Lives of the Stars Lecture x: Binary stars

Presented by
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THE UNIVERSITY OF SYDNEY

In tonight's lecture

- How binaries work
  – *a little background about binaries and how we find them*

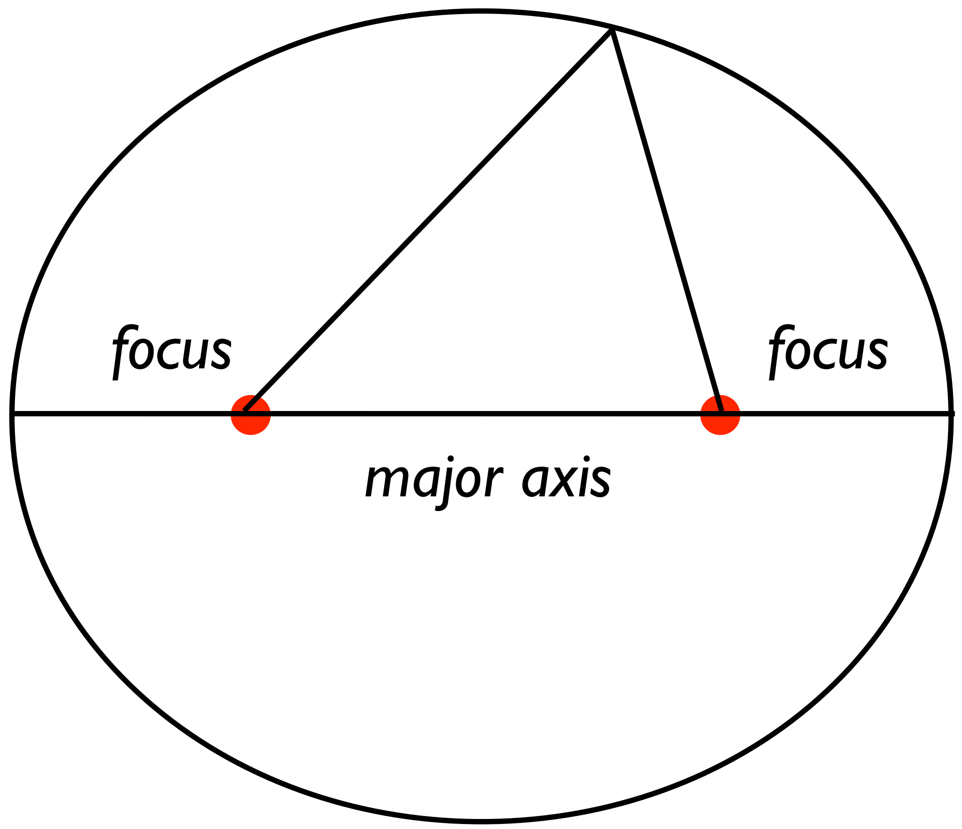
- Stars in binary systems
  – *observations of binary stars*

- Interacting binaries
  – *what happens when binaries evolve*

Binary stars

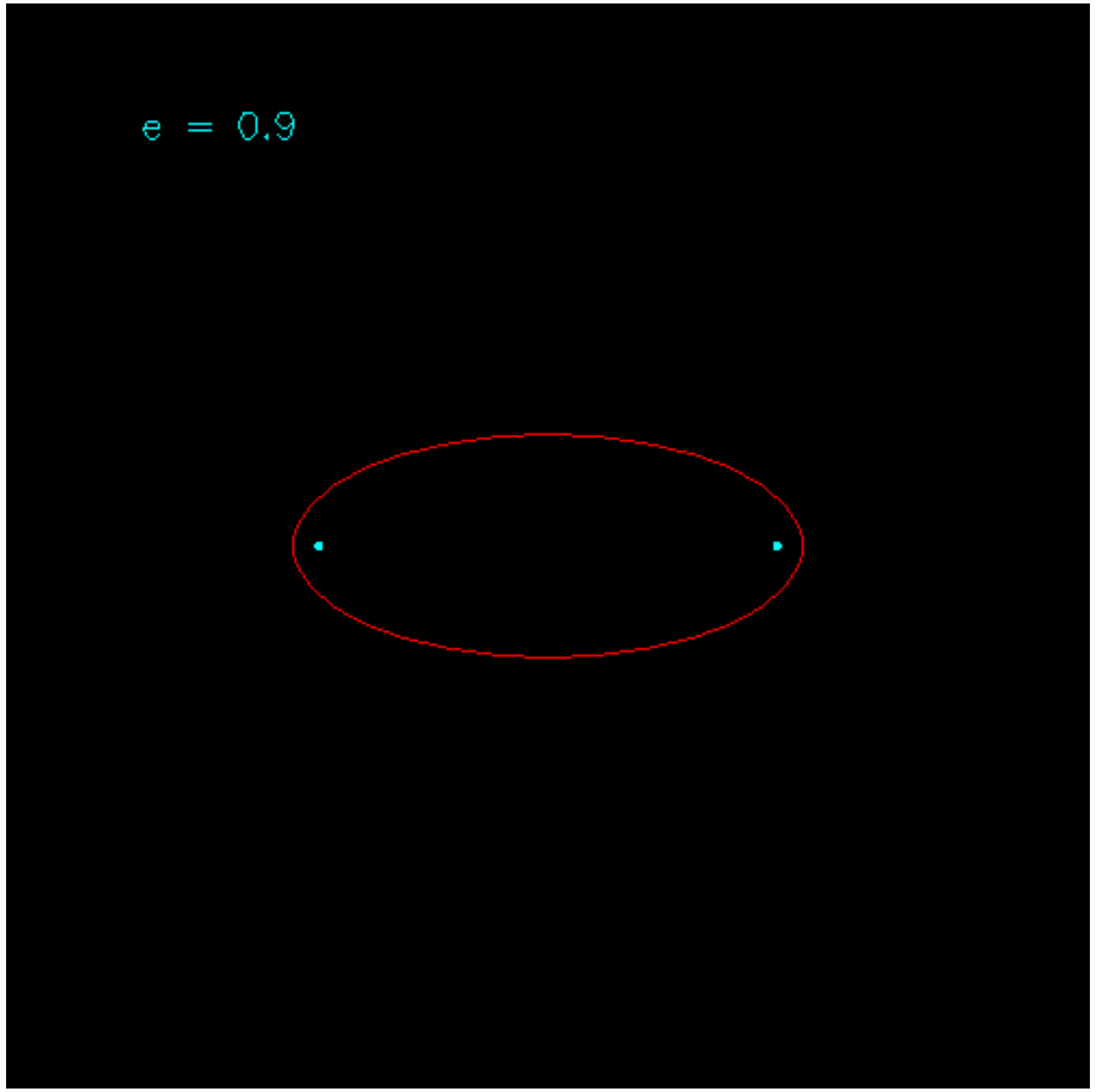
Our Sun is unusual in *not* having a stellar companion. Estimates of what fraction of stars are in binaries vary (as we will see), but at least 50% have at least one companion star, possibly as many as 70%.

Stars orbit about one another in *ellipses*. An ellipse is a curve for which the sum of the distance to the two *foci* is constant.



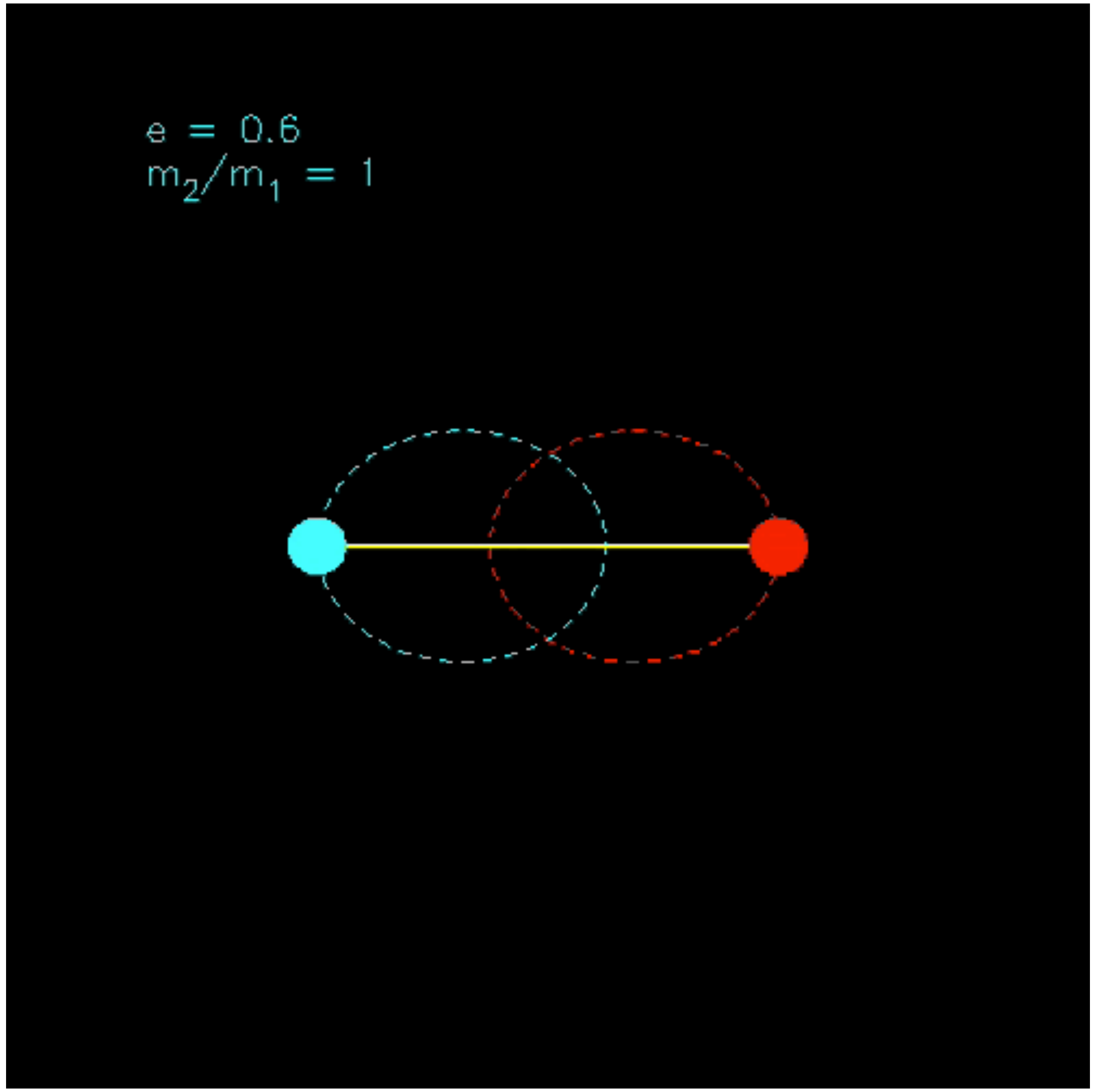
The *eccentricity* is the ratio of the distance between the foci to the major axis: it is a number between 0 and 1. An ellipse with an eccentricity of zero is a circle.

As the foci move further apart, the ellipse becomes flatter.

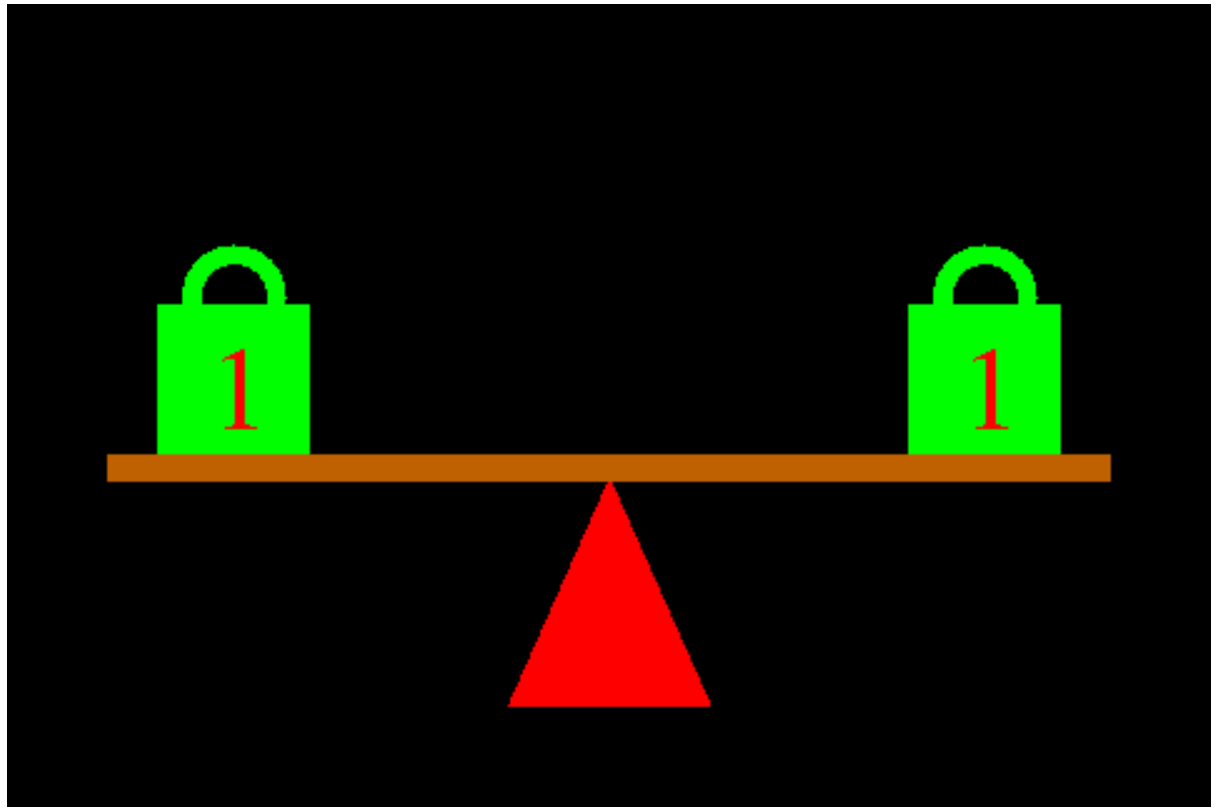


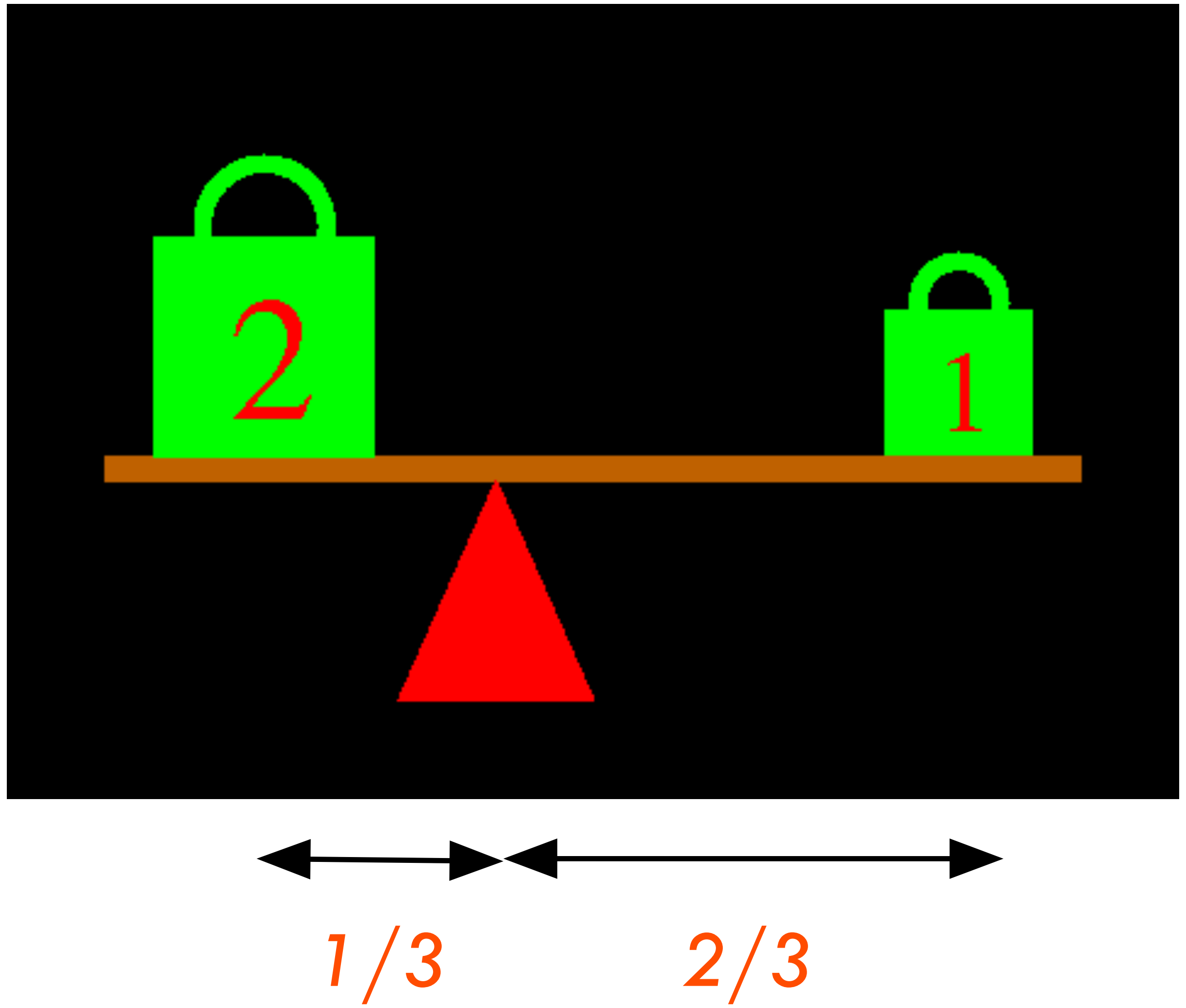
Orbits

Each star orbits in an ellipse of the same shape, such that they are always on opposite sides of the centre of mass.



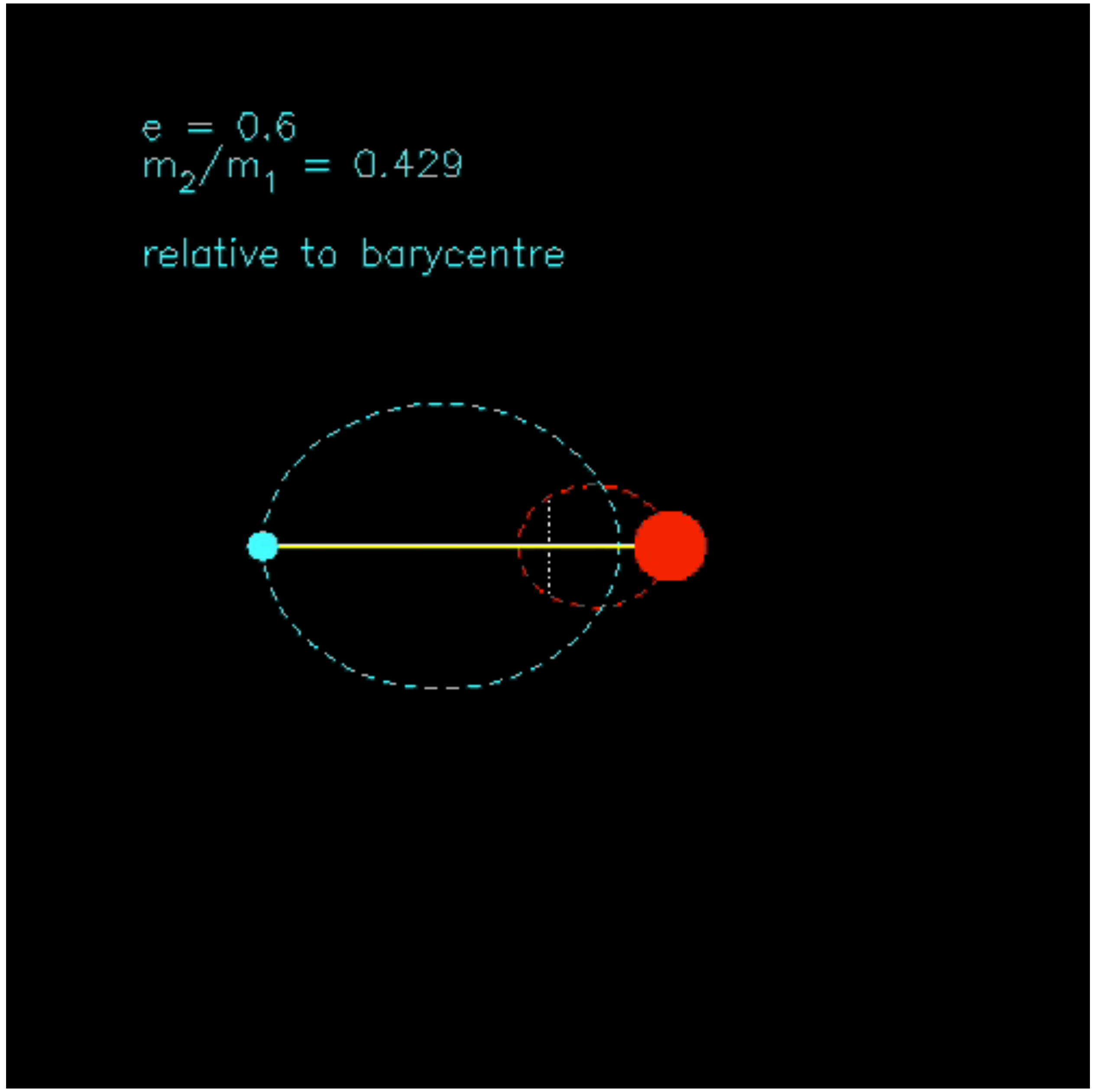
The position of the barycentre, or centre of mass, depends on the mass of the two stars. Just like a see-saw, where the fulcrum has to be placed closer to the heavier child.





In general: $d_1 = \dfrac{m_2}{m_1 + m_2}$ and $d_2 = \dfrac{m_1}{m_1 + m_2}$

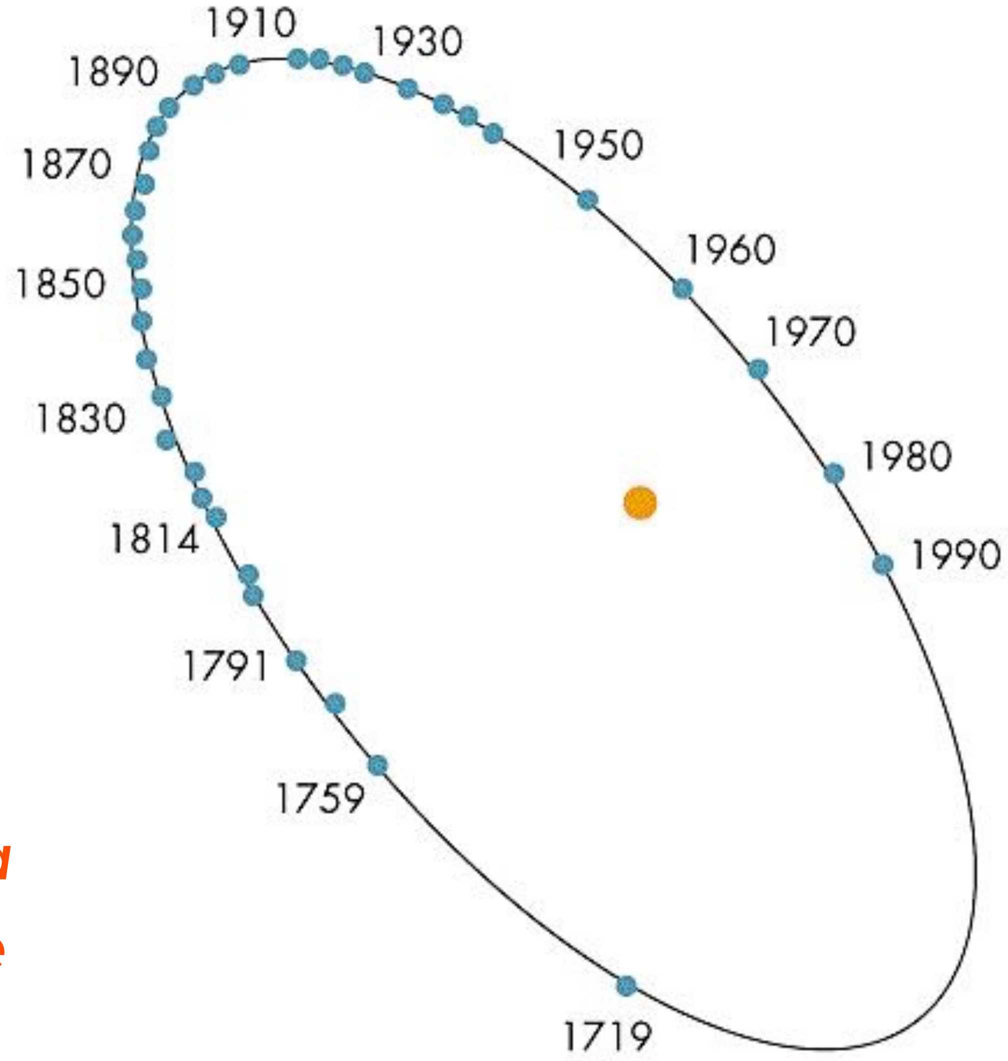
From the point of view of each star, the other star revolves around it in an ellipse of exactly the same shape as the individual orbits.



Finding binaries

Binaries are classified by how they are observed.

Visual binaries are stars which appear as separate images, which can be seen to orbit about one another with the passage of time.

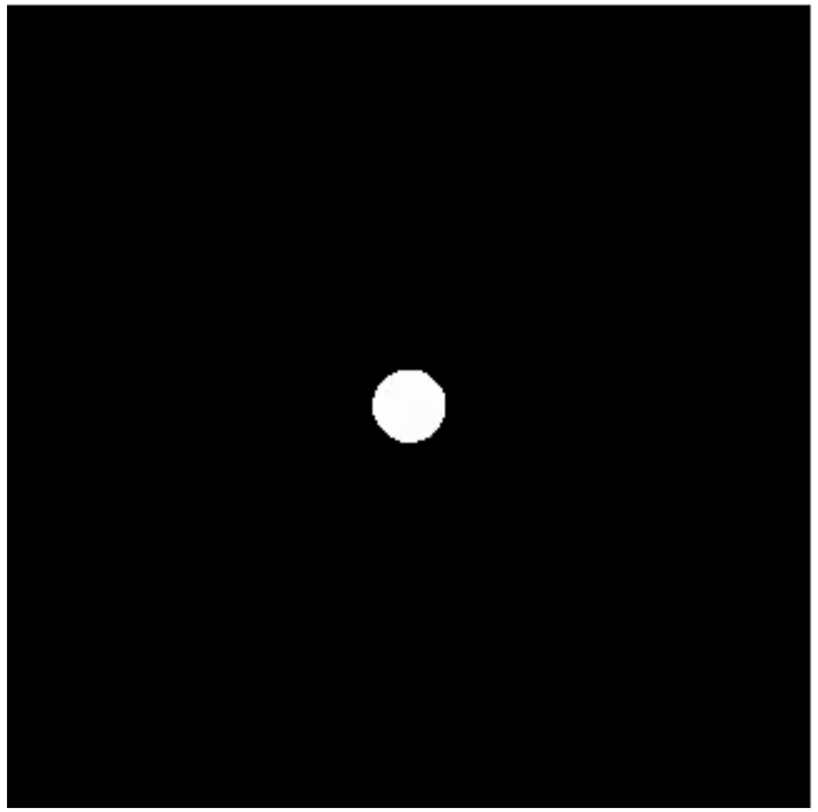


Castor (α Geminorum) is a visual binary with a separation of a couple of seconds of arc. The binary has not yet completed one 467-year orbit since the first observations were made in 1719.

However, in order for the stars to be seen separately, they have to be either very far apart, or very close to us, or both.

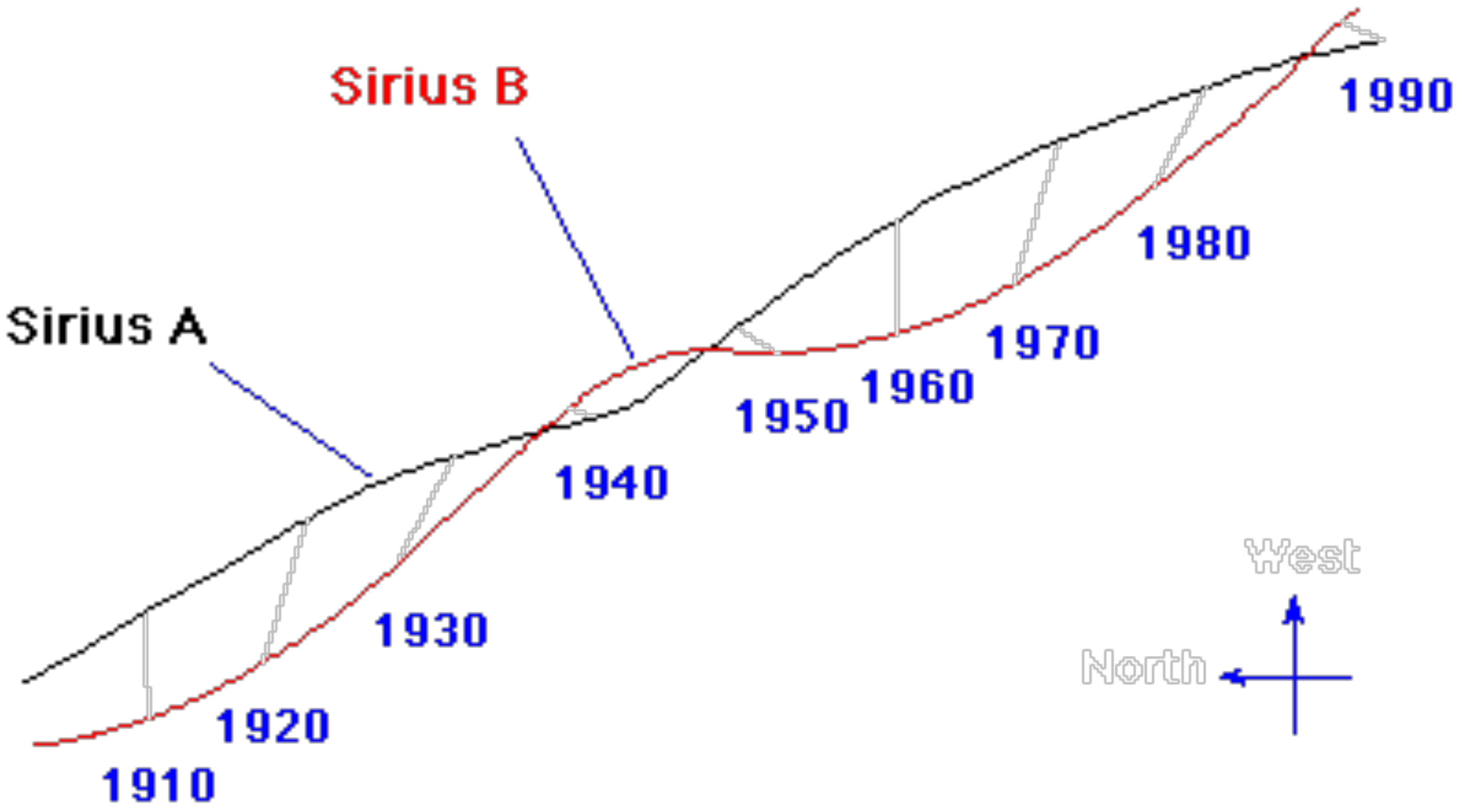
Visible image of the alpha Centauri binary. The separation is 17.6"

Most binary stars appear as a single point of light, and we have to deduce their binarity.

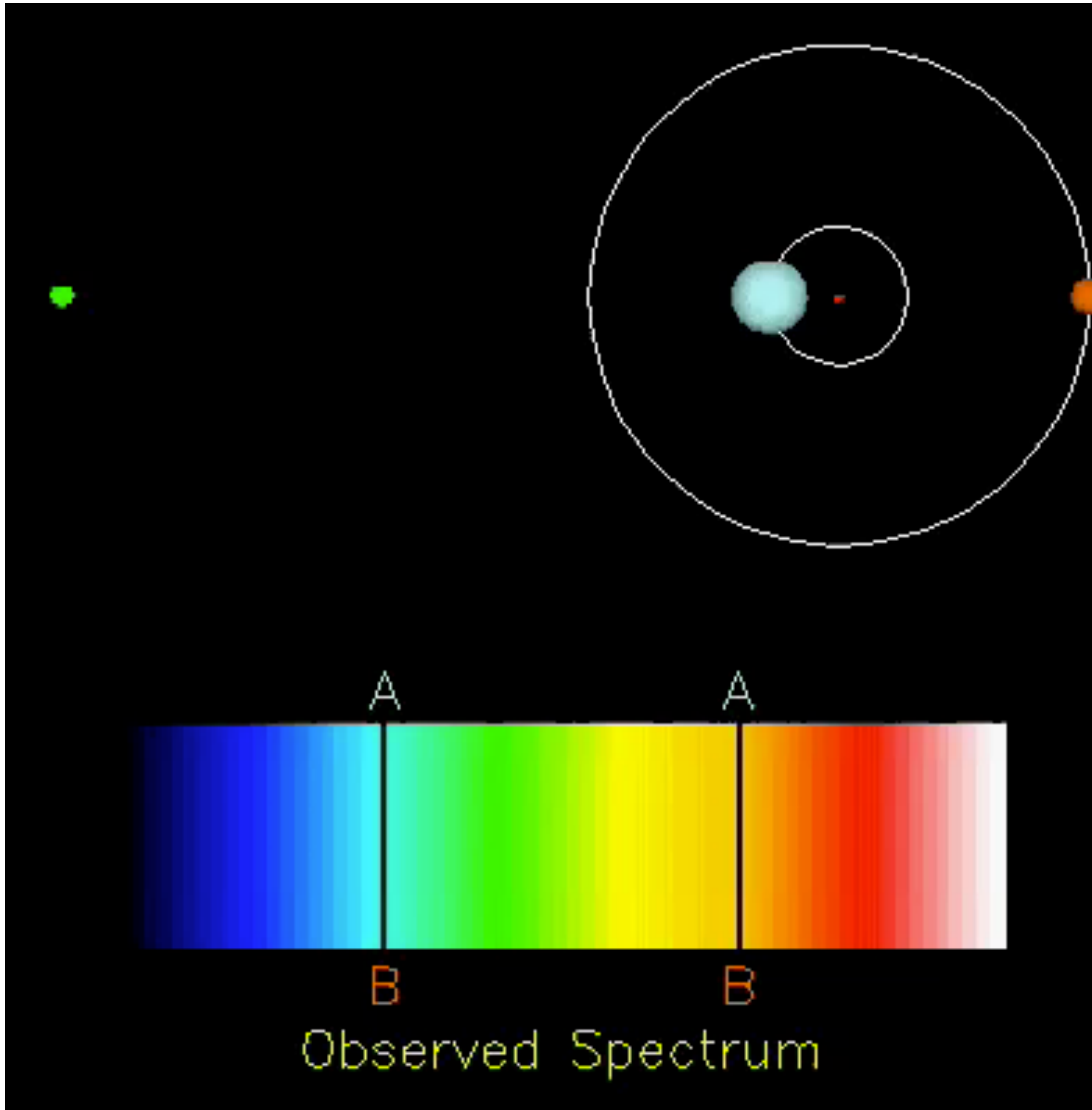


Astrometric binaries are binaries where only one star is observed, but the presence of the second star is inferred because the visible star wobbles in the sky.

Sirius is the most famous example of an astrometric binary.

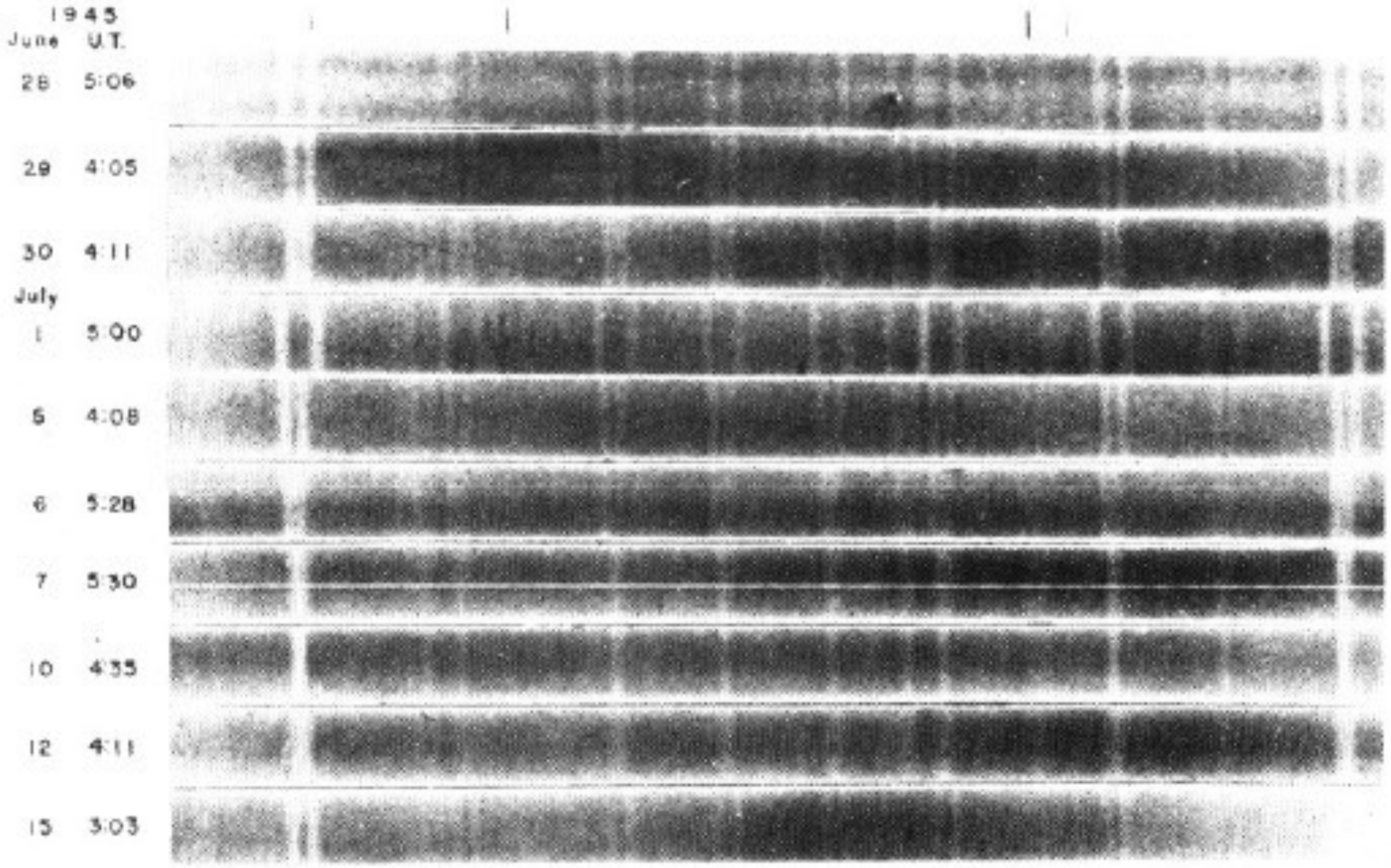


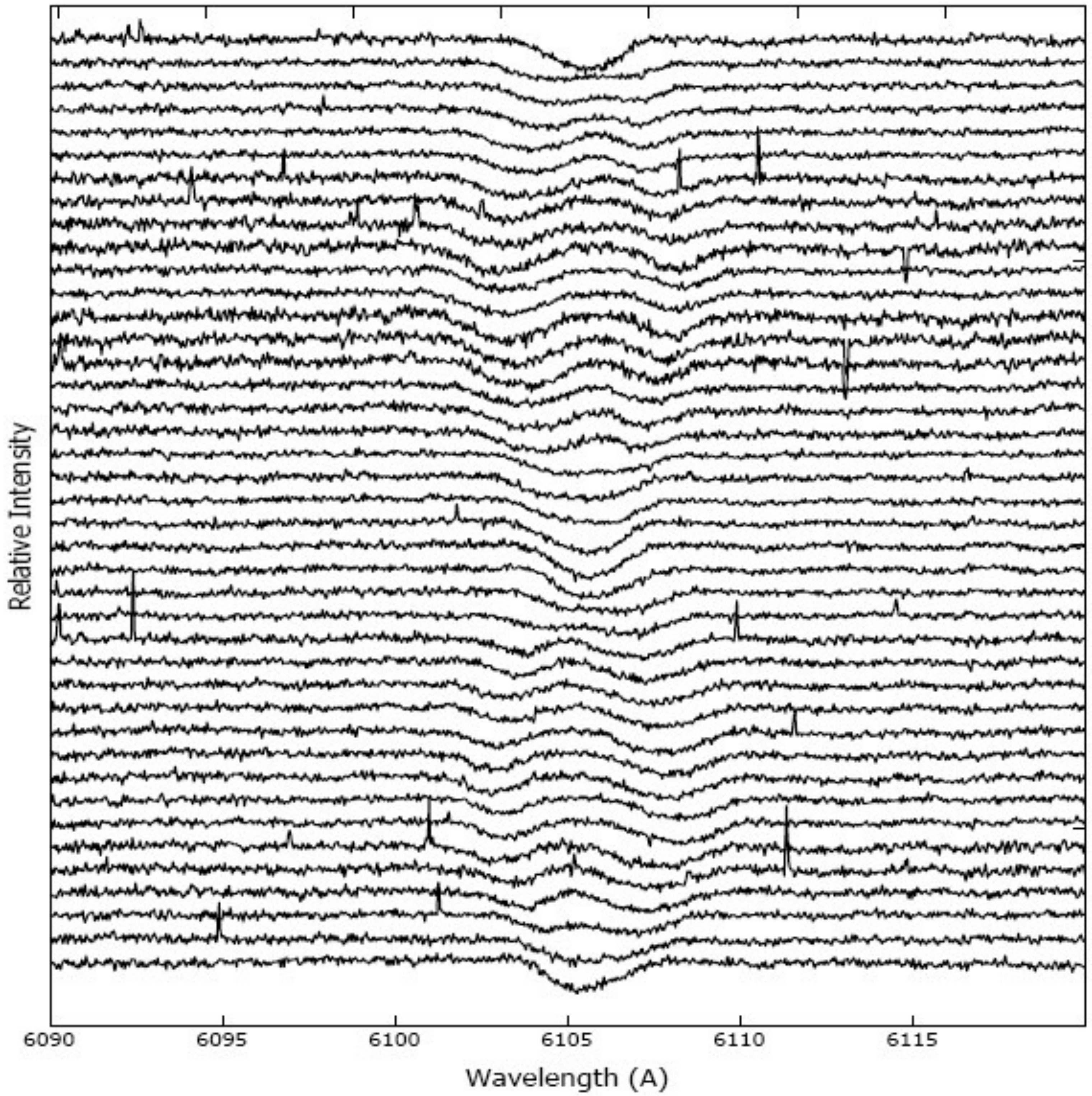
Spectroscopic binaries are binaries which are only found through their spectra, as the motion of the stars causes the spectral lines to be Doppler-shifted alternately to the red and the blue.



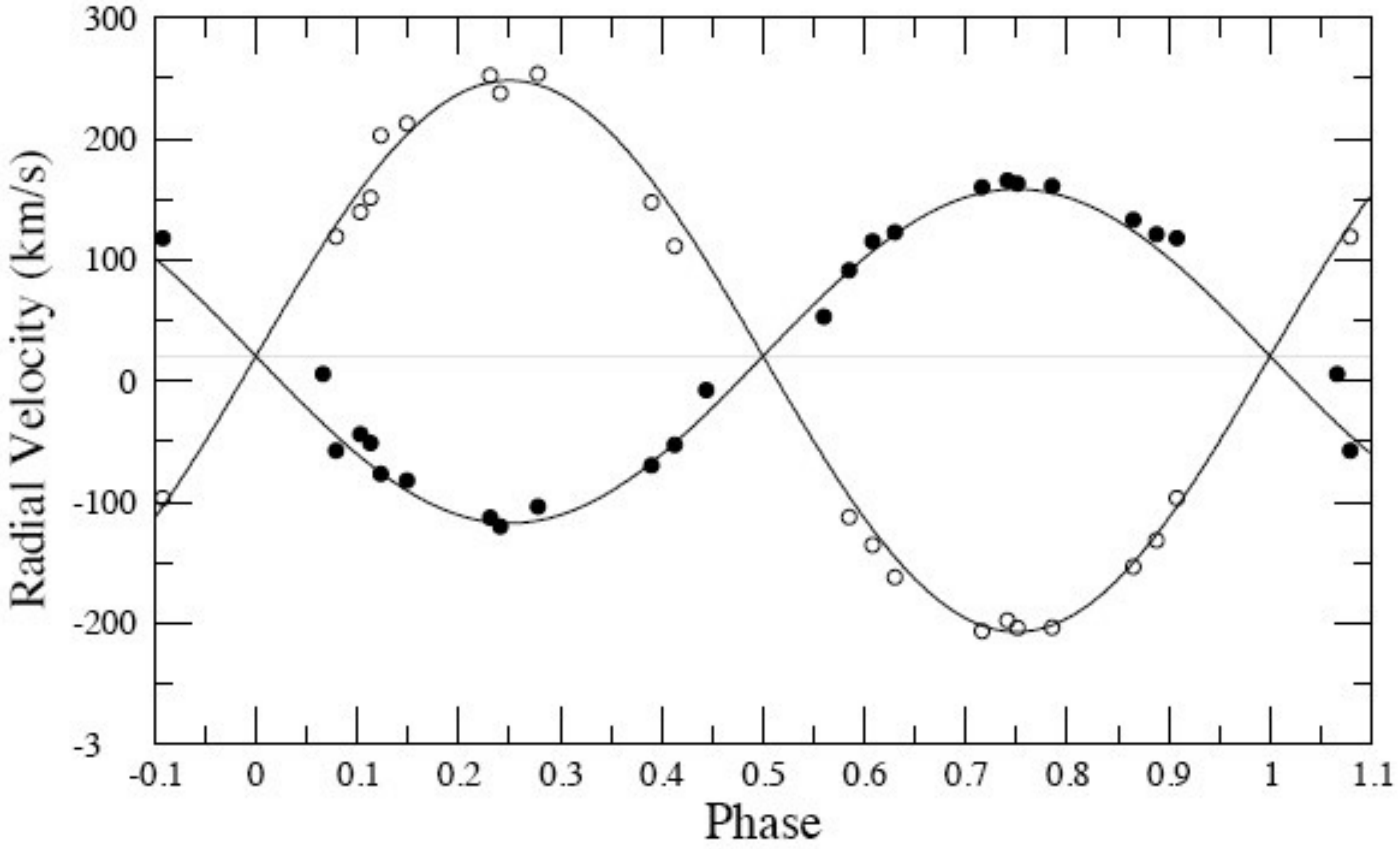
In *double-lined* spectroscopic binaries, two sets of lines can be seen, with the stars moving in opposite directions.

Spectrograms of the binary star Mizar (ζ Ursa Majoris), show the lines becoming double and single as the two stars move in their orbits.

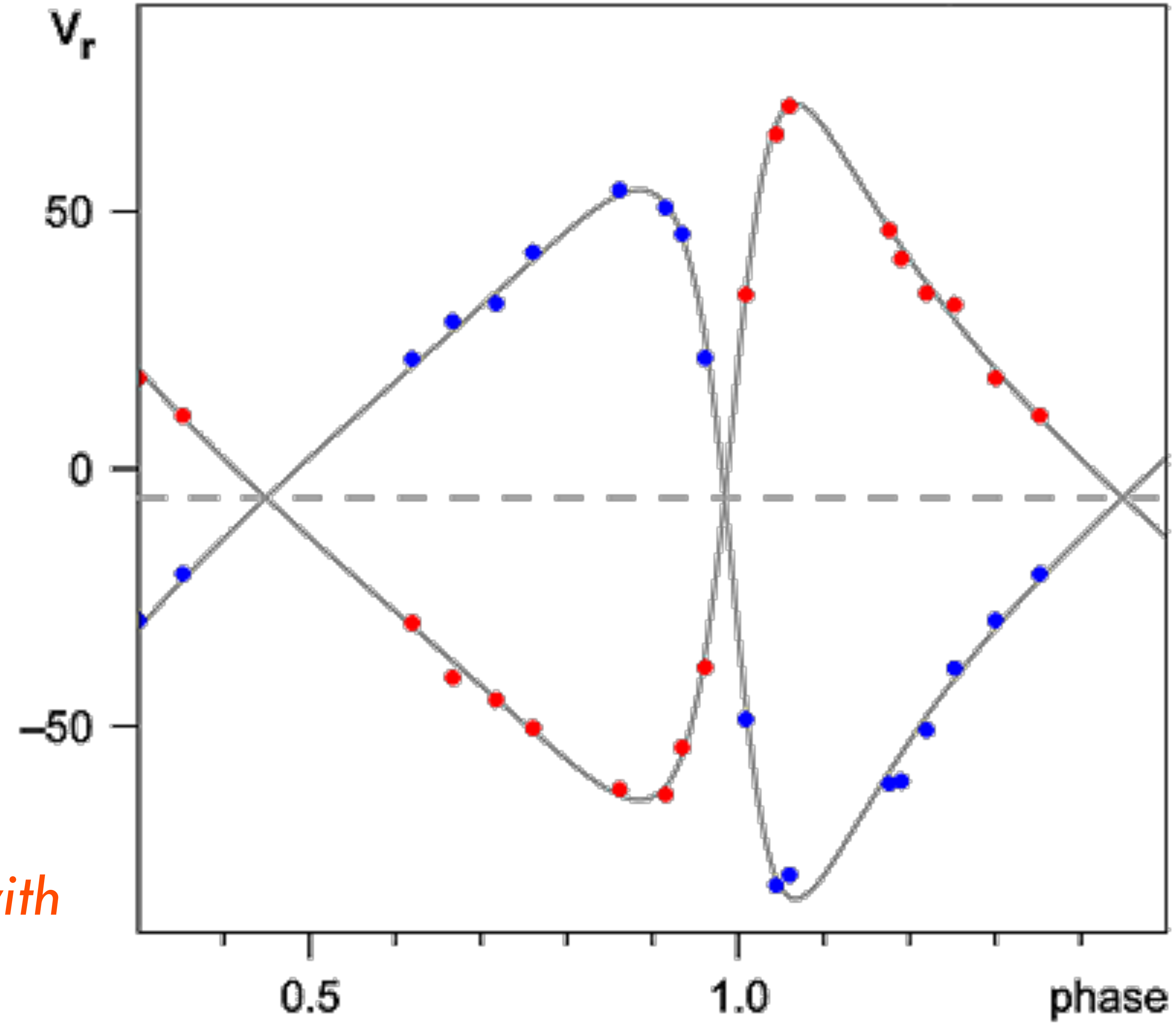




The orbit of the double-lined spectroscopic binary IM Mon, consisting of two B stars in a 1.2 day orbit.

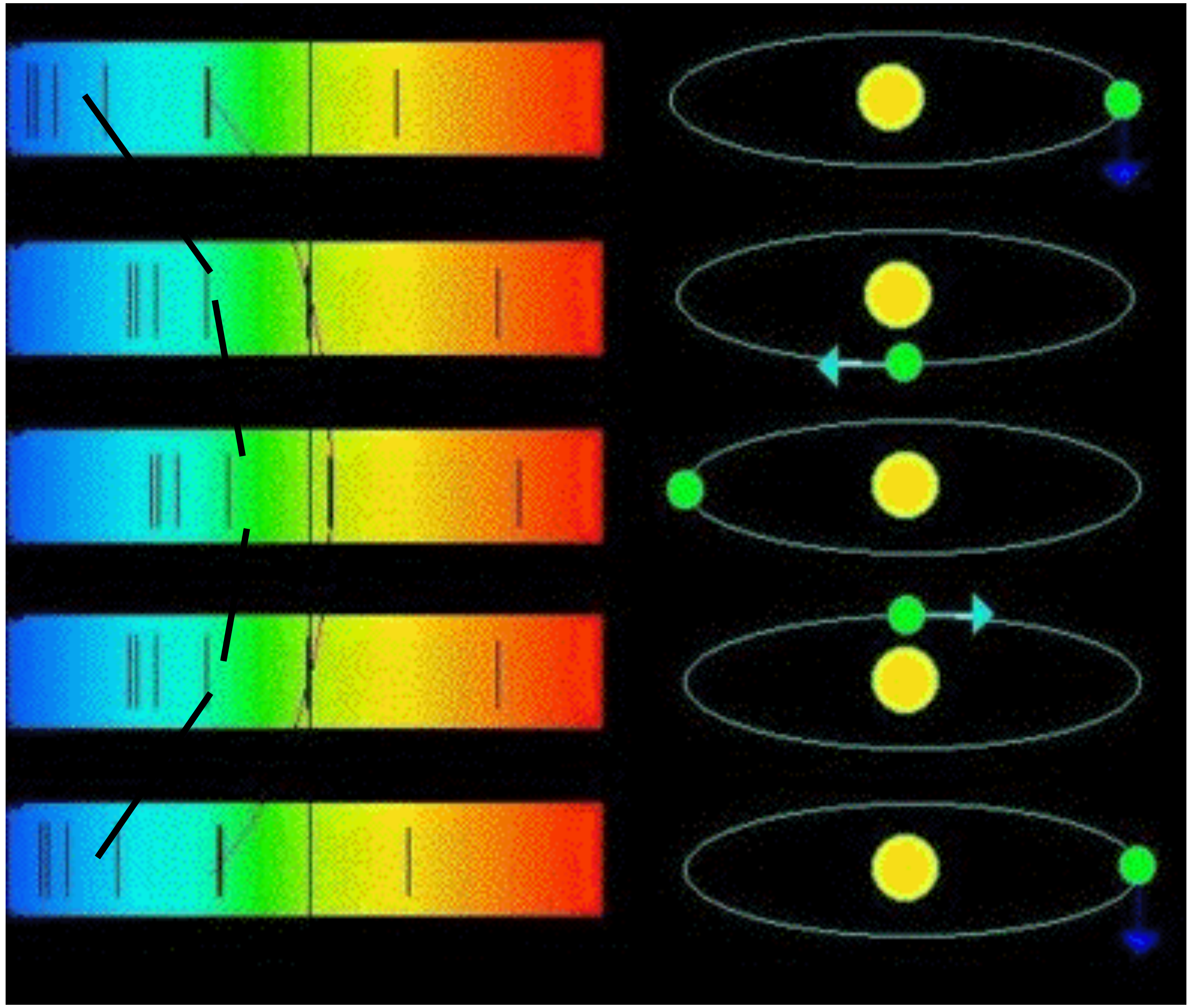


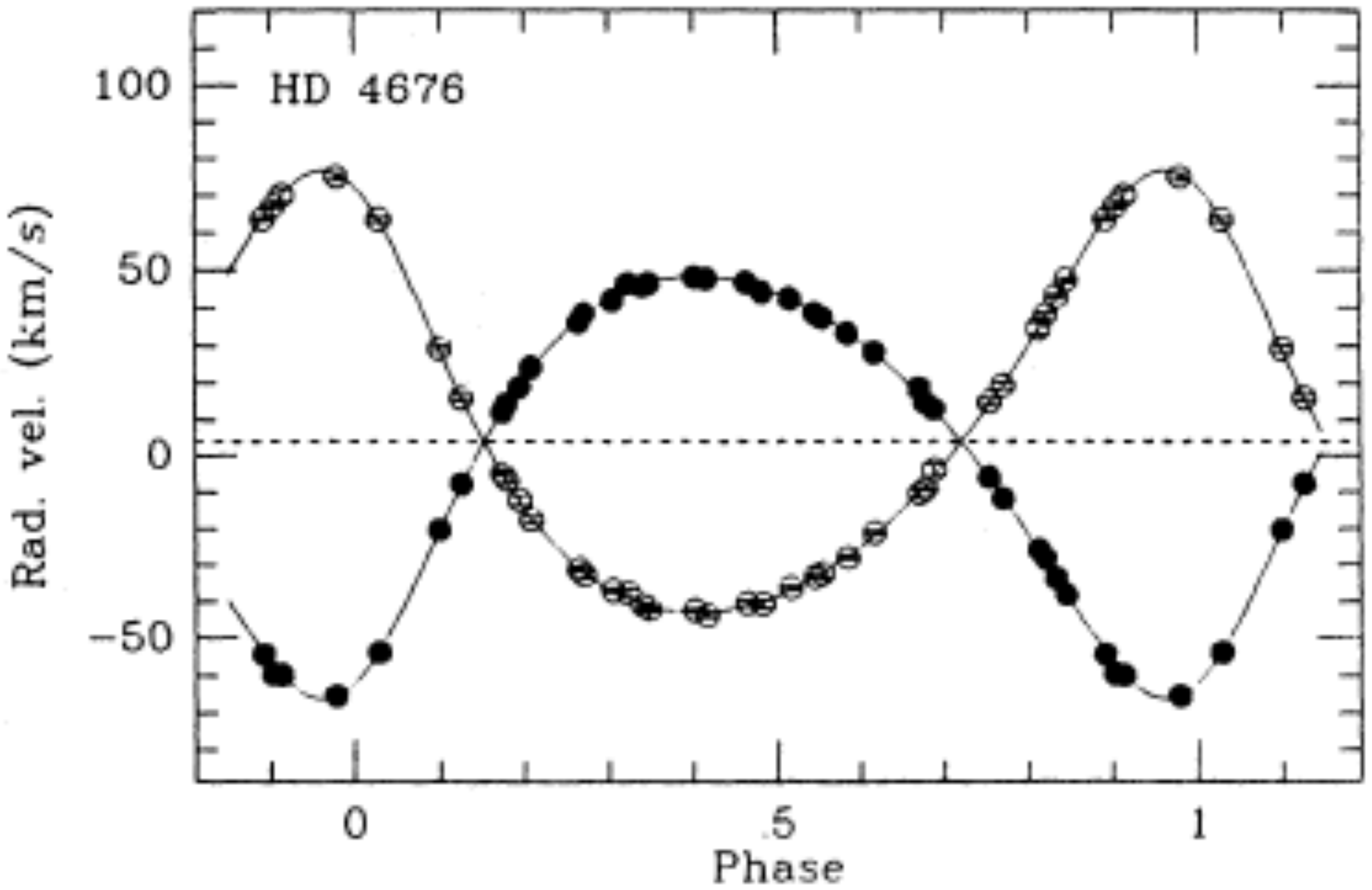
If the orbit is circular, the velocity curve is a sine wave, but if the orbit is elliptical, the curve is very odd indeed!

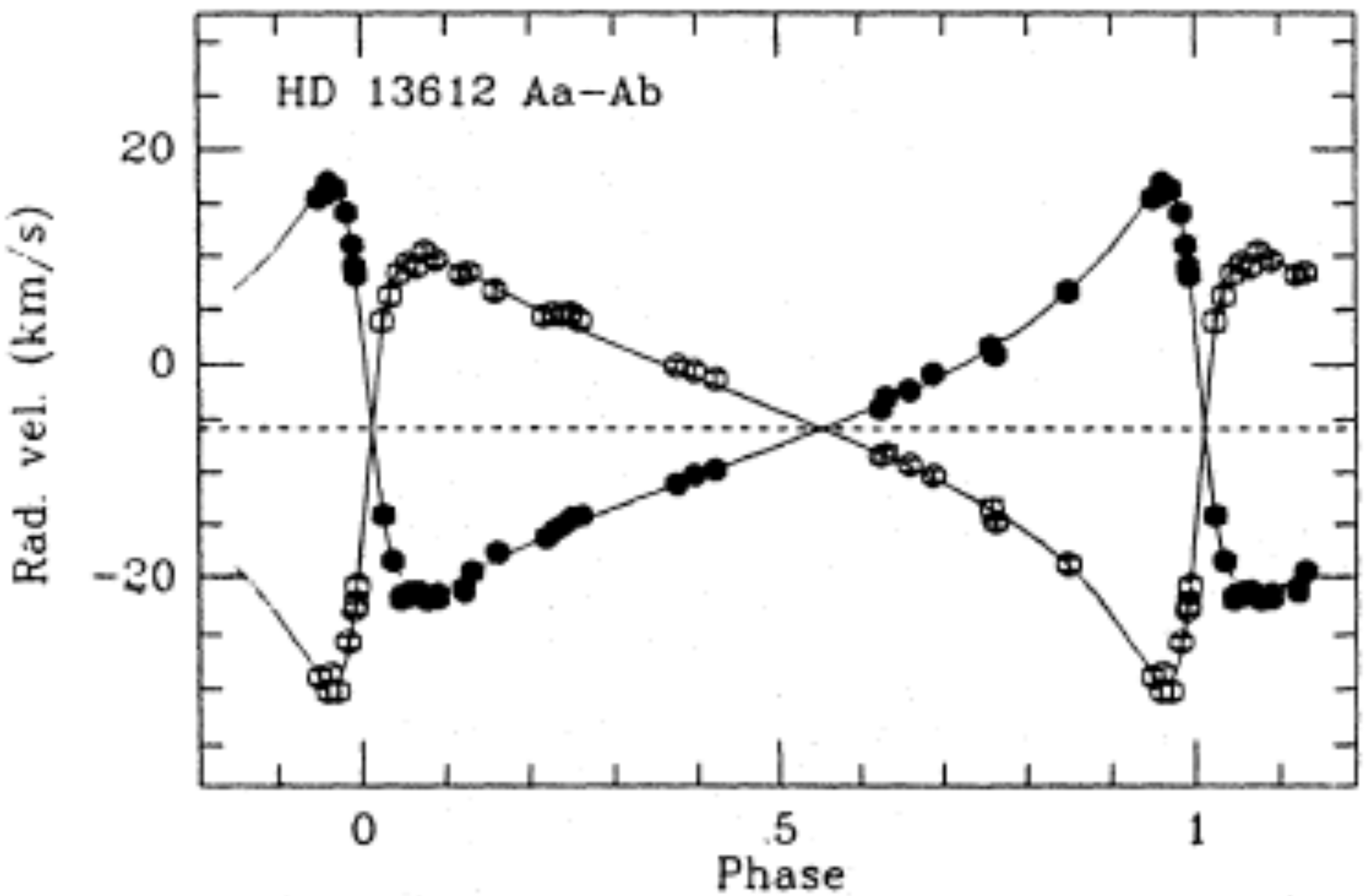


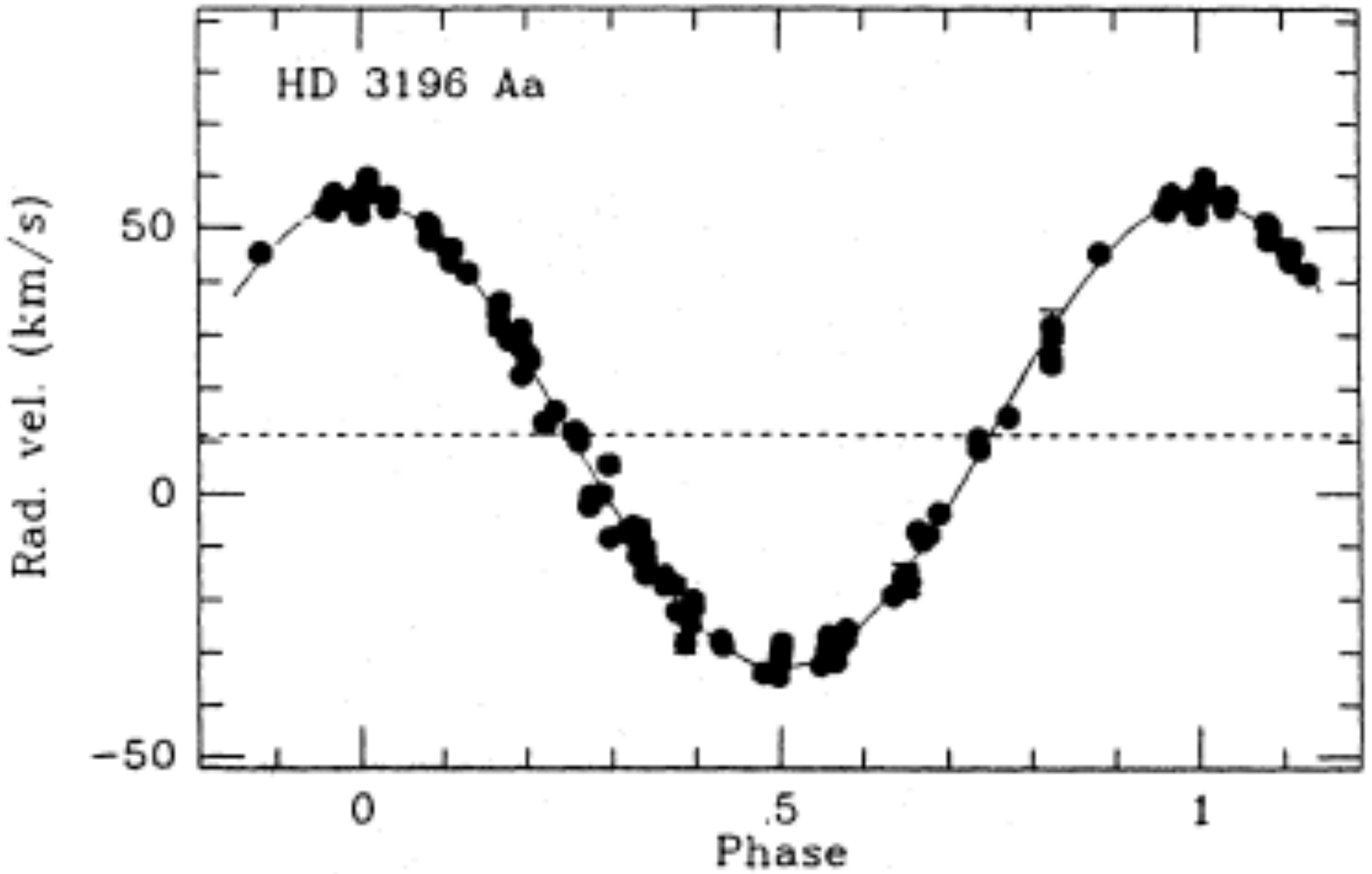
Radial velocities of the two stars of Mizar A. The orbit is non-circular, with an eccentricity of around 0.5.

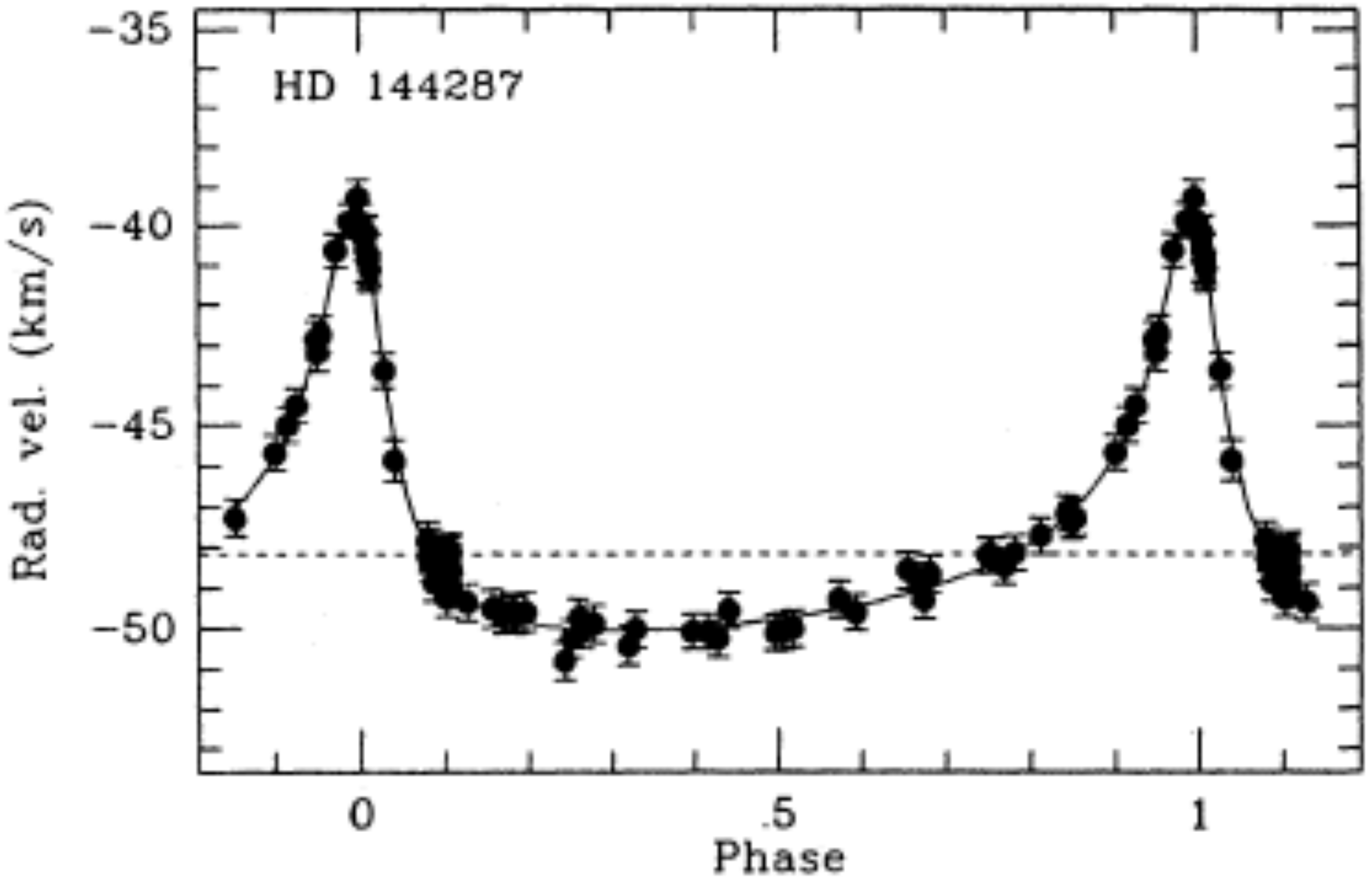
In *single-lined* spectroscopic binaries, only one set of lines can be seen (because the other star is too faint), but the presence of the companion is inferred because of the motion of the primary.




HD 4676
Rad. vel. (km/s)
100
50
0
−50
0
.5
1
Phase


HD 13612 Aa–Ab
Rad. vel. (km/s)
20
0
−20
0
.5
1
Phase


HD 3196 Aa
Rad. vel. (km/s)
50
0
−50
0
.5
1
Phase

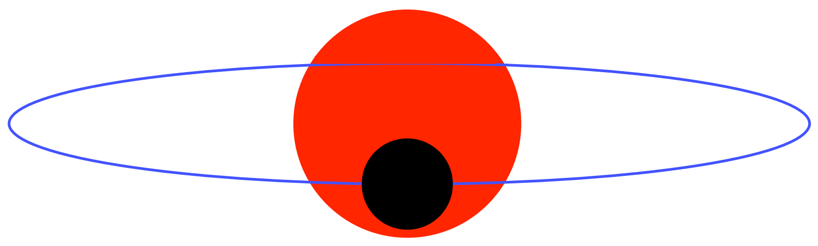

HD 144287
Rad. vel. (km/s)
−35
−40
−45
−50
0
.5
1
Phase

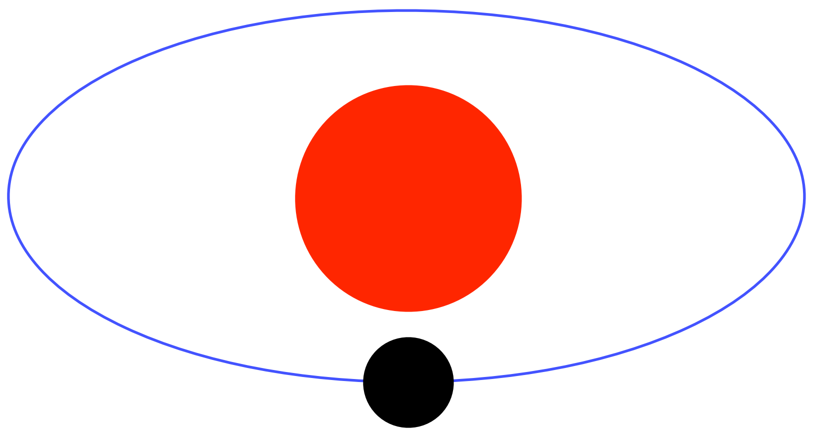
Spectroscopic binaries allow us to measure the masses of the stars directly, since from the velocities we can derive the size of the orbit.

Unfortunately, the Doppler shift only gives us the velocity in our direction. Since we don’t know the tilt of the orbit, we don’t know how fast the stars are moving in the plane of the sky, so we may underestimate the masses.

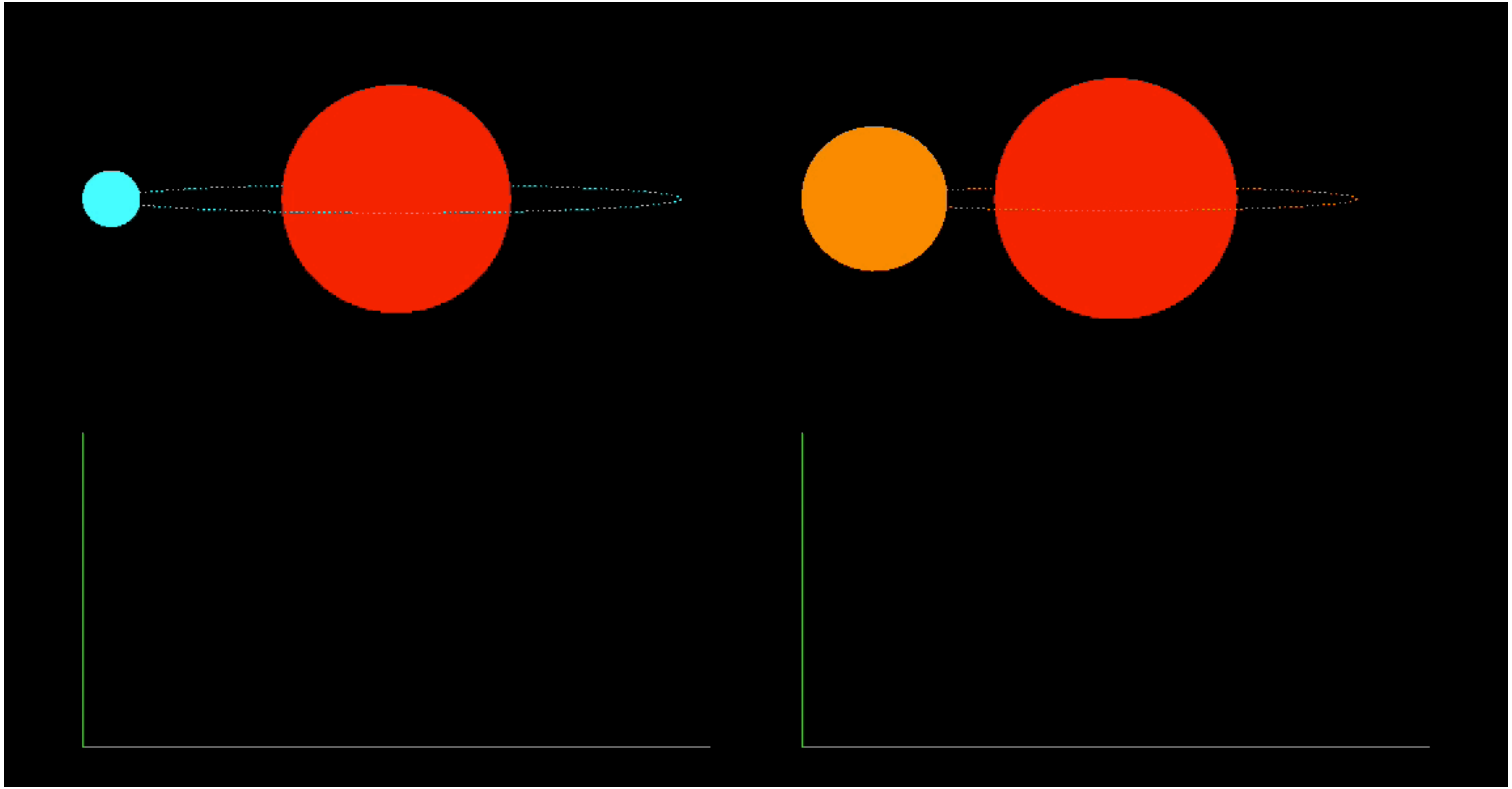
Eclipsing binaries are binaries where periodic drops in brightness occur as the two stars eclipse one another.

Eclipsing binaries can only occur when the plane of the orbit is close enough to our line of sight that the light from one star can be blocked by the other star. If the orbit is tilted too far, the stars will not eclipse.





Eclipsing binaries give us important information about the stars. The shape of the light curve is related to the relative size and brightness of the two stars.



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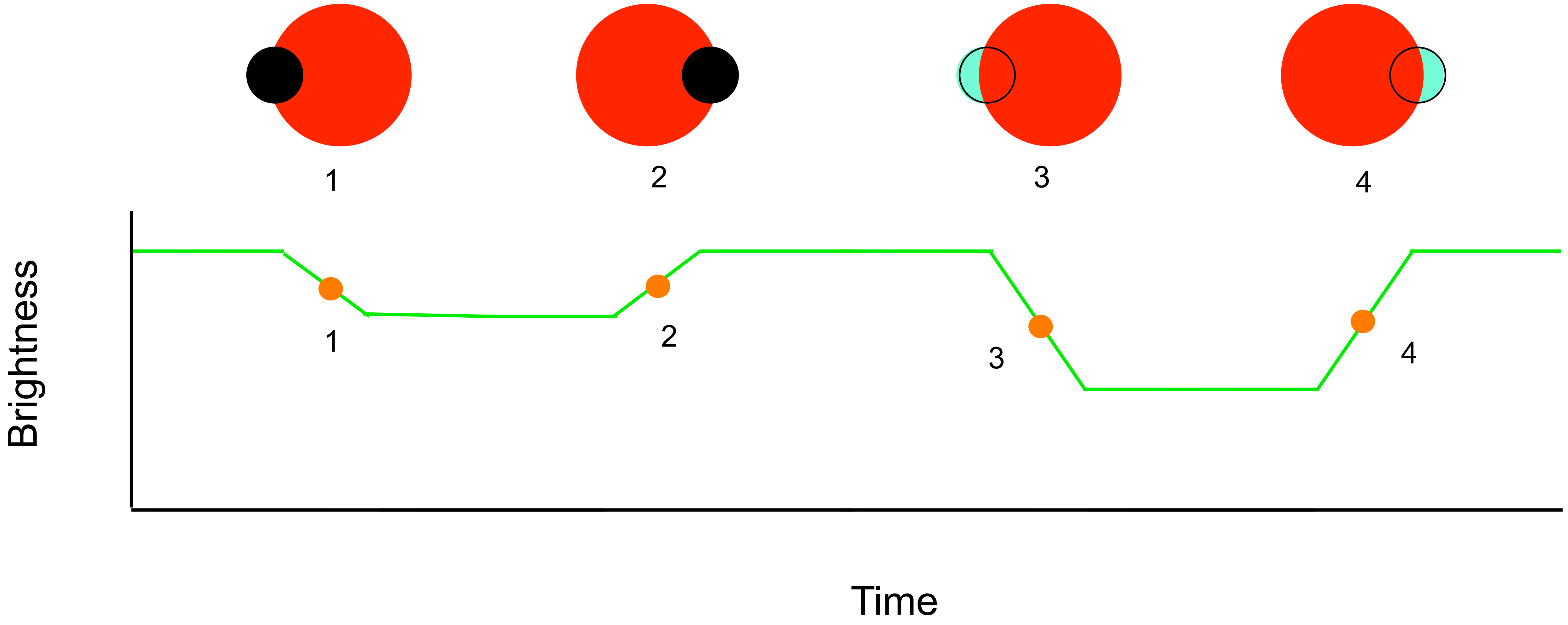
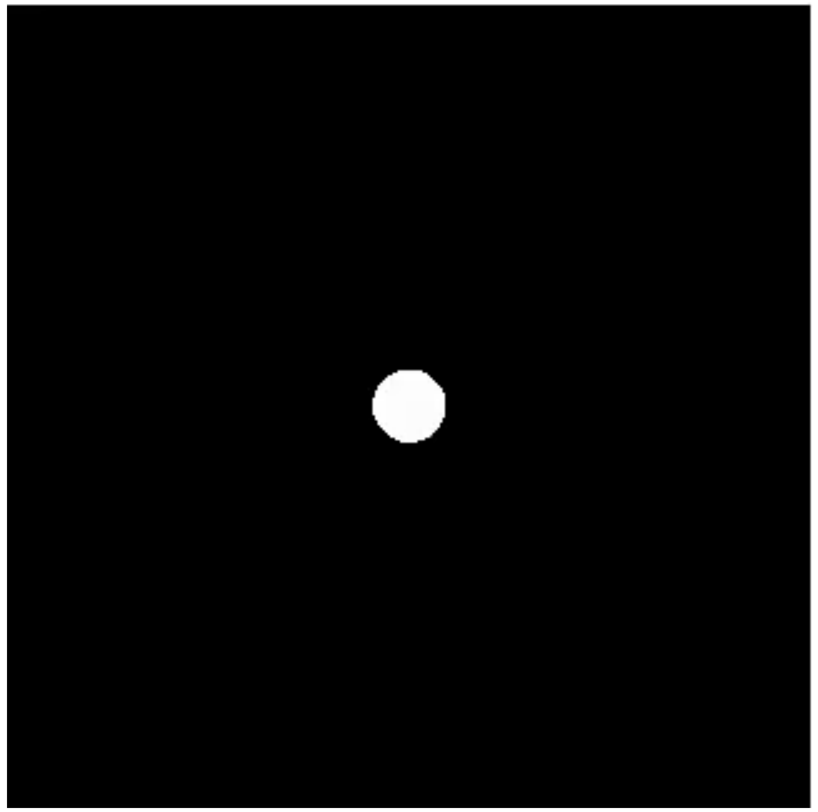


But remember, we’re deducing all this by measuring the brightness of an apparently single “star”, which we see varying with time.



So there are three completely different ways of finding binaries:

- positional changes (*visual/astrometric*)
- velocity changes (*spectroscopic*)
- brightness changes (*eclipsing*)

Each method is biased towards finding different types of binaries.

- *Visual binaries* tend to be widely separated (so they can be resolved) and of similar brightness (or the fainter one is swamped)

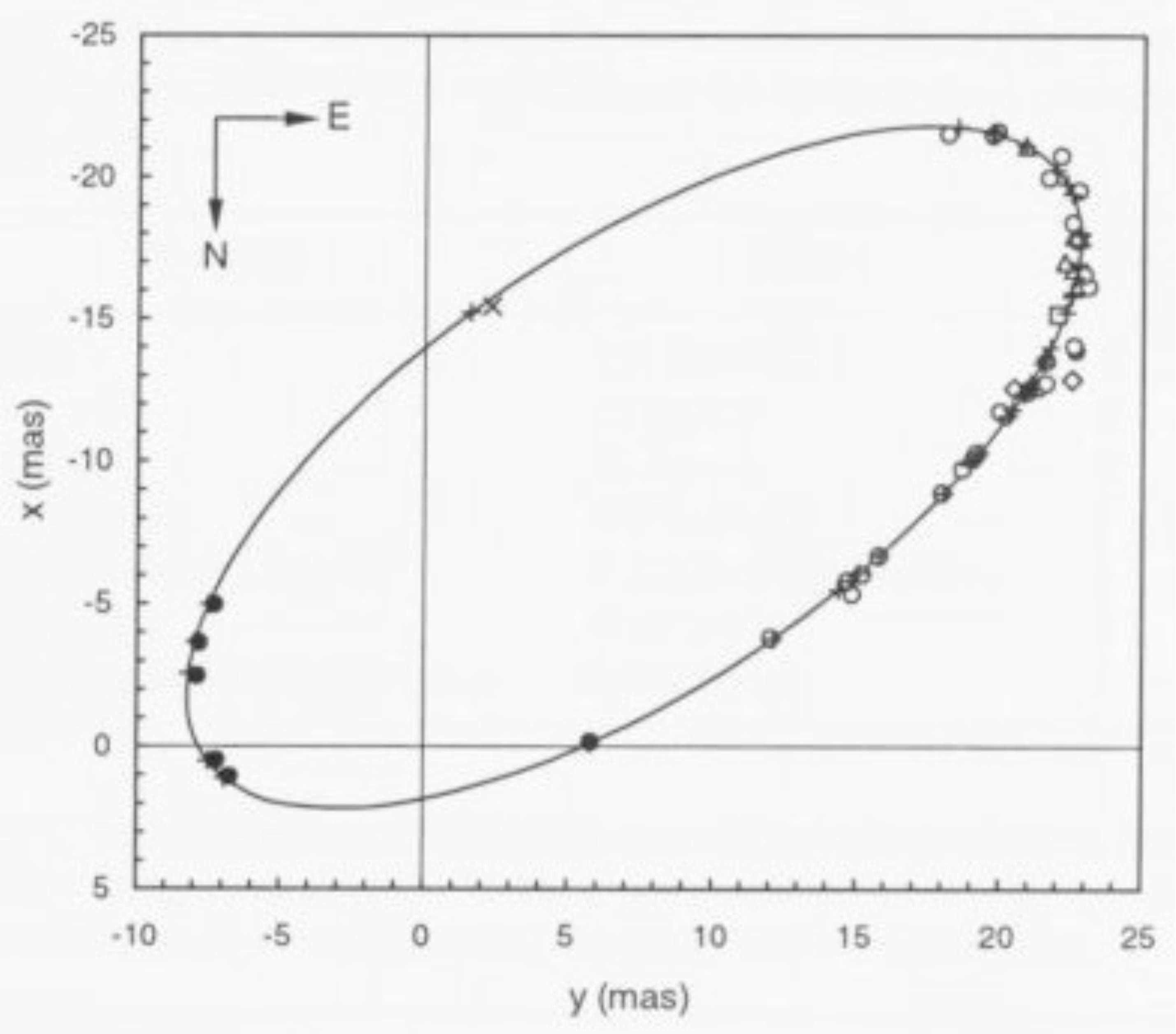
- *Spectroscopic binaries* tend to be closely spaced (so the velocities are high) and not too different in mass

- *Eclipsing binaries* must be edge-on, and tend to be closely spaced (so the chances of eclipse are higher) and similar in size (so the change in light is greater)

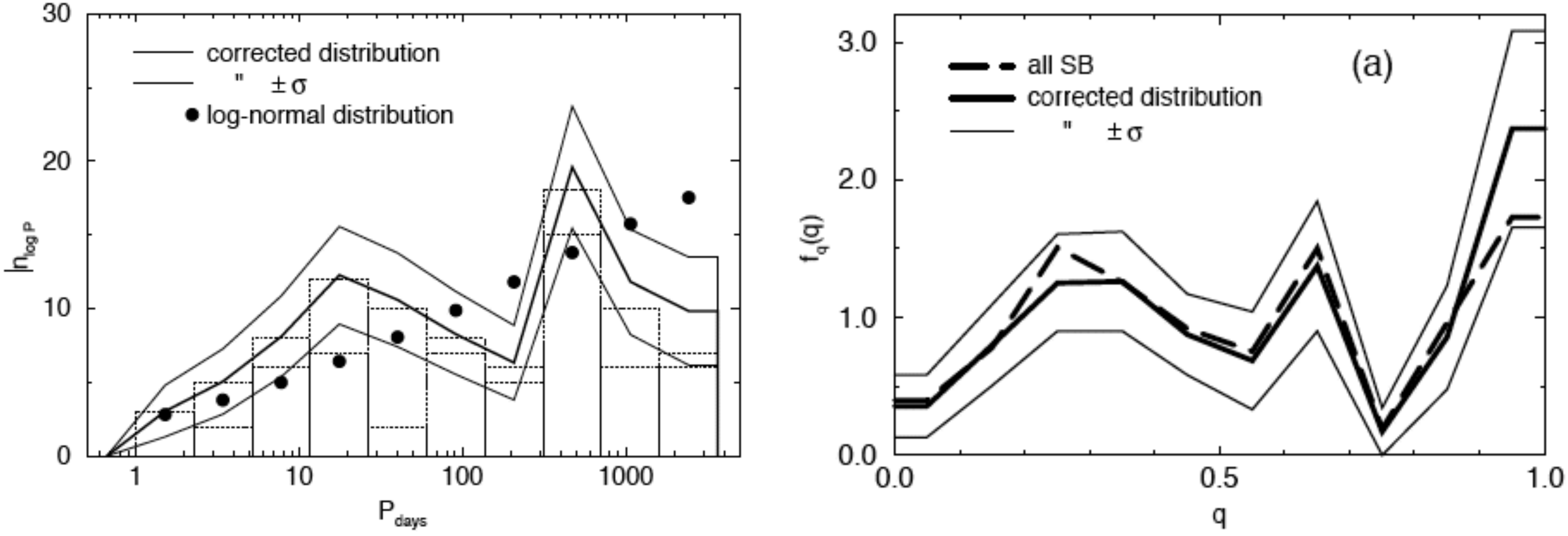
So our estimates of how many stars are in binaries are fairly uncertain: there are very many kinds of binaries we may have missed.

The best guess for stars in the neighbourhood of the Sun is that at least half have at least one companion. However, this may not be true for stars much more or less massive than the Sun: there is evidence that only 40% of M stars have a binary companion.

Conversely, between 70% and 100% of O and B stars appear to have companions. However, the masses of the companion stars are strongly skewed towards also being massive: there are few massive stars with low mass companions.

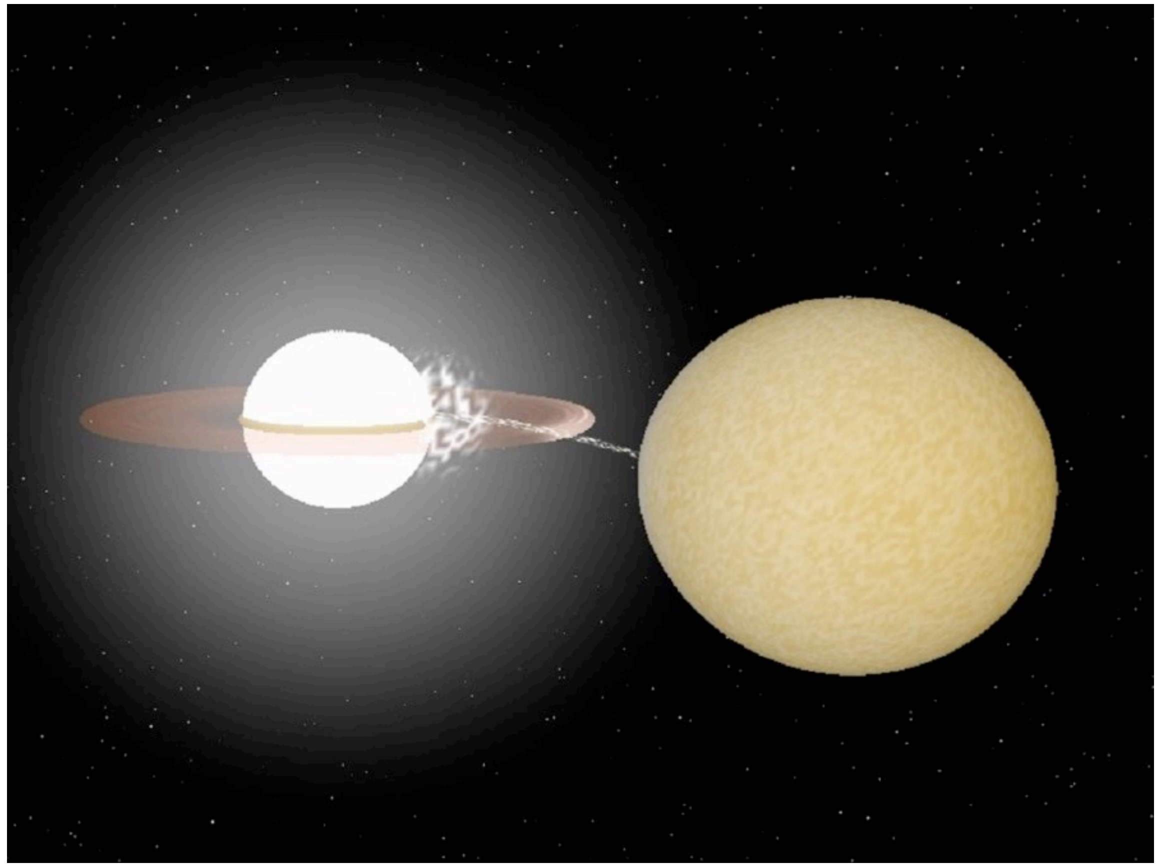


Beta Centauri was recently determined to be a triple B-star system: the inner pair of B stars orbits in a highly eccentric 357 day orbit, while the third star has an orbital period of about 250 years. This shows the orbit of the inner pair.



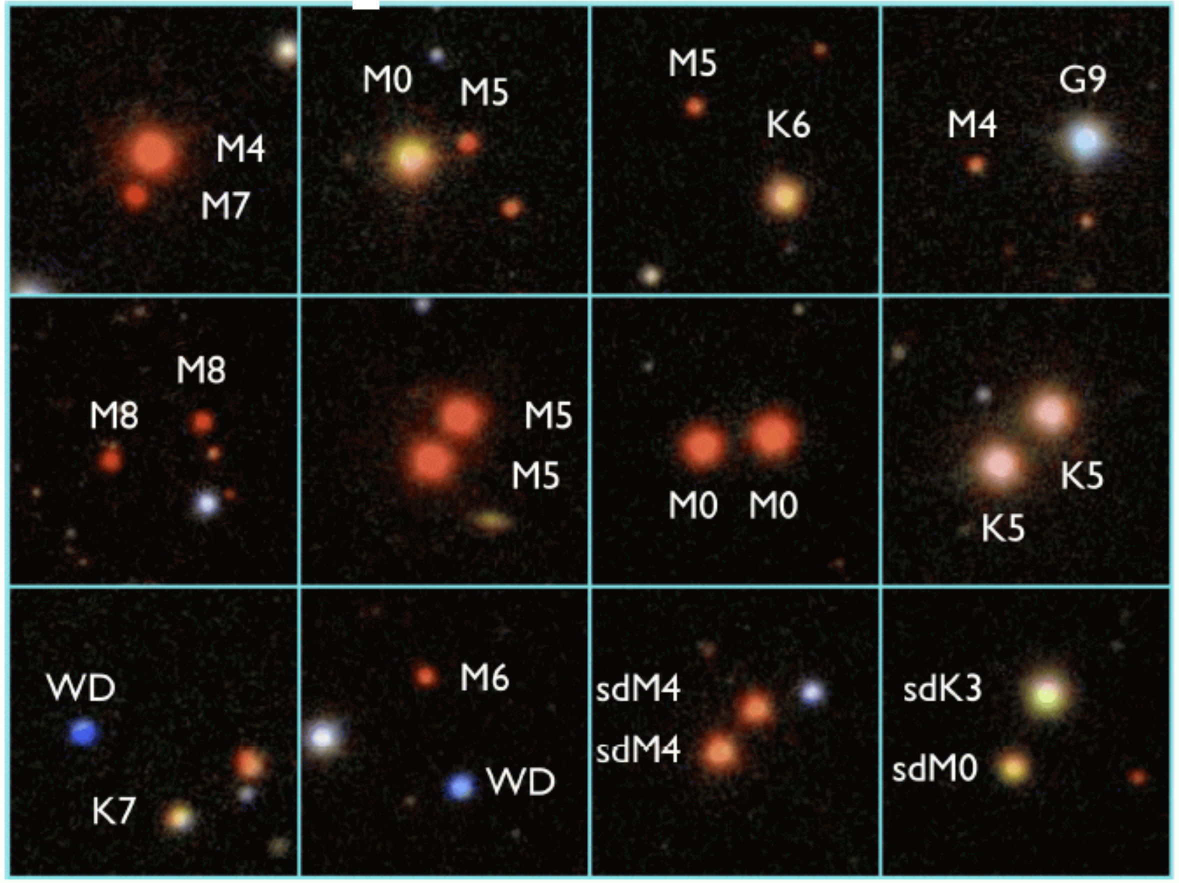
"Best guess" distributions of orbital periods and mass ratios for nearby K to F-type stars. The chance of a period between 10 days and 10 years is roughly constant; the mass ratio q=M2/M1 has two peaks: most are roughly 0.2–0.7, or q>0.8 (twins). From Halbwachs et al. 2003.

Shortest period: HM Cancri, two white dwarfs with $P = 5.4$ minutes, $a = 8\ R_{Earth}$

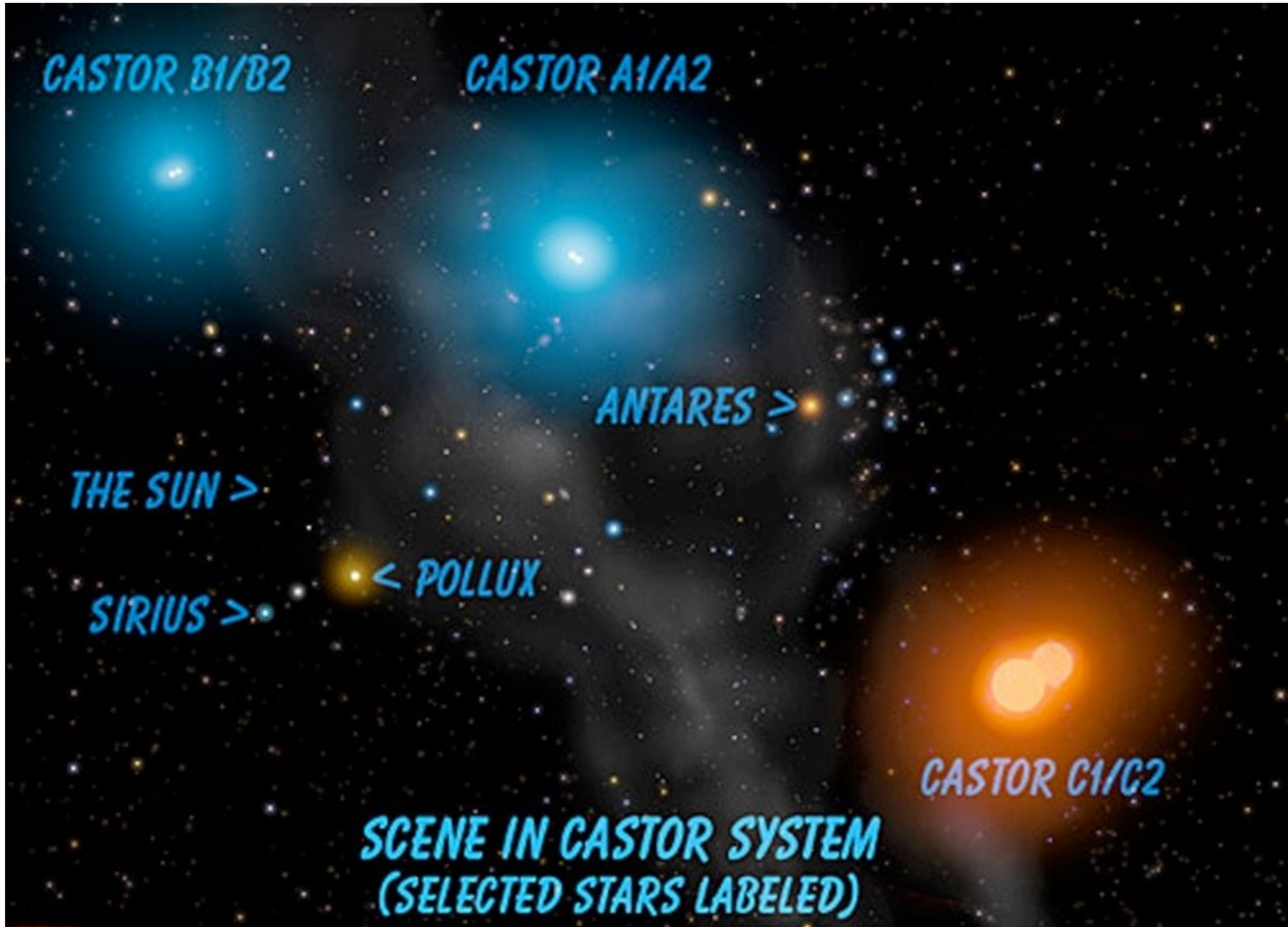


Longest period: ?? Proxima Cen:
$P = 500{,}000$ y

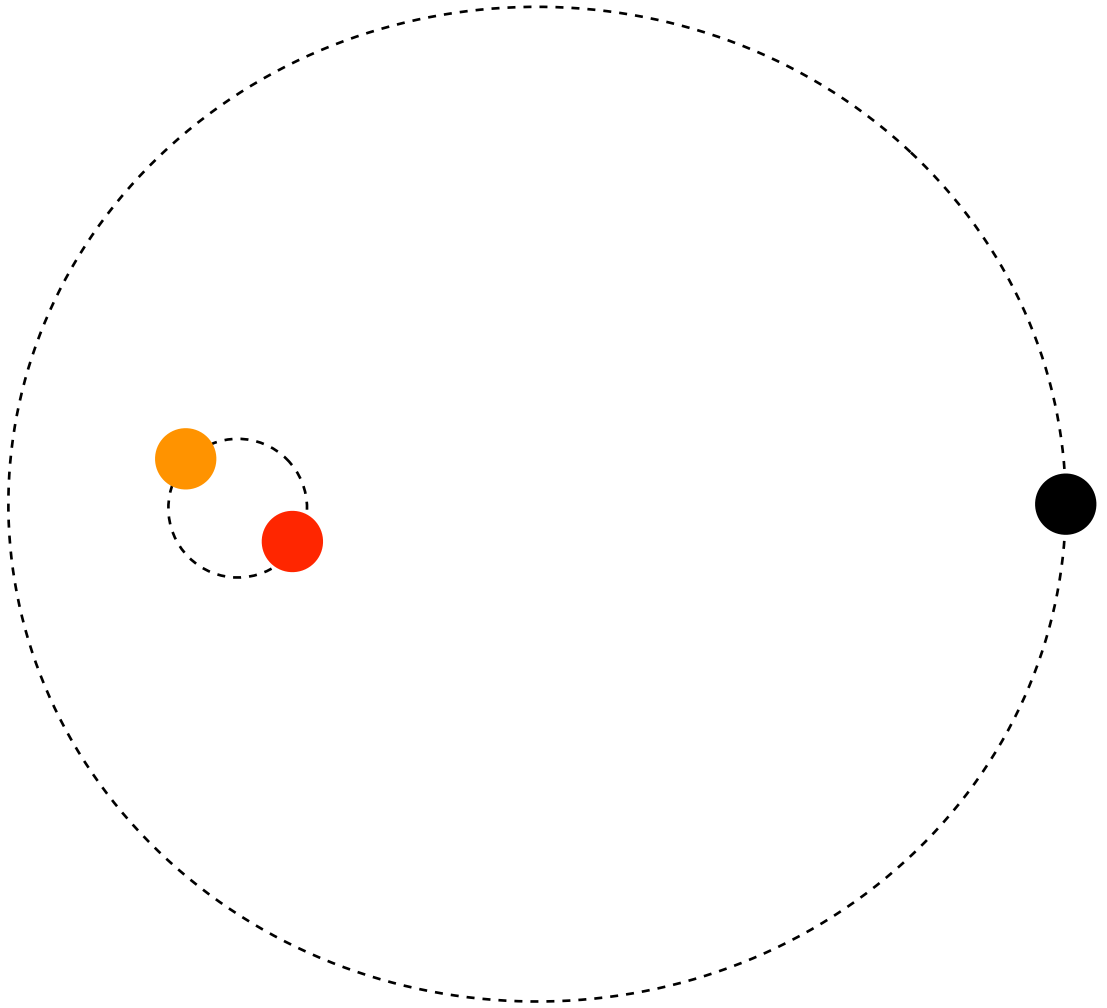
Common proper motion systems: bound?

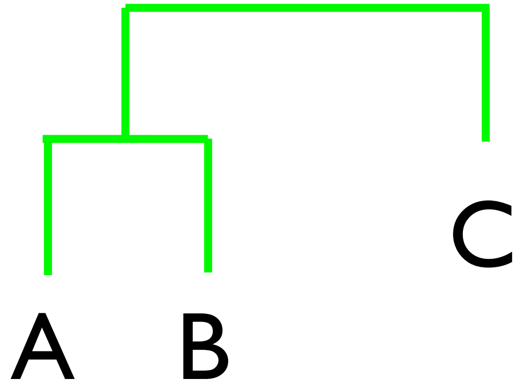


Multiple star systems are also common, containing three or even more stars. For example, Castor (α Geminorum), is in fact a sextuple star system, consisting of an inner pair of binaries, with a third binary orbiting around the inner pair of binaries.

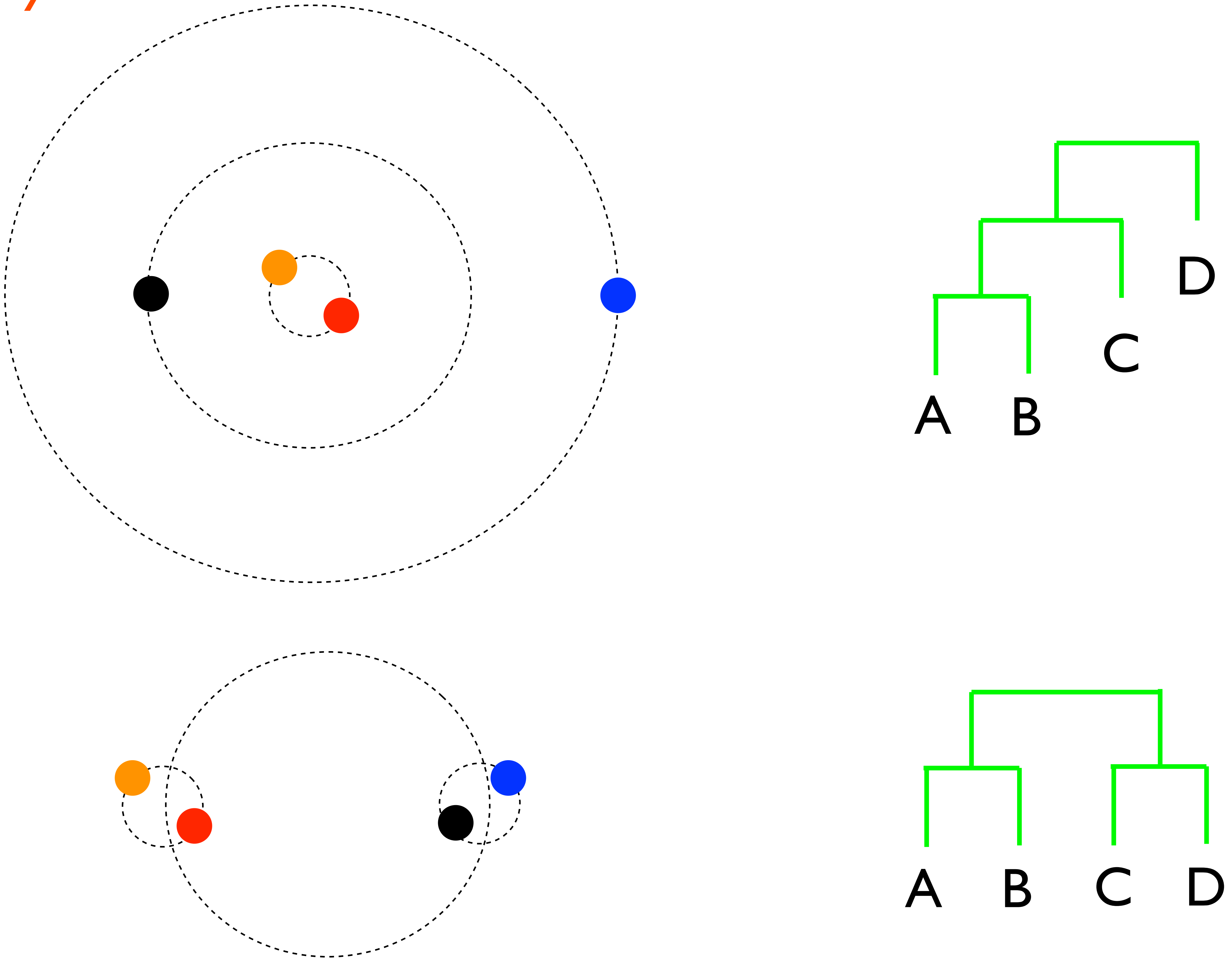


Multiple star systems are always *hierarchical*: they can be decomposed into binaries (whose components may themselves be binaries); non-hierarchical systems are dynamically unstable.

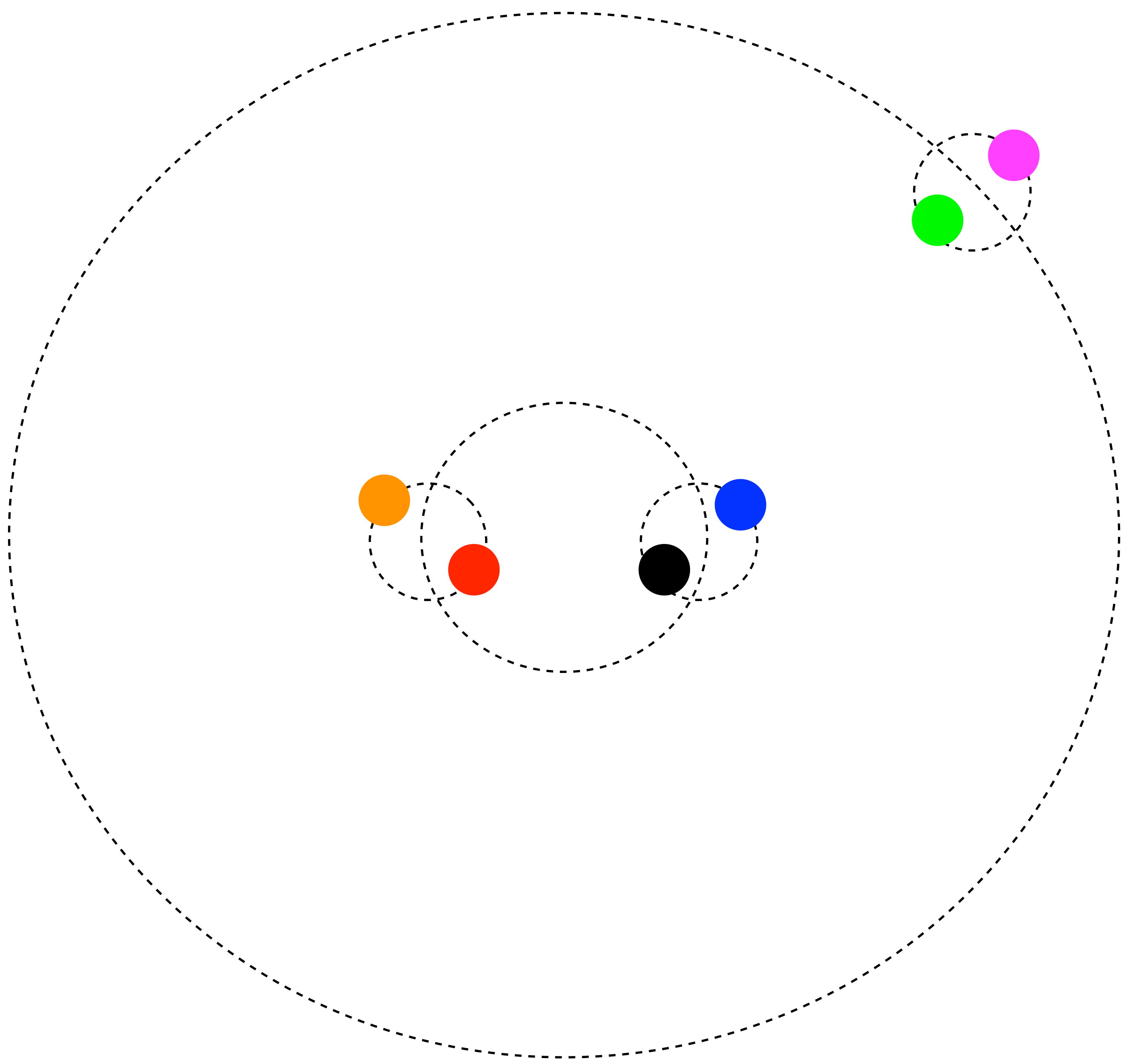


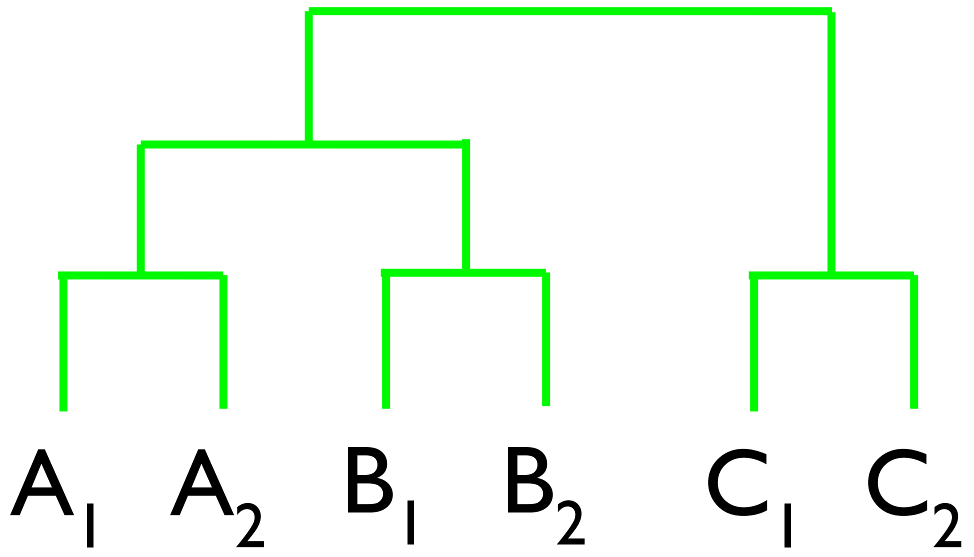


Quadruple systems:

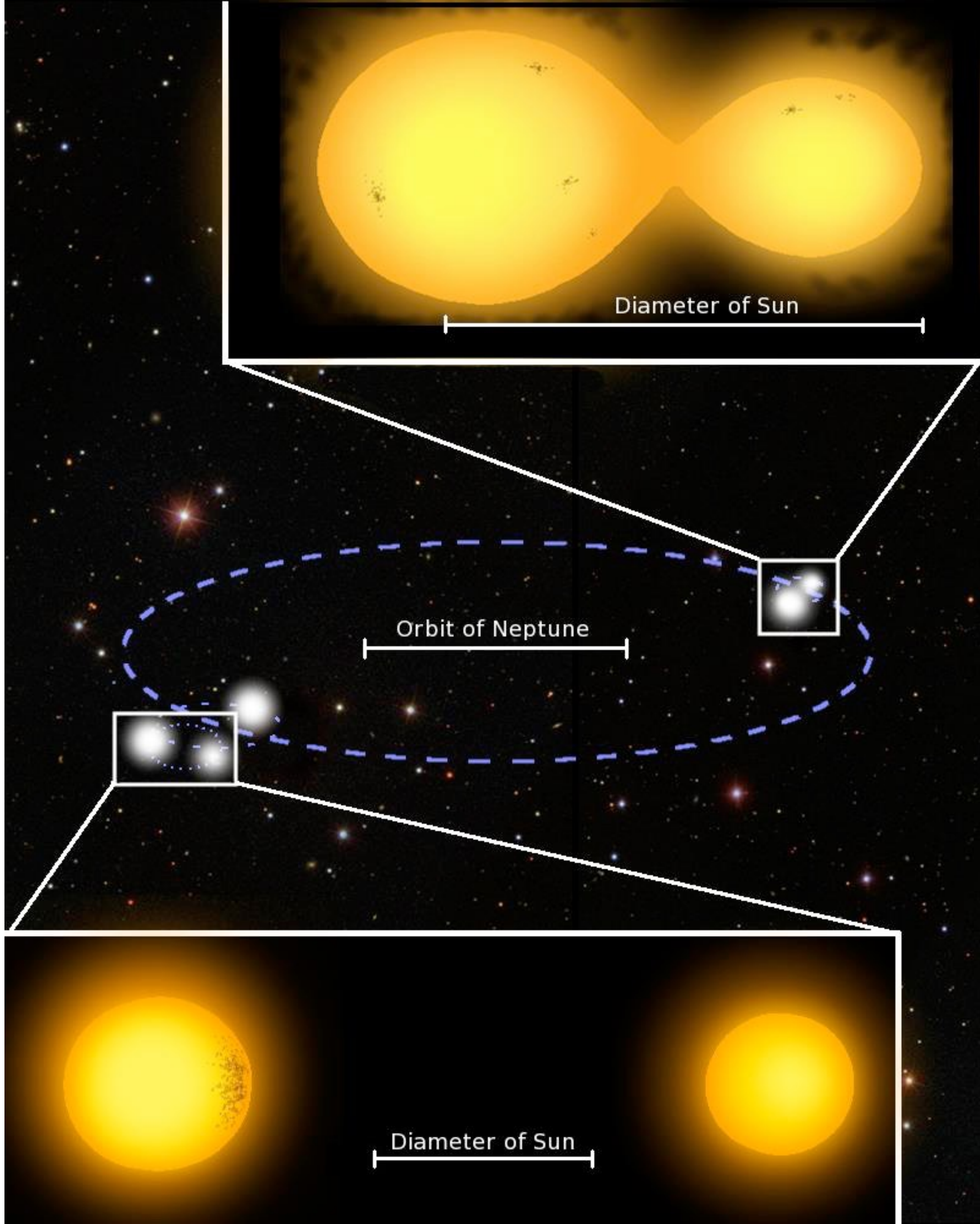


The Castor system:



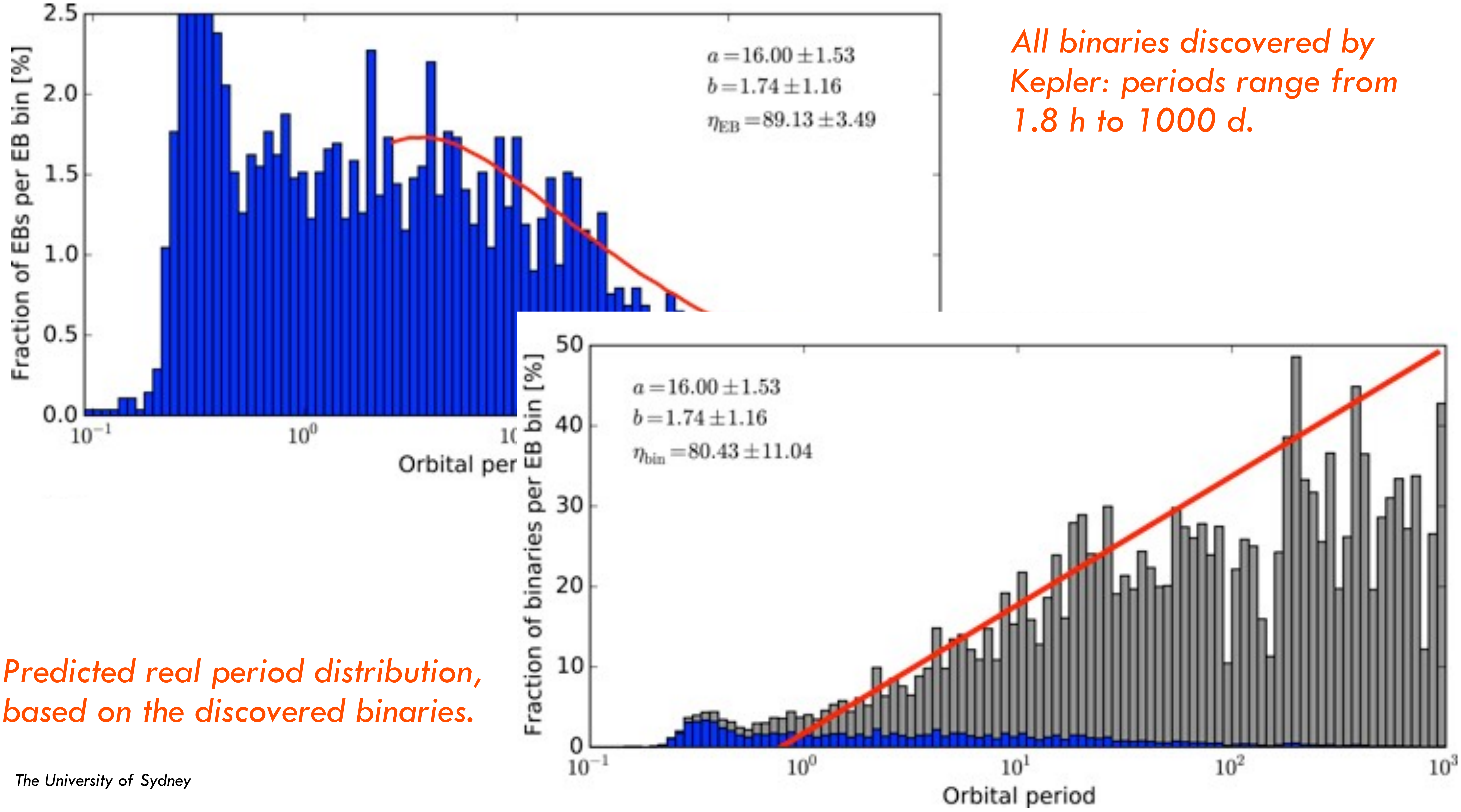


Kepler has found nearly 3000 eclipsing binaries, with periods between 1.8 hours and 1087 days (3 years), including many multiple-star systems.



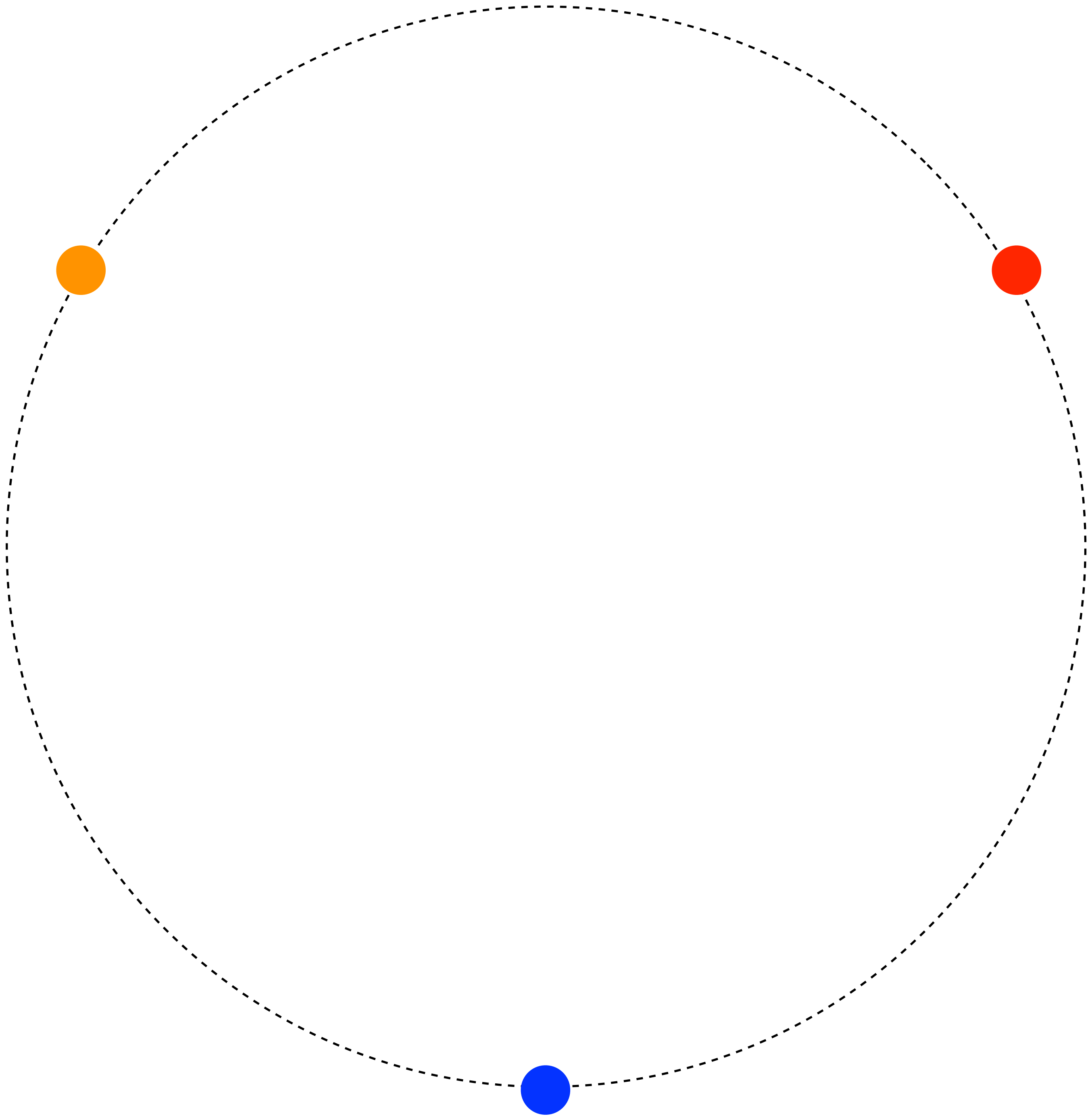
A five star, doubly-eclipsing star system found by Kepler.

All binaries discovered by Kepler: periods range from 1.8 h to 1000 d.

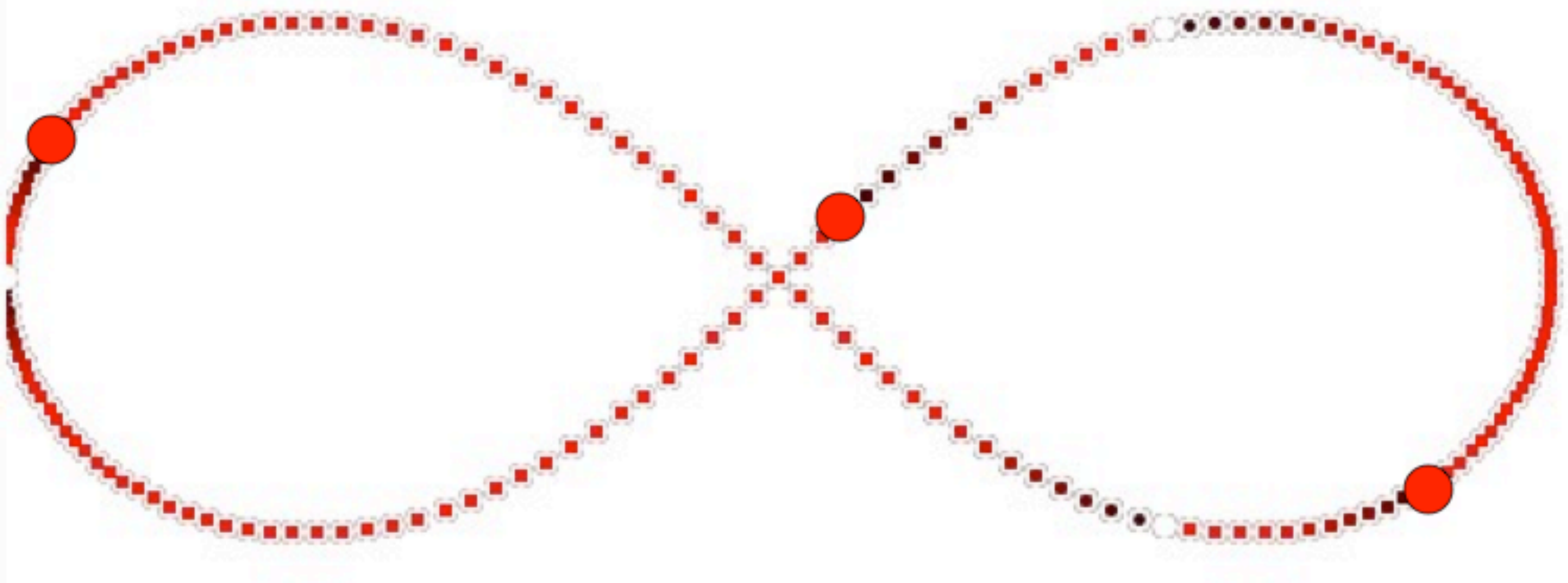


Predicted real period distribution, based on the discovered binaries.

Other orbits are theoretically possible, e.g. the Lagrange configuration, with three objects orbiting in an equilateral triangle



Recently even more bizarre orbits have been found to be stable.



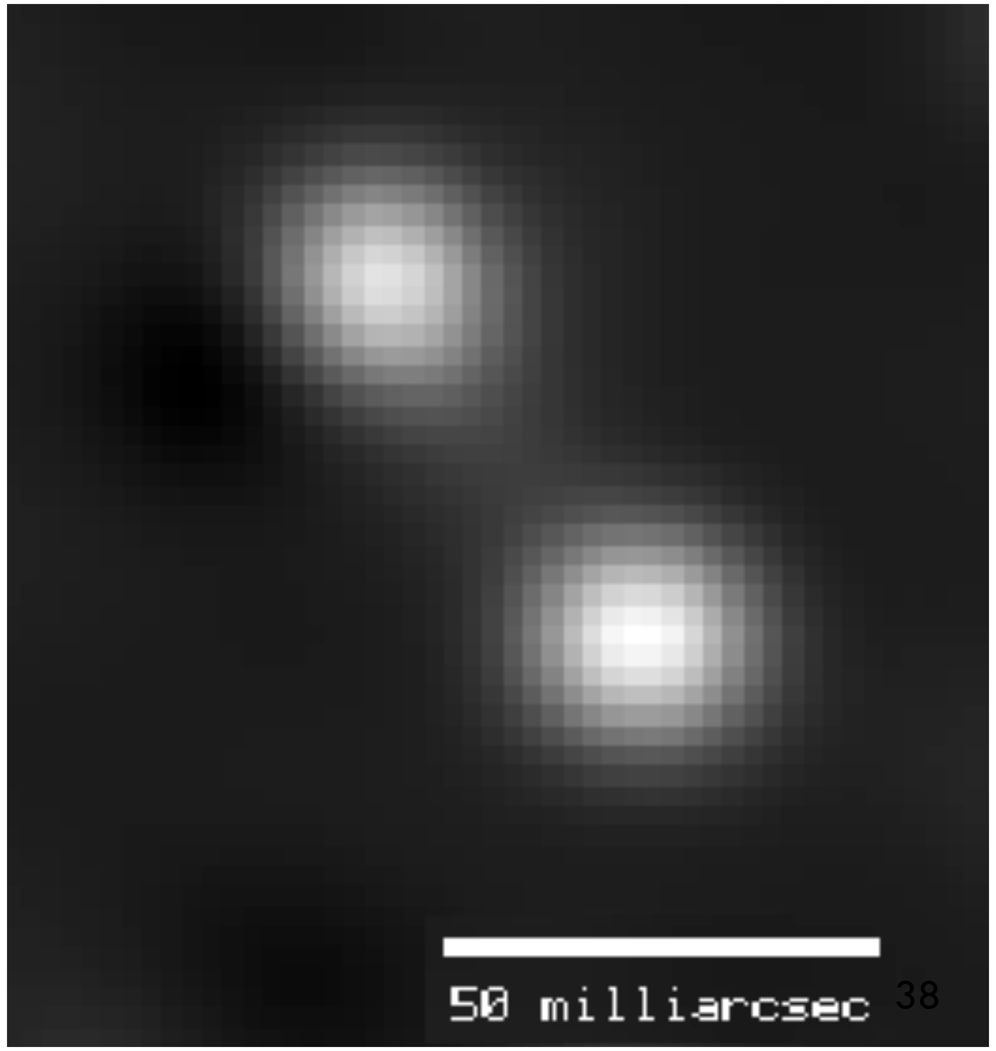
However, it's hard to see how they could form!

Stars in binary systems

So far, in all our discussion of stellar evolution, we have made no mention of what effect the presence of a binary companion has on a star. If up to two-thirds of all stars have at least one companion, how is their evolution affected by not being alone?

Take α Cen, for instance: a binary consisting of a G2 and K1 star in an 80 year orbit – about the distance of Uranus from the Sun. When α Cen A turns into a red giant, it will expand to less than 1/4 of the distance between the two stars. There will probably be no effect from the companion star: it will continue to evolve just like a single star.

But what about much closer binaries? Capella, for instance, consists of two G type stars in a 105 day orbit – about the distance of Venus from the Sun. When the more massive star becomes a red giant, it will swell up to engulf its companion. We can predict this will have a large effect on its evolution!

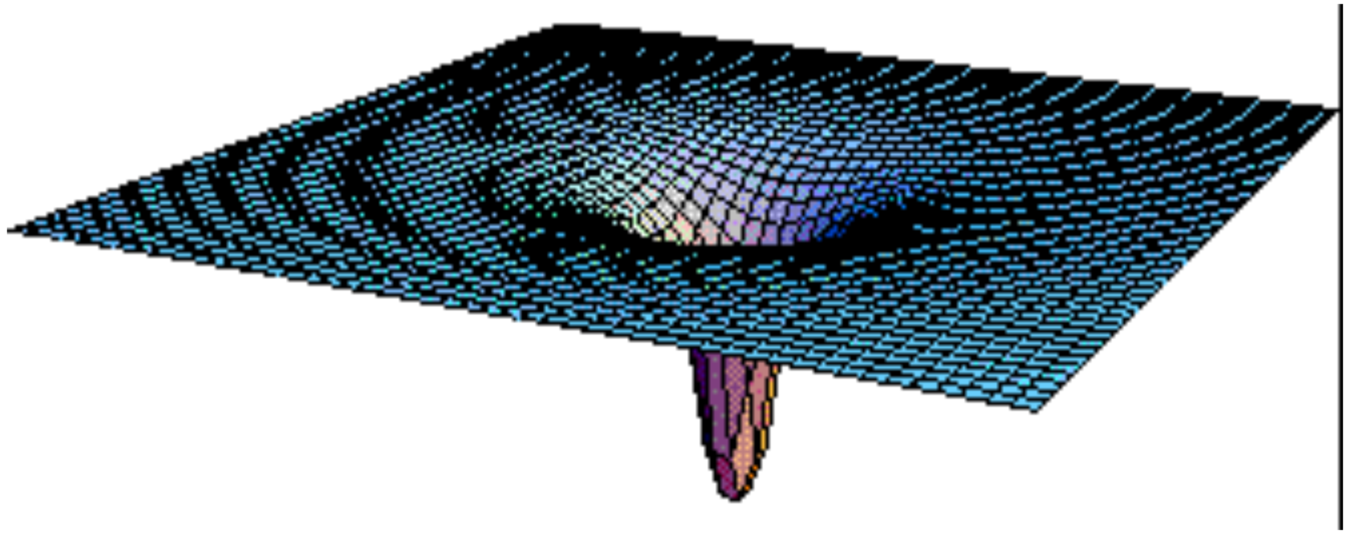


Potential wells

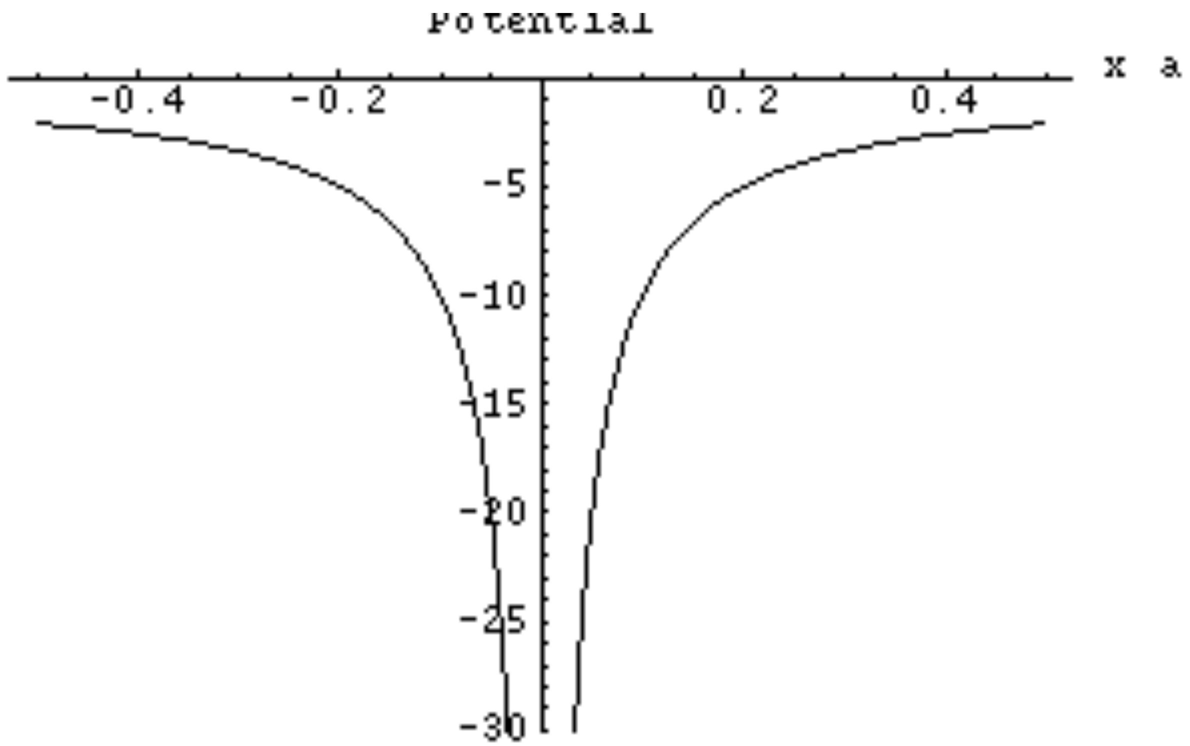
One very instructive way to see what is happening with stars in a binary system is to look at their *potential wells*. A potential well is essentially a picture of the gravity of an object: the name "well" comes because of its shape: things fall into it.

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

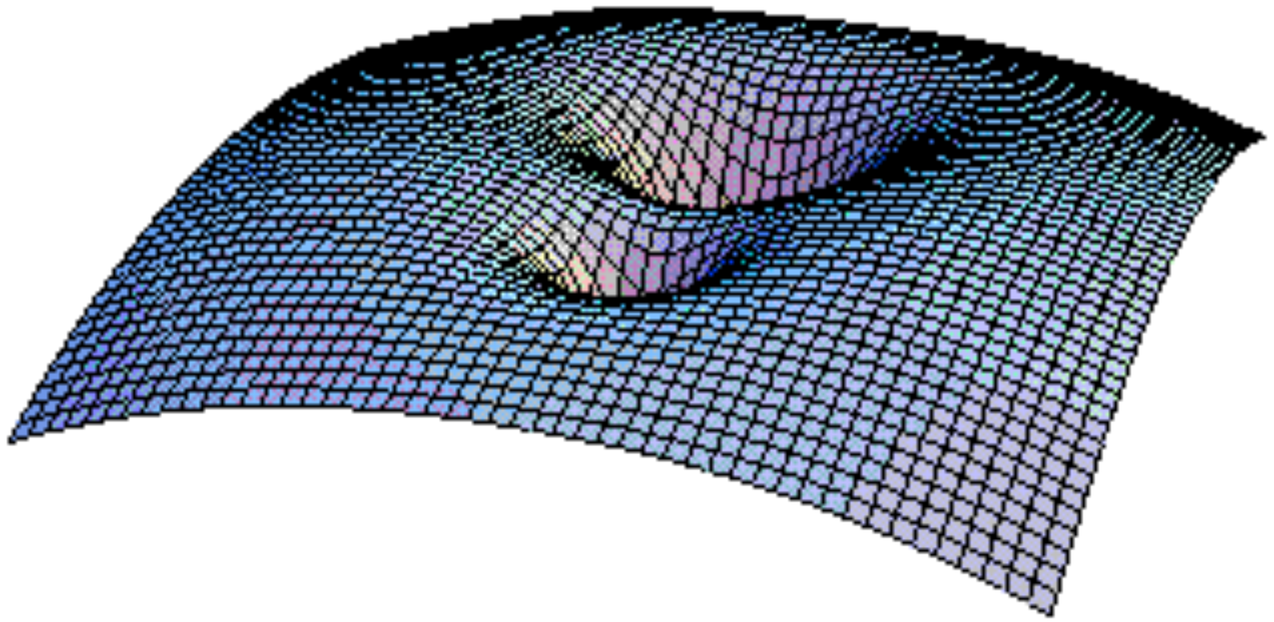
A single star has a potential well like a dimple.



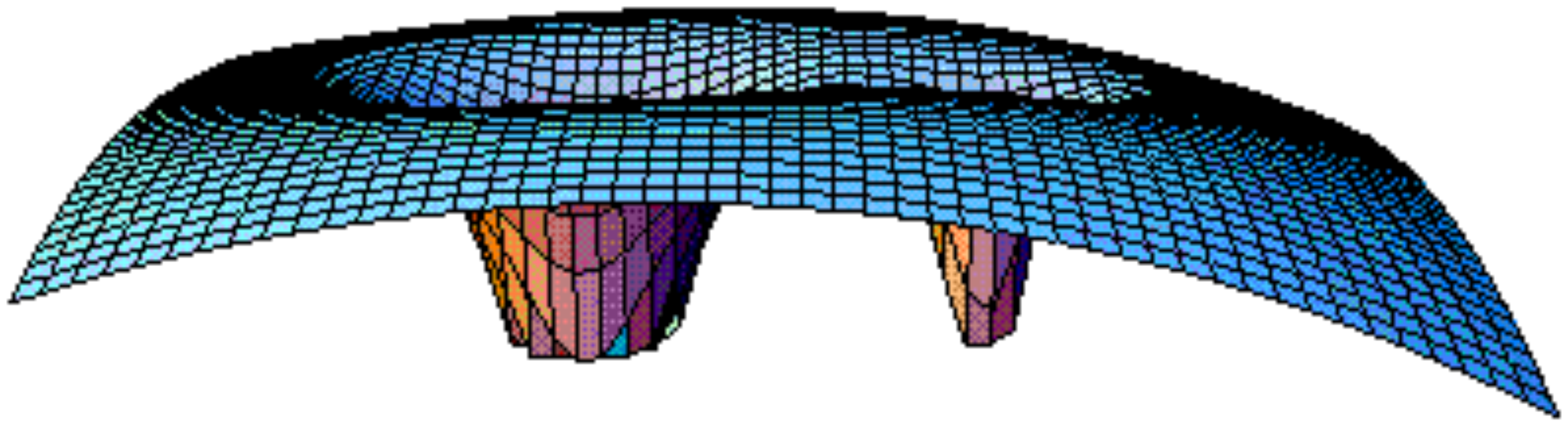
If we look at the cross-section, it looks like this:



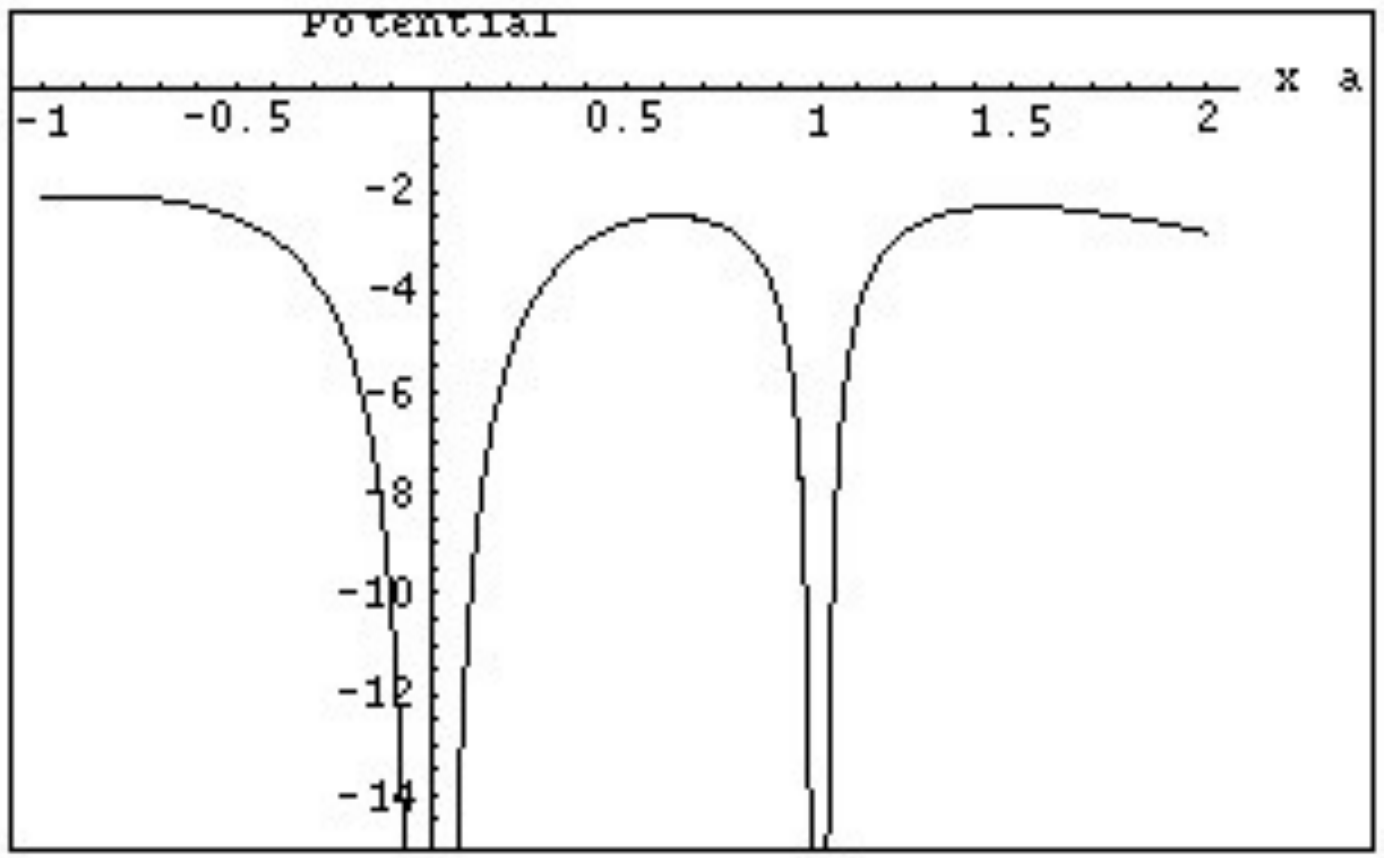
When there are two stars, their potential wells overlap. Near to each star, everything just looks like a single star; but as you travel between the stars, there's a point where the pull from each star is the same: an unstable point where a mass can fall either way.



Looking from a different angle, we can see better two separate wells with a low saddle point between them.

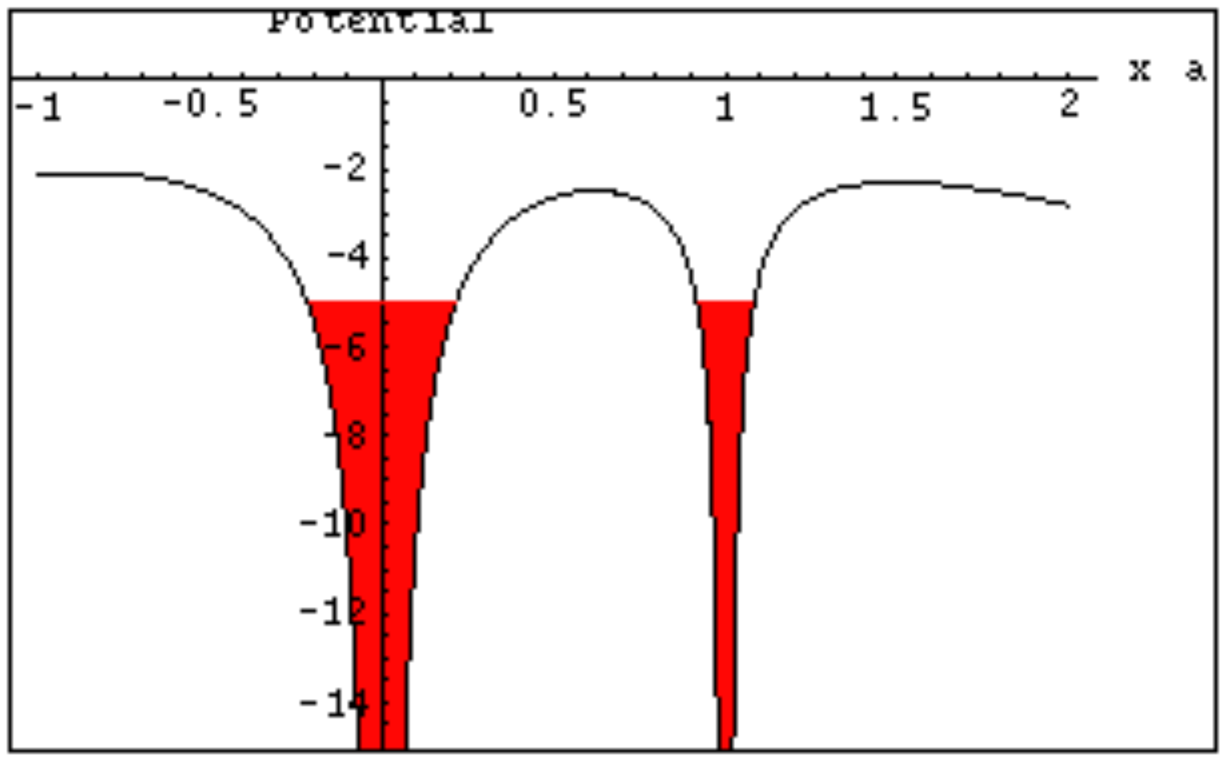


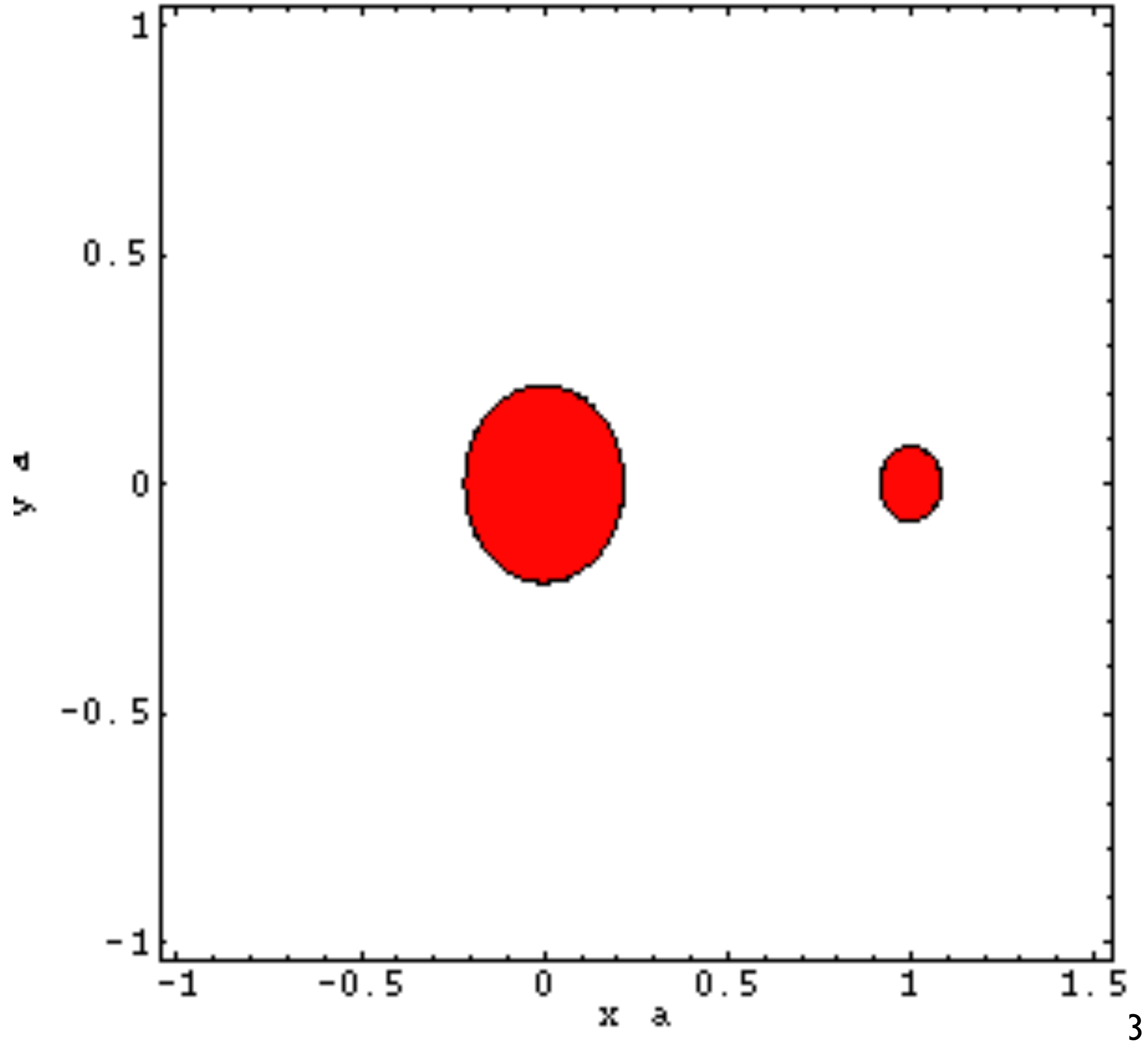
And in cross-section along the lines between the two stars:



Now, if you have matter inside the potential well, it will “fill up” the well to a greater or lesser degree, depending both on its density, and on how close the nearest well is. We can distinguish between several cases.

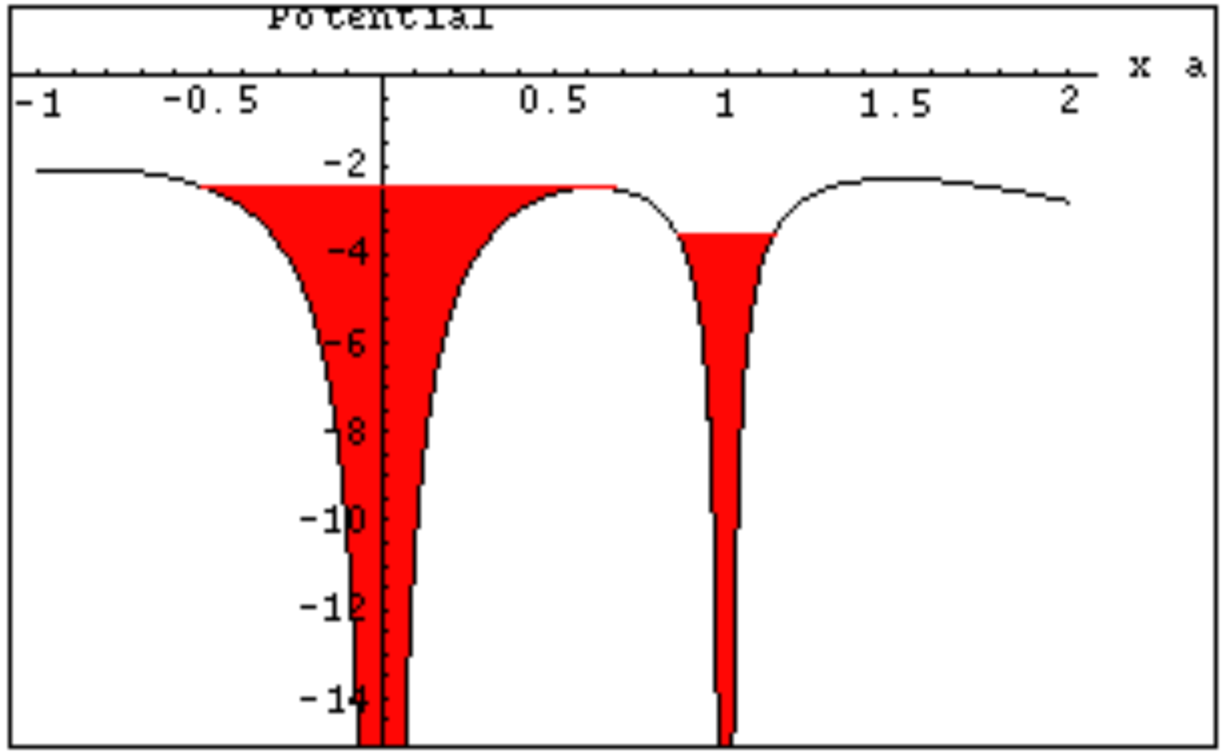
Detached: both stars are within their wells and relatively undistorted

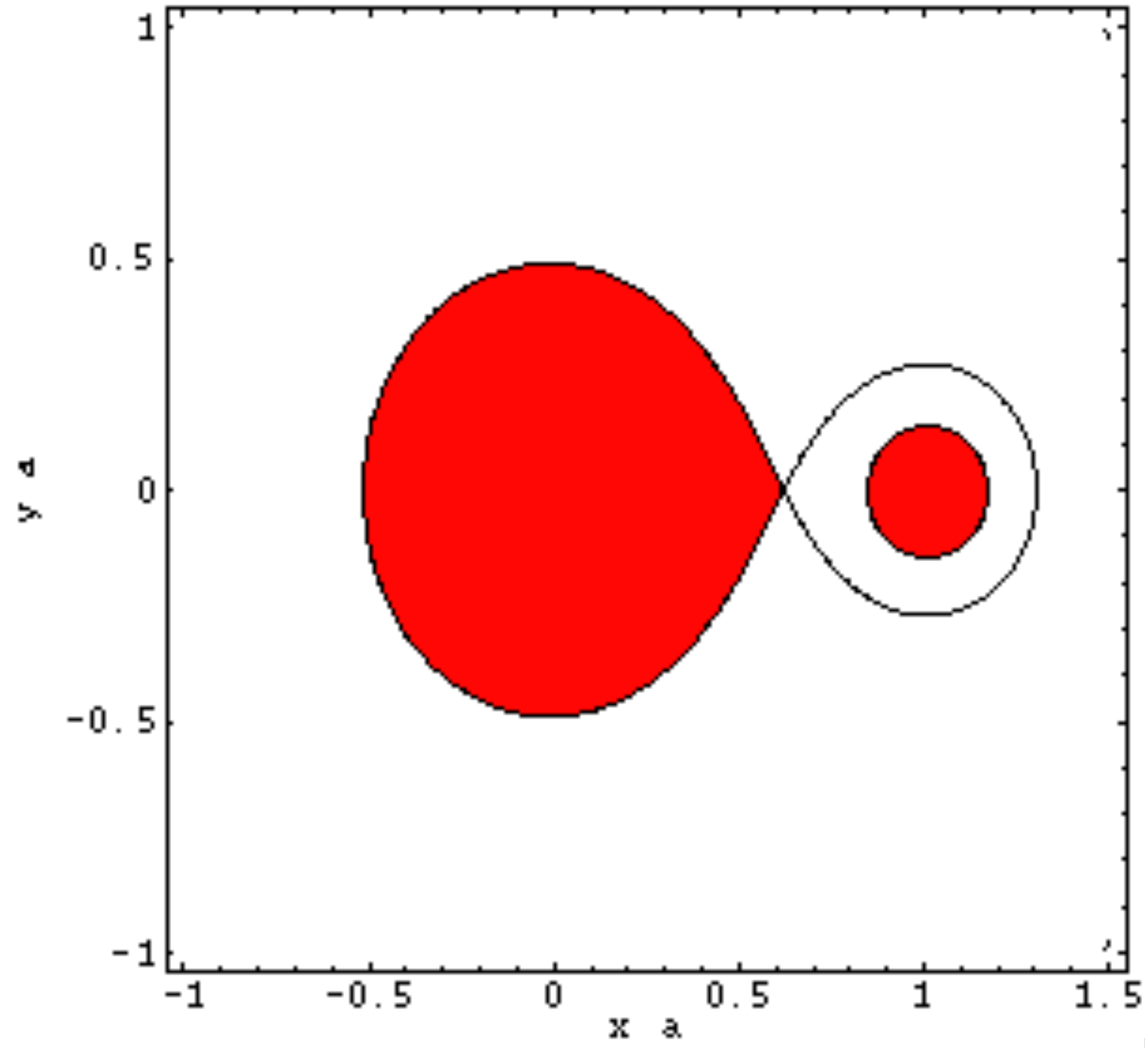




Now, if you have matter inside the potential well, it will "fill up" the well to a greater or lesser degree, depending both on its density, and on how close the nearest well is. We can distinguish between several cases.

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





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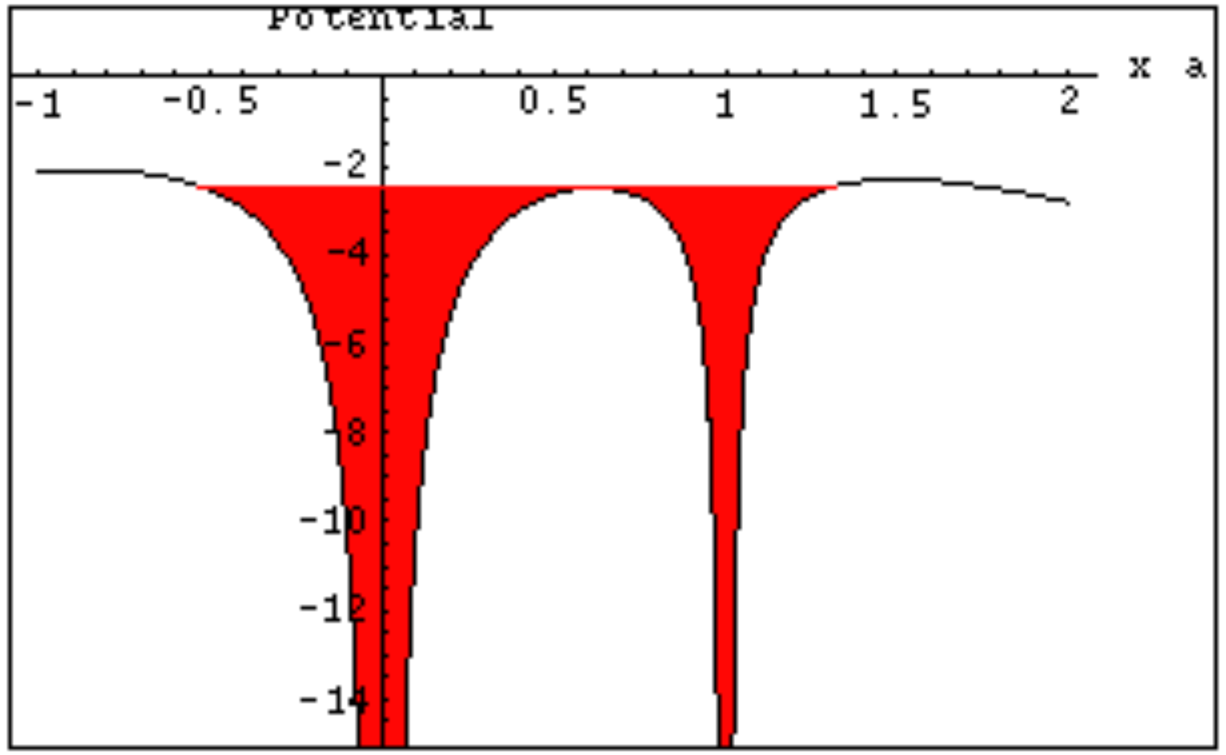
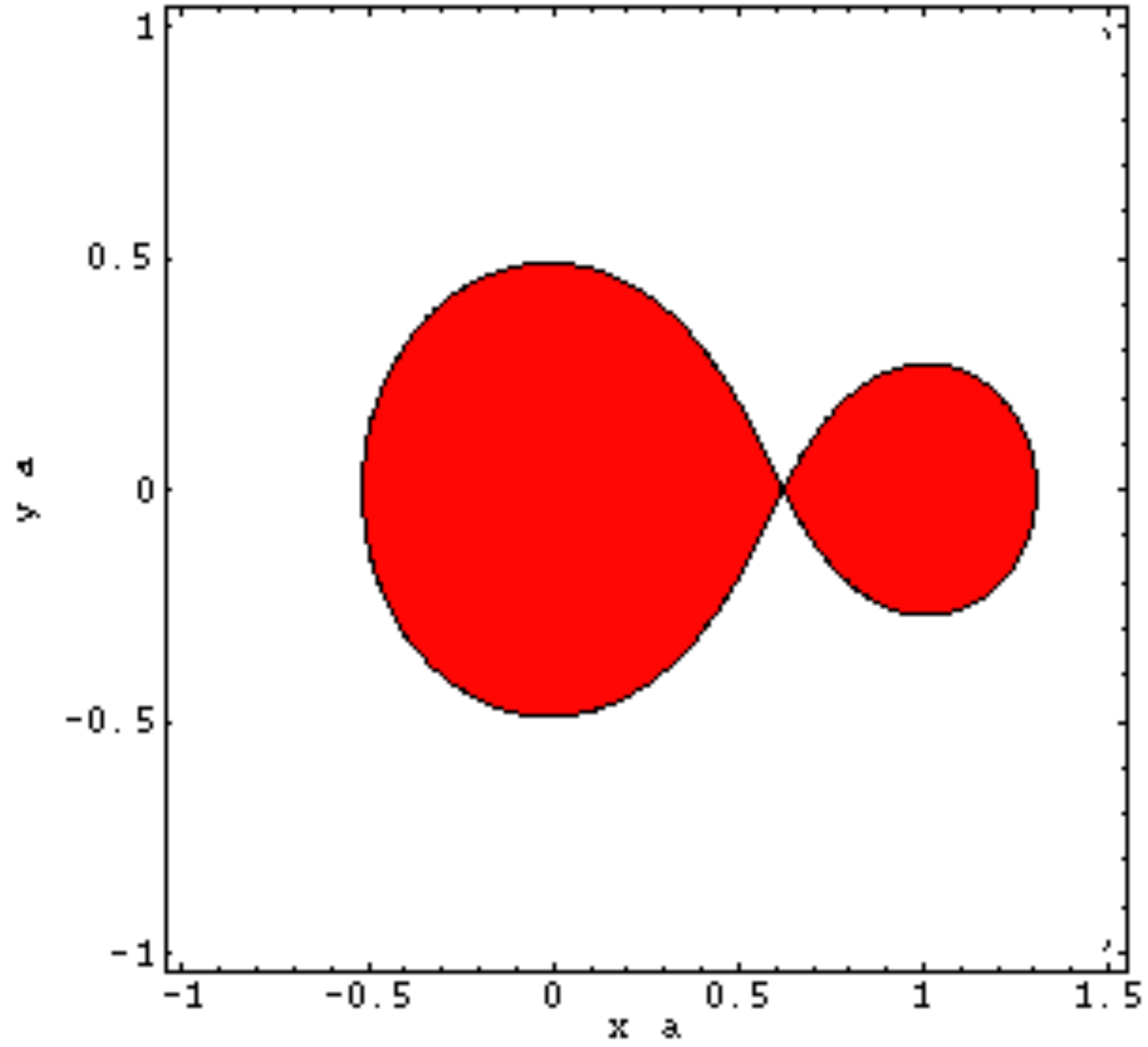
Contact: both stars are filling their wells





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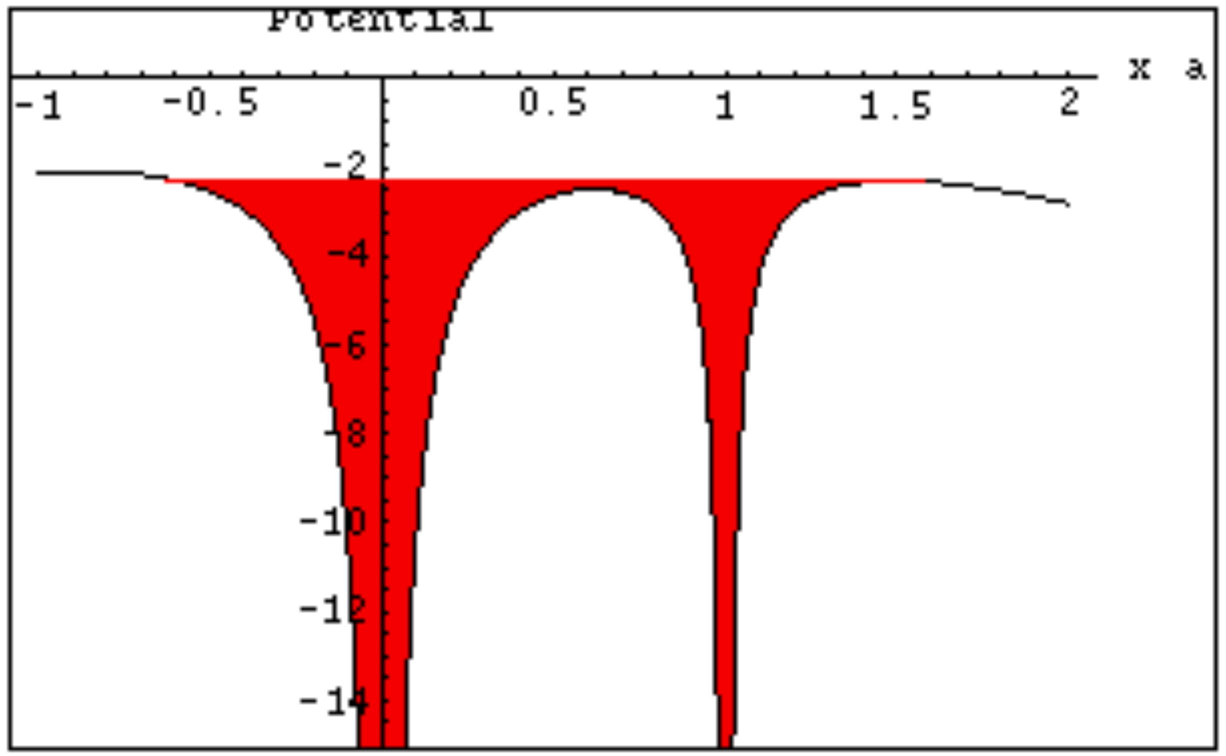
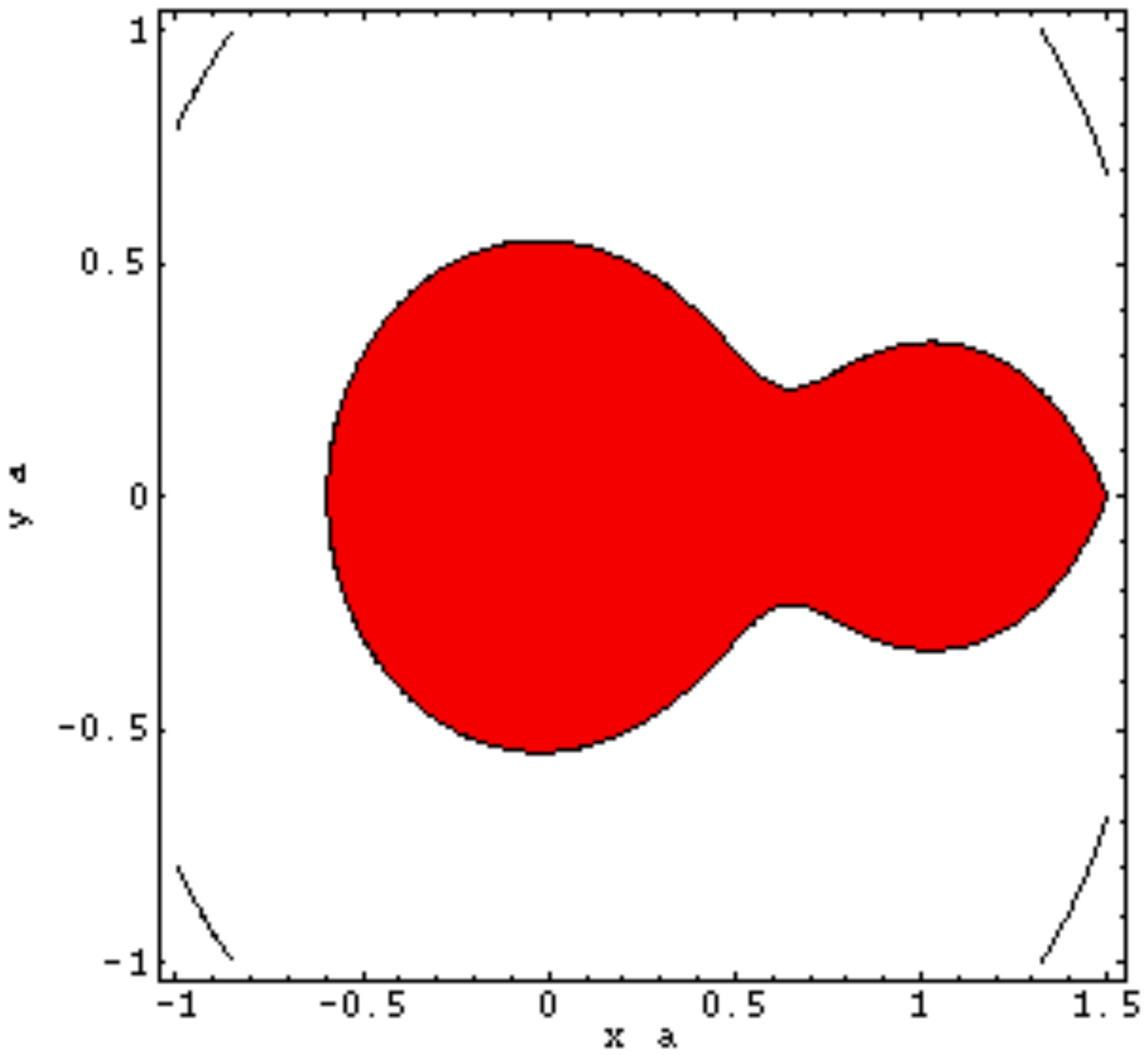
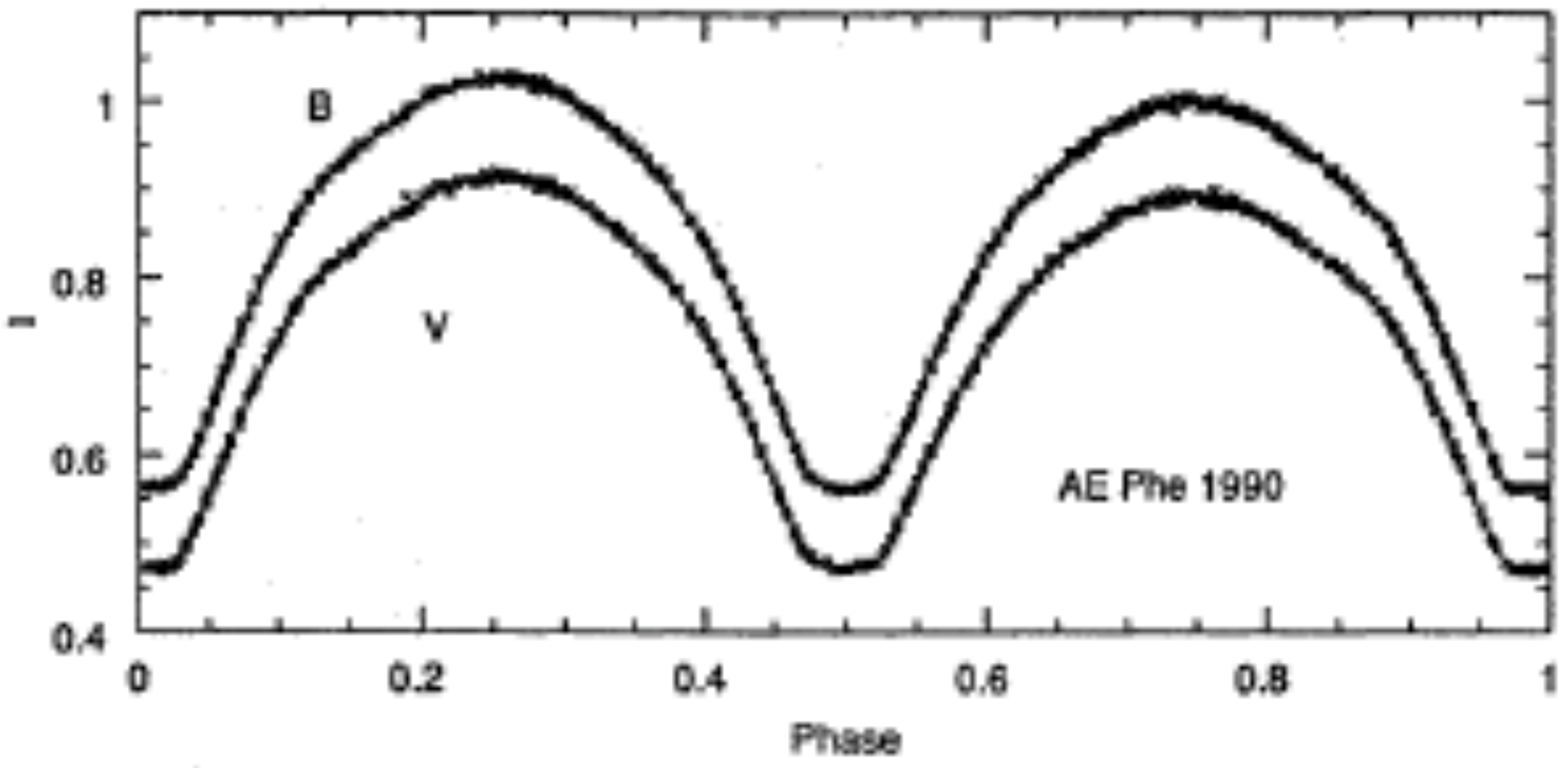
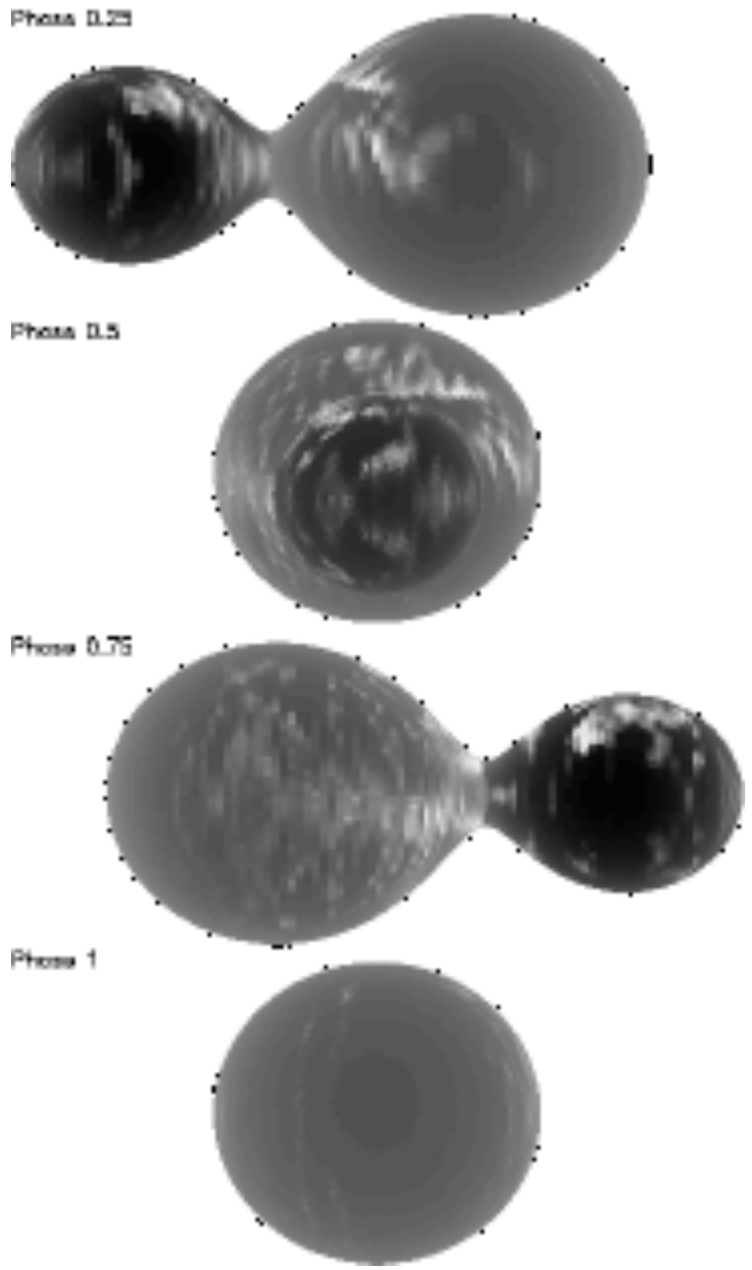
Common envelope: both stars overfill their wells so there is only one surface.





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.

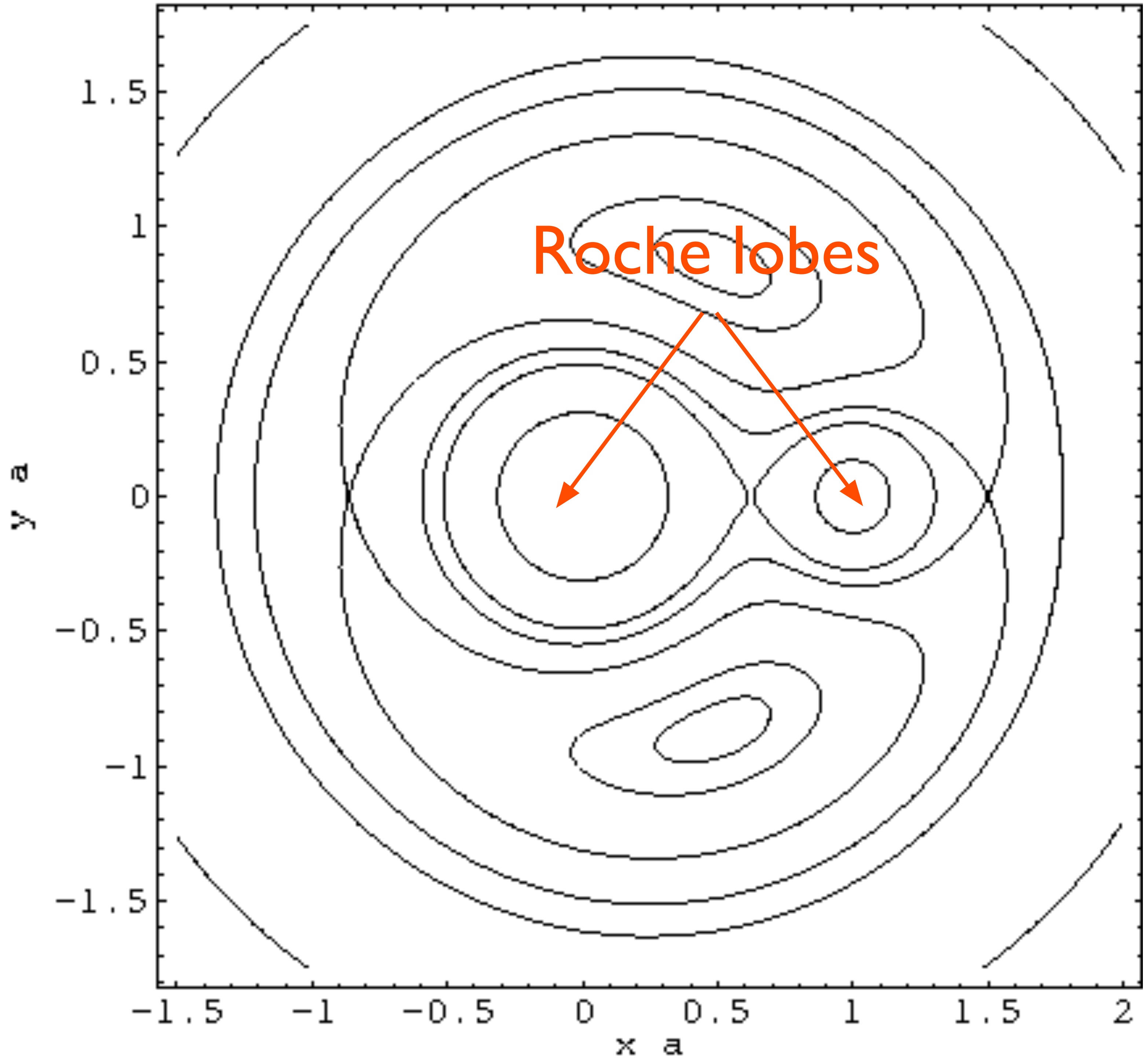




The light curve of the contact binary AE Phoenicis, and the model for the system deduced from Doppler images of the system. The fact that there is no part of the orbit where the light-curve is flat shows that the stars are never separate: they are actually in contact.

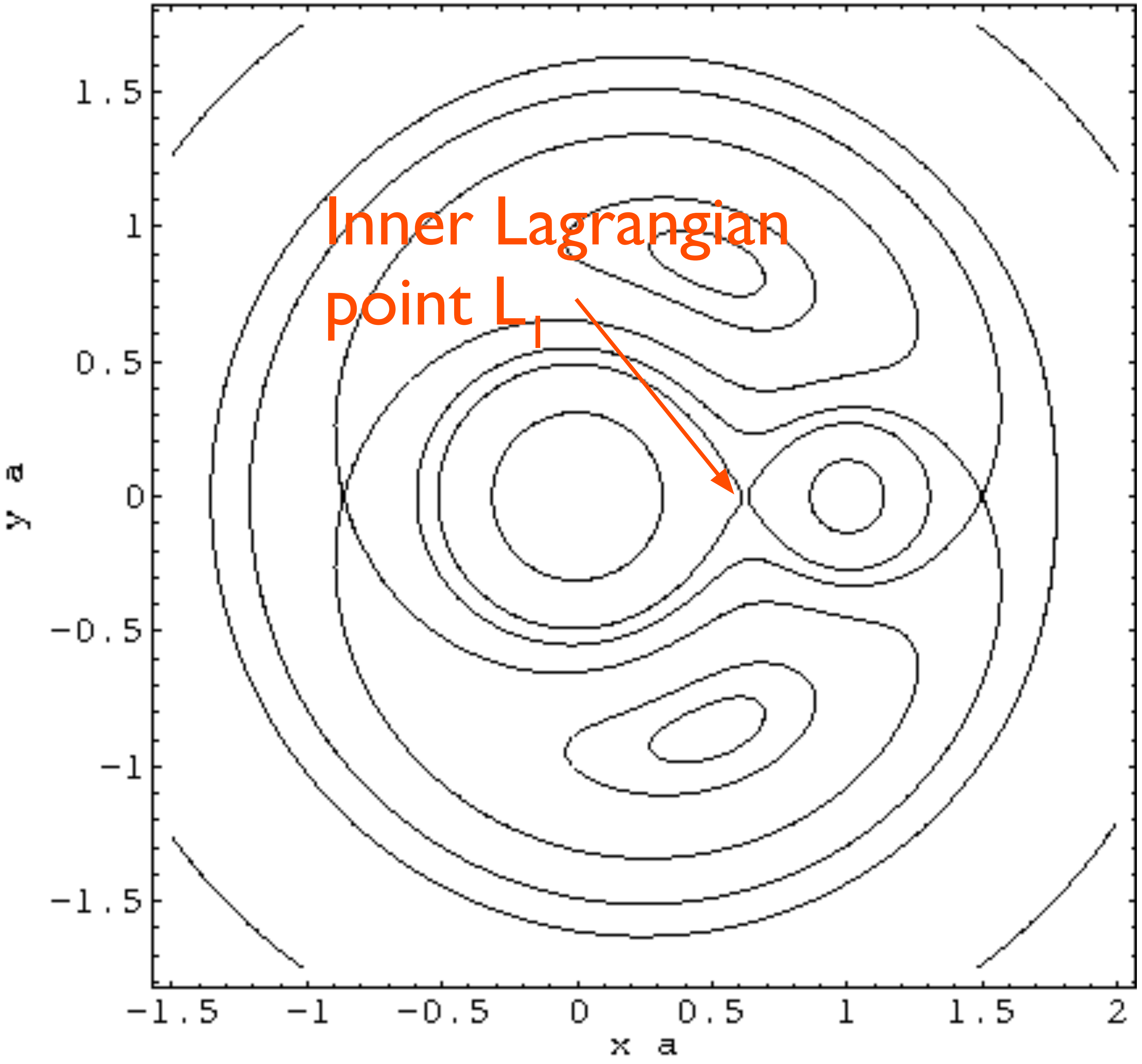
We can summarise the behaviour of interacting binaries this by looking at a contour diagram of the binary potential well instead. There are also some technical terms we will use:

The two cusps around each star are called *Roche lobes*. These are circular in their centre, but become more and more distorted as we get further from the stellar centres.



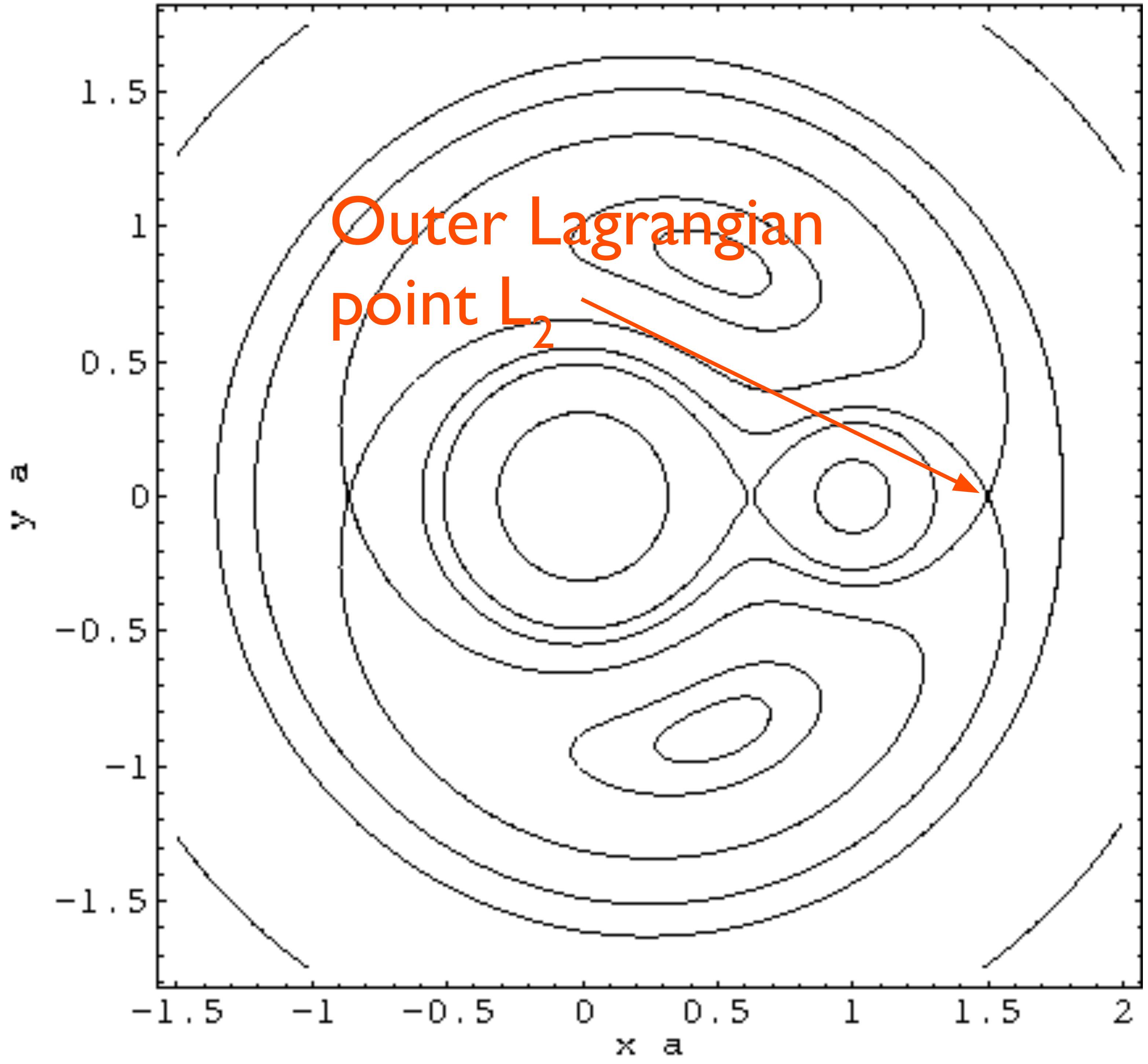
We can summarise the behaviour of interacting binaries this by looking at a contour diagram of the binary potential well instead. There are also some technical terms we will use:

The saddle point between the two stars, where matter can first start spilling from one Roche lobe to the other, is called the *inner Lagrangian point* L_1.



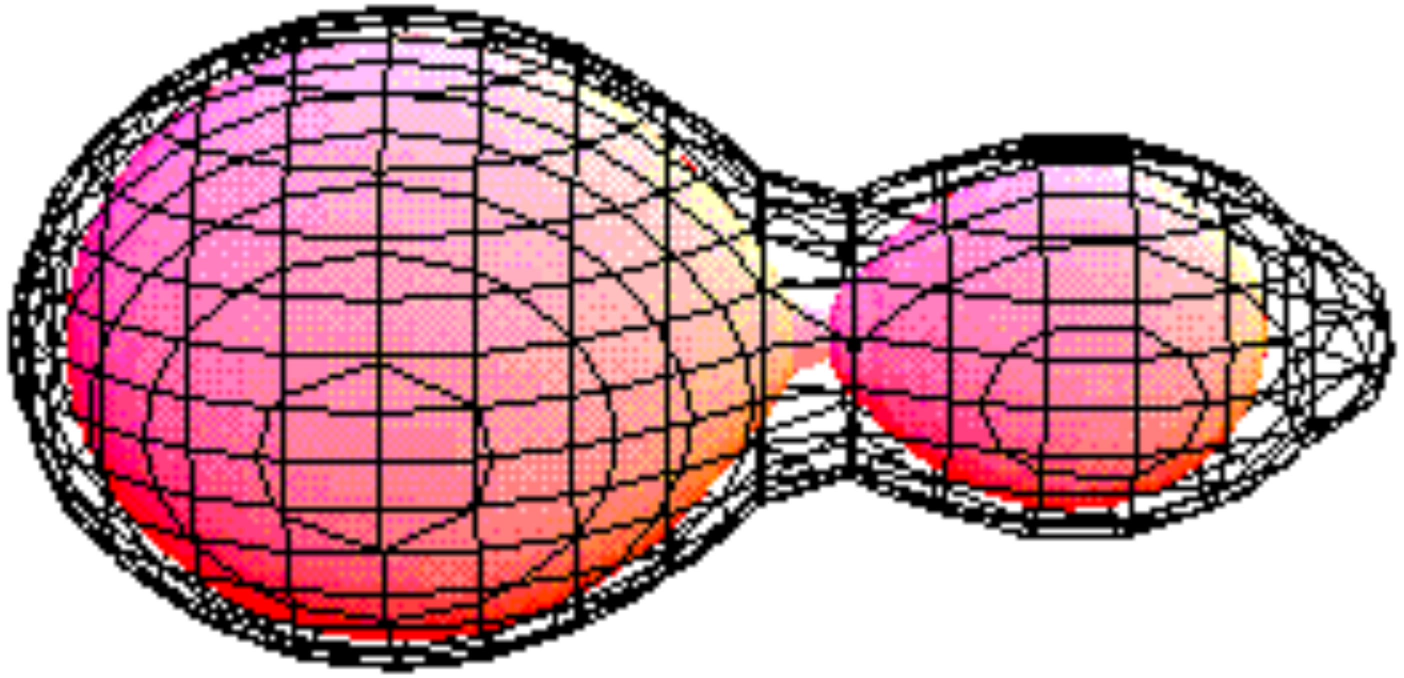
We can summarise the behaviour of interacting binaries this by looking at a contour diagram of the binary potential well instead. There are also some technical terms we will use:

The *outer Lagrangian point* L_2 is a saddle point beyond the lighter star, where matter can escape from the system entirely.



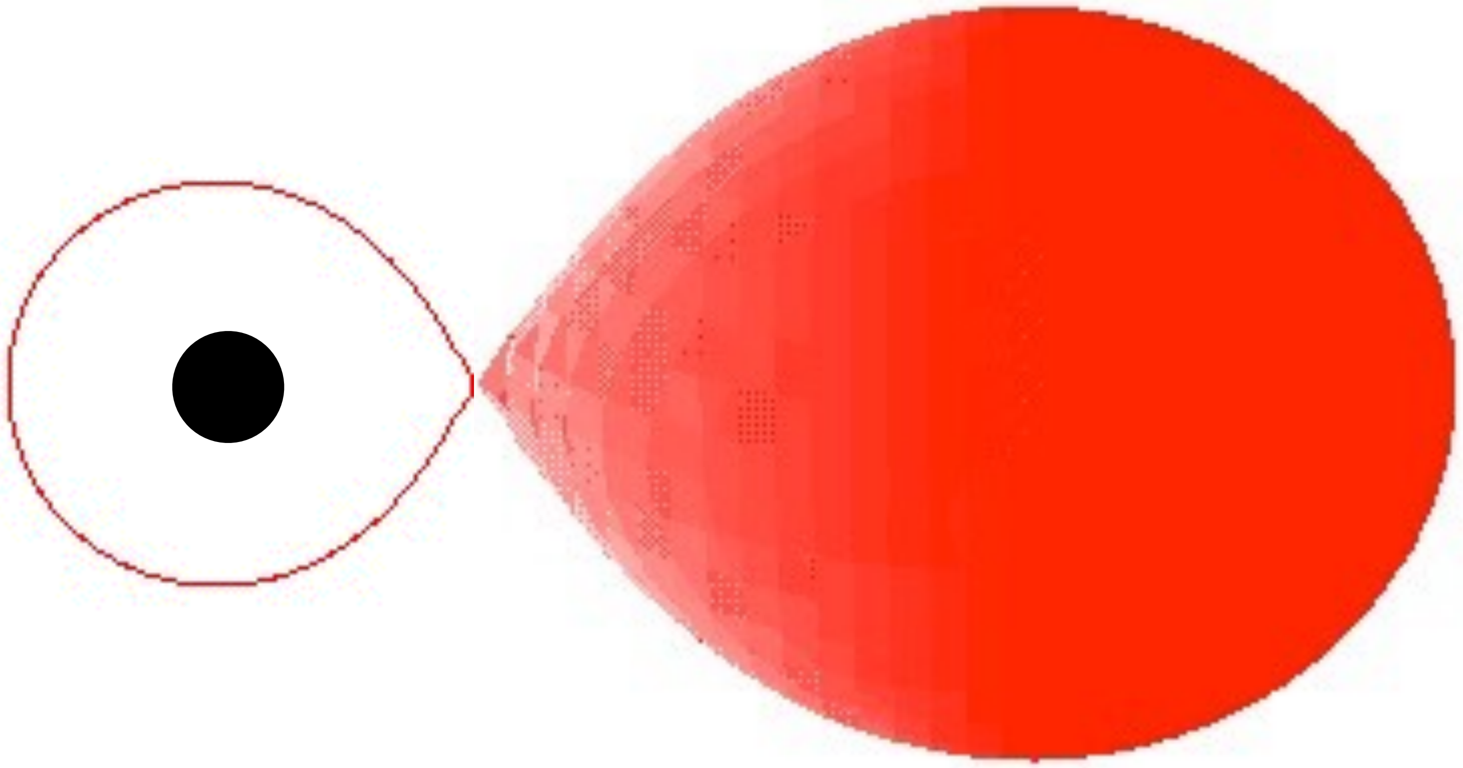
Roche lobes in 3D

Remember we've been looking at representations of the gravitational potential. But the field affects real space in three dimensions, so the Roche lobes, and hence the shapes of the stars inside them, are actually three-dimensional.



The wire frames show the Roche surface through L2, and the solid shapes show two Roche-lobe-filling stars.

A star that fills its Roche lobe will be stretched in a a teardrop shape towards the L_1 point, which is along the line joining the two stars.

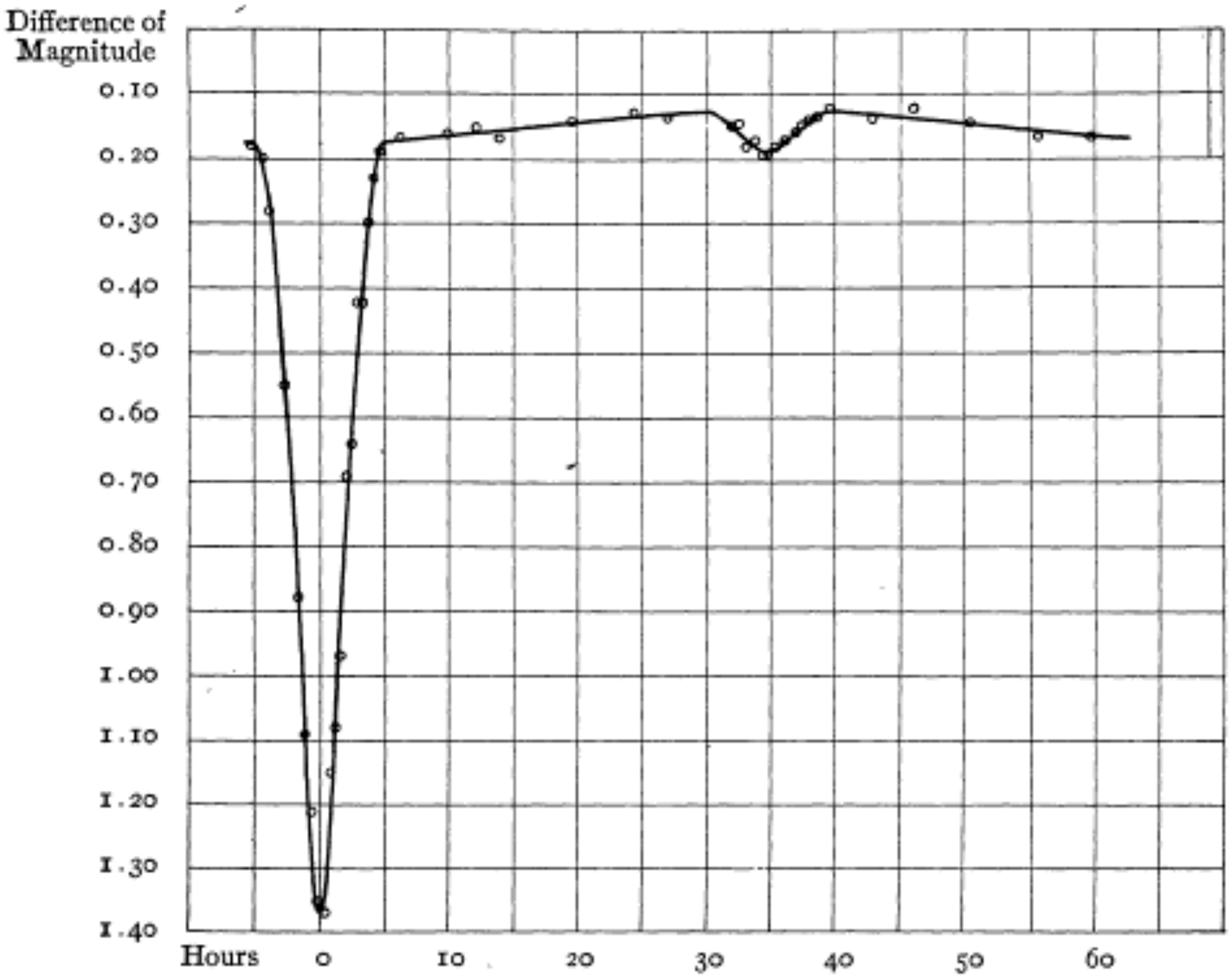


Roche surfaces exist, mathematically, for any pair of stars; they define the region where each star's gravity is dominant.

Things become interesting, however, in the particular case where one star's surface gets close to the Roche lobe. That's when a regular binary turns into an *interacting binary*.

Matter can flow from one star to the other, which can not only affect the star as it is now, but also have a massive effect on the evolution of both stars.

The most famous case of this is the star Algol, which is a close eclipsing binary consisting of a B star in orbit with a K subgiant star in a 2.9 day orbit.



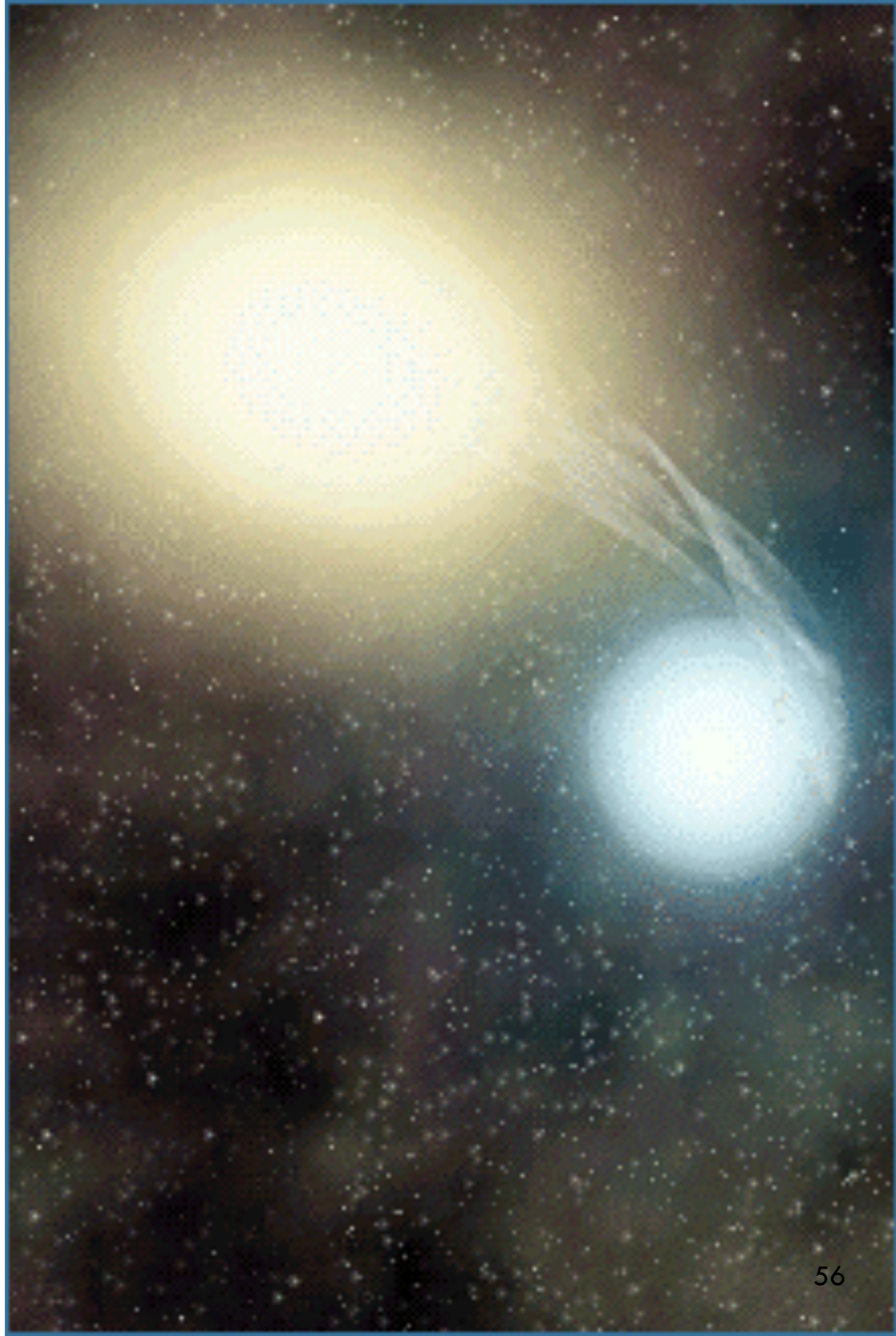
The light curve of Algol. The primary eclipse happens when the bright B star passes behind the much cooler K star.

However, when the masses of the two star were measured, it was found that the B star, still on the main sequence, has a mass of 3.5 solar masses, while the K star, which has already begun evolving off the main sequence, has a mass of only 0.81 solar masses.

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

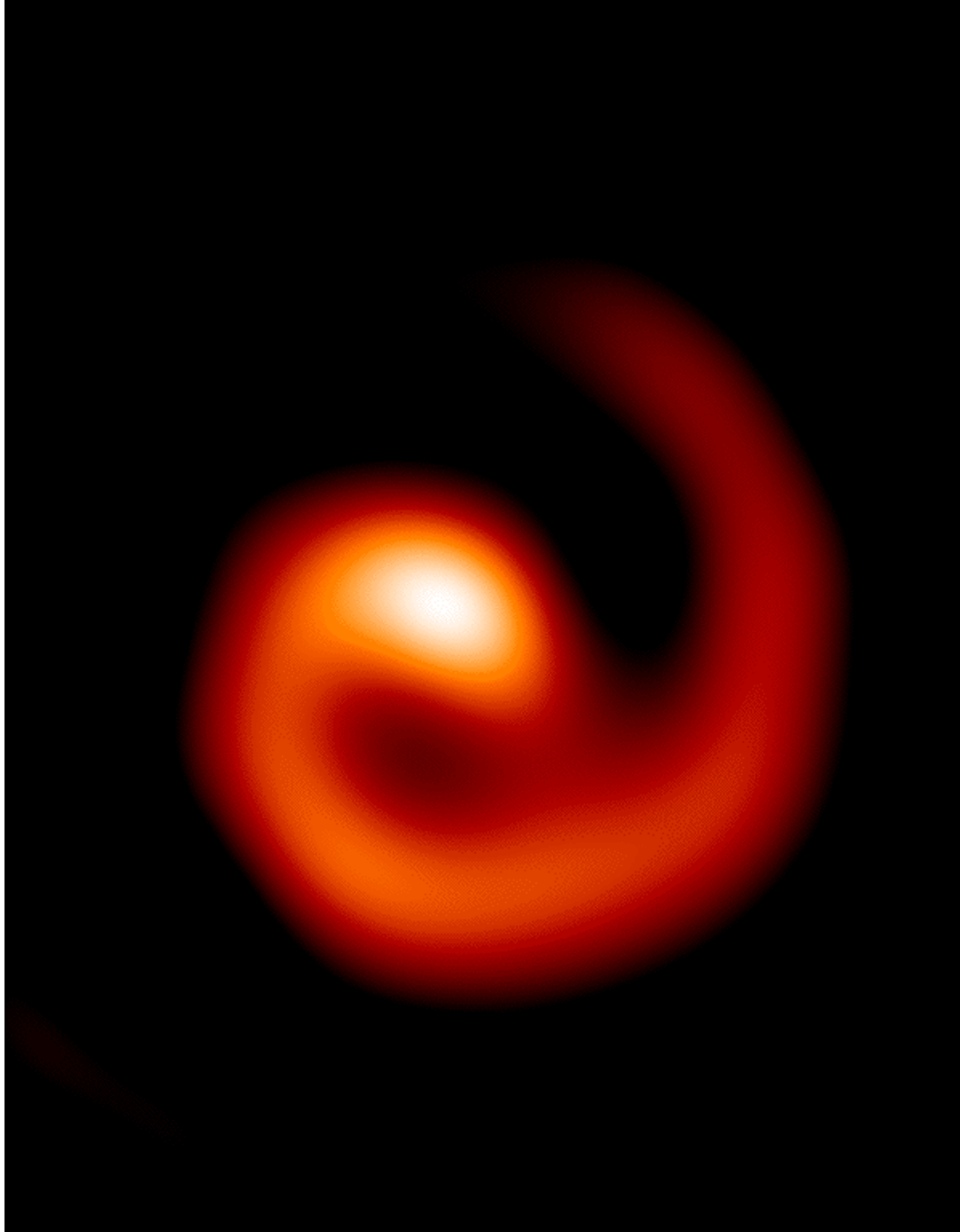
This became known as the *Algol Paradox*.

The explanation lies in the fact that Algol is an interacting binary. The K-star was indeed originally the more massive star. As it evolved, it expanded to fill its Roche lobe and then transferred mass to the companion star. So much mass was transferred that it became the less massive star.



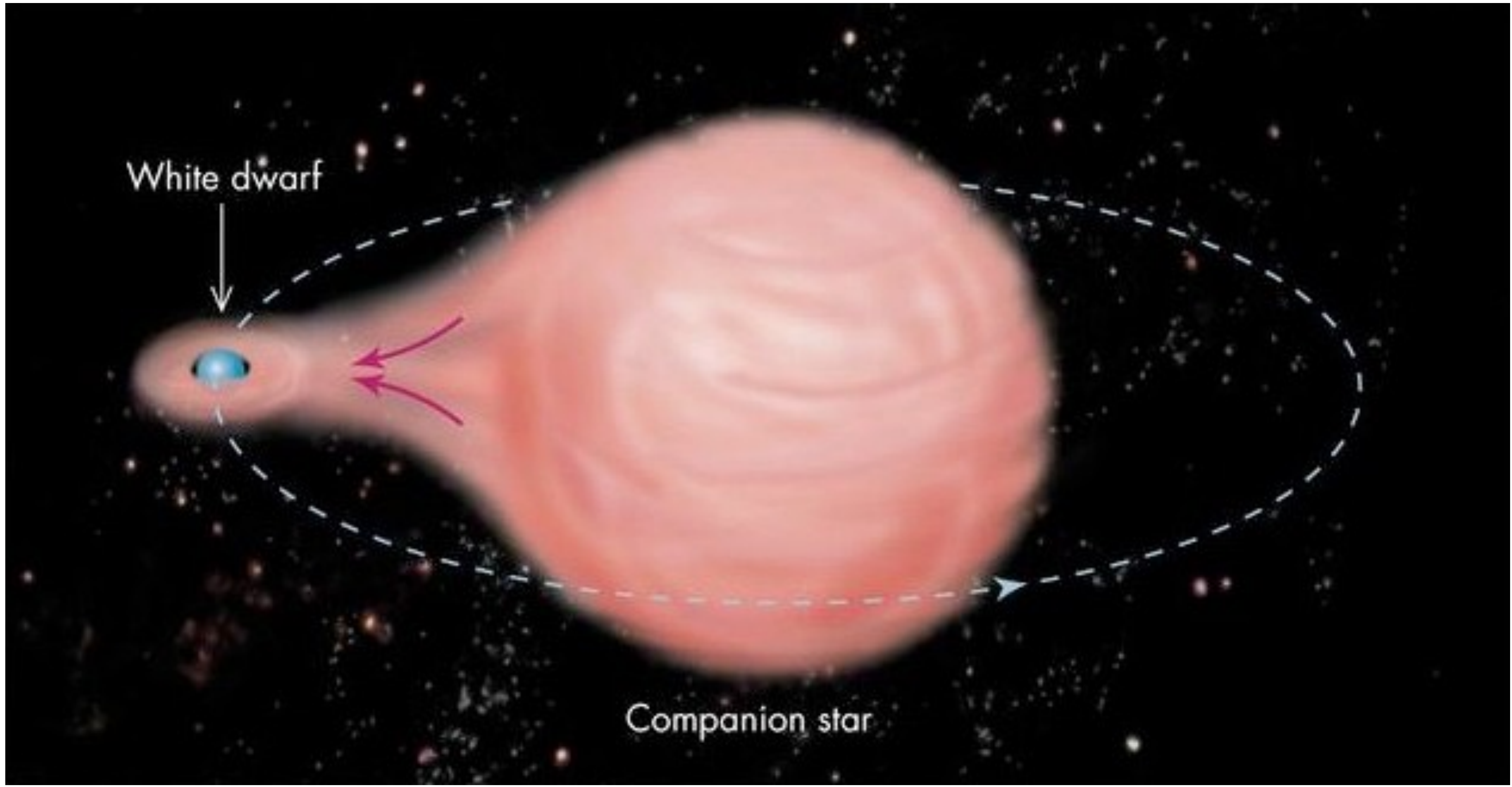
Binaries can also lose matter from the system entirely. The Wolf-Rayet star WR 104 shows a dusty spiral, showing material escaping from the binary stars embedded in its centre.

False colour infrared image of the dusty nebula surrounding WR 104, taken using a technique called aperture masking interferometry.

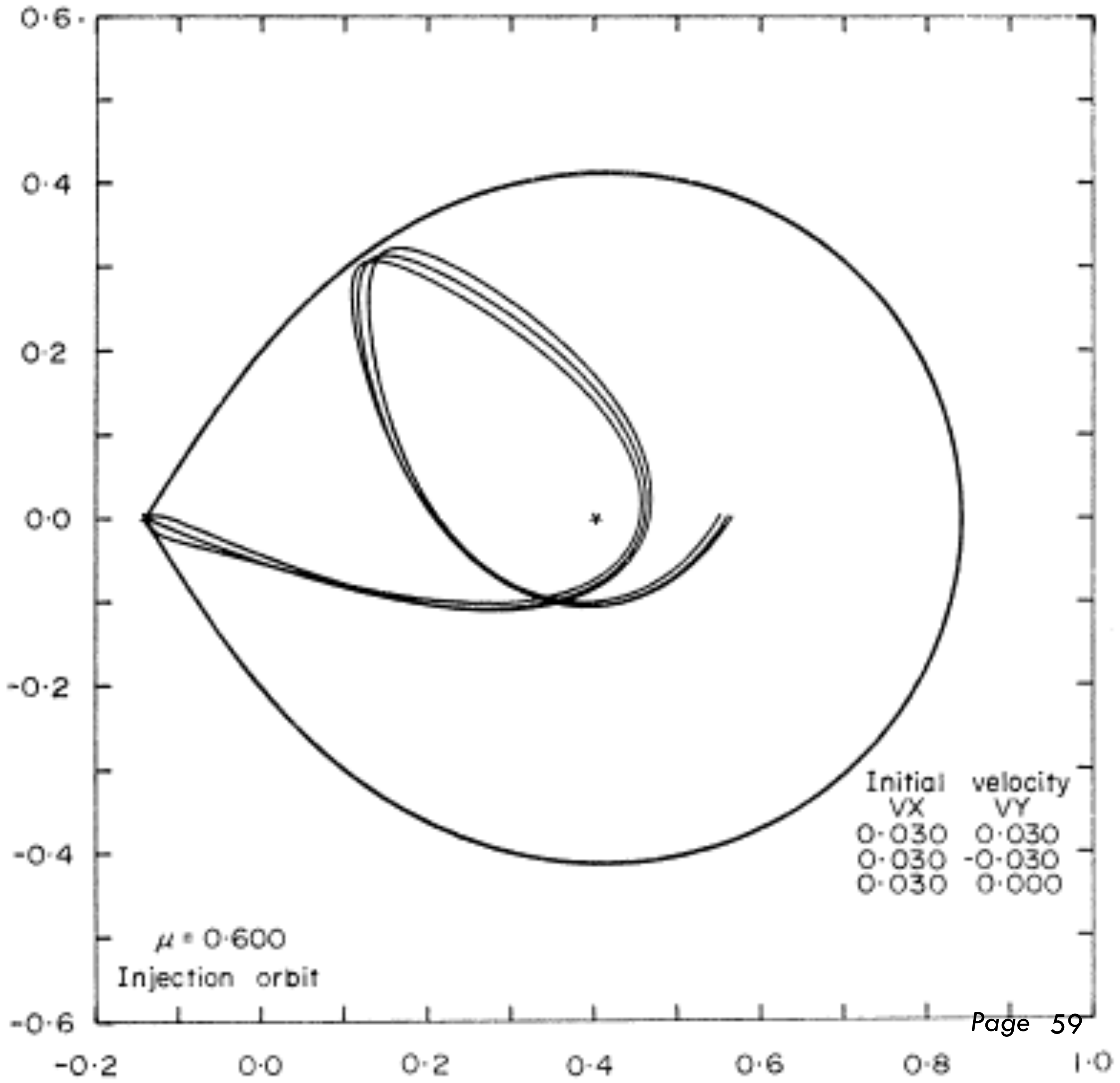


Cataclysmic variables

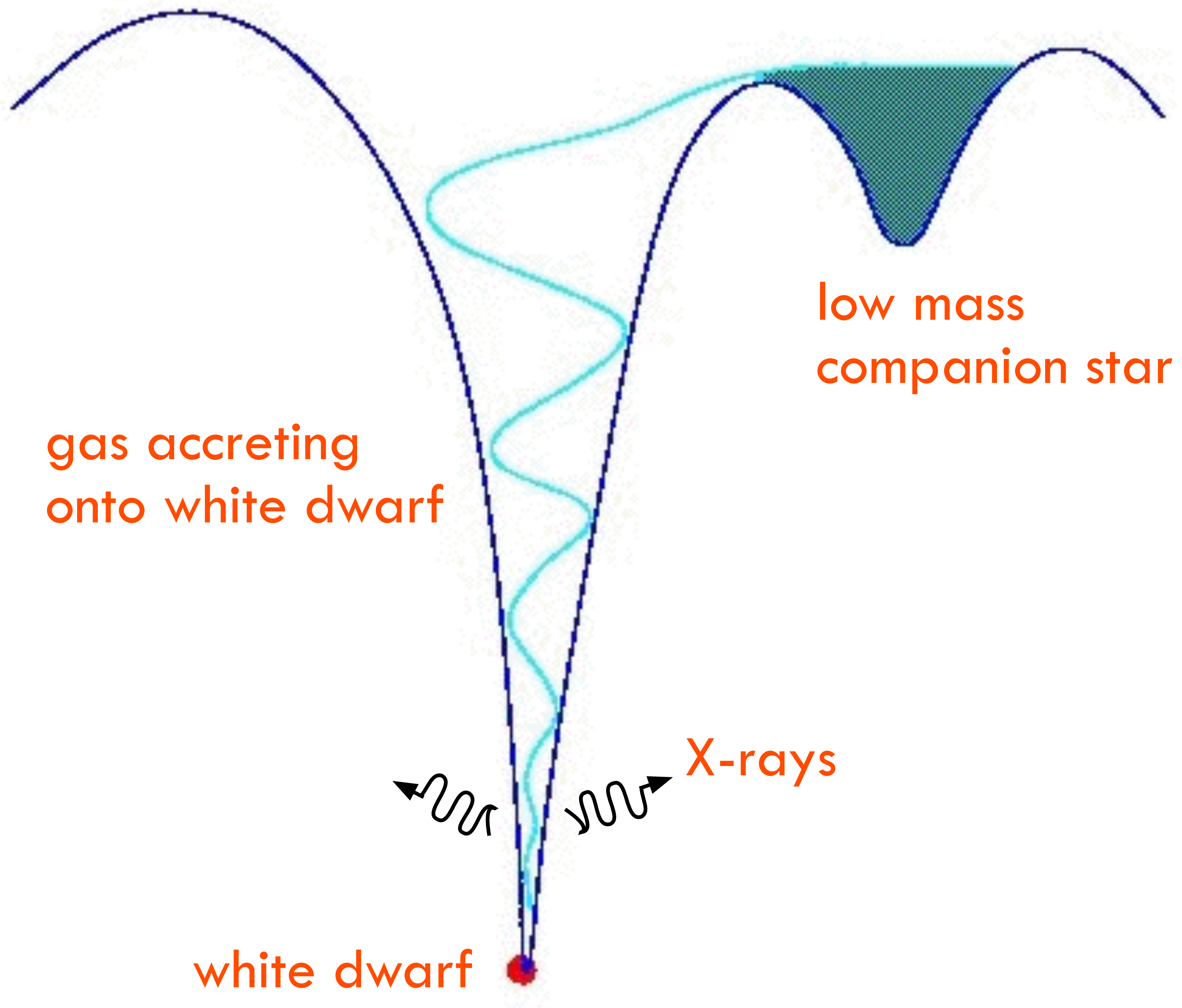
There are several important sub-categories of interacting binaries. In the case where the accreting star is a white dwarf, these binaries are called *cataclysmic variables*, a general term which encompasses several different types of variable stars, including *novae*.



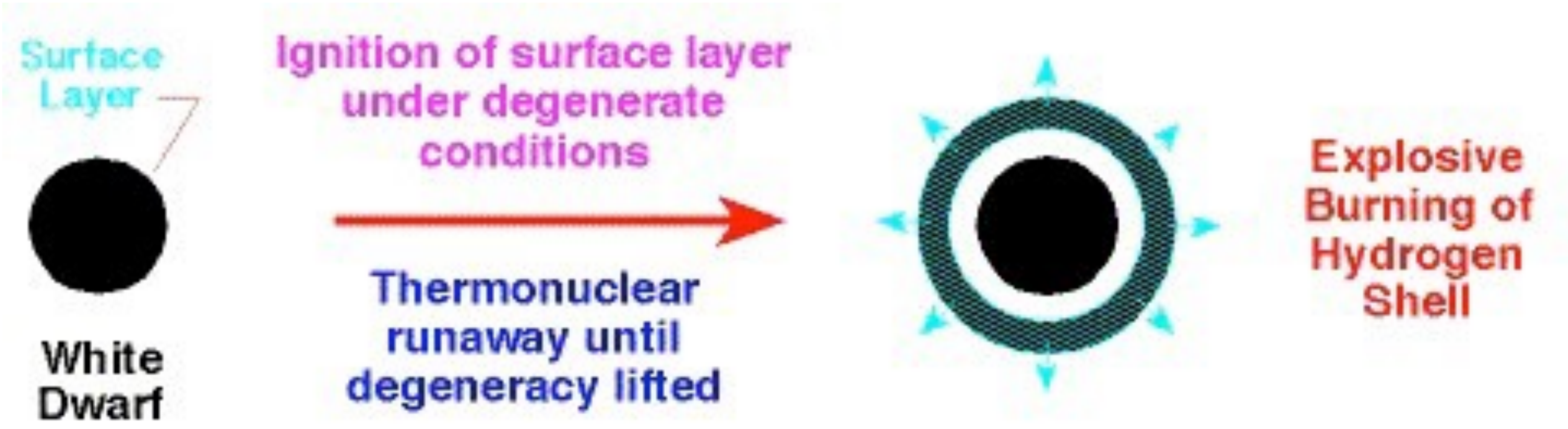
The matter flowing through the L_1 point cannot land straight on the white dwarf, because it has angular momentum. Instead, the gas stream falls through the L_1 point and goes into orbit around the white dwarf. On the return it intersects itself, and friction makes it spread, first into a ring, and then a disk: an *accretion disk*.



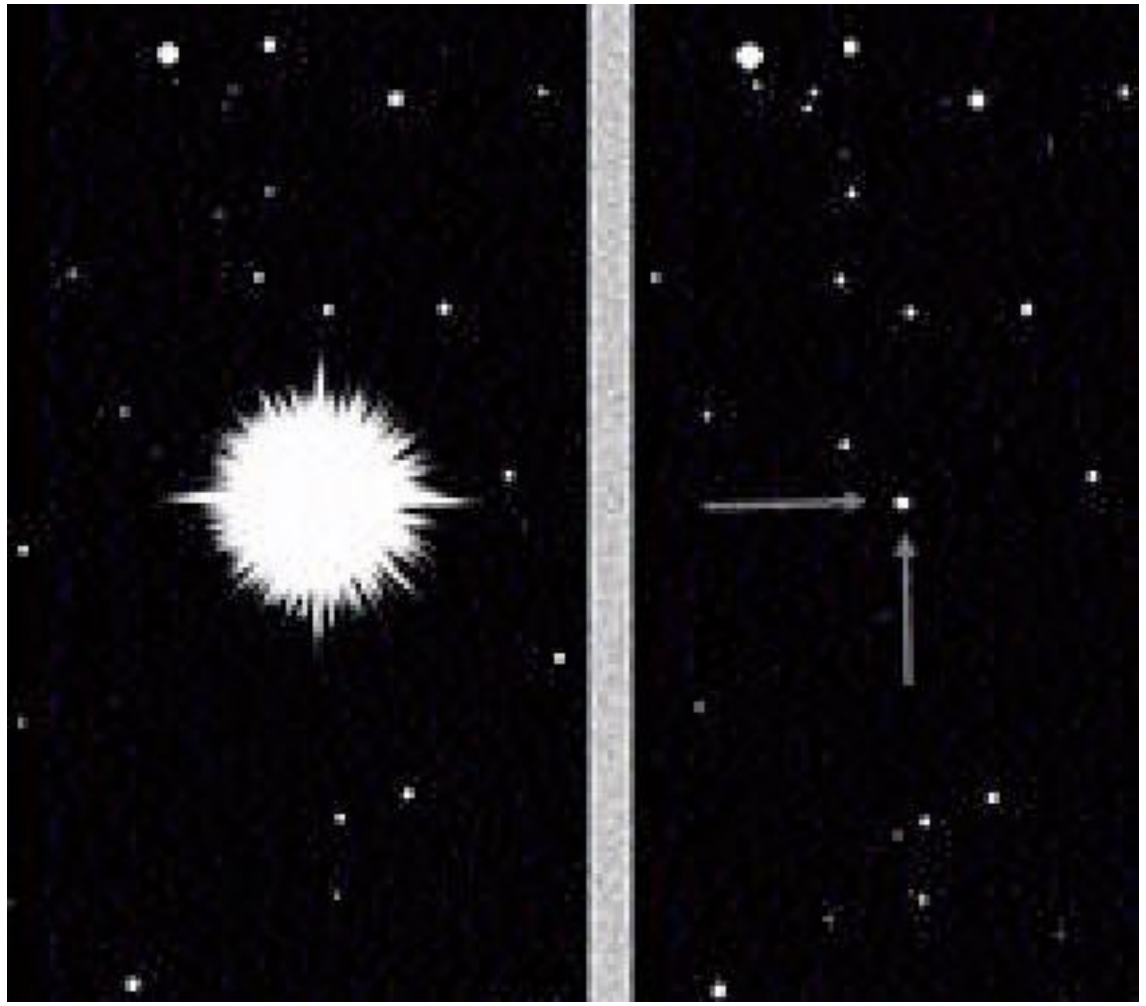
Friction in the disk allows matter to gradually spiral inwards (while angular momentum is transported outwards). When this matter hits the surface of the white dwarf, the gravitational potential energy is suddenly liberated, and we see it as radiation: X-ray, ultraviolet and optical.



The secondary star is transferring hydrogen-rich material from its outer envelope onto the surface of the white dwarf. There it accumulates on the surface, until the pressure and density reach the point when hydrogen fusion can begin. However, since the matter is degenerate, all the hydrogen on the surface ignites almost at once in a *thermonuclear runaway*, which consumes all the accreted material.

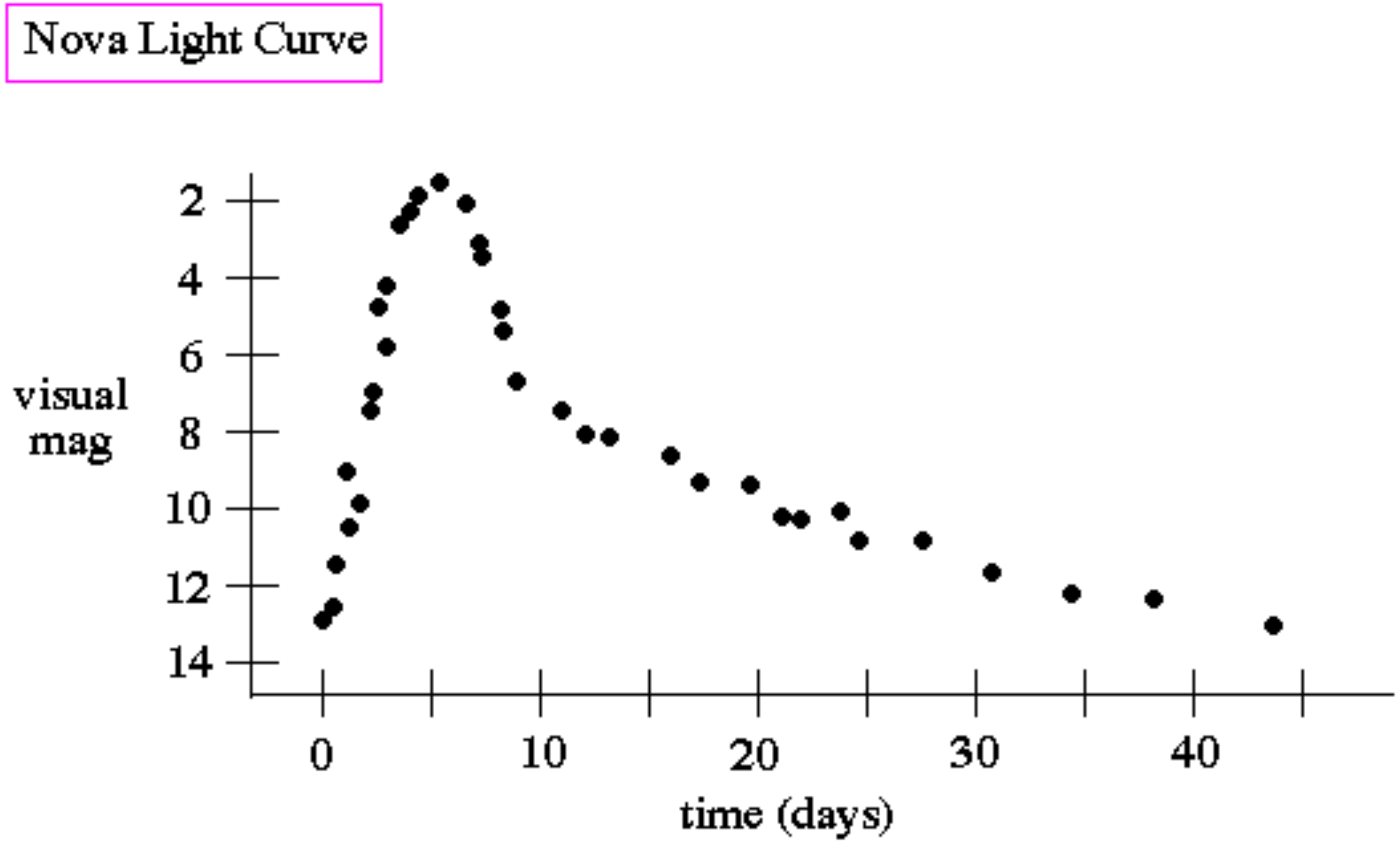


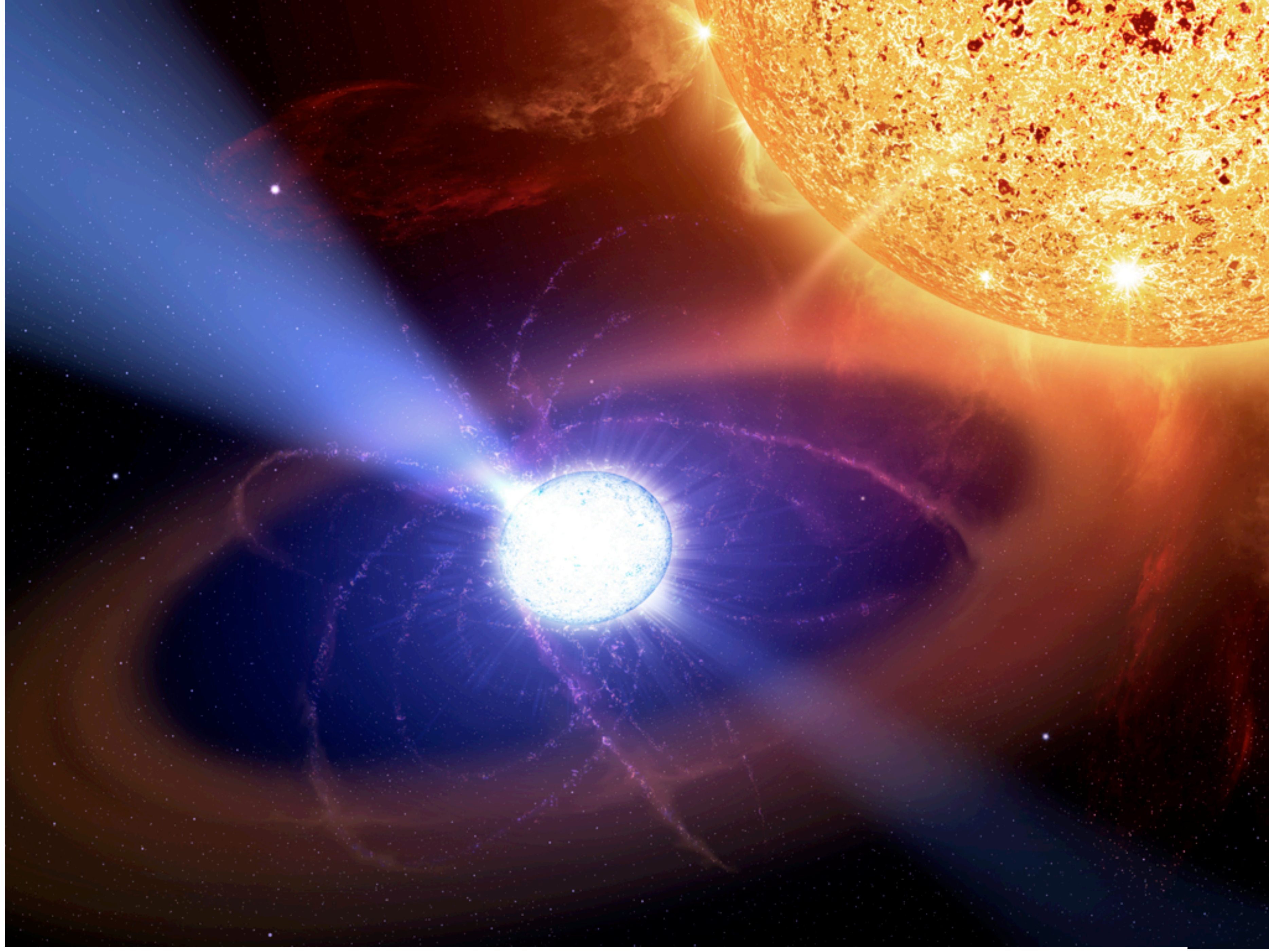
These explosions are visible as a massive increase in brightness of the star: by a factor of 50,000 or more. Because the pre-explosion star was essentially anonymous, the star appears as a “new” star; these are known as *novae*.



Nova Herculis 1934, before and during outburst, when it brightened by a factor of 60,000.

Novae typically brighten in a couple of days, then fade more slowly over a month or more. They brighten by 6–10 magnitudes: there have been seven in the last century which reached magnitude 2 or brighter.





Most novae have only been seen to erupt once, but there are ten known *recurrent novae* which have had more than one recorded eruption. The time between eruptions can be anything from 10 to 80 years. So any ordinary nova might be a recurrent nova, but on a longer timescale than this.

X-ray binaries

We also know of many binaries where the accreting star is a neutron star or a black hole instead of a white dwarf. These are known as *X-ray binaries*. As their name suggests, they emit copious amounts of X-rays. Most of the brightest stars in the X-ray sky are X-ray binaries.

They produce more X-rays than cataclysmic variables because the potential well of the neutron star is much deeper than that of a white dwarf, so the amount of energy released per gram of matter is higher.

Next week

… we'll go back to our main stream, and talk about how stars change as they age, after finishing life on the main sequence.

Further reading

- Most introductory have at least a cursory discussion of the different types of binaries and what you can learn from them. In general, these discussions are only a couple of pages long. One book which has a slightly more detailed look at binaries is "**Astronomy: Journey to the Cosmic Frontier**" by John D. Fix (McGraw-Hill 1999).

- There's a nice applet showing the shapes of binary orbits for different masses and eccentricities at http://www.physics.nwu.edu/ugrad/vpl/mechanics/planets.html

- There are quite a few sites showing you simulations of various types of binaries. "**Astronomy 162 Digital Movie Gallery**" by Richard Pogge, http://www-astronomy.mps.ohio-state.edu/~pogge/Ast162/Movies/, has a nice collection.

Sources for images used:

- Binary star title image: from “How To Find A Binary System's Habitable Zone” http://www.iflscience.com/space/how-find-binary-stars-habitable-zone
- Binary orbits as ellipses: after Fig. 10.2 from “The Physical Universe: An Introduction to Astronomy” by Frank Shu (University Science Books, 1982)
- Orbit of Castor: from “Astronomy: Journey to the Cosmic Frontier” by John Fix, Fig. 21.1 http://www.mhhe.com/physsci/astronomy/fix/student/chapter21/21f01.html
- Image of Castor: from “Double Stars” by Jack Schmidling, http://schmidling.netfirms.com/doubst.htm
- Orbit of Sirius: from “Stars, Galaxies and Cosmology” http://csep10.phys.utk.edu/astr162/lect/binaries/astrometric.html
- Spectroscopic binary animation: from “Astronomy 162 Digital Movie Gallery” by Richard Pogge, http://www-astronomy.mps.ohio-state.edu/~pogge/Ast162/Movies/ . Used with permission.
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- Radial velocity of Mizar A; from “A New View of Mizar” by Leos Ondra, http://leo.astronomy.cz/mizar/article.htm
- Orbit of IM Mon, from Bakis et al. 2010 http://adsabs.harvard.edu/abs/2010NewA...15....1B
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- Kepler 5-star system: from http://phys.org/news/2015-07-star-doubly-eclipsing.html
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- Figure 8 orbit: from Charlie McDowell, http://www.cse.ucsc.edu/~charlie/3body/
- Alpha Centauri image: from Willie’s Modified Vesta Webcam Page, http://www.saao.ac.za/~wpk/vesta/
- Capella image: taken by the Cambridge Optical Aperture Synthesis Telescope, from http://eastbay.astro.org/articles/lore/auriga.htm
- Orbit of Beta Cen A/B: from paper by Davis et al., MNRAS 356, 1362 (2005), copy at http://www.astro.uiuc.edu/~kaler/sow/hadar.html
- Castor: from Jodrell Bank Constellations, http://www.jb.man.ac.uk/public/AList/Gemini.html
- Light curve of AE Phe: from Maceroni et al. 1994, “Surface imaging of late-type contact binaries I: AE Phoenicis and YY Eridani”, A&A 288, 529; Doppler image from Barnes et al. 2004, “High-resolution Doppler images of the spotted contact binary AE Phe”, MNRAS 348, 1321
- Algol light curve: from Stebbins 1920, “The measurement of the light of stars with a selenium photometer, with an application to the variations of Algol”, ApJ 32, 185
- Orbital element distributions: from Halbwachs et al., “Multiplicity among solar-type stars. III. Statistical properties of the F7-K binaries with periods up to 10 years”, A&A 397 159 (2003), available at http://adsabs.harvard.edu/abs/2003A%26A...397..159H
- Artist’s impression of the Algol system: from The Electronic Sky, http://www.glyphweb.com/esky/default.htm?http://www.glyphweb.com/esky/stars/algol.html
- WR 104: from “The Twisted Tale of Wolf-Rayet 104” by Peter Tuthill, http://www.physics.usyd.edu.au/~gekko/wr104.html
- Cataclysmic variable: from “Explorations: An Introduction to Astronomy” by Thomas Arny, Fig. 14.3 http://www.mhhe.com/physsci/astronomy/arny/instructor/graphics/ch14/1403.html
- Formation of accretion disk: from Flannery 1975, “The location of the hot spot in cataclysmic variable stars as determined from particle trajectories”, MNRAS 170, 325
- Nova Herculis and nova light curve: from Astronomy 122: Birth and Death of Stars by Jim Schombert, http://zebu.oregon.edu/~js/ast122/lectures/lec17.html