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Hard X-ray observations of Galactic sources: the HMXB population and black hole spin

John A. Tomsick

Space Sciences Laboratory, 7 Gauss Way, University of California, Berkeley, CA 94720-7450, USA, e-mail: jtomsick@berkeley.edu

Abstract. Observations with the *INTEGRAL* and *NuSTAR* satellites are both greatly advancing our knowledge of hard X-ray sources in the Galaxy. Ever since the start of the *INTEGRAL* mission, it has uncovered new high mass X-ray binaries (HMXBs). That is continuing today as we have been using *NuSTAR*, *Chandra*, and ground-based observations to classify *INTEGRAL* sources. In addition, *NuSTAR* is extending the HMXB search to lower flux levels through the *NuSTAR* serendipitous survey. This proceedings paper is on these programs and what they are telling us about the Galactic population of HMXBs. This population has received much recent attention because some of the HMXBs are the progenitors of double compact object binaries, which eventually merge and produce gravitational waves. However, measurements of black hole (BH) spin in HMXBs appear to be in conflict with the BH spins measured in binary BH mergers, and we also discuss this topic.

Key words. Surveys – Stars: black holes – X-rays: stars

1. Introduction

With the discovery of merging binary black holes (BBHs), there has been increased interest in HMXBs and their evolution. A main reason for the focus on HMXBs is to answer the question of whether they are the progenitors of the BBHs that have been detected. The theory of the evolution of a binary system starting as two massive (>10 $M_{\odot}$) stars (e.g., van den Heuvel, 1976; Mandel & Farmer, 2018) predicts that there will be two phases where systems might appear as HMXBs. In one of these phases, the BH will accrete matter from a supergiant, and the system will have a relatively long (days to hundreds of days) orbital period. Although the well-known BH system Cyg X-1 might be an example of this phase, it is predicted that Cyg X-1 will evolve to be a binary with a BH and a neutron star (NS), if it survives the end of its supergiant's life (Belczynski et al., 2011). The second HMXB phase consists of a BH accreting from a Wolf-Rayet star. The Wolf-Rayet star is the helium core that remains after the star loses its hydrogen envelope, and the orbital period can be very short. Cygnus X-3 is an example with an orbital period of 4.8 hrs.

Constraints on the size of the Galactic population of HMXBs and measurements of their properties can help to address the question of whether HMXBs are the main progenitors of BBHs. Constraining the size of the population is a topic where *INTEGRAL* has had a very large impact. Through the Galactic Plane Survey and other programs that have led to large Galactic exposures, the number of known HMXBs has increased dramatically, including an increase in the number of known supergiant HMXBs by a factor of three or more (Bird et al., 2010; Krivonos et al., 2012; Bodaghee et al., 2012; Bird et al., 2016; Krivonos et al., 2017). One reason for the large increase is that many of the supergiant HMXBs have compact objects embedded in the stellar winds, making them highly obscured. While they were missed in previous soft X-ray surveys, *INTEGRAL*'s hard X-ray bandpass combined with its large field of view has led to the discoveries of "IGR" HMXBs. One place where discoveries of new HMXBs can have a big impact on the question of the BBH progenitors is to look for HMXBs with BH accretors. Many of the IGR HMXBs have been identified as having NS accretors, but the compact object type is unknown for the majority of them. While none of the IGR HMXBs have been proven to have BH accretors, more are expected to exist, and evidence for this is the discovery of MWC 656, for which an optical radial velocity curve showed that its compact object has a mass above the NS limit (Casares et al., 2014).

Another measurement that provides a test of the possible evolutionary connection between HMXBs and BBHs is determining the rotation rates of the BHs (i.e., the BH spin). For a BH's spin to be changed appreciably by accretion, the BH needs to accrete a lot of mass. Specifically, for a slowly rotating ($a_* <$ 0.1 or 0.2) BH to be spun up to rapid rotation rates ($a_* > 0.8$), the BH must double its mass (Fragos & McClintock, 2015). For Cyg X-1, the mass accretion rate is $\sim 5 \times 10^{-9}\,M_\odot\,yr^{-1}$, and the Eddington limit for a $10\,M_\odot$ BH corresponds to an accretion rate of about $10^{-7}\,M_\odot\,yr^{-1}$. Thus, since the lifetimes of HMXBs are limited by the lifetimes of their massive stars, they do not accrete for more than 10^6 or 10^7 years, making it impossible to change the spins of their BHs significantly by accretion. For this reason, a prediction is that the spins of the BHs in HMXBs and the spins of the BHs in BBHs should be drawn from the same distribution if the two populations have an evolutionary connection.

In the following, we first describe observing programs to search for HMXBs in the Galaxy. We summarize results from two programs: one involves using the *Chandra X-ray Observatory* to follow-up IGR sources and the other is the Galactic part of the *Nuclear Spectroscopic Telescope Array (NuSTAR)* (Harrison et al., 2013) serendipitous survey. Then, we describe measurements of BH spins, recent improvements on measuring the reflection component with *NuSTAR*, and a comparison between the spins of BHs in HMXBs and BBHs.

2. Searches for HMXBs

We are conducting surveys that are at least partially motiviated by searching for HMXBs. The first one is directly connected to *INTEGRAL* since we have been using *Chandra* to localize IGR sources to facilitate their identification. This program was initially inspired by the discovery of IGR sources in the Norma spiral arm region (Tomsick et al., 2004), many of which turned out to be HMXBs. In approximately 100 *Chandra* observations, we obtained 68 detections, allowing for the error circles of the IGR sources to be reduced from a few arcminutes to less than an arcsecond (Tomsick et al., 2006, 2008, 2009, 2012, 2016). This has allowed for optical or near-IR follow-up by our group and other groups (Chaty et al., 2008; Butler et al., 2009; Zurita Heras et al., 2009; Masetti et al., 2013; Coleiro et al., 2013; Fortin et al., 2018), resulting in 12 new IGR HMXBs and 4 candidate IGR HMXBs.

We also were inspired by *INTEGRAL* in carrying out dedicated surveys of the Norma spiral arm region with *Chandra* and *NuSTAR* (Fornasini et al., 2014; Rahoui et al., 2014; Fornasini et al., 2017). With detailed analysis of source properties, we have uncovered a few HMXB candidates, and we are currently working to obtain radial velocity curves of these candidates to constrain the masses of their binary components. Another *NuSTAR* survey was of the Galactic Center region (Hong et al., 2016), and we are following up a few HMXB candidates found in that survey. *NuSTAR* has also been carrying out a Legacy program to observe unidentified IGR sources (Clavel et al., submitted to ApJ; also see the paper in these proceedings by Clavel).

Finally, we have been working on the *NuSTAR* serendipitous survey (Alexander et al., 2013). The most recent large publication was on serendipitous 3–24 keV sources found in 331 *NuSTAR* observations taken over the first 40 months of the mission (Lansbury et al., 2017). In total, 497 sources were detected, and optical spectroscopy resulted in classification for 276 of them. The classifications of 260 are AGN, and 16 sources were identified as being Galactic (Lansbury et al., 2017; Tomsick et al., 2017), although the classifications in the Galactic plane are far from being complete (Tomsick et al., 2017, 2018). Two HMXBs or likely HMXBs are among the serendipitous sources. IGR J13020–6359 is a previously known accreting pulsar, and NuSTAR J105008–5958.8 is a newly discovered source that is likely an HMXB. The optical spectrum (Tomsick et al., 2017) shows hydrogen Balmer and helium emission lines as well as a DIB line that indicates $A_V = 4.7 \pm 0.5$, and at the Galactic position (l = 288.3°, b = –0.6°), we use A_V to estimate a distance of $d = 7 \pm 1$ kpc. Combining this information with the optical magnitudes (R = 15.1 and V = 16.5), we estimate an absolute magnitude of $M_V = –2.4 \pm 0.6$, indicating a likely spectral type of B2Ve. We encourage a radial velocity study of this source to determine the mass of the compact object.

The surface density of HMXBs (see Figure 1) shows the implications of the discovery of NuSTAR J1050008–5958.8 within the context of the *NuSTAR* serendipitous survey (Tomsick et al., 2017). The *NuSTAR* survey is extending the HMXB search to flux levels that are more than two orders of magnitude lower than *INTEGRAL*. While the discovery of an HMXB in the *NuSTAR* survey is still consistent with an extrapolation of the *INTEGRAL* curve (Lutovinov et al., 2013), the fact that many of the serendipitously-discovered *NuSTAR* sources in the Galactic plane are still unclassified means that the actual curve could still be much higher. Work to classify more of the *NuSTAR* sources in the Galactic plane, which will lead to improved constraints at low flux levels, is ongoing.

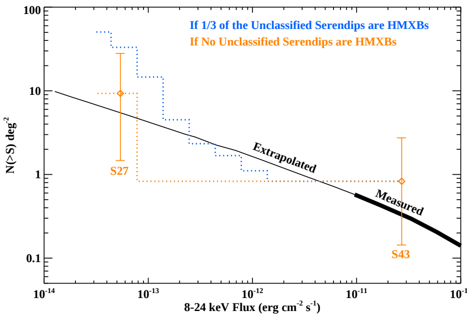

Fig. 1. Surface density vs. 8–24 keV flux for HMXBs. The thick black solid line corresponds to the measurement by *INTEGRAL* (Lutovinov et al., 2013), and the thin black solid line is an extrapolation of the *INTEGRAL* measurement. The *NuSTAR* serendipitous survey is extending the measurement to lower flux levels. The point labeled S43 represents IGR J13020–6359, and S27 represents NuSTAR J1050008–5958.8, which was discovered in the *NuSTAR* survey. The blue curve shows one possible correction for incompleteness in the *NuSTAR* survey. Adapted from Tomsick et al. (2017), where additional explanation can be found.

3. BH spins

The X-ray measurement of the rotation rates of BHs is possible because of the theoretical prediction that the innermost stable circular orbit (ISCO) for a BH depends on the BH's spin. Thus, if an accretion disk extends to the ISCO, and its inner radius ($R_{\rm in}$) is measured, then the BH spin (a_*) can be calculated. Although we need to be aware that the disk might not extend to the ISCO, it is still true that any measurement of $R_{\rm in}$ that is less than the radius of the ISCO for a non-rotating BH places a lower limit on a_*.

The two techniques that have been most widely used for measuring $R_{\rm in}$ are modeling the multi-temperature thermal component in the soft X-ray spectrum (Davis et al., 2006; Steiner et al., 2010, 2014; McClintock et al., 2014) and modeling the reflection component, which arises when hard X-rays shine on the accretion disk producing a fluorescnt iron line near 6.4 keV (Fabian et al., 1989; Miller, 2007) and a reflection hump peaking near 20–30 keV. In the case of reflection, the relativistic smearing due to Doppler broadening and gravitational redshift allow for the measurement of R_{in}. While BH spin measurements have been obtained for more than a dozen low-mass X-ray binaries (Miller & Miller, 2015; Middleton, 2016), a_* has only been measured for BHs in four HMXBs.

NuSTAR's combination of bandpass (3–79 keV), energy resolution, and throughput for high count rates with no photon pile-up have made it an excellent instrument for reflection studies, and BH spin measurements have been made for several systems (e.g., Miller et al., 2013; King et al., 2014; Xu et al., 2018). For the HMXBs, *NuSTAR* observations of Cyg X-1 have greatly strengthened the conclusion that it harbors a rapidly rotating BH. Meausrements of Cyg X-1 in the soft state have measured spin rates in the range $a_* = 0.93$–0.96 and inner disk inclinations in the range $i_{\mathrm{innerdisk}} = 37$–$42°$ (Walton et al., 2016). While a high spin for Cyg X-1 has previously been measured with the thermal technique (Gou et al., 2014), the fact that $i_{\mathrm{innerdisk}}$ is higher than the binary inclination obtained by optical measurements, $i_{\mathrm{binary}} = 27.1° \pm 0.8°$ (Orosz et al., 2011), is surprising and may indicate that the BH spin is misaligned from the binary angular momentum axis (see also Tomsick et al., 2014), which could also mean that the accretion disk is warped (Schandl & Meyer, 1994; King & Nixon, 2016). Table 1 and Figure 2 show the spin measurements for the four HMXBs: Cyg X-1; LMC X-1 (Steiner et al., 2012; Gou et al., 2009); M33 X-7 (Liu et al., 2008, 2010); and LMC X-3 (Steiner et al., 2014). In the two cases where we have both thermal and reflection measurements, the values are consistent with each other. The fact that three of them have $a_* > 0.8$ indicates that this is a population that tends to have high BH spins.

While the HMXBs tend to have BHs with high spin, there is no evidence yet that the BHs in BBH mergers do. The effective spins (χ_{eff}) for the 10 BBH mergers seen by LIGO/Virgo during the O1 and O2 runs (Abbott et al., 2016, 2017; The LIGO Scientific Collaboration & The Virgo Collaboration, 2018) are shown in Figure 3. The χ_{eff} values are consistent with zero except for GW170729 and GW151226, for which the values are $0.36^{+0.21}_{-0.25}$ and $0.18^{+0.20}_{-0.12}$, respectively. While none of these values require BHs with high spin, the effective spin does not directly measure the individual BH spins. Instead, it corresponds to the sum of the spin vectors of the two BHs projected onto the binary angular momentum direction. Thus, low values of χ_{eff} can either indicate low spins or

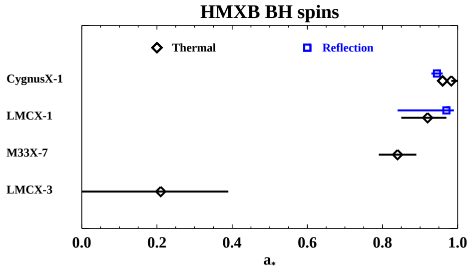

Fig. 2. BH spin measurements made for HMXBs using the thermal (black diamonds) and reflection (blue squares) methods. Two thermal values are shown for Cyg X-1 using the binary and inner disk inclinations. See Table 1 for the exact numbers and references.

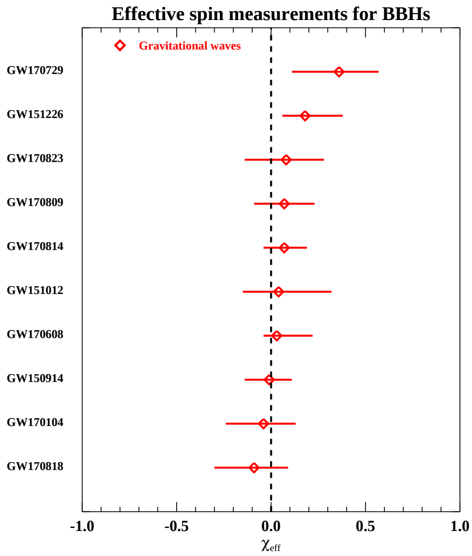

Fig. 3. Effective spin measurements for the 10 BBH mergers detected by LIGO/Virgo in the O1 and O2 runs (Abbott et al., 2016, 2017; The LIGO Scientific Collaboration & The Virgo Collaboration, 2018).

Table 1. Summary of HMXB BH spin measurements

Source	a_* (reflection)	a_* (thermal, $i_{\rm binary}$)	a_* (thermal, $i_{\rm innerdisk}$)	References
Cyg X-1	0.945 ± 0.015	>0.983	~0.96	Walton et al. 2016, Gou et al. 2014
LMC X-1	$0.97^{+0.02}_{-0.13}$	$0.92^{+0.05}_{-0.07}$	-	Steiner et al. 2012, Gou et al. 2009
M33 X-7	-	0.84 ± 0.05	-	Liu et al. 2008, 2010
LMC X-3	-	$0.25^{+0.20}_{-0.29}$	-	Steiner et al. 2014

spins that have large misalignments from the binary angular momentum direction.

Even though Cyg X-1 shows evidence for a small (~10–15°) misalignment between the inclination of the BH spin axis (based on $i_{\rm innerdisk}$) and the binary inclination, we should not conclude that large misalignments are expected for HMXBs. Thus, it seems difficult to explain the $\chi_{\rm eff}$ values measured for the BBH mergers if these particular BBHs have HMXB progenitors like the HMXBs that we have found to date. This could indicate a different channel for BBHs such as capture events in globular clusters (Rodriguez et al., 2016).

4. Summary and conclusions

We are in the process of conducting several surveys to better constrain the HMXB population in the Galaxy. Although these surveys have been inspired by or are directly related to *INTEGRAL*'s success in finding new HMXBs, they have not yet matched *INTEGRAL*'s rate of discovery. The *NuSTAR* surveys have been carried out in a systematic way, and we have developed a framework for placing constraints on the faint HMXB population, which we plan to use going forward. We have also presented results on spin measurements of BHs in HMXBs. The current data do not support a direct connection between the population of known BH-HMXBs and the BBHs detected during merging events in O1 and O2. However, as of this writing, the O3 run is starting, and we may see higher spin BHs for the lower mass BBH or if a BH-NS merger is seen.

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