Modeling High-Mass X-ray Binary Formation in the Chandra Era

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Numerical Modeling of HMXBs

- Have Evolutionary Models for the evolution of single stars (use Single Star Evolution)

- At each step in stellar evolution, calculate if there are important binary interactions, these generally happen on a faster timescale than stellar evolution

- Make adjustments to the stellar properties (assume the star is in equilibrium) based on the outcome of the binary interaction, and continue single star evolution
HMXBs Formed by Starbursts

- Largest population of HMXBs is formed in the first 4-10 Myr after star formation
- The number of HMXBs is highly luminosity dependent
  - Different types of HMXBs!
- Also depends strongly on metallicity
Roche Lobe Overflow vs. Wind Accretion

- Two Methods for producing bright X-Ray emission from accretion onto a compact object

- These methods require different evolution pathways:
  - Different orbital separations
  - Different evolution states for the donor star
  - Different epochs of mass transfer
Wind Accretion HMXBs

- Luminosity depends on:
  - Wind strength of the donor star (evolution state, metallicity)
  - Orbital Separation

- These systems have low X-Ray luminosities

- All systems with a main sequence donor have a luminosity below \(10^{34}\) erg s\(^{-1}\).

- Metallicity greatly influences system formation (see slides below)
Wind Accretion HMXBs

- One method to form very bright HMXBs, systems with very strong winds
  - e.g. (super)giant donor stars
- Can maintain X-Ray luminosities above $10^{36}$ erg s$^{-1}$, even for orbital periods larger than 10,000 days
  - However, these systems are not observed
  - Even small natal kicks (to direct collapse black holes) can disrupt these systems
  - More closely bound systems can still survive
Roche-Lobe Overflow HMXBs

- Complex Evolutionary Mechanism:
  - Binary system begins in relatively tight orbit
  - Common Envelope of primary star draws systems closer together
  - Systems survive natal kick
  - Roche Lobe overflow of the secondary system onto the primary compact object
Roche-Lobe Overflow HMXBs

- **Ingredients:**
  - Need a large initial mass ratio between the primary and secondary

Calculated by Single Star Evolution (SSE) code Hurley et al. (2000)
Roche-Lobe Overflow HMXBs

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  - Need a large initial mass ratio between the primary and secondary.
  - Initial orbital separation must be large enough to avoid a common envelope when the primary star evolves through the Hertzsprung Gap (Taam & Sandquist 2000).

Capture Zone calculated by Single Star Evolution (SSE) code Hurley et al. (2000)
Roche-Lobe Overflow HMXBs

- **Ingredients:**
  - Need a large initial mass ratio between the primary and secondary.
  - Initial orbital separation must be large enough to avoid a common envelope when the primary star evolves through the Hertzsprung Gap (Taam & Sandquist 2000).
  - Initial orbital separation must be small enough to produce a common envelope during the supergiant stage of the primary star.

*Graph showing the relationship between maximum radius and metallicity, calculated by Single Star Evolution (SSE) code Hurley et al. (2000).*
Roche-Lobe Overflow HMXBs

- To Survive the CE, the potential energy in the binary orbit must exceed the envelope binding energy (Webbink 1984)

- **Note**: Strong metallicity dependence in the parameter space for survivable CEs.

- Produces a population of HMXBs which is strongly metallicity dependent

![Capture Zone](calculated by Single Star Evolution (SSE) code Hurley et al. (2000))
Effect of Natal Kicks on RLO-HMXBs

- Interestingly, this is not enough:
  - At the termination of the CE, the systems must not be in Roche-Lobe Overflow
  - However, the binary must re-enter Roche-Lobe Overflow.

- Two possibilities:
  - Evolution of donor star (expanding radius)
  - Supernova Natal Kicks!

*Linden et al. (2010)
*also observed in LMXBs (Kalogera & Webbink 1998)
Apply these Models to Three Current Problems

• The Population of Ultra-luminous X-Ray Sources (ULX)

• The population of HMXBs with a B[e] type donor (Be-HMXBs)

• The paucity of HMXBs with a Wolf-Rayet donor
ULX as a Function of Metallicity

Mapelli et al. (2010)

- Observations indicate that ULX formation rate increases with decreasing metallicity.
- Previous Theory: Low metallicity means heavier black holes and brighter HMXBs.

Belczynski et al. (2004)
Ultra-Luminous X-Ray Sources

- The majority of ULX are powered by Roche Lobe Overflow
- Binary evolution provides you with a mechanism to explain the observed overabundance of ULX in low-metallicity environments

Linden et al. (2010)

Prestwich et al. (2013)
These Models are Testable!

- In the **single star evolution** mechanism there is a clear **negative correlation** between the metallicity and the compact object mass.

- In the **binary evolution mechanism**, there is a **positive correlation** between the metallicity and the black hole mass.
A Neutron Star ULX in M82 !?

• Observation of an ULX with a neutron star compact object

• Obviously, is not formed due to single star evolution properties

• A strong indication that binary evolution plays a critical role in ULX formation

Bachetti et al. (2014)
Be-HMXBs

- At lower luminosities, Be-HMXBs form a substantial fraction of the total HMXB number
- Be-HMXBs require a negligible natal kick in the primary NS
- Electron Capture Supernovae provide a natural explanation
  - **Age** (form in stars with ZAMS mass 8-12 M$_\odot$, lifetime ~ 30 Myr)
  - **Natal Kick Velocities**
  - **Spin-up** (stable, long term mass transfer prior to SN pushes angular momentum onto the donor)
- This forms a powerful probe of neutron star formation at relatively low masses (8-12 M$_\odot$)

TL, Sepinsky, Kalogera, Belczynski (2009)
• A primary theoretical question is the lack of observed HMXBs with a Wolf-Rayet donor

• These systems should be extremely bright, and detectable.

• They should be the formed as a final evolution state of the observed B[e]-HMXB population

• This constrains modeling uncertainties to the CE phase between the B[e]-HXMB and WR-HMXB periods

• Find that this constraints the common envelope efficiency to be smaller than 1 ($\alpha_{CE} < 0.88$)
Conclusions

• Multiple evolutionary pathways can produce a bright HMXB — different pathways lead to different characteristics of the system

• Metallicity plays an important role in determining the HMXB population
  
  • Not in determining the parameters of a system moving through an evolutionary pathway

  • Primarily in determining the efficiency of each evolutionary pathway