How Well Can SIM-Lite Measure Parameters of Neutron Star and Black Hole Binaries?

PI: John A. Tomsick
(Previous SIM work as a Co-I on Mission Scientist project “Masses and Luminosities of X-ray Binaries”)

Co-I: Matthew Muterspaugh
(Previous SIM work as PI of planet-finding analysis team “Characterizing Exoplanet Systems with Astrometric and Radial Velocity Measurements”)

UC Berkeley
Space Sciences Laboratory

- Measurement of even a single NS with a high mass can rule out soft EOSs and Strange Quark Matter EOSs
  \[ M_{X,\text{VelaX}-1} = 1.86 \pm 0.16 \, M_{\odot} \]
  \[ M_{X,\text{4U1700-377}} = 2.44 \pm 0.27 \, M_{\odot} \]

- Black Holes
  - Masses interesting for stellar evolution and BH formation.
  - Binary inclinations are important for interpreting the X-ray emission that comes from the accretion disk.

Mass-Radius Relationships for different Neutron Star Equations of State (Lattimer & Prakash 2007)
Predicted Astrometric Signatures for Neutron Star and Black Hole Binaries

X-ray Pulsars

Black Holes, BH and NS Candidates

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Measuring Masses of Neutron Stars in High-Mass X-ray Binaries

• For X-ray pulsars with orbital time delay measurements (i.e., $a_x \sin(i)$ measured), SIM Lite will be able to obtain a direct neutron star mass measurement ($M_{NS}$) according to:

$$M_{NS} = \frac{(4\pi/GP_{orb})}{[d \tan(a_{opt})/\sin^2i]} \left[ a_x \sin(i) + d \tan(a_{opt}) \sin(i) \right]^2$$

where

- $P_{orb}$ = Binary orbital period (previously known)
- $a_x \sin(i)$ = Projected size of NS orbit (previously known)
- $d$ = source distance (measured by SIM Lite – Wide Angle)
- $a_{opt}$ = angular size of optical companion’s orbit (measured by SIM Lite – Narrow Angle)
- $i$ = binary inclination (measured by SIM Lite – Narrow Angle)
Orbital Parameters for HMXBs

Primary Goal of the Project: Use simulations to determine how well SIM Lite will measure the compact object masses for these 10 systems.

<table>
<thead>
<tr>
<th>Source Name</th>
<th>P$_{orb}$ (days)</th>
<th>a$_x$sin(i)</th>
<th>Ecc.</th>
<th>M$<em>{opt}$/M$</em>{sun}$</th>
<th>M$<em>{NS}$/M$</em>{sun}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vela X-1</td>
<td>8.964368(40)</td>
<td>113.89(13)</td>
<td>0.0898(12)</td>
<td>24</td>
<td>1.86(16)</td>
</tr>
<tr>
<td>V725 Tau</td>
<td>110.3(3)</td>
<td>267(13)</td>
<td>0.47(2)</td>
<td>15</td>
<td>?</td>
</tr>
<tr>
<td>GX 301-2</td>
<td>41.498(2)</td>
<td>368.3(37)</td>
<td>0.462(14)</td>
<td>55</td>
<td>?</td>
</tr>
<tr>
<td>X Per</td>
<td>250.3(6)</td>
<td>454(4)</td>
<td>0.111(18)</td>
<td>15</td>
<td>?</td>
</tr>
<tr>
<td>PSR B1259-63</td>
<td>1236.724(1)</td>
<td>1296.3(1)</td>
<td>0.86989(1)</td>
<td>10</td>
<td>?</td>
</tr>
<tr>
<td>Cyg X-1 (BH)</td>
<td>5.599829(16)</td>
<td>-</td>
<td>&lt;0.05</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>4U 1700-377 (NSC)</td>
<td>3.411581(27)</td>
<td>-</td>
<td>0.22(4)</td>
<td>58</td>
<td>2.44(27)</td>
</tr>
<tr>
<td>LS I +61 303 (NSC)</td>
<td>26.4960(28)</td>
<td>-</td>
<td>0.72(15)</td>
<td>10</td>
<td>?</td>
</tr>
<tr>
<td>LS 5039 (NSC)</td>
<td>3.90603(17)</td>
<td>-</td>
<td>0.35(4)</td>
<td>23</td>
<td>3.7$^{+1.3}_{-1.0}$</td>
</tr>
<tr>
<td>SS 433 (BHC)</td>
<td>13.08211</td>
<td>-</td>
<td>&lt;0.05</td>
<td>12</td>
<td>4.3(8)</td>
</tr>
</tbody>
</table>

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Approach to Simulations: Observing Scenario and Data Stream

- Calculate **actual positions** of the target (with orbital, parallax, and proper motion) and \( N_{\text{ref}} \) reference stars (with parallax and proper motion) vs. time, \( t \).
- Randomly choose a **SIM Lite baseline angle** (\( \theta \)) for each of the \( N_{\text{obs}} \) visits to the target.
- Simulate **1-d differential measurements** between the target and each of the \( N_{\text{ref}} \) reference stars. (The “noise” estimates come from tables or websites provided by the SIM project.)
- A data set consists of: \( N_{\text{obs}} \) timestamps, \( N_{\text{obs}} \theta s \), and \( N_{\text{ref}} \times N_{\text{obs}} \) measurements of target/reference star angles.

Tomsick et al. 2005, AAS presentation
Approach to Simulations: Fitting and Results for Vela X-1

- $\chi^2$ fitting with the same functional form that was used in simulating the data stream
- Vela X-1 work done with $N_{\text{ref}} = 4$. The function has 24 free parameters:
  - 4x5 non-orbital parameters: $x_{0k}$, $y_{0k}$, $u_{xk}$, $u_{yk}$, $\pi_k$, and $\pi_{T_k}$, $k = 1-4$
  - 4 orbital parameters: $a_{\text{opt}}$, $i$, $t_{\text{ref}}$, and $\Omega$ (position angle of the line of nodes)
- Result: 4% measurement of $M_{\text{NS}}$ in 40 hours of mission time.
Plan for this Study

• Compare simulation results for my code and the code developed for the planet studies (Muterspaugh “orbit-fitting” code)

• Improvements to my code:
  – two more orbital parameters: e and ω
  – optimize observing strategy (e.g., N_{obs} vs. T_{obs}, more observations at periastron, N_{ref})
  – more realistic (e.g., non-random baselines, reference star wobble, SIM-Lite rather than SIM numbers)

• Optimize and check simulation code and obtain results for the 10 systems (5 X-ray pulsars, 1 BH, 3 NSCs, 1 BHC)
Summary

• **Science:**
  – $M_{NS}$ and constraining Neutron Star EOSs
  – $M_{BH}$ and $i$: Stellar evolution, BH creation, accretion physics
  – BHC/NSC: Masses can constrain BH/NS nature

• **Targets:**
  – HMXBs are best: Large orbits and the optical light is dominated by the one component (companion)
  – X-ray pulsars give the most direct mass measurement

• **This Study:**
  – Cross-check and improvement of simulation code
  – Detailed paper on simulation results for 10 HMXBs

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