Astronomía Avanzada I (Semester 1 2024)

Stellar Variability (II)

Non-Pulsating Variable Stars

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Motivation

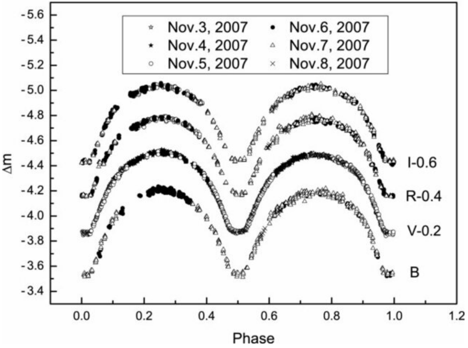
So far, we saw periodic variability in pulsating stars as an example for variability caused by stellar atmospheres.

Up to two-thirds of all stars have at least one companion, i.e. are in binary or multiple star systems. When this is the case, their atmospheres might interact.

How does this lead to effects we can observe as variability?

Interacting Binary Stars

Sometimes the two stars are so close that their outer atmospheres merge: these are known as **contact binaries**.



The light curve of the contact binary AE Phoenicis. The fact that there is no part of the orbit where the light curve is flat shows that the stars are never separate but are actually in contact. Credit: He at al. (2009)

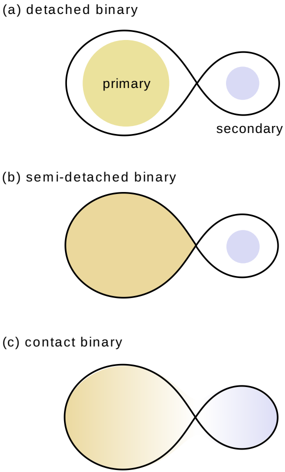
Interacting Binary Stars

If two stars in a binary system are far enough apart, they will have little or no effect on each other.

However, if they are close, then this has a major effect on **stellar evolution** as each star's radius changes with time.

The observed properties of some binaries are inexplicable without taking this into account.

E.g. some compact binaries, containing a white dwarf, have orbital periods $P < 2$ hours, implying orbital separations $a < R_\odot$.



The Algol Paradox

Algol, which consists of Algol Aa1, a main-sequence B8 star with $M = 3.5\ M_\odot$, plus Aa2, a less massive K0 subgiant star with $M = 0.81\ M_\odot$.
The more massive star should have left the main sequence and started up the RGB before the less massive star.

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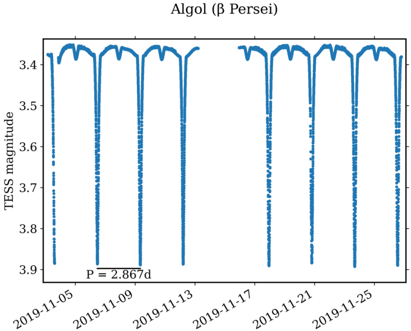
?

How can the less massive star be further advanced in its evolution?

The Algol Paradox



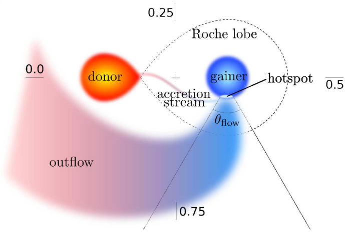
left: The Algol system observed with the CHARA interferometer with 0.5 mas resolution in the near-IR H-band. The elongated appearance of Algol Aa2 (labelled B) and the round appearance of Algol Aa1 (labelled A) are real, but the form of Algol Ab (labelled C) is an artifact.

right: Light curve of Algol recorded by NASA's Transiting Exoplanet Survey Satellite (TESS). The primary eclipse happens when the bright B star passes behind the much cooler K star.

Interacting Stars

What is going on here?

The key is the **short-period orbit**.



Schematic overview of an Algol system.
Credit: Deschamps et al. (2015)

The paradox can be solved by **mass transfer**: When the more massive star became a subgiant, it filled its Roche lobe, and most of the mass was transferred to the other star, which is still in the main sequence. The gas flow between the primary and secondary stars in Algol has been imaged using Doppler Tomography (e.g. Richards et al. 1995,2012). Observed x-ray flares are thought to be caused by the magnetic fields of the A and B components interacting with the mass transfer.

This is known as the **Algol paradox** in the theory of stellar evolution and seen in similar **Algol systems**.

Interacting Stars

Star systems such as Algol are **Mass Transfer Binaries**.

Think about the continued evolution of Algol and you have the explanation for **novae**.

If the original primary transfers most of its mass to the original secondary, you are left with a massive main-sequence star and a helium white dwarf.

When the original secondary starts to evolve up the RGB, it transfers some material back onto the helium WD.

Interacting Stars

Interaction means the transfer of material as of gravitational interaction.
In general, interaction occurs when $R \to a$.

an **example**:
For $M_1 = M_2 = 1M_\odot$, $a = 1000R_\odot \sim 5\ \mathrm{AU}$, with Kepler we get

$$\left(\frac{P}{2\pi}\right)^2 = \frac{a^3}{GM}$$

$\Rightarrow P \approx 7$ years

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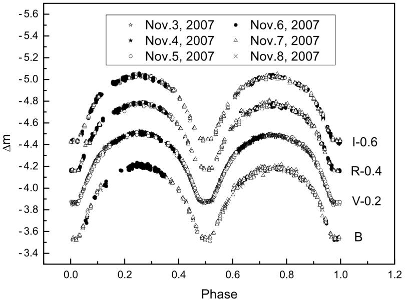
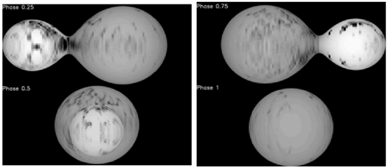
$\Rightarrow$ Anything closer with interact strongly.

Observing Contact Binaries

Contact binaries can be observed; while we can't actually see the two stars in an image, we can infer their shape from the study of the light curve.





The light curve of the contact binary AE Phoenicis (left, He et al. 2009), and the model for the system deduced from Doppler images of the system (right, Barnes et. al. (2004). The fact that there is no part of the orbit where the light curve is flat shows that the stars never separate.

Observing Contact Binaries

Betelgeuse is a red supergiant star which is, after Rigel, the second-brightest in the constellation of Orion.
Betelgeuse is a rapid rotator of $15 - 20\ M_\odot$, $P \approx 36$ yr. That's way too fast for the average massive star.

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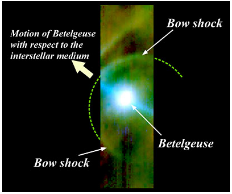
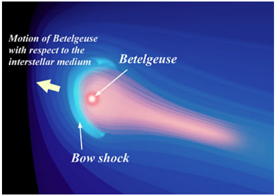
Chatzopoulos et al. (2020): Betelgeuse might be the **result of a merger** of two binary stars about 100,000 years ago.
Betelgeuse has a bow shock outer shell of matter in front of it as it moves through space. It could be the leftovers of Betelgeuse's companion.





Left: Betelgeuse creates a bow shock. Right: An artist's rendering of the bow shock created by Betelgeuse. Image Credit: ESA

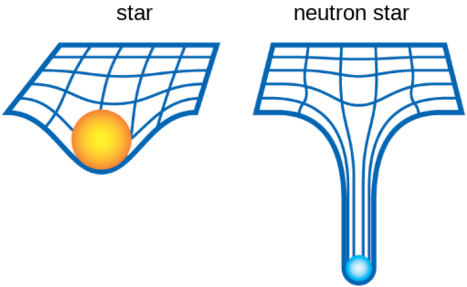
Potential Wells

One very instructive way to see what is happening with stars in a binary system is to look at their **potential wells**. A potential well is essentially a picture of the gravitational potential of an object.

The following diagrams are plots of the gravitational potential surface near a star. Because matter tries to reach the lowest energy state, it will tend to run downhill in these diagrams.

Potential Wells

An isolated star has a potential well like a dimple:



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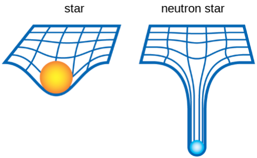
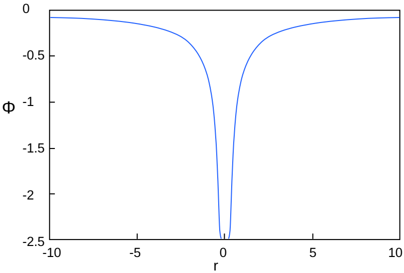


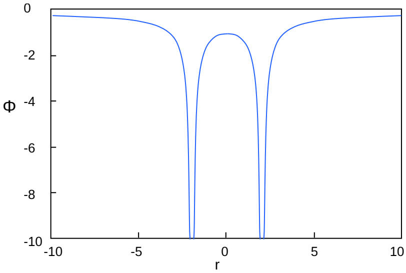
If we look at the cross-section, it looks like this:



$$\Phi = -\frac{GM}{r}$$

Potential Wells

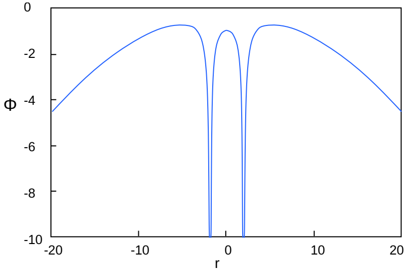
When there are two stars, their potential wells overlap. Near to each star, everything just looks like a single star; but as you travel between the stars, there's a point where the pull from each star is the same: an unstable point where a mass can fall either way.



$$\Phi = -\frac{GM_1}{r_1} - \frac{GM_2}{r_2}$$

Potential Wells

This is how the potential wells of two stars look in a **corotating frame**:



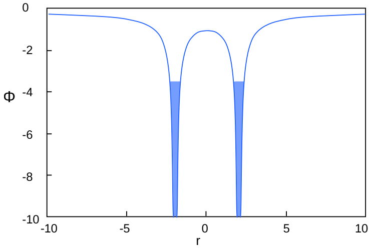
$$\Phi = -\frac{GM_1}{r_1} - \frac{GM_2}{r_2} - \frac{1}{2}\omega^2 s^2$$

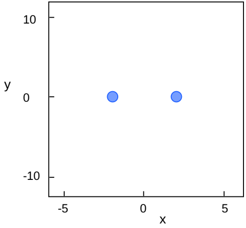
with ω: angular velocity
s: distance from the rotation axis, which passes through the center of mass

Potential Wells

If there is **matter** inside the potential well, which is the case for stellar systems, it will fill up the well to a more or less degree, depending both on the density and on how close the nearest well is. We can distinguish between several cases.

Detached: both stars are within their wells and relatively undistorted.





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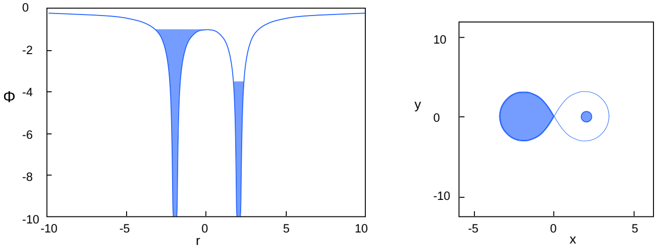
Semi-detached: one star has expanded so its outer surface meets the saddle point.



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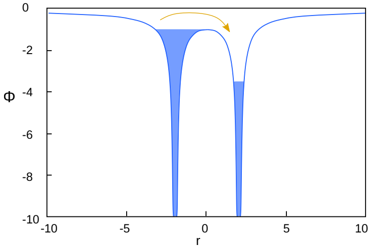
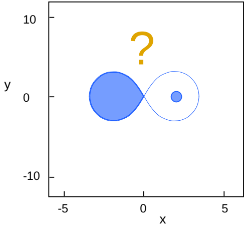
Roche Lobe Overflow: the primary expands over its Roche lobe volume. How does this overflow happen? What are the responses?





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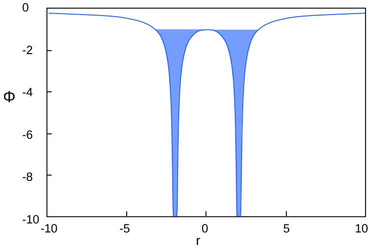
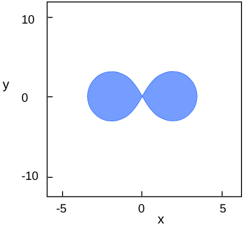
Contact: both stars are filling their wells.





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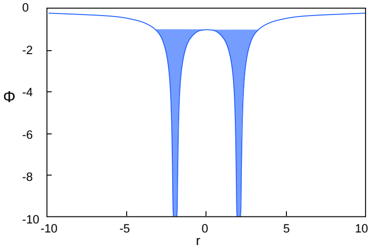
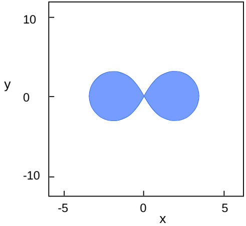
Common envelope: both stars are overfilling their wells so there is only one surface.





Mass Transfer

The gravitational interaction happens due to the gravitational field, which is for a single star $\Phi = -\frac{GM}{r}$. The companion star will feel the pull from the other star. This leads to distortion known as **tides**, similar to ocean tides in the Earth-Moon system.

Tides lead to **energy dissipation** and a time lag, called tidal torque, due to angular momentum exchange.

Conservative Mass Transfer

Assume that all the mass lost by one star is gained by the other,

$$\frac{\mathrm{d}M}{\mathrm{d}t} = \dot{M}_1 + \dot{M}_2 = 0 \Rightarrow \dot{M}_2 = -\dot{M}_1$$

So we have for the change in distance (semi-major axis a):

$$\frac{\dot{a}}{a} = \frac{2\dot{J}}{J} - \frac{2\dot{M}_1}{M_1}\left(1 - \frac{M_1}{M_2}\right)$$

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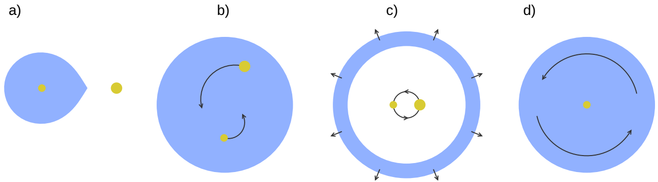
Assume that the primary star (star 1) is losing mass, $\dot{M}_1 < 0$. Then:

- if $M_1 < M_2$, then $\frac{\dot{a}}{a} > 0$, i.e. the orbit **widens**
- if $M_1 > M_2$, then $1 - \frac{M_1}{M_2} < 0 \Rightarrow \frac{\dot{a}}{a} < 0$, i.e. the orbit **shrinks**.

In the latter case, the Roche lobe shrinks, more mass is transferred, so the orbit shrinks even more. This is a **runaway mass transfer**.

Unstable Mass Transfer

In the case of a runaway mass transfer, we can get a **spiral-in**. The donor's envelope contains both stars, since the Roche lobe of the donor has shrunk so much - a **common envelope** around both stras is formed.
Both stars experience a **frictional drag**. Energy is extracted from the orbit and imparted to the envelope. The two stars spiral together, and the envelope is ejected. The **angular momentum** is not longer conserved.

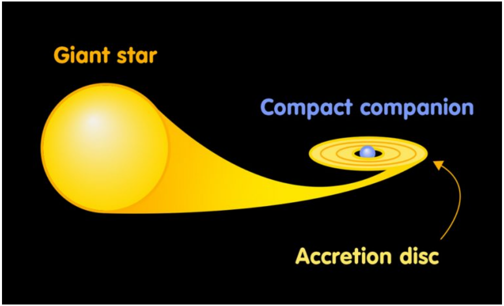


Key stages in a common envelope phase.
a) A star fills its Roche lobe. b) The companion is engulfed; the core and companion spiral towards one another inside a common envelope. Finally, the envelope is ejected (c) or the two stars merge (d).

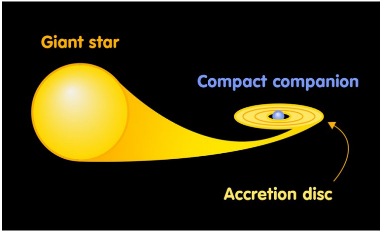
Accretion Disks

The large angular momentum prevents the gas from directly falling onto the surface of the star.

Instead, it falls through the L_1 point and goes into orbit around the second star. On the return it intersects itself, and friction makes it spread, first into a ring, then an accretion disk.



Accretion Disks



The collisions of particles on intercepting orbits will **heat up the disk**, which is then emitting energy as EM radiation.

To conserve energy, some particles must spiral inwards. But this requires angular momentum to be lost, so other particles must spiral outwards.

Thus we may view an accretion disk as a way to **slowly lower particles** in the gravitational field of the primary until they accrete on its surface.

Accretion Disks

Accretion can be found in many areas of astrophysics:

Stars, galaxies and planets grow by accretion.

Quasars are powered by accretion onto a black hole.

Novae and type Ia supernovae are triggered by accretion.

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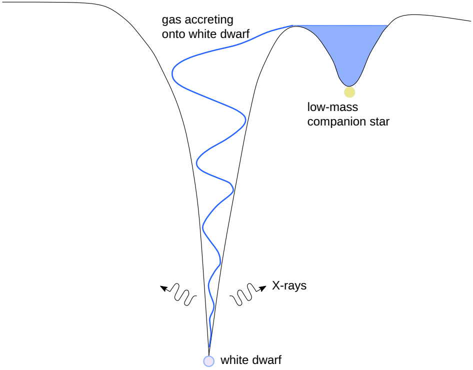
⇒ As accretion liberates gravitational potential energy, accreting objects are **very powerful sources of energy**.

Accretion Disks

Friction in the disk allows matter to gradually spiral inwards while angular momentum is transported outwards.

What then happens depends on the accreting star. When the matter hits e.g. a white dwarf, the gravitational potential energy is suddenly liberated. We see this in the form of radiation in the X-ray, ultraviolet and optical.



Accretion Disks

We can make an estimate about how much **energy can be released** through accretion.

Consider a mass $m = 1\,\mathrm{kg}$ which starts at rest far from a star with mass M and radius R. The initial total mechanical energy of the mass is

$$E = K + U = 0$$

with kinetic energy K, potential energy U.

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On impact with the star, kinetic energy is converted into heat and light. Thus the gravitational energy release per mass unit is

$$\Delta E_{acc} = \frac{GM}{R}$$

which increases with **compactness** M/R: for a given M, the yield is greatest for the smallest accretor radius R.

Accretion Disks

Consider the amount of energy released by 1 kg of infalling matter onto different objects:

White dwarf: $M = 0.85\ \mathrm{M}_\odot$, $R = 6.6 \times^{6}\ \mathrm{m} = 0.0095\ \mathrm{M}_\odot$
$\Rightarrow \Delta E_{wd} = \frac{GM}{R} = 1.71 \times 10^{13}\ \mathrm{J}$
which is 0.019 % of the rest energy (mc^2); $\epsilon \sim 0.0002$

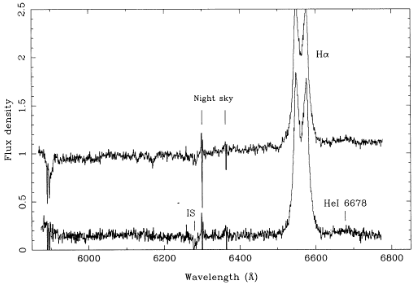
Neutron star: $M = 1.14\ \mathrm{M}_\odot$, $R = 10\ \mathrm{km}$
$\Rightarrow \Delta E_{ns} = 1.86 \times 10^{16}\ \mathrm{J} \Rightarrow \epsilon \sim 0.0002$

Recall that the energy released by the fusion of 1 kg of H is $0.007mc^2 = 6.29 \times 10^{14}\ \mathrm{J} \Rightarrow \epsilon \sim 0.007$.

Hence accretion is the **most efficient known way of getting energy from matter**; accreting neutron stars are sources of immense amounts of energy.

Observing Accretion Disks

As material works its way to the center of the disk, it heats up, reaching in excess of 10^5 K for white dwarfs and 10^7 K for neutron stars.
Compact binaries are powerful sources of high-energy radiation (X-ray and UV). Lines from the accretion disk are characteristically double-peaked shape.



The average spectrum of the black hole binary A0620-00 in our rest frame is plotted along with the same spectrum after subtraction of the K star from each spectrum before averaging. The result is the spectrum of the disk and bright spot. Credit: Marsh et al. (1994)

Wind-Driven Accretion

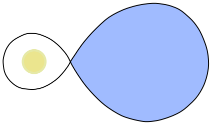
In contrast to accretion by Roche-lobe overflow, **wind-driven accretion** is understood much less.

This type of accretion is particularly important for binaries containing massive stars (O and B stars).

Only a tiny fraction (0.01 - 0.1 %) of the matter in the wind is accreted onto the companion, unlike RL overflow (close to 100 %).

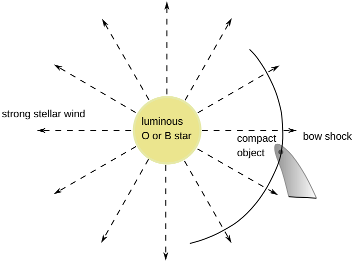
We will not necessarily get an accretion disk in wind-driven systems; the angular momentum of the transferred particles makes it less probable than in Roche-lobe overflow.

However, some wind-driven systems do not show evidence of accretion disks.



Roche Lobe Overflow

(Low-Mass X-Ray Binaries)



Observable Evolving Binary Star Systems

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As fresh hydrogen from the outer layers of its companion accumulates on the surface of the hot white dwarf, it begins to build up a layer of hydrogen. As more and more hydrogen accumulates and heats up on the surface of the degenerate star, the new layer eventually reaches a temperature that causes fusion to begin in a sudden, explosive way, blasting much of the new material away.

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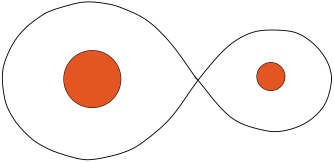
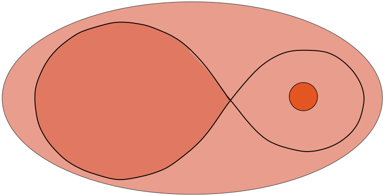
In this way, the white dwarf briefly becomes quite bright, hundreds or thousands of times its previous luminosity. To observers before the invention of the telescope, it seemed that a new star suddenly appeared, and they called it a **nova**. Novae fade away in a few months to a few years.

Cataclysmic Variables

main-sequence binary,
$M_1 > M_2 \sim 0.3 M_\odot$

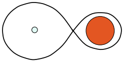


primary evolves to a Red Giant

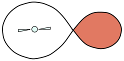


$\Rightarrow$ **Instable mass transfer**

White Dwarf and
Main Sequence star in short
P orbit, $M_{wd} > M_{ms}$



secondary evolves
& transfers mass
$\Rightarrow$ cataclysmic variable

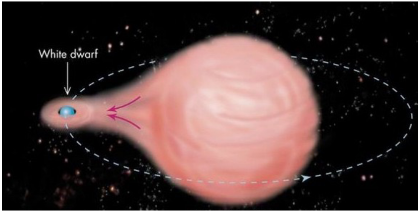


$\Rightarrow$ **Stable mass transfer**

Cataclysmic Variables

Once the envelope has been ejected (on very short timescales, t_{th}), the binary remains quiescent until the **second** star comes in contact with the roche lobe. Then the white dwarf begins accreting matter via an accretion disk, and the system becomes visible as a **cataclysmic variable**. Because $M_2 < M_1$, the transfer is stable.

H-rich gas from the outer envelope accumulates on the **surface** of the white dwarf until P and ρ reach the point where fusion can begin. All of the H on the surface ignites almost at once in a thermonucelear nrunaway, which consumes all the accreted material.

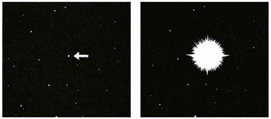


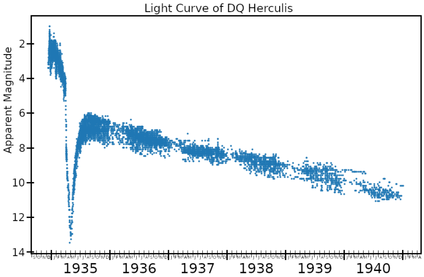
Novae

Hundreds of novae have been observed, each occurring in a binary star system and each later showing a shell of expelled material. A number of stars have more than one nova episode, as more material from its neighboring star accumulates on the white dwarf and the whole process repeats.

Novae

Novae are visible as a massive brightness increase in a star, by a factor of 50,000 or more. Because of the pre-explosion star was essentially anonymous (barely visible star among others, or not visible to the naked eye at all) the star appears as a "new" star, thus a **nova**.



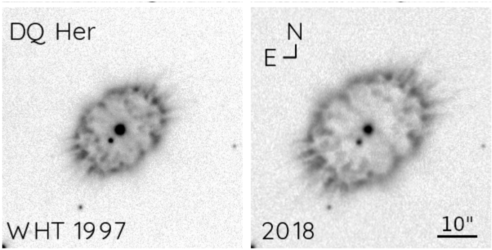


left: Nova Herculis 1934, before and during outburst, when it brightened by a factor of 60000.
right: The light curve of Herculis 1934, from AAVSO data. The pronounced "dust dip" about four months after peak brightness was caused by dust forming as the ejected shell expanded and cooled.

Novae

The accreted layer which is blown off in the explosion produces an expanding shell. The velocity of the material in such shells can reach $\sim$2000 km/sec.

Some novae are **recurrent**: The process **repeats** on timescales of decades to thousands of years.



Two images of the shell surrounding DQ Hercules taken 21 years apart, showing the nebula's expansion. Both images were taken with Hα filters, left at the William Herschel Telescope, and right with the Nordic Optical Telescope.

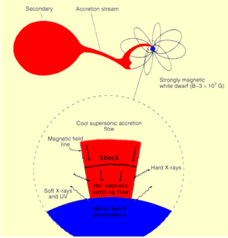
Polars (AM Her systems) - A magnetic polar cataclysmic variable

In a polar system such as the prototype AM Her, matter will overflow the Roche lobe of the companion star. However, the white dwarf possesses a strong **magnetic field**, preventing the formation of a accretion disk.

The overflowing material is directed by the magnetic field structure until it impacts on the white dwarf at its magnetic pole. The collision generates a shock wave which is the source of hard (energetic) X-rays.

The strong magnetic field locks the orientation of the white dwarf relative to the companion, making orbital and rotational periods identical.

As the X-ray emission comes entirely from accretion and impact, when matter is not accreting onto the system, the entire system is much dimmer.



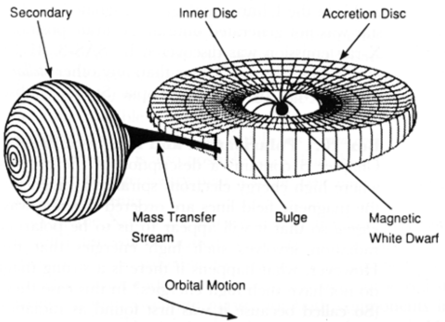
Credit: NASA

Intermediate Polars (DQ Her systems)

In systems which have less strong magnetic fields, or wider separations between the companion and white dwarf, an accretion disk can form. CVs which possess both an accretion disk and magnetic fields which disrupt the inner edge of the disk are known as *intermediate polars*.

Intermediate polars, either due to weaker magnetic fields or wider star separations, will not necessarily have orbital and spin rates locked.

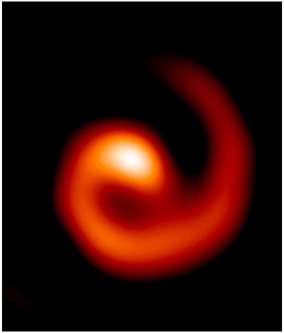
Observed systems have longer orbital periods than polars, which given that the systems have comparable masses verifies their wider separation.



Credit: NASA

Wolf-Rayet Stars

Binaries can also lose matter from the system entirely. The Wolf-Rayet star WR 104 shows a dusty spiral, shwoing material escaping from the binary stars embedded in its center.



False-color infrared image of the nebula surrounding WR 104, taken using a technique called aperture masking inferometry.

Habitable Zones

In 2015, astrophysicist Paul Sutter wrote that it seems unlikely that life could exist in most binary systems.

While binary systems certainly have a habitable zone, where liquid water could potentially exist on the surface of a planet, life might find it difficult to gain a foothold. Orbiting two stars at once, as our friend Kepler-47c does, makes life very elliptical, occasionally bringing the planet out of the zone. Life doesn't take too kindly to frequently freezing over.

Though binary and multiple systems appear initially daunting, changing the amount of light, heat and radiation they receive from one extreme to the other, systems such as wide r close binaries could actually produce stable conditions.

Summary

We have seen how mass transfer cann occur when one (or both) star in a binary system comes in conact with its Roche lobe.

We have seen how the material is transferred with either a Roche lobe overflow and accretion disk, or via stellar wind.

We have seen which effect this has on the binary system: When material transfer occurs, both mass and angular momentum are redistributed within the binary system - or may even be lost alltogether into space, depending on the physical mechanisms at work. When this happens, both the orbital separation and the mass ratio will change.