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

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Are HMXBs the progenitors of BH-BH binaries (BBH)?

- Massive binary evolution has two HMXB phases
  - However, we don’t know of very many BH-HMXBs
  - Motivates searches for HMXBs

- BH spin should not change very much from formation to merger
  - HMXB spins should match BBH spins
  - Motivates BH spin measurements

Mandel & Farmer (2018)
van den Heuvel 1976, 2018
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HMXBs accrete for <10^{6-7} years
- Cyg X-1: dM/dt\sim5\times10^{-9} \, M_{\odot}/year
- L_{\text{Edd}}\sim10^{-7} \, M_{\odot}/year

Fragos & McClintock (2015)
Overview

- Searches for HMXBs
  - Surveys with INTEGRAL and NuSTAR
  - Follow-up with NuSTAR, Chandra, and ground-based optical/NIR

- Black hole spin
  - Thermal and reflection methods
  - Improvements on reflection measurements with NuSTAR
  - Spins of BHs in HMXBs and in BBHs
HMXBs and INTEGRAL

- TOO observation of 4U 1630-47 in early 2003
- Turns out that Norma region is full of HMXBs

293 ks INTEGRAL/IBIS image
Tomsick+04 (proceedings of Munich workshop)
**HMXB searches**

- Chandra follow-up of IGR sources

- Norma Arm Region Chandra Survey (NARCS) and NuSTAR survey
  - Few HMXB candidates (Fornasini+14+17, Rahoui+14)

- Galactic Center NuSTAR survey
  - Few HMXB candidates (Hong+16)

- NuSTAR Legacy program to observe unidentified IGR sources
  - See talk by Maïca Clavel on Thursday

- NuSTAR serendipitous source survey
**Chandra follow-up of IGR sources**

- Going from few arcminute INTEGRAL positions to subarcsecond Chandra positions
- In total, we have obtained 68 Chandra counterparts

INTEGRAL 90% confidence error circle (3.3 arcminute radius) on a 3.6 micron Spitzer/GLIMPSE image
Chandra follow-up of IGR sources

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Tomsick+08
Optical/NIR spectroscopy

- **Our effort**
  - Chaty+08
  - Butler+09
  - Zurita Heras+09
  - Tomsick+11
  - Coleiro+13
  - Fortin+18
  - Hare+19, in prep.

- **Many other groups**
  such as Masetti et al.

Bird+16 catalog listed 116 detected HMXBs (previously known and new). Our effort has yielded 12 new IGR HMXBs and 4 candidates.
View of the HMXB population from INTEGRAL observations

INTEGRAL hugely successful in ~ tripling the number of known supergiant HMXBs

However, need better sensitivity to constrain the faint end

logN-logS for persistent HMXBs

Lutovinov+13
The Nuclear Spectroscopic Telescope Array

- Harrison+13
- Hard X-ray optics
- 10 meter deployable mast
- CdZnTe detectors

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Range</td>
<td>3-79 keV</td>
</tr>
<tr>
<td>Angular Resolution</td>
<td>58 arcsec (HPD)</td>
</tr>
<tr>
<td></td>
<td>18 arcsec (FWHM)</td>
</tr>
<tr>
<td>Sensitivity (3σ, 1 Ms)</td>
<td>$2 \times 10^{-15}$ erg/cm$^2$/s (6-10 keV)</td>
</tr>
<tr>
<td></td>
<td>$1 \times 10^{-14}$ erg/cm$^2$/s (10-30 keV)</td>
</tr>
<tr>
<td>Field of View</td>
<td>12 x 12 arcmin</td>
</tr>
<tr>
<td>Spectral Resolution</td>
<td>400 eV at 6 keV</td>
</tr>
<tr>
<td></td>
<td>900 eV at 60 keV</td>
</tr>
<tr>
<td>Effective Area</td>
<td>900 cm$^2$ at 9 keV</td>
</tr>
<tr>
<td></td>
<td>100 cm$^2$ at 60 keV</td>
</tr>
<tr>
<td>Throughput</td>
<td>~400 events/s/module</td>
</tr>
</tbody>
</table>

NuSTAR Serendipitous Survey
- Alexander+13
- Lansbury+17 (40 month)
- Tomsick+17+18 (Galactic)
The 40 month survey used 3-24 keV images from 331 observations.
Masking out the target sources and the stray light
Sky coverage and source classifications

Results from 40 month catalog
- 276 of 497 sources classified (NuSTAR/X-ray/optical spectroscopy)
- 260 AGN (Lansbury+17)
- 16 Galactic
  - Active stars, CVs, X-ray binaries, and a magnetar (Tomsick+17)
  - HMXB and likely HMXB classified so far
    - IGR J13020-6359 (=S43): previously known accreting pulsar
    - NuSTAR J105008-5958.8 (=S27): new HMXB candidate
**NuSTAR J105008-5958.8: new HMXB candidate**

- **XMM+NuSTAR**
  - $\Gamma = 1.7^{+0.6}_{-0.5}$
  - $N_H = (3.1^{+2.3}_{-1.5}) \times 10^{22}$ cm$^{-2}$

- **Optical counterpart**
  - $A_V = 4.7 \pm 0.5$ (DIB line)
  - $d = 7 \pm 1$ kpc ($l,b = 288.3^\circ, -0.6^\circ$)
  - Gaia parallax = $-0.007 \pm 0.039$ mas
  - $R = 15.1$, $V=16.5$

- **Absolute mag and L$_X$ ($d = 7$ kpc)**
  - $M_V = -2.4 \pm 0.6$ (B2Ve)
  - $L_X = (4 \pm 2) \times 10^{32}$ erg/s

- **Similarities to the first BH/Be system MWC 656 (Casares+14)**
  - From radial velocity curve: $P_{\text{orb}} \sim 60$ d, $M_{\text{BH}} \sim 5$ $M_{\odot}$, $M_2 \sim 13$ $M_{\odot}$
  - **Please do a similar study for J1050**
Extending the logN-logS

- HMXB logN-logS only well-measured down to $10^{-11}$ erg/cm$^2$/s
- Two serendips are likely or definite HMXBs (S27 and S43)
- The survey is highly incomplete near the Galactic plane
- Data still allow for an unknown low flux HMXB population
- Still more work to do to fully characterize the Galactic HMXB population

- Surface density (logN-logS) for HMXBs at $-5^\circ < b < 5^\circ$ (adapted from Tomsick+17)
- Black curve from Lutovinov+13 based on the INTEGRAL survey
What HMXB properties provide information about whether they are BBH progenitors?

- Orbital parameters: $P_{\text{orb}}$, $e$
  - Important for understanding binary evolution (merging times, kicks)

- BH mass
  - Distributions show higher values for BBHs (Perna+19)

- BH spin
  - If HMXBs are the progenitors of BBHs, then their distributions of spin magnitudes should match
  - Spin orientation

Mass distributions for 24 BHs in X-ray binaries (“X-rays”) and 20 BHs in mergers (“GWs”). Maybe not a selection effect after all?
Measuring BH spin for X-ray binaries

- Methods for measuring $a_*$ rely on constraining the inner radius of the accretion disk ($R_{\text{in}}$)

- If $R_{\text{in}} = R_{\text{ISCO}}$, then determining $R_{\text{in}}$ gives a measurement of $a_*$

- As long as $R_{\text{in}} < 6R_g$, we have a lower limit on $a_*$

For example:
- A measurement of $R_{\text{in}} = 4R_g$ means that $R_{\text{ISCO}} \leq 4R_g$ and $a_* \geq 0.55$
Modeling spectra to constrain BH spin: Thermal

- Measuring $a_*$ by modeling the thermal disk component
  - Free parameters are $R_{\text{in}}(a_*)$ and $dM/dt$
- Concept is simple, but you need to know:
  - $M_{\text{BH}}$
  - Source distance
  - Inner disk inclination

Modeling the LMC X-3 thermal component (Davis+06; Steiner+10; Steiner +14 McClintock+14)
Using reflection to measure BH spin

- Critical region of the spectrum a few to $\sim$50 keV
- The NuSTAR capabilities (bandpass, throughput, energy resolution) are very well-suited for reflection studies

adapted from Middleton 2015
Reflection measurements with NuSTAR

- Residuals to a power-law continuum model

Figure credit: Michael Parker

Results published in:
- Miller+13
- Tomsick+14
- Miller+15
- Parker+15
- Walton+16
- Parker+16
- Tomsick+18
Cyg X-1 spectra: model-independent look

- Dip at 6.7 keV due to absorption by stellar wind
- All profiles show red wing due to gravitational redshift
Applying reflection model to Cyg X-1 spectra: BH spin and inclination constraints

- $0.93 < a_* < 0.96$
- $37^\circ < i < 42^\circ$
  - Inner disk inclination

Walton+16
Warped disk?

- From *NuSTAR* studies
  - $i > 40^\circ$ (Tomsick+14)
  - $37^\circ < i < 42^\circ$ (Walton+16)

- These are significantly higher than the measured binary inclination
  - $i_{\text{binary}} = 27.1^\circ \pm 0.8^\circ$ (Orosz+11)

- Possible misalignment between the BH spin axis and the orbital angular momentum vector

  - Warped disk calculation by Schandl & Meyer (1994)
  - See also King & Nixon (2016)
Cyg X-1 thermal method

- $a^* > 0.983$
  - $i = 27.1^\circ$ (binary)

- $a^* \sim 0.96$
  - $i = 40^\circ$ (Walton+16)

- With the higher inclination, the thermal agrees better with the reflection (0.93-0.96)
Summary of HMXB BH spin measurements

<table>
<thead>
<tr>
<th>Source</th>
<th>(a_\ast) reflection</th>
<th>(a_\ast) thermal, (i_{\text{binary}})</th>
<th>(a_\ast) thermal, (i_{\text{inner disk}})</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cyg X-1</td>
<td>0.945±0.015</td>
<td>&gt;0.983</td>
<td>~0.96</td>
<td>Walton+16, Gou+14</td>
</tr>
<tr>
<td>LMC X-1</td>
<td>0.97^{+0.02}_{-0.13}</td>
<td>0.92^{+0.05}_{-0.07}</td>
<td>?</td>
<td>Steiner+12, Gou+09</td>
</tr>
<tr>
<td>M33 X-7</td>
<td>-</td>
<td>0.84±0.05</td>
<td>?</td>
<td>Liu+08+10</td>
</tr>
<tr>
<td>LMC X-3</td>
<td>-</td>
<td>0.25^{+0.20}_{-0.29}</td>
<td>?</td>
<td>Steiner+14</td>
</tr>
</tbody>
</table>

- Lots more LMXB BH spin measurements
  - Very useful for checking consistency between methods
    - Excellent agreement for GX 339-4 and GRS 1915+105
    - Not as good for GRO J1655-40 and 4U 1543-47
HMXB spins vs. BBH effective spins

- \( \chi_{\text{eff}} = \frac{M_1 a_1 \cos \theta_1 + M_2 a_2 \cos \theta_2}{M_1 + M_2} \)
- Spins for BBHs are either low or strongly misaligned
- Neither possibility seems to match with expectations from HMXBs

![Diagram of HMXB BH spins and Effective spin for BBHs]
Possible interpretation for spin mismatch

- If the low $\chi_{\text{eff}}$ BBH values continue to be seen, perhaps BBHs are formed in capture events in dense star clusters rather than HMXBs
  - Estimate of capture rates has a large uncertainty, but could be high enough (Rodriguez+16)
  - BHs still may have at least moderate values of $a*$ but with random $\theta_1$ and $\theta_2$

instead of

?
Summary and Conclusions

- **HMXB population**
  - Better sensitivity (NuSTAR and Chandra) has not yet produced INTEGRAL’s rate of discovery
  - Framework for constraining the faint population (Lutovinov+13, Tomsick+17, Clavel+19)
  - Currently working on classifications of sources detected in the surveys

- **BH spin**
  - Reflection and thermal method measurements show that BHs in HMXBs tend to have high spin
  - BBH tend to have low $\chi_{\text{eff}}$
    - Do they form as captures in clusters or HMXBs?