Unstable Mass Transfer

When the mass ratios are large, or when the donor star has a deep convective layer (so $R \propto M^{-1/3}$), mass loss will occur on a dynamical timescale. The result will be common envelope evolution, in which

- The energy released from the orbit will be greater than the binding energy of the envelope. The envelope will be ejected in all directions (but preferentially in the plane of the orbit).
- The system’s semi-major axis will shrink (by a factor of $\sim 100$) and the orbit will circularize on a dynamical timescale.

Eventually, the star reaches the denser layers of the giant, and mass ejection becomes harder. The mass ejected is similar to the mass of the companion.
Towards the end of the common envelope phase, there (probably) will still be two stars: a low mass star still burning hydrogen, and a helium proto-white dwarf. The separation will be very small, and the hot core will ionize the ejected envelope, producing a planetary nebula.
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Common Envelope Evolution

At the end of common envelope evolution:

- The binary will have a very small separation, less than the radius of the Sun.
- Since the separation is so small, the remains of the main sequence companion may/will overflow its Roche Lobe. It will then transfer mass onto the white dwarf on a thermal or nuclear timescale. This matter will form an accretion disk.
Accretion Disk Formation

- Particles that are lost via the L1 Lagrange point have trajectories that miss the compact object.
- The mass-loss stream self-intersects after coming about the compact object and eventually forms disk.
- Continued accretion from L1 hits the outer rim of this disk.
Accretion Disk Basics

Accretion disks are thin, with $h << R$.

The interaction of particles in the disk will cause material to spiral in towards the central object, and release energy. Since the orbital velocity of any particle is

$$\frac{mv^2}{r} = \frac{GMm}{r^2} \Rightarrow v^2 = \frac{GM}{r}$$

An object spiraling from radius $r$ to the companion’s surface must release

$$\Delta E = \frac{GM}{R_*} - \frac{GM}{r} + \frac{1}{2} v^2 = GM\left(\frac{1}{R_*} - \frac{1}{2r}\right)$$

Energy to be Radiated

<table>
<thead>
<tr>
<th>Object</th>
<th>ergs/M_{\odot}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Sequence Star</td>
<td>\sim 3 \times 10^{48}</td>
</tr>
<tr>
<td>White Dwarf</td>
<td>\sim 4 \times 10^{50}</td>
</tr>
<tr>
<td>Neutron Star</td>
<td>\sim 2 \times 10^{53}</td>
</tr>
<tr>
<td>Black Hole</td>
<td>\sim 9 \times 10^{53}</td>
</tr>
</tbody>
</table>
Accretion Disk Basics

Accretion disks are thin, with $h << R$.

Note: the potential energy involved in releasing a particle from infinity to the stellar surface is $GM/r$, but the kinematic energy just before impact is

$$\frac{mv^2}{r} = \frac{GMm}{r^2} \Rightarrow \frac{1}{2}v^2 = \frac{1}{2} \frac{GM}{r}$$

Thus, half the energy must be lost during accretion, and the other half during the impact at the boundary layer.
Accretion Disk Basics

Energy is released from an accretion disk via friction, or *viscosity*. The origin of the viscosity is poorly known, but is likely either turbulence (eddies) or magnetic field tension. In either case, \( v = \alpha c_s h \), where \( c_s \) is the local sound speed and \( h \) the disk thickness. All unknowns are lumped into \( \alpha \), which could be almost anything. The disk structure is then given be

\[
\frac{h}{r} \approx \frac{c_s}{v} \quad \frac{v_R}{v} \approx \alpha \left( \frac{c_s}{v} \right)^2 \quad \text{with} \quad \frac{c_s}{v} \ll 1
\]

\[
L(r) = \left( \frac{3G M \dot{m}}{8\pi} \right) r^{-3} \left\{ 1 - \left( \frac{r}{R_*} \right)^{-1/2} \right\}
\]

\[
T(r) = \left( \frac{3G M \dot{m}}{8\pi R_* \sigma_{SB}} \right)^{1/4} \left( \frac{r}{R_*} \right)^{-3/4}
\]

Note that the outside of the disk has a smaller rotation speed, hence a lower temperature and lower luminosity.
Accretion Disk Basics

Disk emission can be approximated by a series of concentric annuli, each with its own blackbody temperature and luminosity.

\[
f_v = \frac{\cos i}{d^2} \int_{R_*}^{r_{\text{out}}} B_v[T(r)] \cdot 2\pi r \, dr
\]

Typical accretion disks emit from the infrared through the x-ray and often outshine their stars.
Accretion Disk Basics

The area of the disk probed depends on the wavelength of the observation. Virtually the entire disk emits in the infrared, but the UV light comes exclusively from the disk’s inner regions.

X-rays are emitted from the boundary layer, as the matter impacts on the surface.

Note: accretion can spin-up a star, causing a white dwarf to rotate once a minute, and a neutron star to have a period of ~ 0.001 sec!
Cataclysmic Variables

If the accreting object is a white dwarf, the system is called a cataclysmic variable. There are different classes of CVs depending on the stability of the accreting process and the mode of accretion:

- Dwarf novae
- Classical Novae
- Recurrent Novae
- Nova-like Variables
- AM Her Systems
- DQ Her Systems

The absence of CVs with ~ 2 hour periods (the “period gap”) is real and is probably due to accretion temporarily stopping.
Types of Cataclysmic Variables

• **Dwarf novae**: The accretion flow in disks is not necessarily stable. When the gas reaches a critical temperature, the opacity changes, the viscosity drops and mass is quickly dumped on the white dwarf creating an outburst of several mag. The cycle repeats on timescales of weeks to years.

There are several sub-classes of dwarf novae, including **U Gem** (normal dwarf novae), **Z Cam** (which pause at intermediate brightness for months or years), and **SU Ursa Majoris** (which have normal and “super” outbursts).
Types of Cataclysmic Variables

- **Classical Novae**: The accretion deposits hydrogen onto the surface of a white dwarf. In time, the hydrogen ignites in a thermal runaway (CNO burning) which lasts for weeks to a year. This outburst can be over 10 mag, with a brightness inversely proportional to decay time.

- **Recurrent Novae**: All classical novae (probably) recur. The timescale for this depends on the white dwarf mass: it will take a $0.6 \, M_\odot$ white dwarf many millennia to accumulate enough hydrogen to erupt, while a $1.2 \, M_\odot$ object can erupt every few years.

- **Nova-like Variables**: Non-eruptive cataclysmic variables. The mass transfer rates are higher than those of dwarf novae, thus avoiding the problem of disk instability. (The “standard star” Feige 24 is a nova-like star.)
Types of Cataclysmic Variables

- **AM Her Stars** (Polars): Some white dwarfs are highly magnetized ($\sim 10^7$ Gauss). Mass passing beyond the L1 point is forced to follow field lines until impacting on the magnetic poles of the white dwarf. No accretion disk is formed, and the system rotates as a solid body. Because most of the emission is coming from the impact region and because the star is likely spinning rapidly ($P \sim 1$ min), these systems can show rapid “pulsations”.

![Diagram of AM Her Stars](image)
Types of Cataclysmic Variables

- **DQ Her Stars** (Intermediate Polars): The magnetic field strength is not quite as strong as in the AM Her stars, so an outer accretion disk exists. However, close to the white dwarf, the disk is disrupted as again, matter is forced to flow along with the field lines to the pole. Intermediate polars and AM Her stars may erupt as classical novae (such as DQ Her = Nova Her 1934).
Other Accreting Binaries

• **Super-Soft X-ray Sources:** Probably the result of continuous accretion and fusion of matter onto a white dwarf.

• **LMXBs (Low-Mass X-ray Binaries):** The donor object is a low-mass (convective) star and the accreting object is a neutron star or black hole. Because of the greater potential, \( \sim 99\% \) of their energy is released in the x-ray portion of the spectrum.

• **HMXBs (High-Mass X-ray Binaries):** The donor object is a high-mass star (spectral type O or B) with a strong stellar wind. These winds are captured by the neutron star and produce x-rays when they impact the surface.

• **Millisecond Pulsars:** Accretion can spin-up a dead neutron star (with \( P > \sim 4 \text{ sec} \)) until it pulses again. It can spin it up even further, close to the break-up speed, so that the rotation period is milliseconds. Note: the hard x-rays coming from the accretion can evaporate the donor star, so some millisecond pulsars no longer have companions.