binary inclination angle $i$ with two quantities to be extracted directly from the radial velocity curve of the companion star: the orbital period $P_{\text{orb}}$ and the radial velocity semi-amplitude $K$:

$$f(M) = \frac{K^3 P_{\text{orb}}}{2\pi G} = \frac{M_x^3 \sin^3 i}{(M_x + M_c)^2} = \frac{M_x \sin^3 i}{(1 + q)^2}$$ (1)

Since $M_c > 0$ and $0 < i < 90^\circ$ it is straightforward to show that $f(M)$ is a lower limit on $M_x$. Therefore, a mass function larger than $3 M_\odot$, i.e. the maximum gravitational mass of a NS (Rhoades & Ruffini 1974), is taken as a secure proof for the existence of a BH, independently of the actual values of $i$ and $q$.

Table 1 presents an updated list of confirmed BHs based on this simple dynamical argument. We currently have 20 BHs, with orbital periods ranging from 4.1 hours to 33.5 days. There are 17 transient LMXBs and only 3 persistent systems, the HMXBs Cyg X-1 and two sources from the Large Magellanic Clouds: LMC X-1 and LMC X-3. Note that, in addition to the three HMXBs, six transient LMXBs have mass functions < $3 M_\odot$. However, we have solid constraints on the inclination and the companion’s mass for these binaries which result in $M_x > 3 M_\odot$. The last one added to the list, BW Cir, contains an evolved G5 donor star in a 2.5 day orbit. Its optical luminosity places the binary at a distance $\geq 27$ kpc and makes BW Cir the furthest BH binary in the Galaxy yet. Remarkably, its large systemic velocity (103 km s$^{-1}$) is in good agreement with the projected velocity of the Galactic differential rotation at that distance (see more details in Casares et al. 2004a).

In addition to the mass function, one obviously needs a knowledge of the inclination and the mass ratio to fully determine the masses of the two stars. In the case of a BH binary, we face a "single-line spectroscopic binary" problem and all the information must be extracted from the optical companion. However, there is a complete solution to the problem which involves: (i) the determination of the binary mass ratio through the rotational broadening $V_{\text{rot}} \sin i$ of the companion’s absorption lines and (ii) the determination of the inclination angle by fitting synthetic models to ellipsoidal lightcurves. This is the classic method to derive masses. Further details of these techniques and the systematics involved can be found in several review papers e.g. Casares (2001), Charles & Coe (2004).

Following this prescription, we currently have 15 reliable BH masses which are listed in the last column of Table 1, updated from the compilations in Orosz (2003) and Charles & Coe (2004). Figure 1 plots these masses with their $1\sigma$ errorbars. BH masses spread between 4 and $14 M_\odot$, with typical uncertainties
Table 1.  Confirmed black holes and mass determinations

| System          | $P_{\text{orb}}$ (days) | $f(M_x)$ (M$_\odot$) | Spect. Type | Classification   | $M_x$ (M$_\odot$) |
|-----------------|--------------------------|----------------------|-------------|------------------|------------------|
| GRS 1915+105    | 33.5                     | 9.5 ± 3.0            | K/M III     | LMXB/Transient   | 14 ± 4           |
| V404 Cyg        | 6.470                    | 6.08 ± 0.06          | K0 IV       |                  | 12 ± 2           |
| Cyg X-1         | 5.600                    | 0.244 ± 0.005        | O9.7 IIab   | HMXB/Persistent  | 10 ± 3           |
| LMC X-1         | 4.229                    | 0.14 ± 0.05          | 07 III      |                  | > 4              |
| XTE J1819-254   | 2.816                    | 3.13 ± 0.13          | B9 III      | LMXB/Transient   | 7.1 ± 0.3        |
| GRO J1655-40    | 2.620                    | 2.73 ± 0.09          | F3/5 IV     |                  | 6.3 ± 0.3        |
| BW Cir $^a$     | 2.545                    | 5.75 ± 0.30          | G5 IV       |                  | > 7.8            |
| GX 339-4        | 1.754                    | 5.8 ± 0.5            |            |                  |                  |
| LMC X-3         | 1.704                    | 2.3 ± 0.3            | B3 V        | HMXB/Persistent  | 7.6 ± 1.3        |
| XTE J1550-564   | 1.542                    | 6.86 ± 0.71          | G8/K8 IV    | LMXB/Transient   | 9.6 ± 1.2        |
| 4U 1543-475     | 1.125                    | 0.25 ± 0.01          | A2 V        |                  | 9.4 ± 1.0        |
| H1705-250       | 0.520                    | 4.86 ± 0.13          | K3/7 V      |                  | 6 ± 2            |
| GS 1124-684     | 0.433                    | 3.01 ± 0.15          | K3/5 V      |                  | 7.0 ± 0.6        |
| XTE J1859+226   | 0.382                    | 7.4 ± 1.1            |            |                  |                  |
| GS2000+250      | 0.345                    | 5.01 ± 0.12          | K3/7 V      |                  | 7.5 ± 0.3        |
| A0620-003       | 0.325                    | 2.72 ± 0.06          | K4 V        |                  | 11 ± 2           |
| XTE J1650-500   | 0.321                    | 2.73 ± 0.56          | K4 V        |                  |                  |
| GRS 1009-45     | 0.283                    | 3.17 ± 0.12          | K7/M0 V     |                  | 5.2 ± 0.6        |
| GRO J0422+32    | 0.212                    | 1.19 ± 0.02          | M2 V        |                  | 4 ± 1            |
| XTE J1118+480   | 0.171                    | 6.3 ± 0.2            | K5/M0 V     |                  | 6.8 ± 0.4        |

$^a$ The 1-year alias period at 2.564 days is equally significant. In this case the BH would be even strengthen with $f(M_x) = 6.60 ± 0.36$ M$_\odot$ (see Casares et al. 2004a).

$^b$ Period is uncertain, with another possibility at 0.319 days (see Zurita et al. 2002). This would drop the mass function to $f(M_x) = 6.18$ M$_\odot$.

$^c$ Mass function updated after Torres et al. (2004).

In the range 5-33%. Also in Fig. 1 we show 33 well determined NS masses, extracted from Stairs (2004) and Lattimer & Prakash (2004), also with 1σ uncertainties. The most precise NS masses have been measured in a group of binary radio-pulsars. They are descendants of HMXBs, composed of two young pulsars whose orbits are known to great accuracy from pulse time delays. Relativistic effects lead to NS mass determinations with exquisite accuracy and they display a normal distribution centered at the canonical value of 1.35 M$_\odot$ with a very small dispersion of ±0.04 M$_\odot$. Dynamical masses are also available from pulsing NS in seven HMXBs, six of which are eclipsing. However, the uncertainties are much larger because the radial velocities of the optical stars are distorted by non-Keplerian perturbations, caused by their strong winds. A few measurements also exist for LMXBs and binary millisecond pulsars (BMPs). BMPs are descendants of LMXBs, composed of a millisecond NS (spun up by accretion) and a detached white dwarf. Both LMXBs and BMPs are poten-
A fundamental result for the understanding of nuclear matter would be to find a NS more massive than 1.6 M\(_{\odot}\) since this would rule out soft EOS (Brown & Bethe 1994). Currently the best candidates are found in the LMXB Cyg X-2 (1.78 ± 0.23 M\(_{\odot}\): Casares, Charles & Kuulkers 1998, Orosz & Kuulkers 1999), the BMP J0751+1807 (2.2 ± 0.2 M\(_{\odot}\): Nice, Splaver & Stairs 2004) and the HMXBs 4U 1700-37 (2.44 ± 0.27 M\(_{\odot}\): Clark et al. 2002) and Vela X-1 (1.86 ± 0.16 M\(_{\odot}\): Barziv et al. 2001). The latter case, however, is less secure since the radial velocity curve of the companion is affected by systematic excursions which prevents a confirmation of the mass estimate (see Barziv et al. 2001). In the case of J0751+1807 and 4U 1700-37, soft EOS are ruled out even at the 95\% level.

Very recently, large NS masses have also been reported for 2S0921-630 (=V395 Car) by two different groups: 2.0–4.3 M\(_{\odot}\) (Shahbaz et al. 2004) and 1.9–2.9 M\(_{\odot}\) (Jonker et al. 2004). However, the compact object in this LMXB has never shown any evidence for X-ray bursts or pulsations, so it could be a low-mass BH. This is also the situation for the compact object in 4U 1700-37, since it has never shown any NS signature.
Figure 2 presents the histogram of compact object masses compared to the theoretical distribution of remnants computed in Fryer & Kalogera (2001) for the case of binary interaction under Case C mass transfer (i.e. Common Envelope evolution after core helium ignition) and mass loss through winds in the Wolf-Rayet phase. This is the most realistic scenario since evolution through Case B mass transfer (i.e. Common Envelope and H envelope removal before core helium ignition) fails to produce BH remnants $> 3 \, M_\odot$ with the current Wolf-Rayet mass loss rates (Woosley, Langer & Weaver 1995). The model predicts a BH mass cut at $12 \, M_\odot$ which is difficult to reconcile with the high masses measured in V404 Cyg ($12 \pm 2 \, M_\odot$) and GRS 1915+105 ($14 \pm 4 \, M_\odot$). Despite the large uncertainties in the masses, these two X-ray binaries seem to pose a challenge to BH formation theories and, in particular, suggest that mass loss rates in the WR phase are overestimated.

Our histogram also shows a shortage of objects at 3–4 $M_\odot$, not predicted by the model distribution. If the gap is eventually confirmed, it could strongly restrict the supernova explosion energy since, as explained in Fryer & Kalogera (2001), it can be reproduced by a step function dependence with the progenitor's mass. However, selection effects could also be playing a role here since low mass BHs are likely to show up as persistent X-ray sources, where dynamical masses are difficult to obtain. The case of 2S0921-630 could well be an example. Obviously we are limited by low number statistics in the observed
distribution of compact remnants. Clearly more X-ray transient discoveries and lower uncertainties in the mass determinations are required before these issues can be addressed and the form of the distribution can be used to constrain supernova models and X-ray binary evolution.

2. Mass Determination in Persistent LMXBs

So far we have been dealing with mass determination in quiescent X-ray binaries. Dynamical studies in persistent LMXBs are, on the other hand, hampered by the huge optical luminosity of the accretion disc. This is driven by reprocessing of the powerful (Eddington limited) X-ray luminosity and completely swamps the spectroscopic features of the faint companion stars.

New prospects for mass determination have been opened by the discovery of high-excitation emission lines arising from the donor star in Sco X-1 (Steeghs & Casares 2002). The most prominent are found in the core of the Bowen blend, namely the triplets NIII $\lambda 4634$-40 and CIII $\lambda 4647$-50. In particular, the NIII lines are powered by fluorescence resonance which requires seed photons of HeII Ly-$\alpha$. These narrow components move in phase with each other and are not resolved (FWHM=50 km s$^{-1}$ i.e. the instrumental resolution), an indication that the reprocessing region is very localized (Fig. 3). The extreme narrowness rules out the accretion flow or the hot spot and points to the companion star as the reprocessing site.

![Figure 3. Trailed spectra of the narrow CIII+NIII Bowen emission lines and HeII $\lambda 4686$ in Sco X-1. After Steeghs & Casares (2002).](image3)

![Figure 4. Radial velocity curve of the sharp CIII+NIII Bowen lines (top) and the wings of HeII $\lambda 4686$ (bottom) in Sco X-1.](image4)

The radial velocity curve of the donor star can be extracted through a combined multigaussian fit to the three CIII/NIII lines (top panel of Fig. 4) or using more sophisticated Doppler tomography techniques (see e.g. Casares et
Furthermore, the velocities are in antiphase with the wings of the HeII $\lambda$4686 emission, which approximately trace the motion of the compact star (bottom panel of Fig. 4). This work represents the first detection of the companion star in Sco X-1 and opens a new window for extracting dynamical information and deriving mass functions in the population of $\sim$20 LMXBs with established optical counterparts.

Follow-up campaigns, using the AAT, NTT and VLT telescopes, have enabled us to extend this analysis to other fainter LMXBs leading to the detection of the secondary stars in 2A1822-371, MXB1636-536, MXB1735-444 and XTE J1814-338 and the determination of their orbital velocities, which lie in the range 200-300 km s$^{-1}$ (see Casares et al. 2003, Casares et al. 2004b). In addition, the application of this technique to the BH candidate GX339-4 during its 2002 outburst provided the first determination of its mass function and hence dynamical proof that it is a BH (Hynes et al. 2003).

LMXBs are considered to be the progenitors of BMPs because they provide a mechanism for spinning up NS to millisecond periods, through the sustained accretion of matter with high angular momentum during their long active lives. Despite intensive efforts over 2 decades, the detection of millisecond pulsations in LMXBs proved elusive but the advent of XTE changed things dramatically with the discovery of: (i) persistent pulses in 5 transient LMXBs with spin periods in the range 185-435 Hz (ii) nearly coherent oscillations during X-ray bursts in 13 LMXBs. Figure 5 presents an example of a train of oscillations, with a frequency of 580 Hz, detected during an X-ray burst in MXB1636-536.
In two LMXBs, SAX J1808.3658 (Chakrabarty et al. 2003) and XTE J1814-338 (Strohmayer et al. 2003), burst oscillations were detected in addition to persistent pulses and they showed identical frequencies. This confirmed that burst oscillations are indeed modulated with the spin of the NS.

Moreover, burst oscillations were detected in an 800 s interval during a superburst in MXB 1636-536. The oscillations showed a clear frequency drift which was attributed to the orbital Doppler shift of the NS (see fig. 6). A circular orbit model was fitted to the data and used to constrain the projected NS velocity to between 90 and 175 km s\(^{-1}\) (Strohmayer & Markwardt 2002). This is a remarkable result which shows that burst oscillations can be used to trace NS orbits and, in combination with information provided by the Bowen fluorescent lines, turn persistent LMXBs into double-lined spectroscopic binaries.

3. Conclusions

In the past 15 years the field of X-ray binaries has experienced significant progress with the discovery of 16 new BHs and 6 millisecond pulsars in LMXBs. Reliable mass determinations have been provided for 15 BHs and 33 NS which are starting to reveal the mass spectrum of compact remnants. Two X-ray binaries, V404 Cyg and GRS 1915+105, contain BHs too massive to be explained by current theoretical modelling. However, better statistics are required in order to use the observed distribution to constrain fundamental parameters of X-ray binary evolution and supernova models, such as the mass-loss rate in the W-R phase, the explosion energy dependence on progenitor mass, the amount of fallback or details of the Common Envelope phase. The discovery of fluorescence emission from the companion star, together with X-ray burst oscillations has opened the door to derive NS masses in persistent X-ray binaries. This new technique, which will benefit from new instrumentation on large telescopes (e.g. OSIRIS on GTC), will likely provide further evidence for the existence of massive NS in LMXBs.

Note added. Two new NS spin periods were discovered when finishing writing this contribution: burst oscillations at 45 Hz in the persistent LMXB EXO 0748-676 (Villarreal & Strohmayer 2004) and persistent pulsations at 598.9 Hz in the new transient LMXB IGR J00291+5934 (Markwardt, Swank & Strohmayer 2004), discovered by INTEGRAL in December 2004.

Acknowledgments

The would like to acknowledge helpful comments from my colleagues Phil Charles, Danny Steeghs and Tariq Shahbaz. I’m also grateful for support from the Spanish MCYT grant AYA2002-0036 and the programme Ramon y Cajal.
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