Optical and Infrared Studies of X-ray Binaries in the Gaia Era

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My Connection to Jeff

• Circa 2003, Jeff became extremely interested in measuring the spins of stellar mass black holes. He assembled a large team, and I was thrilled to be invited.
### Chronological List of Team Members

<table>
<thead>
<tr>
<th>CfA</th>
<th>Year</th>
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<tbody>
<tr>
<td>Jeffrey McClintock</td>
<td>2004.3</td>
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<tr>
<td>Ramesh Narayan</td>
<td>2004.3</td>
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<tr>
<td>Rebecca Shafee</td>
<td>2005.1</td>
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<td>Mark Reid</td>
<td>2006.7</td>
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<td>James Steiner</td>
<td>2007.2</td>
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<td>Manuel Torres</td>
<td>2007.2</td>
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<td>Jifeng Liu</td>
<td>2007.2</td>
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<tr>
<td>Lijun Gou</td>
<td>2007.9</td>
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<th>Elsewhere</th>
<th>Year</th>
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<tr>
<td>Jerome Orosz (SDSU)</td>
<td>2004.3</td>
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<td>Li-Xin Li (MPI)</td>
<td>2004.3</td>
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<tr>
<td>Ronald Remillard (MIT)</td>
<td>2005.2</td>
</tr>
<tr>
<td>Shane Davis (IAS)</td>
<td>2005.3</td>
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<tr>
<td>Danny Steeghs (UK)</td>
<td>2005.9</td>
</tr>
<tr>
<td>Charles Bailyn (Yale)</td>
<td>2006.2</td>
</tr>
<tr>
<td>Ken Ebiswa (ISAS)</td>
<td>2008.1</td>
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<td>+ several others</td>
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#### Leaders
- Full-time
- Occasional

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_This effort to measure spin requires a 50-50 mix of theory & observation._
My Connection to Jeff

• Circa 2003, Jeff became extremely interested in measuring the spins of stellar mass black holes. He assembled a large team, and I was thrilled to be invited.

• To measure the black hole spin, you need the distance to the source...
• How can good distances and proper motions be of use in the study of the Galactic X-ray binary population?
Outline

• How can good distances and proper motions be of use in the study of the Galactic X-ray binary population?
  * Black hole and neutron star masses.
  * Black hole spins.
• X-ray binary populations and constraints on formation scenarios.
Two Classes of X-ray Binaries

- **High Mass X-ray Binaries (HMXBs):**
  - Have a massive O- or B-type companion, where $L_{\text{opt}} \approx L_x$.
  - Mass transfer is via a stellar wind.

- **Low Mass X-ray Binaries (LMXBs):**
  - Have a low mass companion (typically a solar mass or less).
  - Mass transfer is via Roche lobe overflow.
  - In persistent sources, $L_x >> L_{\text{opt}}$ always.
  - In transient sources, $L_x < L_{\text{opt}}$, except for occasional flares.
Dynamical Masses

• The donor star is a single-lined spectroscopic binary...
Dynamical Masses

- Circular orbit, period $P$ and separation $a$:

$$V_2 = \frac{2\pi a}{P} \left( \frac{M_1}{M_1 + M_2} \right)$$

where $M_2$ is the donor star mass.

- Kepler’s Third Law:

$$\rho^2 = \frac{4\pi^2 a^3}{G(M_1 + M_2)}$$

- Define $K = V_2 \sin i$, combine the above to get:

$$f(M_1) = \frac{PK_2^3}{2\pi G} = \frac{M_1^3 \sin^2 i}{(M_1 + M_2)^3} \geq M_1$$

- The optical mass function is a lower limit on the mass of the compact object.
Dynamical Masses

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- The optical mass function is a lower limit on the mass of the compact object.

- To get the actual mass of the compact object (and that of the donor star), we need to find the orbital inclination $i$ and the mass ratio $q = M_2/M_1$.

- The rotational velocity of the donor is (for synchronous rotation):
  \[ V_{\text{rot}} = \frac{2\pi R_L}{P} \]
  where $R_L$ is the radius of the Roche lobe.

- Hence:
  \[ V_{\text{rot}} \sin i = \frac{V_{\text{rot}}}{K_2} \frac{R_L}{\alpha} \left( M_1 + M_2 \right) = \frac{R_L}{\alpha} (1 + q) \]

- Thus, the observed rotational velocity of the donor gives a measurement of the mass ratio of the binary.
Dynamical Masses

- Ellipsoidal modulations seen in the light curve can be modeled to get the inclination.
Dynamical Masses

• Ellipsoidal modulations seen in the light curve can be modeled to get the inclination.

• Here is 4U 1543-47:
  • $P = 1.123$ days
  • $f(M) = 0.22 \pm 0.02 \, M_\odot$
  • $i = 20.7 \pm 1.1 \, \text{degrees}$
  • $V_{\text{rot}} = 46 \pm 2 \, \text{km/sec}$
Dynamical Masses

• The donor star is a single-lined spectroscopic binary...
• Take $K_2$, $i$, and $q$, solve for $M_1$, $M_2$, and $a$. 
Dynamical Masses

• The donor star is a single-lined spectroscopic binary...
• Take $K_2$, $i$, and $q$, solve for $M_1$, $M_2$, and $a$.
• **We can calculate the distance:**
  - Find the donor star radius $R_2$ (use $a$ and $R_L$).
  - Using $T_{\text{eff}}$, find $L_2$.
  - Using model atmospheres, compute bolometric corrections.
  - Using the apparent magnitude, find the distance modulus (apply reddening corrections, use IR bands if possible).
Dynamical Masses

- What if we knew the distance independently?
Dynamical Masses

• What if we knew the distance independently?
  • Use $d$, the apparent magnitude, and extinction to find $L_2$
  • Use $L_2$ and $T_{\text{eff}}$ to find $R_2$
  • Use the $R_2$ constraint as another prior and include it in the likelihood function: $\chi^2_{\text{tot}} = \chi^2_{\text{photo}} + \chi^2_{\text{RV}} + \chi^2_{R2}$
Dynamical Masses

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  • Use \( L_2 \) and \( T_{\text{eff}} \) to find \( R_2 \)
  • Use the \( R_2 \) constraint as another prior and include it in the likelihood function: \( \chi^2_{\text{tot}} = \chi^2_{\text{photo}} + \chi^2_{\text{RV}} + \chi^2_{R2} \)
• This was done for M33 X-7 (\( d=840\pm20 \) kpc, Orosz et al. 2007), LMC X-1 (\( d=48\pm1 \) kpc, Orosz et al. 2009), and Cyg X-1 (\( d=1.86\pm0.12 \) kpc, Reid et al. 2011).
There is a $\approx 2\sigma$ detection of the orbital motion in the VLBI observations ($a_x=0.18\pm0.09$ AU, Reid et al. 2011).
Distance Measurements

- Gandhi et al. (2018) compared Gaia DR2 distances with previous distance measurements for a sample of 24 BHs.
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• The agreement is generally OK, except for BW Cir.
Gandhi et al. (2018) compared Gaia DR2 distances with previous distance measurements for a sample of 24 BHs. The DR2 uncertainties are a factor of a few to several times more than previous uncertainties.
Distance Measurements

- As it stands now, the Gaia distance measurements to the black hole X-ray binaries don’t help constrain the mass measurements. Need to reduce the uncertainties by a factor of \( \approx 5 \) in order to help.

- The radio parallax distance to Cyg X-1 is \( 1.86 \pm 0.12 \) kpc, and the Gaia distance is \( 2.37 \pm 0.22 \) kpc. Note that the Gaia measurement does not include the “wobble” corrections.

- The final Gaia catalog presumably will have smaller parallax uncertainties, but probably not a factor of \( \approx 5 \) smaller (???).
Distance Measurements

• In spite of the relatively large uncertainties, the Gaia parallax measurements provide a good check on potential systematic errors.
Distance Measurements

- V4641 Sgr has textbook ellipsoidal variations, good model fits.
  - Gaia: $5.77 \pm 1.70$ kpc
  - Previous: $6.2 \pm 0.7$ kpc
Distance Measurements

- Same for 4U 1543-47.
- Gaia: 7.02±2.85 kpc
- Previous: 7.5±0.5 kpc
Distance Measurements

- However, A0620-00 has asymmetric quiescent light curves (Cantrell et al. 2010).
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Distance Measurements

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• The asymmetries were modeled as spots on the accretion disk.
  • Gaia: $1.66 \pm 0.71$ kpc
  • Previous: $1.06 \pm 0.12$ kpc
Dynamical Masses

• For Cyg X-1, imagine if the parallax errors were \( \approx 5 \) times smaller. We would have a secure astrometric orbit for the black hole.

• Gaia could potentially provide an optical astrometric orbit (although with larger uncertainties).

• Direct mass ratio measurement!
Dynamical Masses

- A survey with ngVLA could potentially find systems like Cyg X-1 but with longer periods, and hence much lower X-ray luminosities, via the wobble (Maccarone et al. 2018).
Black Hole Spin

• You need the distance (among other things) to measure the spin of the black hole.
Black Hole Spin

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• Having uniformly measured distances for all of the sources in your sample has never hurt anyone.
• Proper motion measurements (in addition to parallax) gives you 3D space motions, which can help constrain formation scenarios.
Black Hole Kinematics

• Proper motion measurements (in addition to parallax) gives you 3D space motions, which can help constrain formation scenarios.
• Cyg X-1 is co-moving with Cyg OB3. It also has almost no “peculiar” velocity, indicating no “kick” at birth (Reid et al. 2011). The BH probably formed by implosion.
• These 5 BH X-ray binaries have peculiar velocities measured (Mirabel 2017).
Black Hole Kinematics

• Proper motion measurements (in addition to parallax) gives you 3D space motions, which can help constrain formation scenarios.

• GRO J1655-40 and XTE J1118+480 have large linear momenta (similar to typical neutron stars). These BHs probably formed by infall onto a proto-neutron star.
Black Hole Kinematics

- White & van Paradijs (1996) showed BH X-ray binaries have a smaller dispersion in the z-distance from the plane, compared to neutron star systems.
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• This suggests BH systems received fewer “kicks” compared to neutron stars.

• Jonker & Nelemans (2004) found no differences in the distributions, suggesting no differences in the kick velocities. **Better distances wouldn’t hurt here either.**
Summary

• Good distance measurements to X-ray binaries can help constrain the mass measurements if the uncertainties are small enough.
• Presently, the Gaia distances are too uncertain to help in this regard.
• Regular monitoring observations with ngVLA could provide useful distance and proper motion measurements for a number of X-ray binaries.