Main questions

1. How do binary stars interact?
2. How does it affect the stars’ evolution?
3. How does the type of binary system fit into the binary evolution scenario?
Outline

Lecture 1
1. Roche-lobe approximation
2. Mass-transfer & its consequences
3. Evolutionary scenarios

Lecture 2
1. Exotic binary systems
2. Binaries producing Supernova events
3. Methods of observing/analyzing binary evolution
Binary Evolution can be more important then we thought!

In these lectures, we will touch upon a few examples:

- Massive Star Evolution
- Supernovae
- Exoplanets
Typical Evolutionary Tracks of Massive Stars (Single Star Evolution)

- Assuming single star tracks (Mzams): evolve along H-R diagram through mass loss.
- But ~70% of all massive stars: thought to be interacting binaries!
- At times high mass transfer!
- The “typical” evolution of a massive star from Mzams to end-stage is uncertain for most stars.

Conclusion: We need to model binary evolution to solve this problem!

*Smith, Nathan. 2014. Annual Reviews of Astronomy
Q: Give example on some processes that occur in binary stars that affect the binary evolution.

A: Angular momentum loss, changing orbital period, mass loss, the evolution of one star affects the other.
Different type of binary systems...

...have components with different masses, and are in different evolutionary states, and have different channels for mass-loss.

We will mainly be discussing:

- Cataclysmic variables
- X-ray binaries
Binary physics

Study of eclipsing systems are particularly favorable since it gives us orbital periods!
Keplerian Motion

Keplerian velocity:

\[ v = \sqrt{\frac{GM}{r}} \]

Circumference:

\[ 2\pi r \rightarrow P_{\text{orb}} = \frac{2\pi r}{v} \]

Combine:

\[ P_{\text{orb}}^2 = \frac{4\pi^2 r^3}{GM} \]

Newton’s generalisation of Kepler’s 3d law:

\[ P_{\text{orb}}^2 = \frac{4\pi^2 a^3}{G(M + m)} \]

- Binary star systems → periods, masses, radius, density
- Also important for finding masses of single stars through mass-luminosity relationship
  (First attempt: Eddington, 1924)
Roche-lobe approximation

3 main assumptions

1. Gravitation field of stars approximated as those of point masses.

2. Lowest energy = circular orbit (tidal interaction)

3. Forced synchronous rotation (removing initial eccentricity)
Roche-lobe approximation

The space around a star where material is gravitationally bound to that star.

- L1 = point of contact of the two Roche lobes
- Mass transfer occur if star overfills its Roche lobe.

**How?**

1. Roche lobe shrinks in size
2. or if the star expands its radius
3 cases:

- **Detached system:** evolution can be approximated to single star evolution

- **Semi-detached systems:** one star overfills its Roche lobe, expanding into L1 point

- **Contact binaries:** exchange mass and heat
Gray scale: three possible stable configurations: Detached (dark grey), semi-detached (grey), contact (light grey)
Roch-lobe overflow (RLOF) consequences

- Rotation and tidal distortion!
- To further understand the effects of RLOF - we must understand the time scales for stellar evolution
Stellar timescales

Important for understanding binary evolution

1. Dynamical time scale
2. Kelvin-Helmholtz (thermal)
3. Nuclear time scale
Dynamical timescale

\[ \tau_{\text{dyn}} = \frac{R}{c_s} \approx 0.04 \left( \frac{M_\odot}{M} \right)^{1/2} \left( \frac{R}{R_\odot} \right)^{3/2} \text{ day} \]

Time scale on which a star counteracts a perturbation of its hydrostatic equilibrium (HE)*

*HE: star is neither expanding nor contracting

Nuclear Energy Generation

Thermal pressure

Gravity

Radiation escapes from surface
Thermal timescale
Kelvin-Helmholtz

\[ \tau_{KH} = \frac{E_{\text{th}}}{L} \approx \frac{GM^2}{2RL} \approx 1.5 \times 10^7 \left( \frac{M}{M_\odot} \right)^2 \frac{R_\odot}{R} \frac{L_\odot}{L} \text{ yr} \]

Time scale on which the donor is able to adjust its structure to stay in thermal equilibrium (TE)*

*TE: E generated in the core = E transported to surface (radiated away)

Gravity
Thermal pressure
Nuclear Energy Generation
Radiation escapes from surface
Nuclear timescale

Time scale on which the star uses its nuclear fuel

\[ \tau_{\text{nuc}} = 0.007 \frac{M_{\text{core}} c^2}{L} \approx 10^{10} \frac{M}{M_\odot} \frac{L}{L_\odot} \text{ yr} \]
Roch-lobe overflow (RLOF) consequences

- RLOF can push the donor out of TE
- Donor is in TE if:

\[ \frac{\tau_{\dot{M}_2}}{M_2} = \frac{\dot{M}_2}{\ddot{M}_2} > \tau_{th} = \frac{GM^2}{L_2 R_2} \]

(Means that the donor can adjust as a response to mass-loss)

TE if low accretion rate: \[ \tau_{\dot{M}_2} \gg \tau_{th} \]
Non-TE if high accretion rate: \[ \tau_{\dot{M}_2} \ll \tau_{th} \]
Using CVs as an example

$T_{M_2} \sim T_{th}$

Can’t quite stay in TE $\rightarrow$
larger radius compared to MS stars by $\sim 30\%$

Cataclysmic Variable (CV)

White dwarf (primary)

loses mass

Late type main-sequence (donor)

$M = M\odot$

$R = R\odot$
Using CVs as an example

Mass - transferring system

The radius of a Roche-lobe filling star depends only on the binary separation and the mass ratio \( q = M_2/M_1 \) (Paczynski 1971)

\[
\frac{R_2}{a} \approx \frac{2}{3^{4/3}} \left( \frac{q}{1 + q} \right)^{1/3}
\]

\( P_{\text{orb}} \) depends on binary separation and masses (Newton’s generalization of Kepler’s 3d law):

\[
P = 2\pi \sqrt{\frac{a^3}{G(M_1 + M_2)}}
\]
Period-density relation

Combining these yields the well-known period-density relation for lobe-filling stars

\[
\bar{\rho}_2 = \frac{3M_2}{4\pi R_2^3} \approx \frac{95.4}{G} \frac{1}{P^2}
\]
Using CVs as an example

Special case: donor is a low-mass star near the main sequence
(for lower main sequence, we know that its radius and mass are approximately equal in solar units)

\[
\frac{M_2}{M_\odot} \approx \frac{R_2}{R_\odot} \approx 0.1 P_{hr}
\]

M and R (of donor) only depend on the \( P_{orb} \)
This results in the mass-radius/period relation

Knigge et al. 2006
Mass-transfer Qs:

- Why do mass-transfer start in the first place?
- What drives the mass-transfer?
- How are the stars affected by mass-transfer? \((q, P, a)\)
Mass-transfer

Assumption: mass-transfer is conservative

Orbital angular momentum of the binary system is given by:

\[ J_{\text{orb}} = \sqrt{G \frac{M_1^2 M_2^2}{M_1 + M_2}} a \]

Q: What does the following equation imply?

\[ \frac{d}{dt} (M_1 + M_2) = 0 \]

Assuming conservative mass-transfer

\[ \dot{M}_1 = -\dot{M}_2 \]

Conservation of angular momentum: (no angular momentum is lost due to mass leaving the system or to rotational angular momentum of stellar components)

\[ \frac{d}{dt} (J_{\text{orb}}) = 0 \]
Mass-transfer

Combining these equations yield:

\[ \frac{\dot{P}}{P} = \frac{3\dot{M}_1 (M_1 - M_2)}{M_1 M_2} \]

**Implications:**

★ Change of \( P_{\text{orb}} \) is proportional to change in \( M_{\text{dot}} \)!

★ sign depends on which star is loosing mass - the heavier or lighter (also, degeneracy matters).

★ prolonged, slow, conservative mass-transfer is achieved when the lighter star is the donor

★ In some cases: A small initial mass-transfer \( \rightarrow \) period decreases \( \rightarrow \) stars move closer together \( \rightarrow \) exponentially increase in mass-transfer rate!
Binary Evolution (leading to a CV)

Binaries start out as detached (no mass-exchange)

1. **Starts with two main-sequence stars** *(NOTE: lifetime is shorter for more massive stars)*

2. The more massive of the two first becomes a red giant. It will fill its Roche lobe and start transferring mass. However, a giant cannot decrease its radius to stabilize mass-transfer → **run-away mass-transfer phase**

3. **Mass is transferred faster than accepted by the donor → formation of common envelope (CE)** (phase can last 1000-10000 yrs). Orbital energy lost due to frictional interaction in the envelope material. **Orbital separation shrinks drastically.**

4. **Phase ends when the deposited energy exceeds the envelopes own binding energy → planetary nebula**

5. **Left is a compact object + MS star** (second detached phase lasts $10^7 - 10^8$ yrs)

6. **AML continues until donor is in contact with its Roche lobe and mass transfer begins again - now from the lower mass companion to the compact object.**
Binary Evolution: evidence of CE phase?

- UU Sagittae binary found in center of the planetary nebula Abell 63 (Abell 1966)

- Total-eclipsing, short $P_{\text{orb}}$ binary

- Currently a pre-cataclysmic variable

- Primary is a O subdwarf (sdO) not yet contracted to a WD (Bond et al. 1978)

- Secondary is a MS star (K or M dwarf)

- Short $P_{\text{orb}}$ + large-mass primary of 0.8 M$_\odot$

- Now THAT's a problem... core-M-L relation says a 0.8 M$_\odot$ WD only can be grown inside a giant (~1 AU in radius)

- $\rightarrow P_{\text{orb}}$ must have shrunk from ~1 yr to 11.7 hrs; within 30 000 yrs, the lifetime of a planetary nebula! (problem for AML)
Expansion due to nuclear evolution or angular momentum loss (AML) keep the donor in contact with its Roche lobe (even if the donor is shrinking) **Q: Why is the donor shrinking?**

Mechanisms to get rid of angular momentum
- *Magnetic stellar winds*
- *Gravitational wave radiation*
- *Tidal torques*
- *3-body interactions*

A detached binary can thus evolve into a semi-detached binary (or contact binary)
Mechanisms for AML

Gravitational wave radiation and magnetic braking

Magnetic braking:

donor has magnetic field & weak ionized wind → wind travels along field lines → wind co-rotates → magnetic braking torque → rot. vel removed. BUT synchronous rotation → MBT removes orbital angular momentum → decrease in P

Gravitational radiation simulation (black hole mergers)

What happens to magnetic breaking when a donor becomes fully convective? (dynamo is killed)
AML for magnetic braking - not so easy to understand in reality!

A comparison of all angular-momentum-loss recipes

- Plot shows: 0.75 M⊙ primary and unevolved Roche-lobe-filling MS donor
- Red line corresponds to GR-driven AML
- Orders of magnitude differences between recipes at fixed P
- Different recipes do not even agree in basic form
- The saturated ones don’t even beat GR below ~0.5 M⊙

Knigge et al. 2011
Binary evolution

Angular momentum loss drives the evolution of a binary!
Binary evolution for Supernova Ia progenitor

1. **Binary MS pair.** *Q: what factors will determine their evolutionary fate?*

2. The more massive star becomes a giant

3. → Run-away mass-transfer, engulfing both stars

4. AML increased due to friction in common envelope (CE)

5. CE is ejected, now with the components significantly closer together

6. Core of giant collapses to WD

7. The lower-mass companion ages and swells, AML continues shrink the orbit, accretion sets in

Evolution for Cygnus X-1

1. Starting with 2 hot MS stars: 20-25 $M_\odot$ + a larger mass companion

2. The heavier one is the first to become a red supergiant

3. When resources depleted, it explodes as a supernova

4. Left is a black hole orbiting the MS star (7-14 $M_\odot$) Q: where did the rest of the mass go?

5. AML → smaller orbit, settler wind accretion CURRENT SCENARIO!

6. Donor star evolves to a red supergiant, run-away mass-transfer sets in

7. Donor goes supernova, BH can absorb much of the gas from the explosion and grow

8. Q: What are the fate for the stars left?
Artist's impression of the evolution of a hot high-mass binary star (annotated version)

Simulation from ESO:
http://www.eso.org/public/videos/eso1230b/
What else can affect the evolution of a binary system?

- Mass-transfer onto WD leads to nova eruptions (every ~10000 yrs)

- Runaway thermo-nuclear runaway on the surface on the WD occur when a critical pressure is reached (critical envelope mass)

Q: How can this affect the evolution of the binary system?
The Algol paradox

- Red giant (RG) is the less massive one!

- Tranferring to a MS dwarf companion. **Q: How?**

- The RG used to be more massive, but has now transferred considerable mass to companion.
- Next week -

- Methods to analyse binary evolution
- A few exotic binary systems
- The role of binary systems in producing Supernovae
- Can planets influence binary evolution?
- Next week -

• Exercise: study the period evolution of a binary system!

• You will be given real data of a binary

• Bring laptops to exercise class (your own choice of program, Excel, Numbers, IDL, Matlab, Python etc.)