Formation and evolution of compact stellar X-ray sources

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Outline

- Introduction and a brief historical review
- Compact binaries and their observational properties
- Binary stellar evolution and final compact objects
- Roche-lobe overflow: cases A, B and C
- Common envelope evolution
- (Asymmetric) supernova explosions in close binaries
- Evolution of LMXBs: formation of millisecond pulsars
- Evolution of HMXBs
- Spin and B-field evolution of accreting neutron stars
Introduction and a brief historical review

- In our Galaxy there are about 100 bright X-ray sources with fluxes above $10^{-10}$ erg cm$^{-1}$ s$^{-1}$ in the energy range 1-10 keV.

- $10^{34} - 10^{38}$ erg s$^{-1}$ are typical source luminosities (25 000 times the total energy output of our Sun)

- **Distribution:**
  - => galactic center/plane (majority)
  - => Galactic globular clusters and Magellanic Clouds. (a dozen)

- Sco X-1, the first discovered source
### Energies of accretion

<table>
<thead>
<tr>
<th>Stellar object</th>
<th>Radius (km)</th>
<th>$\Delta U/mc^2$ (erg/g)</th>
<th>$\Delta U/m$ (erg/g)</th>
<th>$dM/dt^a$ (M$_\odot$/yr)</th>
<th>Column density$^a$ (g/cm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sun</td>
<td>7 x 10$^5$</td>
<td>2 x 10$^{-6}$</td>
<td>2 x 10$^{15}$</td>
<td>1 x 10$^{-4}$</td>
<td>140</td>
</tr>
<tr>
<td>White dwarf</td>
<td>10 000</td>
<td>2 x 10$^{-4}$</td>
<td>1 x 10$^{17}$</td>
<td>1 x 10$^{-6}$</td>
<td>16</td>
</tr>
<tr>
<td>Neutron star</td>
<td>10</td>
<td>0.15</td>
<td>1 x 10$^{20}$</td>
<td>1 x 10$^{-9}$</td>
<td>0.5</td>
</tr>
<tr>
<td>Black hole</td>
<td>3</td>
<td>0.1 ~ 0.4</td>
<td>4 x 10$^{20}$</td>
<td>4 x 10$^{-10}$</td>
<td>0.3</td>
</tr>
</tbody>
</table>

$^a L_X = 10^{37}$ erg/s

**Table 1.** The rates of accretion required to generate a typical X-ray luminosity of $10^{37}$ erg/s. Also listed in the amount of gravitational potential energy released per unit mass ($\Delta U/mc^2 = \frac{GM}{R}$) by accretion of 1 M$_\odot$ (compact) object as well as the column density towards the stellar surface (Schwarzschild radius) in the case of spherical accretion, $\sigma = L_X4\pi\sqrt{R/(MG)^3}$. 
Webster and Murdin (1972) and Bolton (1972) discovered that 
- Cyg X-1 is a binary system with an orbital period of 5.6 days 
- radial velocity curve of O9.7 (supergiant counterpart) was 72km/s 
- => independently concluded that the X-ray emission is the result of accretion onto a compact object, which is probably a black hole.

Shortly after Schreier et al. (1972) discovered that the regularly pulsing source Cen X-3 is a member of an eclipsing binary system because 
- regular X-ray pulsations with period of 4.84 s 
- regular X-ray eclipses with a duration of 0.488 days 
- those eclipses repeat every 2.087 days 
- the pulse period shows a sinusoidal Doppler modulation with the same 2.087 day period and is in phase with X-ray eclipses 

⇒ the X-ray pulsar is moving in a circular orbit with a projected velocity of 415.1 km/s, the 4.84 s period of the X-ray pulsations is the rotation period of the neutron star and the binary orbital period is 2.087 days.
• Mass function of the binary:

• Using Kepler’s third Law \( (\Omega^2 = \frac{GM}{a^3}) \) combined with eccentricity and measured radial velocity amplitude \( (K_x = \Omega a_x \sin i / \sqrt{1 - e^2}) \) of the X-ray pulsar.

• \( f(M) = \frac{(M_2)^3 \sin^3 i}{(M_x + M_2)^2} = \frac{1}{2\pi G} K_x^3 P_{orb} (1 - e^2)^{3/2} \)

• For Cen X-3 the mass function is \( f = 15.5 M_\odot \)
• Neutron stars & black holes in close binaries??
• It was known that the initially more massive stars should first evolve and explode in SN
• From Virial theorem: the orbit of the post-SN system should be disrupted if more than half of the total mass of the binary is suddenly ejected (Blaauw 1961)

⇒ Due to large mass-scale transfer for X-ray binaries like Cen X-3

• Formation of LMXB ($M_{\text{donor}} \leq 1.5 M_\odot$) with orbital periods mostly between 11 min to 12 hr
• the discovery of the double neutron star system PSR 1913+16 (Hulse & Taylor 1975) with an orbital period of 7.75 hr.

⇒ Large amount of orbital angular momentum loss
Model

- From the models generated by several astrophysicists of that time we now know that a neutron star is captured by the expansion of a giant companion star and is forced to move through the giant’s envelope.
- The resulting frictional drag will cause its orbit to shrink rapidly while, at the same time, ejecting the envelope before the naked core of the giant star explodes to form another neutron star.
- The other neutron star in the system was then produced by the second supernova explosion and must be a young, strong B-field neutron star.
- The fact that millisecond pulsars are found in LMXBs was confirmed with the discovery of the first millisecond X-ray pulsar in the LMXB system SAX 1808.4–3658 (Wijnands & van der Klis 1998).
- “kick” imparted to newborn neutron stars as a result of an asymmetric SN is another evidence explaining the space velocities of pulsars and the dynamical effects on surviving binaries.
Compact binaries and their observational properties

- High-mass X-ray binaries (HMXBs)
- Low-mass X-ray binaries (LMXBs)
- Intermediate-mass X-ray binaries (IMXBs)
- Soft X-ray transients (SXTs)
- Peculiar X-ray binaries
- The binary and millisecond radio pulsars

90% of the strong Galactic X-Ray sources
Fig. 1. Examples of a typical HMXB (top) and LMXB (bottom). The neutron star in the HMXB is fed by a strong high-velocity stellar wind and/or by beginning atmospheric Roche-lobe overflow. The neutron star in an LMXB is surrounded by an accretion disk which is fed by Roche-lobe overflow.

High-mass X-ray binaries (HMXBs)

- ~ 130 known HMXBs (25 have well-measured orbital parameters)
- ~40 pulsating HMXB sources with typical pulse periods between 10 and 300s (the entire observed range spans between 0.069 seconds and 20 minutes)

- Among the systems with $P_{\text{orb}} \leq 10$ days and $e \leq 0.1$ are the strong sources and “standard” systems such as Cen X-3 and SMC X-1
  - Characterized by regular X-ray eclipses and double-wave ellipsoidal light variations produced by tidally deformed (“pear-shaped”) giant or sub-giant companion stars with masses $>10M_{\odot}$
  - the optical luminosities ($L_{\text{opt}} > 10^5L_{\odot}$) and spectral types of the companions indicate original ZAMS masses $\geq 10M_{\odot}$, corresponding to O-type progenitors
  - The companions have radii $10−30 R_{\odot}$
  - there are absorption/emission features in the X-ray spectrum that are most probably cyclotron lines, resulting from magnetic fields with strengths $B \cong 5 \times 10^{12}$ G (Kirk & Trumper 1983). (X0115+63 source)
  - at least two systems that are thought to harbor black holes: Cyg X-1 and LMC X-3
- HMXBs are located along the Galactic plane among their OB-type progenitor stars
Be-star X-ray binaries

- $P_{\text{orb}} \approx 20-100$ days and $e \approx 0.3-0.5$
- $P_{\text{orb}} \approx 30-250$ days and $e \leq 0.2$

a separate sub-class of HMXBs: **Be-star X-ray binaries**

- the companions are rapidly rotating B-emission stars situated on, or close to, the main sequence (luminosity class III–V)
- more than 50 such systems
- Be-stars are deep inside their Roche-lobes (indicated by their generally long orbital periods, 15 days, and by the absence of X-ray eclipses and of ellipsoidal light variations)
- companion stars have masses in the range about 8–20$M_\odot$
- the X-ray emissions are extremely variable, ranging from complete absence to giant transient outbursts lasting weeks to months.
- Transient sources
Fig. 2. Schematic model of a Be-star X-ray binary system. The neutron star moves in an eccentric orbit around the Be-star which is not filling its Roche-lobe. However, near the periastron passage the neutron star accretes circumstellar matter, ejected from the rotating Be-star, resulting in an X-ray outburst lasting several days.

Low-mass X-ray binaries (LMXBs)

- 30 systems have measured orbital periods
- range from 11 minutes to 17 days (similar to the orbital periods of cataclysmic variables)
- The spectrum of the optical companion can be seen only in the widest few of them (in others the optical spectrum of accretion disk is seen)
- The LMXBs are very seldom X-ray pulsars
- These sources show X-ray bursts
- The discovery of QPOs in the X-ray flux of LMXBs has provided a clear timing signature of the accreting neutron stars and black holes in these systems.
- There are more than a dozen LMXBs systems for which there is strong evidence for the presence of a black hole
- Located mostly in Galactic bulge and globular clusters ➔ old stellar population
- They do not show considerable run-away characteristics.
Table 2. **The two main classes of strong Galactic X-ray sources**

<table>
<thead>
<tr>
<th></th>
<th>HMXB</th>
<th>LMXB</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-ray spectra</td>
<td>( kT \geq 15 \text{ keV} ) (hard)</td>
<td>( kT \leq 10 \text{ keV} ) (soft)</td>
</tr>
<tr>
<td>Type of time variability</td>
<td>regular X-ray pulsations</td>
<td>only a very few pulsars</td>
</tr>
<tr>
<td></td>
<td>no X-ray bursts</td>
<td>often X-ray bursts</td>
</tr>
<tr>
<td>Accretion process</td>
<td>wind (or atmos. RLO)</td>
<td>Roche-lobe overflow</td>
</tr>
<tr>
<td>Timescale of accretion</td>
<td>( 10^5 ) yr</td>
<td>( 10^7 - 10^9 ) yr</td>
</tr>
<tr>
<td>Accreting compact star</td>
<td>high B-field NS (or BH)</td>
<td>low B-field NS (or BH)</td>
</tr>
<tr>
<td>Spatial distribution</td>
<td>Galactic plane</td>
<td>Galactic center and spread around the plane</td>
</tr>
<tr>
<td>Stellar population</td>
<td>young, age &lt; ( 10^7 ) yr</td>
<td>old, age &gt; ( 10^9 ) yr</td>
</tr>
<tr>
<td>Companion stars</td>
<td>luminous, ( L_{opt}/L_X &gt; 1 )</td>
<td>faint, ( L_{opt}/L_X \ll 0.1 )</td>
</tr>
<tr>
<td></td>
<td>early-type O(B)-stars ( &gt;10 \text{ M}_\odot ) (Pop. I)</td>
<td>blue optical counterparts ( \leq 1 \text{ M}_\odot ) (Pop. I and II)</td>
</tr>
</tbody>
</table>

Intermediate-mass X-ray binaries (IMXBs)

- Binaries with companion star masses in the interval $1–10M_\odot$
- not easily observed because:
  - not massive enough to produce wind mass-loss rates to power an X-rays observable source.
  - when IMXBs evolve through RLO, it is very short lived (only a few 1000yr)
  - the very high mass-transfer rates make the X-rays to be absorbed from gas surrounding the accreting
- IMXBs explain the formation of binary pulsars with heavy CO or ONeMg white dwarf companions
- Her X-1 and Cyg X-2
- Among the black hole X-ray binaries, IMXBs are more common GRO J1655–40 ($M_d \sim 1.5 M_\odot$); 4U 1543–47 ($M_d \sim 2.5 M_\odot$); LMC X-3 ($M_d \sim 5 M_\odot$); 4U 1543–47 ($M_d \sim 1.5 M_\odot$)
- The mass transfer of these systems via RLO is stable because $M_d$ is less.
Soft X-ray transients (SXTs)

- Black hole systems with a low mass donor star discovery by McClintock and Remillard (1986)
- appear as bright X-ray novae with luminosities $L_X \sim 10^{38}$ erg/s for several weeks
- at the same time, the optical luminosity of these systems brightens by 6 to 10 magnitudes
- After the decay of the X-ray and optical emission, the spectrum of a K or G star becomes visible
- Their orbital periods are between 8 hours and 6.5 days
- A0620–00 with companion K5V ($\geq 740$ km/s), a spectroscopic binary with $P_{\text{orb}} = 7.75$ hr
Peculiar X-ray binaries

- Not all observed X-ray binaries fall into the well-defined SS433 and Cyg X-3, which both have flaring radio emissions and jets.
- Cyg X-3 ($P_{\text{orb}} = 4.8 \text{ hr}$) is probably a later evolutionary phase of a wide HMXB.
The binary and millisecond radio pulsars

- The 50 or so Galactic binary radio pulsars have usually short spin periods, $P$, and small values of period derivative, $\dot{P}$.

\[ B = \sqrt{\frac{3c^3 I}{8\pi^2 R^6}} P \dot{P} \simeq 3 \times 10^{19} \sqrt{P \dot{P}} \text{ gauss}^\text{5g/cm}^2 \]

\[ \tau \equiv \frac{P}{2 \dot{P}} \]

- There are four classes of binary pulsars detected:
  (i) high-mass binary pulsars (HMBPs) with a neutron star or ONeMg/CO white dwarf companion
  (ii) low-mass binary pulsars (LMBPs) with a helium white dwarf companion
  (iii) non-recycled pulsars with a CO white dwarf companion
  (iv) pulsars with an unevolved companion
Fig. 3. $P$–$\dot{P}$ diagram of $\sim$1300 observed radio pulsars (ATNF Pulsar Catalogue data). Binary pulsars are marked by a circle. Soft gamma-ray repeaters (SGR) and anomalous X-ray (AXP) pulsars are marked by stars and triangles, respectively. Also shown are lines of constant surface dipole magnetic field strength (dashed) and characteristic ages (dotted). The arrows marked on a few young pulsars indicate a measurement of the braking index. The “death line” is the pair-creation limit for generating radio pulses.

Table 3. *Main categories and types of binaries with compact objects*

<table>
<thead>
<tr>
<th>Main type</th>
<th>Sub-type</th>
<th>Observed example</th>
<th>$P_{\text{orb}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>X-ray binaries</em></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>high-mass donor ($M_{\text{donor}} \geq 10 , M_\odot$)</td>
<td>“standard” HMXB</td>
<td>Cen X-3</td>
<td>2.087$^d$ (NS)</td>
</tr>
<tr>
<td></td>
<td>Cyg X-1</td>
<td>5.60$^d$ (BH)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>X Per</td>
<td>250$^d$ (NS)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>wide-orbit HMXB</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Be-star HMXB</td>
<td>A0535+26</td>
<td>104$^d$ (NS)</td>
</tr>
<tr>
<td>low-mass donor ($M_{\text{donor}} \leq 1 , M_\odot$)</td>
<td>Galactic disk LMXB</td>
<td>Sco X-1</td>
<td>0.86$^d$ (NS)</td>
</tr>
<tr>
<td></td>
<td>soft X-ray transient</td>
<td>A0620–00</td>
<td>7.75$^{hr}$ (BH)</td>
</tr>
<tr>
<td></td>
<td>globular cluster</td>
<td>X 1820–30</td>
<td>11$^{\text{min}}$ (NS)</td>
</tr>
<tr>
<td></td>
<td>millisecond X-ray pulsar</td>
<td>SAX J1808.4–36</td>
<td>2.0$^d$ (NS)</td>
</tr>
<tr>
<td>intermediate-mass donor</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>($1 &lt; M_{\text{donor}}/M_\odot &lt; 10$)</td>
<td>Her X-1</td>
<td>1.7$^d$ (NS)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cyg X-2</td>
<td>9.8$^d$ (NS)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>V 404 Cyg</td>
<td>6.5$^d$ (NS)</td>
<td></td>
</tr>
<tr>
<td><em>Binary radio pulsars</em></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>“high-mass” companion ($0.5 \leq M_c/, M_\odot \leq 1.4$)</td>
<td>NS + NS (double)</td>
<td>PSR 1913+16</td>
<td>7.75$^{hr}$</td>
</tr>
<tr>
<td></td>
<td>NS + (ONeMg) WD</td>
<td>PSR 1435–6100</td>
<td>1.35$^d$</td>
</tr>
<tr>
<td></td>
<td>NS + (CO) WD</td>
<td>PSR 2145–0750</td>
<td>6.84$^d$</td>
</tr>
<tr>
<td>“low-mass” companion ($M_c &lt; 0.45 , M_\odot$)</td>
<td>NS + (He) WD</td>
<td>PSR 0437–4715</td>
<td>5.74$^d$</td>
</tr>
<tr>
<td>non-recycled pulsar</td>
<td>(CO) WD + NS</td>
<td>PSR 1640+2224</td>
<td>175$^d$</td>
</tr>
<tr>
<td>unevolved companion</td>
<td>B-type companion</td>
<td>PSR 1259–63</td>
<td>3.4$^{\text{rr}}$</td>
</tr>
<tr>
<td></td>
<td>low-mass companion</td>
<td>PSR 1820–11</td>
<td>357$^d$</td>
</tr>
<tr>
<td><em>CV-like binaries</em></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>novae-like systems</td>
<td>($M_{\text{donor}} \leq M_{\text{WD}}$)</td>
<td>DQ Her</td>
<td>4.7$^{hr}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SS Cyg</td>
<td>6.6$^{hr}$</td>
</tr>
<tr>
<td>super-soft X-ray sources</td>
<td>($M_{\text{donor}} &gt; M_{\text{WD}}$)</td>
<td>CAL 83</td>
<td>1.04$^d$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CAL 87</td>
<td>10.6$^{hr}$</td>
</tr>
<tr>
<td>AM CVn systems (RLO)</td>
<td>(CO) WD + (He) WD</td>
<td>AM CVn</td>
<td>22$^{\text{min}}$</td>
</tr>
<tr>
<td>double WD (no RLO)</td>
<td>(CO) WD + (CO) WD</td>
<td>WD1204+450</td>
<td>1.6$^d$</td>
</tr>
<tr>
<td>sdB-star systems</td>
<td>(sdB) He-star + WD</td>
<td>KPD 0422+5421</td>
<td>2.16$^{hr}$</td>
</tr>
</tbody>
</table>
Summary of the evolution of single stars

• self-gravitating gas in hydrostatic equilibrium
• **massive star** \((M \geq 10 \, M_{\odot})\) evolves through cycles of nuclear burning \(\rightarrow\) core mass larger than Chandrasekhar limit \(\rightarrow\) core implodes
  \(\rightarrow\) gravitation energy \((4 \times 10^{53} \, \text{erg} \sim 0.15 \, M_{\text{core}} \, c^2)\)
  \(\gg\) binding energy of the stellar envelope
• The speed of supernova particles \(\sim 10^4 \, \text{km/s}\)
• The final stages during and beyond carbon burning are very short-lived \((\sim 60 \, \text{yr for a } 25M_{\odot} \, \text{star})\)
- **Less massive stars** ($M < 8 \, M_\odot$) occur degeneracy in the core at a certain point of evolution.
- No stabilizing expansion and subsequent cooling after the ignition (since for a degenerate gas the pressure depends on density and not on temperature).
- The sudden temperature rise produce ’flash’
- $M < 2.3 \, M_\odot \implies$ degenerate during H-shell burning,
- $M_{\text{He}} = 0.45 \, M_\odot \implies$ helium ignites with a flash
- $2.3 < M/ \, M_\odot < 8 \implies$ stars ignite carbon with a flash

- Stars in close binary systems will have lost their envelope as a result of mass transfer via Roche-lobe overflow.
Table 4. *End products of stellar evolution as a function of initial mass*

<table>
<thead>
<tr>
<th>Initial mass (£M⊙)</th>
<th>He-core mass (£M⊙)</th>
<th>Single star</th>
<th>Binary star</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 2.3</td>
<td>&lt; 0.45</td>
<td>CO white dwarf</td>
<td>He white dwarf</td>
</tr>
<tr>
<td>2.3—6</td>
<td>0.5—1.9</td>
<td>CO white dwarf</td>
<td>CO white dwarf</td>
</tr>
<tr>
<td>6—8</td>
<td>1.9—2.1</td>
<td>O-Ne-Mg white dwarf or C-deflagration SN?</td>
<td>O-Ne-Mg white dwarf</td>
</tr>
<tr>
<td>8—12</td>
<td>2.1—2.8</td>
<td>neutron star</td>
<td>O-Ne-Mg white dwarf</td>
</tr>
<tr>
<td>12—25</td>
<td>2.8—8</td>
<td>neutron star</td>
<td>neutron star</td>
</tr>
<tr>
<td>&gt; 25</td>
<td>&gt; 8</td>
<td>black hole</td>
<td>black hole</td>
</tr>
</tbody>
</table>
Three timescales of stellar evolution

1. **Dynamical or pulsational timescale** (when the hydrostatic equilibrium of a star is disturbed)

\[ \tau_{\text{dyn}} = \sqrt{\frac{R^3}{GM}} \simeq 50 \text{ min} \left( \frac{R}{R_\odot} \right)^{3/2} \left( \frac{M}{M_\odot} \right)^{-1/2} \]

2. **Thermal (or Kelvin–Helmholtz) timescale** (when the thermal equilibrium of a star is disturbed)

\[ \tau_{\text{th}} = \frac{GM^2}{RL} \simeq 30 \text{ Myr} \left( \frac{M}{M_\odot} \right)^{-2} \]

3. **Nuclear timescale** (time needed for the star to exhaust its nuclear fuel reserve)

\[ \tau_{\text{nuc}} \simeq 10 \text{ Gyr} \left( \frac{M}{M_\odot} \right)^{-2.5} \]
The variation of the outer radius during stellar evolution

Fig. 5. Stellar evolutionary tracks in the H-R diagram

Eggleton’s evolutionary code
Fig. 6. Evolutionary change of the radius of the $5M_\odot$ star plotted in Fig. 5. The ranges of radii for mass transfer to a companion star in a binary system according to RLO cases A, B and C are indicated. (Der Klis, M., & Lewin, W., (Eds.). (2006). Compact Stellar X-Ray Sources, New York, NY: Cambridge University Press)
The core mass–radius relation for low-mass RGB stars

• For a low-mass star \((2.3 \leq M_\odot)\) on RGB

  \(M_{\text{core}} \propto L\) (as this luminosity is entirely generated by hydrogen shell burning)

• When moving to Hayashi track its luminosity increases strongly

  ➔ relation between giant’s radius and the mass of its degenerate helium core

• Very important for LMXBs and wide-orbit binary pulsars because it gives the relationship between orbital period and white dwarf mass.
The evolution of helium stars

- For low mass star, the evolution of helium core is independent of hydrogen-rich envelope
- For more massive stars ($>2.3M_\odot$) the evolution of the core of an isolated star differs from that of a naked helium star
- low-mass helium stars ($M_{\text{He}} < 3.5M_\odot$) swell up to large radii during their late evolution $\rightarrow$ additional mass transfer from the naked helium star to its companion

- For ($Z = 0.03, Y = 0.97$) the helium star ZAMS radii as a function of mass is

$$R_{\text{He}} = 0.212(M_{\text{He}}/M_\odot)^{0.654} R_\odot$$
Fig. 7. Evolutionary tracks of 2.5–6.4M helium stars ($Y = 0.98, Z = 0.02$). The final stellar mass (after wind mass loss) is written at the end of the tracks. The expansion of low-mass helium stars in close binaries often results in a second mass-transfer phase (case BB RLO). (Der Klis, M., & Lewin, W., (Eds.). (2006). *Compact Stellar X-Ray Sources*, New York, NY: Cambridge University Press)
the rate of intense-wind mass loss from Wolf–Rayet (massive) stars is not fully clear.

A best-estimate fit to the wind mass-loss rate of Wolf–Rayet stars is given by Dewi et al. (2002).

\[
\dot{M}_{\text{He, wind}} = \begin{cases} 
2.8 \times 10^{-13} (L/L_\odot)^{1.5} \, M_\odot \, \text{yr}^{-1}, & \log (L/L_\odot) \geq 4.5 \\
4.0 \times 10^{-37} (L/L_\odot)^{6.8} \, M_\odot \, \text{yr}^{-1}, & \log (L/L_\odot) < 4.5
\end{cases}
\]

Is the helium star is “naked” or “embedded”??

Uncertainty in threshold

If isolated star this happens above an initial stellar mass of \(\geq 19 \, M_\odot\) as iron core occurs to \(\geq 1.9 \, M_\odot\) (Woosley & Weaver 1995)

Doesn’t loose very much mass through wind and its burning stages continue until black hole
Roche-lobe overflow: cases A, B and C

- Effective gravitational potential in a binary system is determined

\[ \Phi = - \frac{GM_1}{r_1} - \frac{GM_2}{r_2} - \frac{\Omega^2 r_3^2}{2} \]

- \( R_L / a = \frac{0.49 q^{2/3}}{0.6 q^{2/3} + \ln(1 + q^{1/3})} \)

- \( q = M_{\text{donor}} / M_{\text{accretor}} \)
  - a: orbital separation
Fig. 9. A cross-section in the equatorial plane of the critical equipotential surfaces in a binary. The thick curve crossing through $L_1$ is the Roche-lobe.

A star born in a close binary system with radius smaller than that of the Roche-lobe may begin RLO either because the binary shrinks sufficiently as a result of orbital angular momentum losses or because of expansion of its envelope at a later evolutionary stage.

The further evolution of the system will depend on:
1. the evolutionary state,
2. structure of the donor star (determined by $M_{\text{donor}}$ and $a$),
3. Nature of the accreting star.

Kippenhahn and Weigert (1967) define three types of RLO:

- **Case A** → the system is so close that the donor star begins to fill its Roche-lobe during core-hydrogen burning
- **Case B** → the primary star begins to fill its Roche-lobe after the end of core-hydrogen burning but before helium ignition
- **Case C** → it overflows its Roche-lobe during helium shell burning or beyond
Common envelope evolution

• It is accompanied by drag force that is created from the motion of the companion star through the envelope of the evolved star
  • dissipation of orbital angular momentum
  • deposition of orbital energy in the envelope

• CE-phase $\rightarrow$ reduces the binary separation
  $\rightarrow$ often ejects the envelope

• PSR 1913+16, PSR J1756–5322 and L 870–2

• angular momentum transfer,
• dissipation of orbital energy and
• structural changes of the donor star take place on very short timescales ($\sim 10^3$ yr) as the evolution is often tidal unstable.
• by equating the binding energy of the envelope of the (sub)giant donor to the required difference in orbital energy (before and after the CE-phase) \( \rightarrow \) reduction of the orbital separation

• \( 0 < \eta_{\text{CE}} < 1 \) (efficiency of ejecting the envelope)

• \( E_{\text{env}} \equiv \eta_{\text{CE}} E_{\text{orb}} \) or

\[
\frac{G M_{\text{donor}} M_{\text{env}}}{\lambda a_i r_L} \equiv \eta_{\text{CE}} \left[ \frac{G M_{\text{core}} M_1}{2 a_f} - \frac{G M_{\text{donor}} M_1}{2 a_i} \right]
\]

• yielding the ratio of final (post-CE) to initial (pre-CE) orbital separation:

\[
\frac{a_f}{a_i} = \frac{M_{\text{core}} M_1}{M_{\text{donor}}} \frac{1}{M_1 + 2 M_{\text{env}}/(\eta_{\text{CE}} \lambda r_L)}
\]

• The orbital separation of the surviving binaries is quite often reduced by a factor of \( \sim 100 \) as a result of the spiral-in.

• If there is not enough orbital energy available to eject the envelope the stellar components will merge in this process.
The binding energy of the envelope

\[ E_{\text{bind}} = - \int_{M_{\text{core}}}^{M_{\text{donor}}} \frac{GM(r)}{r} \, dm + \alpha_{\text{th}} \int_{M_{\text{core}}}^{M_{\text{donor}}} U \, dm \]

- The parameter \( \lambda \) can be calculated for different evolutionary stages of a given star by using the above eqns. (Dewi and Tauris (2000))
- 3–10 \( M_\odot \) massive stars \( \Rightarrow \lambda < 1 \) on the RGB, \( \lambda \gg 1 \) on the AGB
- \( \rightarrow \) the envelopes of these donor stars on the AGB are easily ejected; with only a relatively modest decrease in orbital separation resulting from the spiral-in.
- \( M > 10 M_\odot \) \( \Rightarrow \lambda < 0.1–0.01 \) and the internal energy is not very dominant.
Fig. 11. The $\lambda$-parameter for a 20M star as a function of stellar radius. The upper curve includes internal thermodynamic energy ($\alpha_{th} = 1$) whereas the lower curve is based on the sole gravitational binding energy ($\alpha_{th} = 0$). It is a common misconception to use a constant value of $\lambda = 0.5$ (marked by the dashed line).

(Asymmetric) supernova explosions in close binaries

- After a close binary star has lost its H-envelope during RLO and/or CE evolution it will collapse and explode in a supernova (SN) if it is massive enough

- Critical threshold mass for a helium star $\rightarrow 2.8 \, M_\odot$ and somewhat lower for a CO-star
- Corresponds to initial mass of $10 \, M_\odot$ ($\sim 10 \, M_\odot$ for case C, and $\sim 12 \, M_\odot$ for case B/A RLO)

- If the core mass is below this critical threshold mass the star contracts, and settles peacefully as a cooling white dwarf

- If $M_{He} \geq 8 \, M_\odot$ the supernova leaves behind a black hole

- Neutron stars in LMXBs may afterwards possibly accrete up to $\sim 1 \, M_\odot$ before collapsing further into a black hole
• New born neutrons stars receive momentum kick at birth which gives them rise to the high velocities observed.
• Black holes??

For each binary and a sufficiently high value of $w$ there exists a critical angle, $\theta_{\text{crit}}$, for which a SN with $\theta < \theta_{\text{crit}}$ will result in disruption of the orbit.

Orbital energy of a binary:

$$E_{\text{orb}} = -\frac{G M_1 M_2}{2a}$$

Change of the semi-major axis:

$$\frac{a}{a_0} = \left[ \frac{1 - (\Delta M / M)}{1 - 2(\Delta M / M) - (w/v_{\text{rel}})^2 - 2 \cos \theta (w/v_{\text{rel}})} \right]$$

Amount of matter lost in the SN:

$$\text{Amount of matter lost} = \frac{1 - (\Delta M / M)}{1 - 2(\Delta M / M) - (w/v_{\text{rel}})^2 - 2 \cos \theta (w/v_{\text{rel}})}$$

Relative velocity of the two stars in a circular pre-SN binary:

$$\frac{1}{2} \mu v_{\text{rel}}^2$$

Direction of the kick relative to the orientation of the pre-SN velocity:

Magnitude of the kick velocity:

For each binary and a sufficiently high value of $w$ there exists a critical angle, $\theta_{\text{crit}}$, for which a SN with $\theta < \theta_{\text{crit}}$ will result in disruption of the orbit.
• The sudden mass loss in the SN affects the bound orbit with an eccentricity

\[ e = \sqrt{1 + \frac{2E_{\text{orb}}L_{\text{orb}}^2}{\mu G^2 M_1^2 M_2^2}} \]

\[ L_{\text{orb}} = |r \times p| = r \mu \sqrt{(v_{\text{rel}} + w \cos \theta)^2 + (w \sin \theta \sin \phi)^2} \]

• Systems surviving the SN will receive a recoil velocity from the combined effect of instant mass loss and a kick.

• When a star with mass \( M_{\text{core}} \) collapsing to form a neutron star with mass \( M_{\text{NS}} \):

\[ v_{\text{sys}} = \sqrt{\frac{\Delta P_x^2 + \Delta P_y^2 + \Delta P_z^2}{(M_{\text{NS}} + M_2)}} \]

where the change in momentum is

\[ \Delta P_x = M_{\text{NS}}(v_{\text{core}} + w \cos \theta) - M_{\text{core}} v_{\text{core}} \]

\[ \Delta P_y = M_{\text{NS}} w \sin \theta \cos \phi \]

\[ \Delta P_z = M_{\text{NS}} w \sin \theta \sin \phi \]
Fig. 12. Cartoon depicting the evolution of a binary system eventually leading to an LMXB and finally the formation of a binary millisecond pulsar. Parameters governing the specific orbital angular momentum of ejected matter, the common envelope and spiral-in phase, the asymmetric supernova explosion and the stellar evolution of the naked helium star all have a large impact on the exact evolution. Parameters are given for a scenario leading to the formation of the observed binary millisecond pulsar PSR 1855+09. The stellar masses given are in solar units.

Evolution of LMXBs: formation of millisecond pulsars

- more than 40 binary millisecond pulsars (BMSPs) known in the Galactic disk
- **class A:** wide-orbit ($P_{\text{orb}} > 20$ days) BMSPs with low-mass helium white dwarf companions ($M_{\text{WD}} < 0.45M$)
- **class B:** close-orbit BMSPs ($P_{\text{orb}} \geq 15$ days) with low-mass helium white dwarf companions
- **class C:** close-orbit BMSPs ($P_{\text{orb}} \geq 15$ days) with relatively heavy CO/O-Ne-Mg white dwarf companions

- Class C evolved through a phase with significant loss of angular momentum and descends from IMXBs with donors $2 < M_2 / M_\odot < 8$

- The single MSPs are believed to originate from tight class B systems where the companion has been destroyed or evaporated – either from X-ray irradiation when the neutron star was accreting, or in the form of a pulsar radiation/wind of relativistic particles
Fig. 13. The evolution of an IMXB leading to the formation of a BMSP with a CO WD companion in a close orbit. The initial configuration was a 4M donor star and a neutron star with an orbital period of 4 days. The mass-transfer phase is between points A and B. Between points f and g helium is burning in the core of the stripped companion star.

Formation of wide-orbit binary millisecond pulsars

- In LMXBs with initial $P_{\text{orb}} > 2$ days the mass transfer is driven by internal thermonuclear evolution of the donor star since it evolves into a (sub)giant before loss of orbital angular momentum dominates.

- ‘growth in core mass $\propto L’$ of a donor star in RGB
  $\rightarrow R_{\text{giant}} \propto M_{\text{core}}$ independent of envelope mass.

<table>
<thead>
<tr>
<th>$M_{\text{initial}}/M_\odot$</th>
<th>1.0*</th>
<th>1.6*</th>
<th>1.0**</th>
<th>1.6**</th>
</tr>
</thead>
<tbody>
<tr>
<td>log $L/L_\odot$</td>
<td>2.644</td>
<td>2.723</td>
<td>2.566</td>
<td>2.624</td>
</tr>
<tr>
<td>log $T_{\text{eff}}$</td>
<td>3.573</td>
<td>3.593</td>
<td>3.554</td>
<td>3.569</td>
</tr>
<tr>
<td>$M_{\text{core}}/M_\odot$</td>
<td>0.342</td>
<td>0.354</td>
<td>0.336</td>
<td>0.345</td>
</tr>
<tr>
<td>$M_{\text{env}}/M_\odot$</td>
<td>0.615</td>
<td>1.217</td>
<td>0.215</td>
<td>0.514</td>
</tr>
</tbody>
</table>

* Single star ($X = 0.70$, $Z = 0.02$ and $\alpha = 2.0$, $\delta_{\text{ov}} = 0.10$).
** Binary star (at onset of RLO: $P_{\text{orb}} \simeq 60$ days and $M_{\text{NS}} = 1.3$ $M_\odot$).

After Tauris & Savonije (1999).

Table 5. Stellar parameters for giant stars with $R = 50.0$ $R_\odot$. 
• Core mass determines the rate of mass transfer.
• the core mass is uniquely correlated with $P_{\text{orb}}$ of the system since from the moment the star begins RLO.

\[ M_{\text{WD}} = \left( \frac{P_{\text{orb}}}{b} \right)^{1/a} + c \]

\[(a, b, c) = \begin{cases} 4.50 & 1.2 \times 10^5 & 0.120 & \text{Pop. I} \\ 4.75 & 1.1 \times 10^5 & 0.115 & \text{Pop. I+II} \\ 5.00 & 1.0 \times 10^5 & 0.110 & \text{Pop. II} \end{cases} \]

• model predicted rather massive ($>2M_{\odot}$), $P_{\text{orb}} < 30$ days, it failed to explain the mass of PSR B1855+09 ($P_{\text{orb}} = 12.3$ days), $<1.55M_{\odot}$

• large amount of matter must be lost from the LMXB even for sub-Eddington accretion – probably as a result of either accretion disk instabilities or propeller effect
Fig. 16.14. Evolutionary tracks of four LMXBs showing $P_{\text{orb}}$ as a function of $M_{\text{core}}$ of the donor star. The initial donor masses were 1.0 and 1.6M (each calculated at two different initial $P_{\text{orb}}$) and the initial neutron star mass was 1.3M. The total mass of the donors during the evolution is written along the tracks. At the termination of the mass-transfer process the donor only has a tiny ($\leq 0.01$M) H-envelope and the end-points of the evolutionary tracks are located near the curve representing the $(P_{\text{orb}}, M_{\text{WD}})$ correlation for BMSPs. After Tauris & Savonije (1999).

Formation of close-orbit binary millisecond pulsars

- In LMXBs with initial $P_{\text{orb}} < 2$ days the mass transfer is driven by loss of angular momentum due to magnetic braking and gravitational wave radiation.
- The evolution of such systems is very similar to the evolution of CVs.
Masses of binary neutron stars

- Generally only estimated from their observed mass function, which depends on the unknown orbital inclination angle.

- Only in a few tight systems is it possible to directly measure post-Newtonian parameters which yield precise values of the stellar masses.

- PSR 1913+16 the (gravitational) masses are known to be 1.441 and 1.387 $M_\odot$.

- According to standard model the recycled pulsars in double neutron star systems did not have a chance to accrete much material because of the short-lived common envelope and spiral-in phase that these systems evolved through.
**Evolution of HMXBs**

<table>
<thead>
<tr>
<th>Event</th>
<th>Parameters</th>
<th>Age</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZAMS</td>
<td></td>
<td>0.0 Myr</td>
</tr>
<tr>
<td>Roche-lobe overflow</td>
<td>14.4 8.0</td>
<td>100 days</td>
</tr>
<tr>
<td>helium star</td>
<td>14.1 3.5</td>
<td>13.3 Myr</td>
</tr>
<tr>
<td>1. supernova</td>
<td>16.5 3.3</td>
<td>15.0 Myr</td>
</tr>
<tr>
<td>neutron star</td>
<td>16.5 1.4</td>
<td>15.0 Myr</td>
</tr>
<tr>
<td>HMXB</td>
<td>1300 days</td>
<td>24.6 Myr</td>
</tr>
<tr>
<td>common envelope + spiral-in</td>
<td></td>
<td>2.6 hrs.</td>
</tr>
<tr>
<td>helium star RLO</td>
<td>14 4.1</td>
<td>25.6 Myr</td>
</tr>
<tr>
<td>2. supernova</td>
<td>1.4 2.6</td>
<td>25.6 Myr</td>
</tr>
<tr>
<td>recycled pulsar</td>
<td>1.4 1.4</td>
<td>25.6 Myr</td>
</tr>
<tr>
<td>young pulsar (PSR 1913+16)</td>
<td></td>
<td>7.8 hrs.</td>
</tr>
</tbody>
</table>

*Fig. 15.* Cartoon depicting the formation of a Be-star/HMXB and finally a double neutron star system. Such a binary will experience two supernova explosions. In a double pulsar system the recycled pulsar is most likely to be observed as a result of its very long spin-down timescale compared to the young pulsar (a factor of $\sim 10^2$). Tight NS–NS systems will coalesce due to gravitational wave radiation.
Formation of double neutron star/black hole binaries

- Relatively massive stars $> 12 \, M_\odot$
- The first mass-transfer phase, from the primary to the secondary star, is usually assumed to be dynamically stable (semi-conservative) if the mass ratio at the onset of the RLO is not too extreme.
- later on all HMXBs end up in a common envelope phase as the neutron star (or low-mass black hole) is engulfed by the extended envelope of its companion, in an orbit that is rapidly shrinking due to heavy loss of orbital angular momentum.
- stellar winds of massive stars, as well as naked helium cores (Wolf–Rayet stars), are some of the most uncertain aspects of the modeling of HMXB evolution.
- there is an overlap in the mass range for making a neutron star versus a black hole.
Spin and B-field evolution of accreting neutron stars

- Most X-ray pulsars have spin periods between 10 and 1000 s
- HMXBs are powered by a combination of stellar wind and beginning atmospheric RLO
- In most of these systems the X-ray pulsars show a secular decrease of their pulse period (spin-up) on a relatively short timescale \((10^3-10^5 \text{ yr})\);
- the average trend is spin-up.
- In sources that are purely wind-fed the pulse periods are very long, and they vary erratically in time showing no clear secular trends.
- This is because the amount of angular momentum carried by the supersonic winds is negligible, and eddies form in the wind downstream of the neutron star, which alternately may feed co- and counter-rotating angular momentum to it.
The accretion and spin-evolution of a neutron star in a binary system depend on:

I. the magnetodipole radiation pressure

II. the ram pressure of the companion star wind

III. the radius of gravitational capture

IV. the location of the light cylinder

V. the Alfvén radius

VI. the co-rotation radius

VII. the propeller effect and whether or not an accretion disk is formed

The old binary neutron stars reappear as observable millisecond X-ray and radio pulsars.

Their so-called equilibrium spin period is given by

\[ P_{eq} \propto \dot{M}^{-3/7} B^{6/7} R_{NS}^{18/7} M_{NS}^{-5/7} \]
Fig. 17. Illustration of the magnetosphere surrounding a wind-accreting neutron star. The rotation period, the magnetic field strength and the ram pressure of the wind determine whether or not accretion onto the neutron star surface is possible. The spin axis and the magnetic field axis are misaligned (thus: a pulsar). X-rays are emitted along the magnetic field axis as the pulsar accretes near its magnetic poles.

The Eddington accretion limit

- LMXBs and HMXBs have luminosities $\sim 10^{34} - 10^{38}$ erg s$^{-1}$ and mass accretion rates $10^{-11} - 10^{-8} M_\odot$/yr

- When mass transfer exceeds $\dot{M}_{Edd} \sim 1.5 \times 10^{-8} M_\odot$/yr Eddington limit exceeded (at which the radiation pressure force on the accreting matter exceeds the gravitational attraction force of the compact star (Davidson & Ostriker 1973)

- $\dot{M}_{Edd} >$ the excess accreting matter will pile up around the compact object and form a cloud optically thick to X-rays

- However, mass transfer exceeding $10^{-4} M_\odot$/yr may still be dynamically stable

- In cases where super-Eddington mass transfer occurs, the excess material is ejected in a jet – e.g., as observed in the source SS433
Accretion-induced magnetic field decay

- It is often assumed that the magnetic field has been generated in the outer crust by some unspecified mechanism.
- The induction equation to calculate the magnetic field is:
  \[
  \frac{\partial \mathbf{B}}{\partial t} = -\frac{c^2}{4\pi} \nabla \times \left( \frac{1}{\sigma_{el}} \nabla \times \mathbf{B} \right) + \nabla \times (\mathbf{v} \times \mathbf{B})
  \]
  
  - Magnetic field decay is not fully understood.
Thank you 😊