FORMATION AND EVOLUTION OF COMPACT BINARY SYSTEMS

- Main Categories of Compact Systems
- Formation of Compact Objects
- Mass and Angular Momentum Loss
- Evolutionary Links to Classes of Binary Systems
- Future Work
Main Categories of Compact Binary Systems

- Stellar Binary X-ray Sources (Black Holes/Neutron Stars with a Companion) - strong X-ray sources in galaxies
- Binary Radio Pulsars (Neutron Star/Neutron Star or Neutron Star/White Dwarf Star) - important sources of gravitational radiation
• Cataclysmic Variables (White Dwarf Star with a Companion) - possible progenitors for Type Ia supernovae: probes of the curvature of the universe

• Significant Mass and/or Angular Momentum Removed from the System - binary interaction, stellar winds, supernova explosions
# MAIN CLASSES OF X-RAY BINARY SOURCES

<table>
<thead>
<tr>
<th></th>
<th>HMXB</th>
<th>LMXB</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>X-ray Spectra</strong></td>
<td>Hard (&gt;10 keV)</td>
<td>Soft (&lt;10 keV)</td>
</tr>
<tr>
<td><strong>Accreting Star</strong></td>
<td>High B field NS (or BH)</td>
<td>Low B field NS (or BH)</td>
</tr>
<tr>
<td><strong>Accretion Process</strong></td>
<td>Wind</td>
<td>Roche lobe overflow</td>
</tr>
<tr>
<td><strong>Companion Star</strong></td>
<td>High Mass</td>
<td>Low Mass</td>
</tr>
</tbody>
</table>
Examples of Typical Binary X-ray Sources

HMXB

16 $M_\odot$

1.3 $M_\odot$

$P_{\text{orb}} = 3.1$ days

$a = 23$ $R_\odot$

LMXB

0.6 $M_\odot$

1.4 $M_\odot$

$a = 2.0$ $R_\odot$

$P_{\text{orb}} = 5.6$ hours
**CATACLYSMIC VARIABLE BINARIES**

<table>
<thead>
<tr>
<th>Nova-like Systems</th>
<th>Donor less massive than WD</th>
<th>Porb ~ several hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supersoft Sources</td>
<td>Donor more massive than WD</td>
<td>Porb ~ hours to days</td>
</tr>
<tr>
<td>Double compact pair</td>
<td>WD/WD</td>
<td>Porb as short as 10 minutes</td>
</tr>
</tbody>
</table>
# ACCRETION ENERGETIC EFFICIENCIES

<table>
<thead>
<tr>
<th>Star</th>
<th>Radius (km)</th>
<th>$GM/Rc^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sun</td>
<td>700,000</td>
<td>0.0000002</td>
</tr>
<tr>
<td>White Dwarf</td>
<td>10,000</td>
<td>0.0002</td>
</tr>
<tr>
<td>Neutron Star</td>
<td>10</td>
<td>0.15</td>
</tr>
<tr>
<td>Black Hole</td>
<td>3</td>
<td>0.1 - 0.4</td>
</tr>
<tr>
<td>Companion Type</td>
<td>System Type</td>
<td>Period</td>
</tr>
<tr>
<td>------------------------</td>
<td>-------------</td>
<td>-----------------</td>
</tr>
<tr>
<td>High Mass</td>
<td>NS/NS NS/WD</td>
<td>7.5 hours 1.35 days</td>
</tr>
<tr>
<td>Low Mass</td>
<td>NS/WD</td>
<td>175 days</td>
</tr>
<tr>
<td>Unevolved</td>
<td>Noncompact</td>
<td>3.4 years</td>
</tr>
</tbody>
</table>
FORMATION OF COMPACT OBJECTS I.

- For progenitor masses less than about 8-12 solar masses, white dwarfs form as a result of the removal of stellar envelope due to wind mass loss or mass transfer leaving behind an electron degenerate core.

- For progenitor masses between 12-25 solar masses, neutron stars form by the core collapse of massive stars; for masses between 8-12 solar masses formation of neutron stars in binaries by accretion induced collapse of ONeMg white dwarfs is possible.
FORMATION OF COMPACT OBJECTS II.

• For progenitor masses greater than about 25 solar masses, black hole formation is likely

• Black hole formation via accretion induced collapse of a neutron star in a binary star system
Temporal Evolution of Stellar Radius

![Graph showing the temporal evolution of stellar radius. The graph plots radius ($R_{\odot}$) against age (Myr). There are three cases: A, B, and C, each marked with specific points indicating different stages of stellar evolution, such as the Main Sequence, RGB, and AGB phases.]
Need for Angular Momentum Loss

• The specific angular momentum of the observed systems is much less than the specific angular momentum of the progenitor system

• To produce a compact object, the stellar radius of the evolved progenitor star is much larger than the current orbital separation of the system
MASS TRANSFER PRELIMINARIES

• Orbital Evolution

\[ J^2 = \frac{GM_1^2 M_2^2 a}{M_1 + M_2} \]

\[ \frac{\dot{a}}{a} = \frac{2\dot{J}}{J} - \frac{2\dot{M}_1}{M_1} - \frac{2\dot{M}_2}{M_2} + \frac{\dot{M}_1 + \dot{M}_2}{M_1 + M_2} \]

Now if \( \dot{M}_1 = -\dot{M}_2 < 0 \)

\[ \frac{\dot{a}}{a} = \frac{2\dot{J}}{J} + \frac{2\dot{M}_1(M_1 - M_2)}{M_1 M_2} \]

Mass transfer from more to less massive star shrinks binary and vice versa
• Roche lobe condition for a binary with mass ratio $q$

$$R_{lobe} = \frac{0.49q^{2/3}a}{0.6q^{2/3} + \ln(1 + q^{1/3})}$$
MASS AND ANGULAR MOMENTUM LOSS DURING FORMATION PHASE

• Crucial stage for transforming a long period progenitor system (required to incubate the compact object) involves a common envelope phase of evolution - binary departs from synchronous rotation resulting in a tidal instability and unstable mass transfer
EVOLUTION TO THE COMMON ENVELOPE STAGE - ONSET OF SPIRAL-IN PHASE

1. Tidal Instability - Moment of Inertia of giant is $>1/3$ moment of inertia of binary

2. Unstable Mass Transfer - Mass transfer time scale is shorter than the thermal time scale of the accreting component

Common envelope evolution occurs for large mass ratios and/or where the primary develops a deep convective envelope before filling its Roche lobe
Formation of a Short Period Compact Binary System: General Conditions for Ejection of the Common Envelope

1. Energy released from the orbit is greater than the binding energy of the envelope from the binary.

2. Time scale for energy loss from the binary orbit is less than the energy transport time scale.

3. Ejection time scale is shorter than the spiral decay time scale.
Summary of 3D Results

1. Orbital decay is rapid (~ dynamical timescale)

2. Relative orbit is initially eccentric and circularizes as the orbital separation shrinks

3. Mass is ejected in all directions with a preference for mass loss in the orbital plane.
4. Efficiency of the mass ejection process < 40% - 50%

5. Evidence for spin up of gas surrounding the cores

6. Termination of common envelope phase is facilitated by progenitor stars with steep density gradients above the core and where the mass of the common envelope is comparable to the mass of the inspiralling companion
• Cataclysmic Variables - successful ejection of common envelope and survival of a remnant binary is favored on the red giant and asymptotic giant branch: orbit significantly shrinks (more than a factor of 100) and can lead to double degenerate systems and Type Ia supernovae
• LMXBs - successful ejection of the common envelope and survival of a remnant binary is favored for the late core helium burning phase and beyond: systems can lead to the binary millisecond pulsar phase

• HMXBs - same as above, but these systems lead to the formation of binary radio pulsars with a compact neutron star or white dwarf companion
EVOLUTION OF COMPACT BINARY SYSTEMS

• Nuclear evolution dominant - intermediate to massive donors

• Angular momentum loss dominant (magnetic braking, gravitational radiation) - low mass donors at short orbital periods
BINARY MILLISECOND PULSARS

• Neutron star is spun up by the accretion of matter via an accretion disk to millisecond spin periods - “recycled pulsar” is the endpoint of LMXBs

• Mass transfer from donor to neutron star may be either driven by nuclear evolution (long orbital periods ~ months) or by angular momentum losses (short orbital periods ~ hours)
PULSAR SPIN UP

Recycling: \[ \Omega_{\text{equilibrium}} = \Omega_{\text{Kepler}}(r = R_{\text{Mag}}) \]

\[
P_{\text{eq}} = 2.4B_{9}^{6/7}M^{-5/7} \left( \frac{\dot{M}}{\dot{M}_{\text{Edd}}} \right)^{-3/7} R_{6}^{16/7}
\]

where \( \dot{M}_{\text{Edd}} = 1.5 \times 10^{-8} R_{6} M_{\odot} yr^{-1} \)

\[
P_{\text{eq}} = 1.9B_{9}^{6/7} \text{ ms}
\]
Binary Evolutionary History of a LMXB

- **ZAMS**
  - Mass: 15.0, 1.6
  - Orbital Period: 1500 days
  - Age: 0.0 Myr

- **Roche-lobe overflow**
  - Mass: 13.0, 1.6
  - Orbital Period: 1930 days
  - Age: 13.9 Myr

- **Common envelope + spiral-in**
  - Mass: 4.86

- **Helium star**
  - Mass: 4.86, 1.6
  - Orbital Period: 0.75 days
  - Age: 13.9 Myr

- **Supernova**
  - Mass: 3.99, 1.6
  - Orbital Period: 1.00 days
  - Age: 15.0 Myr

- **Neutron star**
  - Mass: 1.3, 1.5
  - Orbital Period: 2.08 days
  - Eccentricity: 0.24
  - Age: 15.0 Myr

- **LMXB**
  - Mass: 1.3, 1.59
  - Orbital Period: 1.41 days
  - Age: 2.24 Gy

- **Millisecond pulsar (PSR 1855+09)**
  - Mass: 1.50, 0.26
  - Orbital Period: 12.3 days
  - Age: 2.64 Gy

- **White dwarf**
Binary Evolutionary Track of HMXB

ZAMS

Roche-lobe overflow

helium star

1. supernova

neutron star

HMXB

common envelope + spiral-in

helium star RLO

2. supernova

recycled pulsar

young pulsar

(PSR 1913+16)

<table>
<thead>
<tr>
<th>Event</th>
<th>P_{orb}</th>
<th>Age</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZAMS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Roche-lobe overflow</td>
<td>102 days</td>
<td>13.3 My</td>
</tr>
<tr>
<td>helium star</td>
<td>416 days</td>
<td>13.3 My</td>
</tr>
<tr>
<td>1. supernova</td>
<td>423 days</td>
<td>15.0 My</td>
</tr>
<tr>
<td>neutron star</td>
<td>5400 days</td>
<td>15.0 My</td>
</tr>
<tr>
<td>HMXB</td>
<td>1300 days</td>
<td>24.6 My</td>
</tr>
<tr>
<td>common envelope + spiral-in</td>
<td></td>
<td></td>
</tr>
<tr>
<td>helium star RLO</td>
<td>2.6 hrs.</td>
<td>24.6 My</td>
</tr>
<tr>
<td>2. supernova</td>
<td>1.5 hrs.</td>
<td>25.6 My</td>
</tr>
<tr>
<td>recycled pulsar</td>
<td>7.8 hrs.</td>
<td>25.6 My</td>
</tr>
</tbody>
</table>
FUTURE WORK

1. Determine efficiency of common envelope phase

\[ \alpha_{CE} = f(M_1, M_2, P_{orb}) \]

to delineate the regimes where a post spiral in system survives and where the system merges

2. Provide input for population synthesis modeling to determine the birth rates for the formation of compact systems for cosmology (Type Ia supernova evolutionary channels) and gravitational wave astronomy (neutron star mergers)