Interacting binary stars

Properties of some binary stars are inexplicable in terms of the ordinary evolution of isolated stars:

Algols

The binary system Algol is made up of:

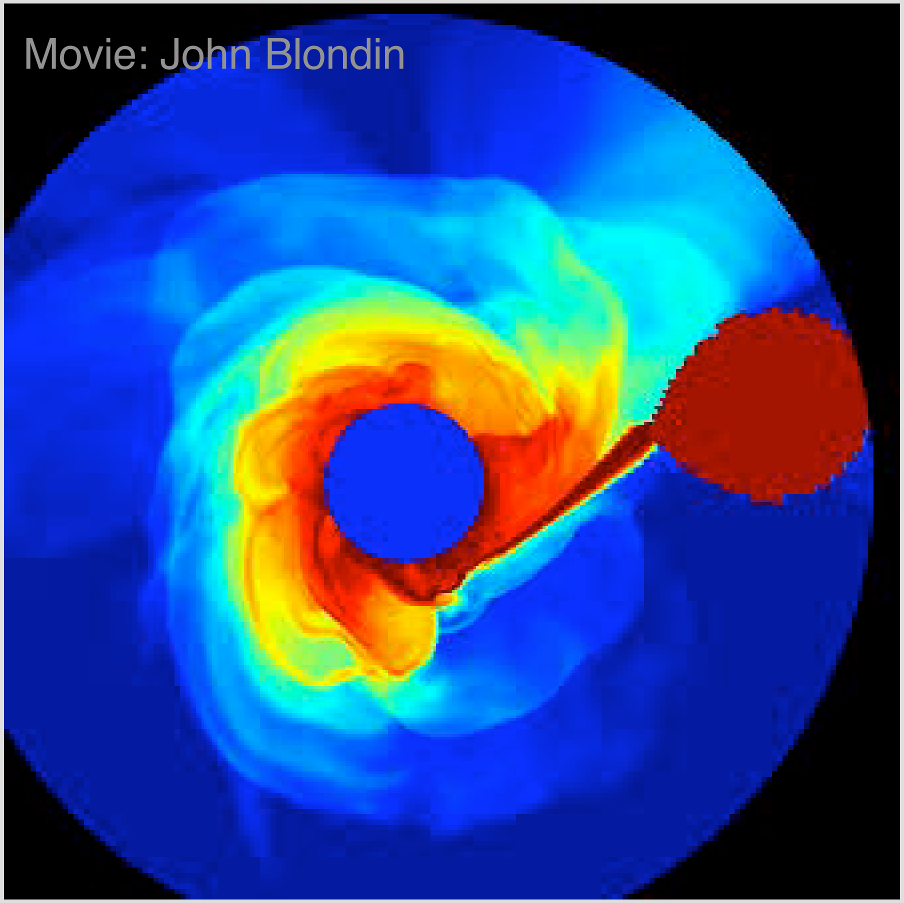
- A main-sequence star with a mass $M_1 = 3.7\ M_{sun}$
- A giant star with a mass of $M_2 = 0.8\ M_{sun}$

Compact binaries

Some binaries containing white dwarfs or other compact stellar remnants have periods $P < 2$ hours, which implies separations $a < R_{sun}$.

Must have been interactions between the progenitors when they were on the main sequence.

Resolution of these paradoxical situations is often **mass transfer** between the components of a close binary:



e.g. for Algol the now less massive star was once the more massive:

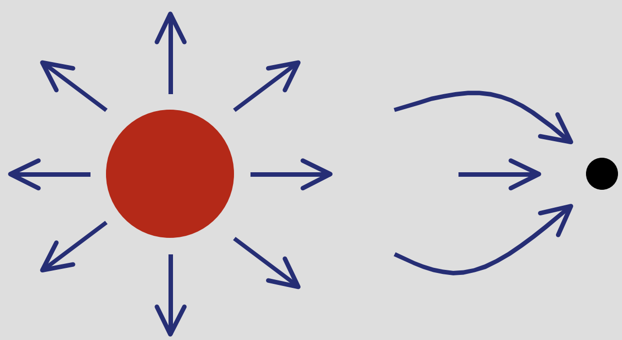
- evolved off the main sequence first
- expanded to become a giant
- lost mass to its binary companion
- mass ratio is now reversed

Many different varieties of mass-transfer or interacting binaries, depending upon the type of stars and stellar remnants that are involved.

How does mass transfer occur?

Two possible mechanisms for mass transfer between stars in a binary system:

<u>Stellar wind accretion</u>



Compact stellar remnant (white dwarf, neutron star or black hole) gravitationally captures part of the stellar wind of a high mass star in the binary.

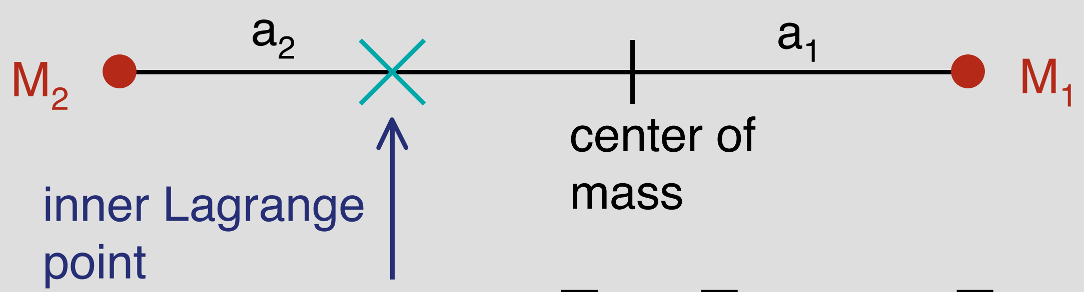
Non-conservative mass transfer (not all the mass lost by one star is accreted by the other).

Mass losing star is normally **more massive** than the accretor.

Accretor is a neutron star or black hole: system is called a **High Mass X-ray Binary (HMXB)**.

Roche lobe overflow

Consider two stars in a binary that corotate with the orbit of the binary. First, assume stars are small compared to separation. Total mass $M = M_1 + M_2$:



Separation: $a = a_1 + a_2$ $\quad a_1 = \left(\frac{M_2}{M}\right)a,\ \ a_2 = \left(\frac{M_1}{M}\right)a$

Binary angular velocity: $\Omega = \sqrt{\frac{G(M_1 + M_2)}{a^3}}$

Inner Lagrangian point L_1 is the location where a particle, *corotating with the binary*, feels no net force - gravity from the two stars plus centrifugal force cancel.

Can plot the total potential for particles corotating with the binary:

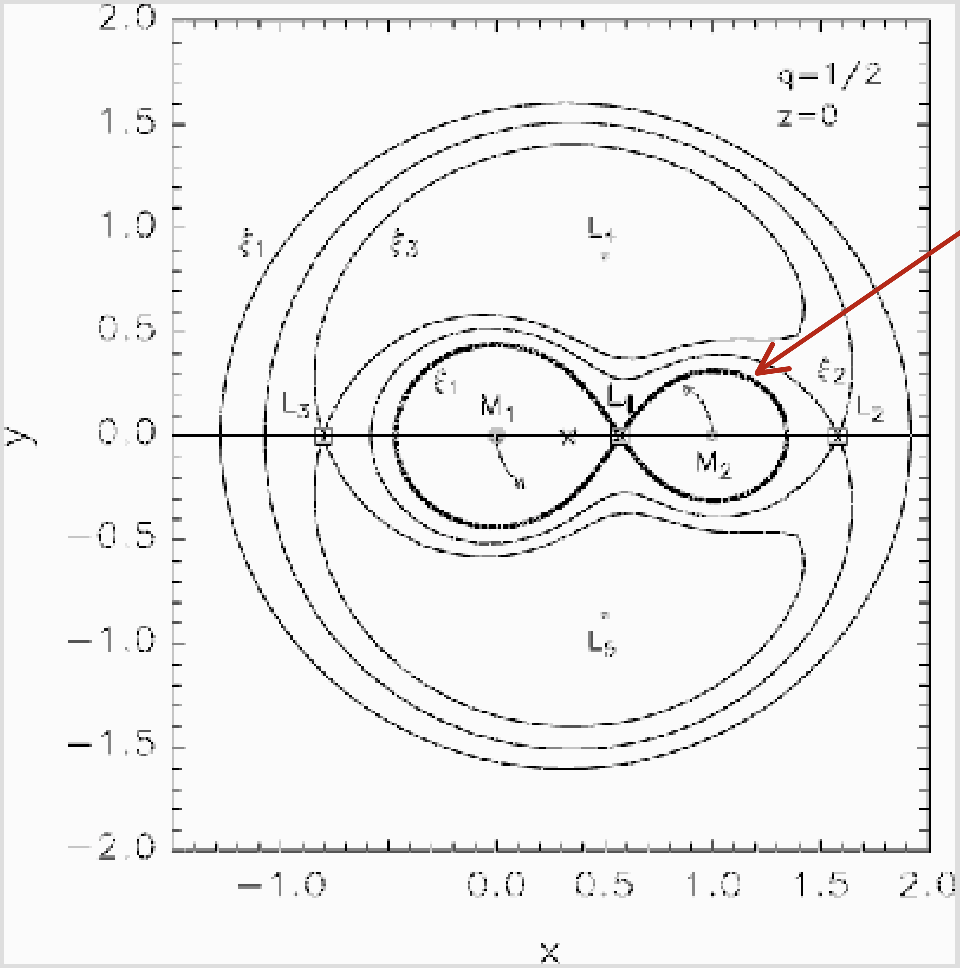


Figure of 8 shaped equipotential that passes through L_1 point defines the **Roche lobes** of the two stars.

If one star fills its Roche lobe, gas can freely escape from the surface through L_1 and will be captured by the other star.

Consequences of Roche lobe overflow

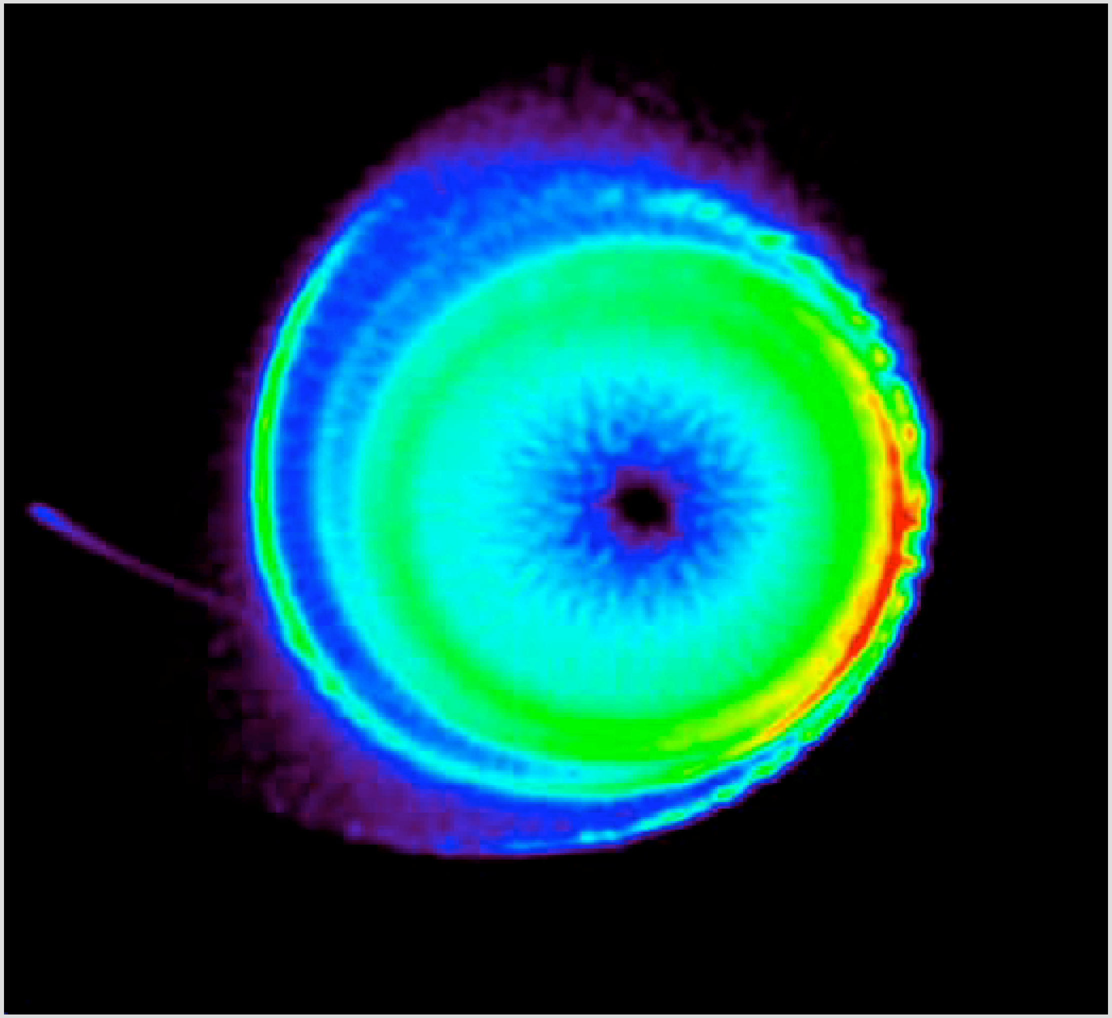
A star can fill its Roche lobe either:

- Due to expansion - e.g. the star swells to become a giant on leaving the main sequence
- Because the Roche lobe shrinks: binary loses angular momentum, stars spiral together, Roche lobe closes in on one or both stars

Describe a binary system as:

- **Detached**: neither star fills its Roche lobe, both are roughly spherical
- **Semi-detached**: one star fills its Roche lobe, and is highly distorted. Mass flows onto the other star in the binary.
- **Contact**: both stars fill their Roche lobes - touch at the L_1 point.

In a semi-detached system, gas flowing through L_1 normally has too much angular momentum to fall directly onto the surface of the other star:



Gas forms an **accretion disk** around the mass gaining star, through which the gas slowly spirals in before being accreted.

This occurs if the accreting star does not have a strong magnetic field.

Energetics of accretion

The gas accreted in a mass transfer binary must lose the gravitational potential energy liberated as it falls toward the mass gaining star. If this energy is radiated, luminosity is:

$$L = \frac{GM_a \dot{M}}{R_a}$$

← accretion rate, units g s^{-1} (often expressed in Solar masses per year)

…where M_a, R_a are the mass and radius of the accreting star.

Compare to the rest mass energy of the gas accreted per unit time: $\dot{M}c^2$

Efficiency of the accretion process (fraction of the rest mass energy that is radiated):

$$\eta = \frac{GM_a \dot{M}}{R_a} \times \frac{1}{\dot{M}c^2} = \frac{GM_a}{R_a c^2}$$

White dwarf: typical radius 10^9 cm, mass 10^{33} g

$$\eta \sim 10^{-4}$$

Compare to nuclear fusion of hydrogen to helium. Energy release is 6 x 10^{18} erg per gram of hydrogen:

$$\eta_{\mathrm{H} \rightarrow \mathrm{He}} = \frac{6 \times 10^{18} \ \mathrm{erg}}{1 \ \mathrm{g} \times c^2} = 7 \times 10^{-3} \qquad (0.7\%)$$

Accretion energy is much smaller - if the accreted hydrogen burns on the surface of the white dwarf can release a lot more energy.

Neutron star: typical radius 10^6 cm, mass 3 x 10^{33} g

$$\eta \sim 0.2$$

Very high efficiency - accreting neutron stars and black holes in binaries are luminous sources, normally in X-ray radiation.

Consequences of mass transfer: binary separation

Do the stars in a binary get closer or move further apart as a result of mass transfer?

- If separation declines - Roche lobes get **smaller**, so more mass transfer will occur. Normally this is unstable.
- If separation increases - Roche lobes expand. This can allow stable mass transfer if there is some mechanism to allow the stars to slowly spiral together.

Binary angular momentum: $J = \left(M_1 a_1^2 + M_2 a_2^2\right)\Omega$

$$a_1 = \left(\frac{M_2}{M}\right)a, \quad a_2 = \left(\frac{M_1}{M}\right)a \qquad \Omega = \sqrt{\frac{G\left(M_1 + M_2\right)}{a^3}}$$

Substitute for a_1, a_2 and Ω in the expression for the angular momentum of the binary system.

$$J = M_1 M_2 \sqrt{\frac{Ga}{M}}$$

Differentiate this expression, assuming that the total mass M of the binary remains constant (all mass lost by one star is gained by the other):

$$\frac{dJ}{dt} = \dot{M}_1 M_2 \left(\frac{Ga}{M}\right)^{1/2} + M_1 \dot{M}_2 \left(\frac{Ga}{M}\right)^{1/2} + M_1 M_2 \times \frac{1}{2}\left(\frac{Ga}{M}\right)^{-1/2} \frac{da}{dt}$$

↑ $\dot{M}_1 = \frac{dM_1}{dt}$

Divide both sides through by J, and use: $\dot{M}_1 + \dot{M}_2 = 0$

$$\frac{\dot{a}}{a} = \frac{2\dot{J}}{J} - 2\frac{\dot{M}_2}{M_2}\left(1 - \frac{M_2}{M_1}\right)$$

…where the dots denote derivatives with respect to time as above.

Finally, assume that no angular momentum is lost from the system - dJ/dt = 0. Then:

$$\frac{\dot{a}}{a} = -2\frac{\dot{M}_2}{M_2}\left(1 - \frac{M_2}{M_1}\right)$$

If the secondary is losing mass: $\dot{M}_2 < 0$

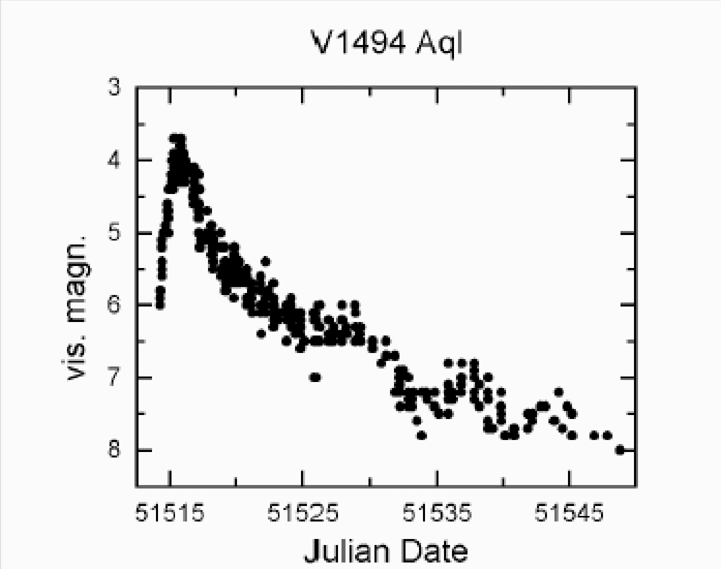
<u>Binary expands</u> if $M_2 < M_1$: mass transfer from the less massive star onto the more massive is self-regulating, too much mass transfer itself slows the inspiral of the binary

<u>Binary shrinks</u> if $M_2 > M_1$: tends to lead to runaway mass flow from the more massive star onto the less massive

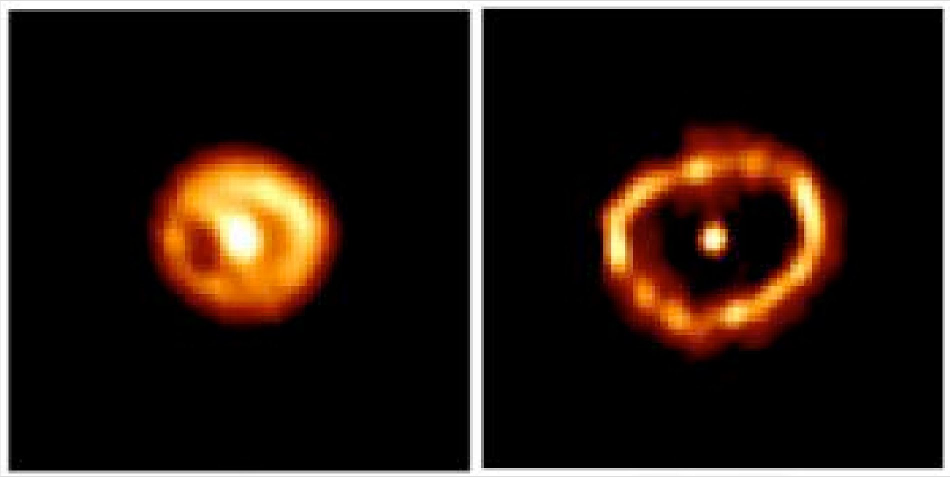
Long lived mass transfer binaries invariably have low mass secondaries losing mass, and higher mass primaries gaining mass.

Novae

A classical nova is a rapid brightening of a star, which then fades over a few weeks:

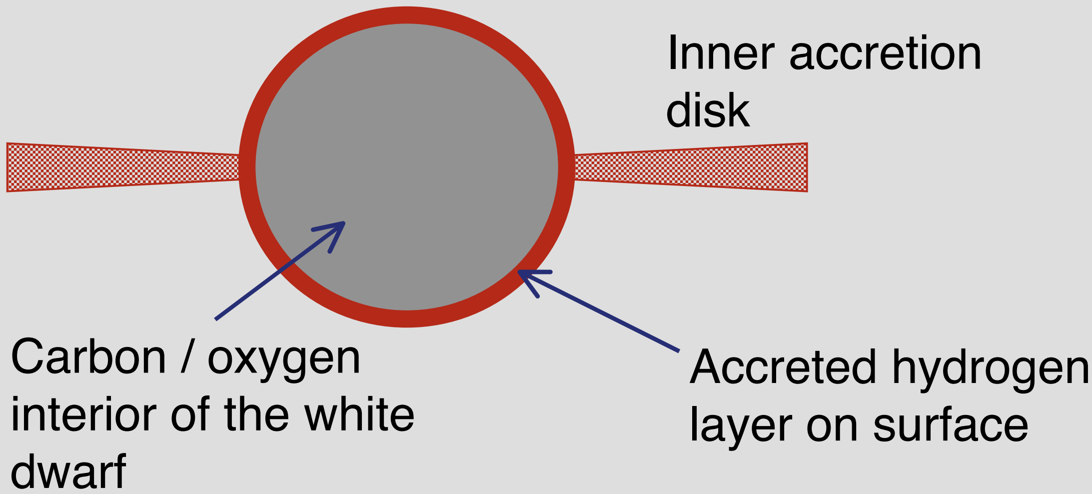


Visual light curve of a classical nova event



Shell of matter expanding subsequent to a nova explosion

Novae are thought to result from the explosion of an accreted gas layer on the **surface** of a white dwarf:



Surface layer builds up until temperature and density at base ignite nuclear fusion.

Layer is blown off in the explosion, which produces a nova plus an expanding shell.

Process repeats on a time scale of thousands of years.

Analogous process on neutron star surfaces is called a Type 1 X-ray burst.