Lecture 13: Binary evolution

Senior Astrophysics

2018-04-18

Outline

Consequences of mass transfer

- We have seen how mass transfer can occur when one (or both) star in a binary system comes in contact with its Roche lobe.
- We have seen how the material is transferred via either an accretion disk or via stellar wind.
- In this lecture, we will see the effect this mass transfer has on the properties of the binary.
- When a pair of stars transfer material, both mass and angular momentum are redistributed in the binary – or may even be lost altogether into space, depending on the physical mechanisms at work. When this happens, both the orbital separation and the mass ratio can change, so in general the Roche-lobe radius will change as well.

Binary angular momentum

- Consider two stars with mass M_1, M_2 (with total mass $M = M_1 + M_2$) in a binary system with semi-major axis a: the system has binary angular velocity

$$\omega = \sqrt{\frac{G(M_1 + M_2)}{a^3}}$$

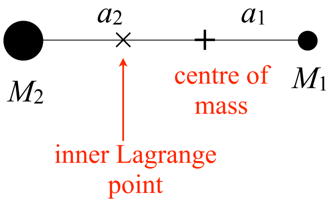
total energy

$$E = K_1 + K_2 + \Omega = \frac{1}{2}M_1 v_1^2 + \frac{1}{2}M_2 v_2^2 - \frac{GM_1 M_2}{a}$$

Angular momentum

- The binary angular momentum is

$$
\begin{aligned}
J &= M_1 a_1^2 \omega + M_2 a_2^2 \omega \\
&= \frac{M_1 M_2}{M} a^2 \omega \\
&= M_1 M_2 \sqrt{\frac{Ga}{M}}
\end{aligned}
$$



Roche lobe overflow

- When mass is transferred from one star to the other, or is lost to the system entirely, the angular momentum of the binary changes, which changes orbital parameters like the radius and the period.
- In particular, if one star fills its Roche lobe, then matter can freely escape from the surface through the inner Lagrange point L_1 and will be captured by the other star.

Roche lobe overflow

- A star can fill its Roche lobe either
  - due to expansion, e.g. on red giant branch; or
  - when the Roche lobe shrinks. If the binary loses angular momentum, the stars will spiral together, and the Roche lobes will close in on one or both stars.
- Note that a star can never be *bigger* than its Roche lobe; otherwise, the excess material would just flow off onto the other star or into space.
- Let's see how the angular momentum changes when the stars transfer mass.

Change of angular momentum

- Differentiate the expression for the angular momentum:

$$\frac{dJ}{dt} = \dot{J} = \dot{M}_1 M_2 \sqrt{\frac{Ga}{M}} + M_1 \dot{M}_2 \sqrt{\frac{Ga}{M}} + M_1 M_2 \sqrt{\frac{G}{M}} \times \frac{1}{2} a^{-\frac{1}{2}} \dot{a}$$

- Divide through by J:

$$\frac{\dot{J}}{J} = \frac{\dot{M}_1}{M_1} + \frac{\dot{M}_2}{M_2} + \frac{\dot{a}}{2a}$$

so

$$\frac{\dot{a}}{a} = \frac{2\dot{J}}{J} - 2\left(\frac{\dot{M}_1}{M_1} + \frac{\dot{M}_2}{M_2}\right)$$

Conservative mass transfer

- Now, assume that all the mass lost by one star is gained by the other, so $\frac{dM}{dt} = \dot{M}_1 + \dot{M}_2 = 0$. Then $\dot{M}_2 = -\dot{M}_1$, so

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

- Now let's assume that angular momentum is conserved, so $\dot{J} = 0$. Then

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

Conservative mass transfer

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

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

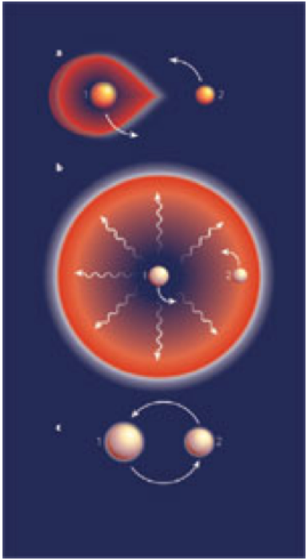
- if $M_1 < M_2$, then $\frac{\dot{a}}{a} > 0$, i.e. orbit widens
- if $M_1 > M_2$, then $1 - \frac{M_1}{M_2} < 0 \Rightarrow \frac{\dot{a}}{a} < 0$,

$$\begin{aligned} \text{i.e. orbit shrinks} \quad &\Rightarrow \quad \text{Roche lobe shrinks} \\ &\Rightarrow \quad \text{more mass transferred} \\ &\Rightarrow \quad \text{orbit shrinks more} \end{aligned}$$

i.e. runaway mass transfer

Unstable mass transfer

- In the case of runaway mass transfer, we can get a **spiral-in**. The donor's envelope engulfs both stars, since the Roche lobe of the donor has shrunk so much $\Rightarrow$ forms a common envelope around both stars.
- Both stars feel a frictional drag $\Rightarrow$ energy is extracted from orbit and imparted to the envelope. The two stars spiral together, and the envelope is ejected.
- Angular momentum is no longer conserved



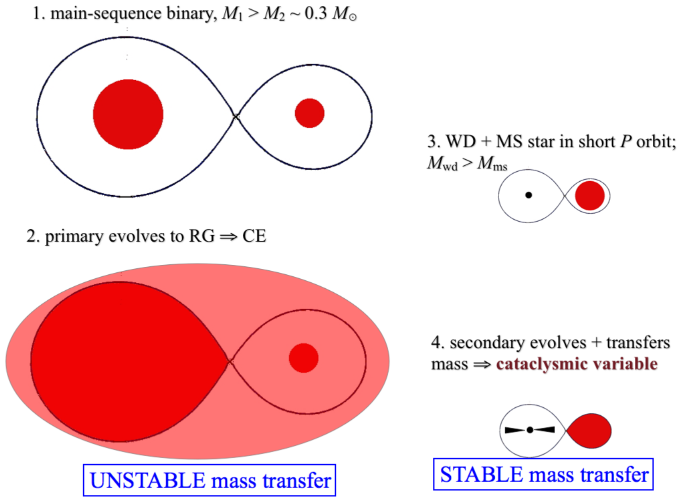
Spiral-in

- The detailed physics of the common-envelope phase is not well understood. Process probably very efficient: a decreases by $\sim 10^3$ in a very short time ($\sim$ 1000 y). Final orbital separation will depend on the binding energy of the envelope. If the binding energy is too large, the stars will merge completely (*cf. progenitor to SN1987A?*)
- Let's now look at some observed classes of interacting binaries.

Cataclysmic variables

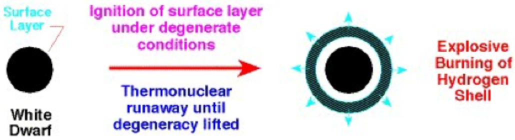
- Cataclysmic variables (CVs) are a class of interacting binary stars consisting of a white dwarf with a low-mass companion star.
- CVs all have very short orbital periods, 1–12h. System originally consisted of two normal main-sequence stars in a large orbit ($\sim$ several years). More massive star evolves to become a red giant, and mass transfer starts. Since $M_{\rm donor} > M_{\rm acccretor}$, orbit shrinks, and a period of common-envelope evolution begins. Stars spiral together until the envelope is ejected; end result is a planetary nebula with a close binary at its centre, consisting of a white dwarf and its companion. The white dwarf is more massive than its companion; typical masses are $M_{\rm wd} \sim 0.8 M_\odot$ and $M_2 \sim 0.3 M_\odot$.

Cataclysmic variables



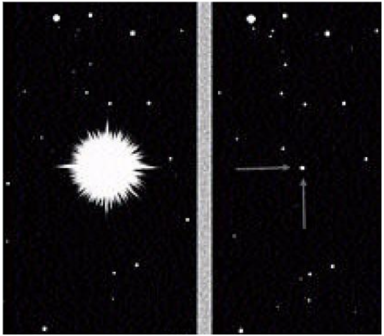
Cataclysmic variables

- Once the envelope has been ejected (on very short timescales, t_{th}), binary remains quiescent until the *second* star comes in contact with its Roche lobe. Then 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 outer envelope accumulates on the surface of the white dwarf, until P and ρ reach the point when fusion can begin. Matter is degenerate $\Rightarrow$ all H on the surface ignites almost at once in a thermonuclear runaway, which consumes all the accreted material.



Novae

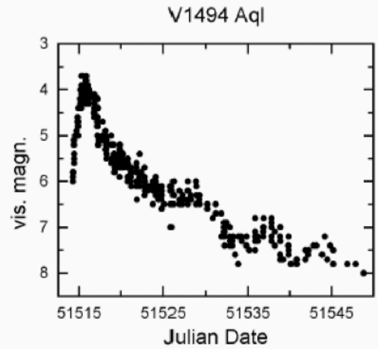
- These explosions are visible as a massive increase in brightness of the star: by a factor of 50,000 or more. Because the pre-explosion star was essentially anonymous, the star appears as a “new” star; these are known as novae.



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

Novae

- 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.



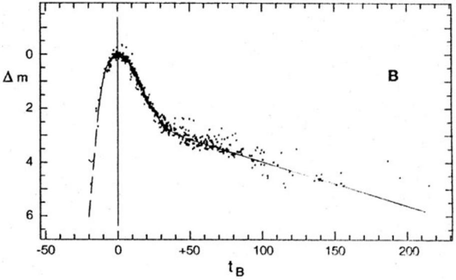
- The accreted layer is blown off in the explosion, which produces an expanding shell. The process repeats on timescales of thousands of years.

Type Ia supernovae

- When we were talking about supernovae, I mentioned that there is a class of supernovae that do not show a bump in their lightcurve. A white dwarf, accreting matter in a binary system, accretes enough to push it over the Chandrasekhar limit, so it starts to collapse. However, unlike the iron core of a massive star, the collapsing white dwarf is made up of carbon and oxygen, which ignites during the collapse. The fury of the resulting explosion tears the star completely apart in a second.
- SN Ia supernovae have leapt into prominence recently with the awarding of the 2011 Nobel Prize to two teams for their discovery of the accelerating universe, based on observations of SNe Ia.

Type Ia supernovae

The light curves for SNe Ia are similar enough that it seems likely they all arise in the same manner: the thermonuclear disruption of Chandrasekhar-mass white dwarfs.
Unfortunately, the observations do not so far support this hypothesis.
I will discuss SNe Ia in the last (ADV) lecture.



Standard B light curve, based on observations of 22 supernovae (Branch 1992, after Cadonau 1987)

X-ray binaries

X-ray binaries are systems where the accreting star is a neutron star or black hole.

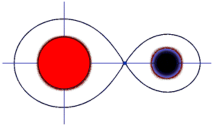
Two classes, based on mass of companion (donor) star:

- the high-mass X-ray binaries (HMXBs), with $M_2 \gtrsim 10 M_\odot$; and
- the low-mass X-ray binaries (LMXBs), with $M_2 \lesssim 2 M_\odot$

Use the same principles to understand how X-ray binaries evolve.

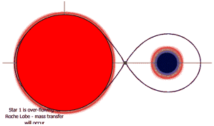
- Let's begin with a binary consisting of two massive stars, $M_1 \sim 25 M_\odot$ and $M_2 \sim 10 M_\odot$.

Evolution of a massive binary



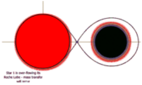
M_1 ($M_\odot$)	M_2 ($M_\odot$)	P_b (d)	a ($R_\odot$)
25	10	10	64

More massive star evolves first.
Primary expands on nuclear timescale $\tau_{nuc} \sim 3\times10^6$ y



M_1 ($M_\odot$)	M_2 ($M_\odot$)	P_b (d)	a ($R_\odot$)
25	10	10	64

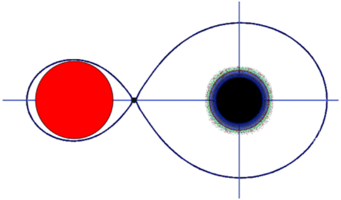
Mass transfer begins: since $M_1 > M_2$ orbit shrinks.
Mass loss $\Rightarrow$ exposes cool inner layers $\Rightarrow$ star shrinks on τ_{dyn}, then expands slightly on τ_{th}
$\Rightarrow$ unstable mass transfer as RL shrinks on $\tau_{th} \sim 2\times10^4$ y



M_1 ($M_\odot$)	M_2 ($M_\odot$)	P_b (d)	a ($R_\odot$)
17.5	17.5	5.4	42

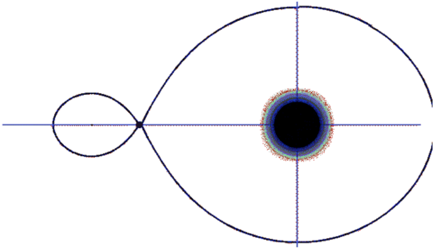
When $M_1 = M_2$ after $\Delta M = 7.5$ $M_\odot$, $q = M_1/M_2 = 1$: minimum P_b
Further mass transfer $\Rightarrow$ RL *expands* $\Rightarrow$ star loses contact $\Rightarrow$ mass transfer *stops* until star expands once again on τ_{th}

Evolution of a massive binary



M_1 ($M_\odot$)	M_2 ($M_\odot$)	P_b (d)	a ($R_\odot$)
7.1	27.9	20.4	103

Mass transfer continues on nuclear timescale, 10^6 y, and orbit *expands*.



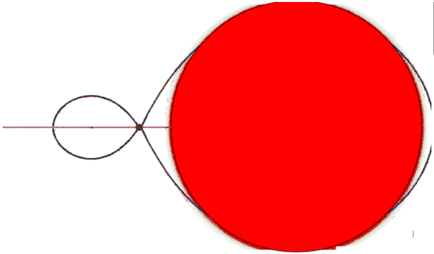
M_1 ($M_\odot$)	M_2 ($M_\odot$)	P_b (d)	a ($R_\odot$)
1.4	27.9	30.7	127

When He burning stops, M_1 shrinks drastically and mass transfer stops completely.

Then M_1 undergoes SN explosion. leaves behind neutron star: binary stays bound

$e = 0.19$, $v_{sys} = 39$ km/s

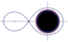
Evolution of a massive binary



M_1 ($M_\odot$)	M_2 ($M_\odot$)	P_b (d)	a ($R_\odot$)
1.4	27.9	30.7	127

Then secondary evolves and fills Roche lobe: mass transfer is again unstable, since now $M_2 > M_1$, and M_2 is the donor.

This time get a spiral-in: evolution is highly non-conservative! If cores don't merge, result is a He core orbiting a NS.



M_1 ($M_\odot$)	M_2 ($M_\odot$)	P_b (d)	a ($R_\odot$)
1.4	3	0.333	3.3

He core either remains as a heavy (~ 1 $M_\odot$) WD or explodes and forms another NS in a SN explosion.
This leaves system in highly eccentric orbit, with large systemic velocity.

Unbinding the binary

- It is easy to show[1] that if more than half the mass of the system is lost in the supernova explosion, the binary will be unbound.
- This is a particular problem for low-mass X-ray binaries. In order to form a neutron star, the primary must have $M_1 \gtrsim 10M_\odot$, and we observe the secondary to have $M_2 \sim 0.8M_\odot$. This means that in the supernova explosion which forms the neutron star, the amount of mass lost is

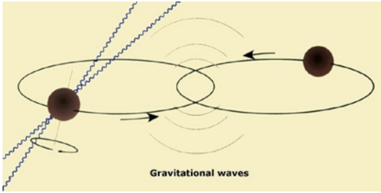
$$\Delta M \gtrsim (10 - 1.4)\, M_\odot = 8.6\, M_\odot$$

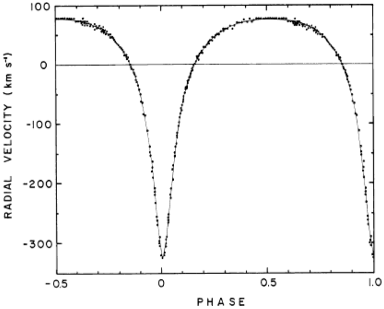
which is more than half the mass of the initial binary.
- $\Rightarrow$ low-mass X-ray binaries should not exist!

[1] see tutorial 3

The binary pulsar PSR 1913+16

- The end result of the evolution of a HMXB is a pair of neutron stars in a highly eccentric orbit. We can see these as binary pulsars. The first binary pulsar was found by Taylor and Hulse in 1974: a 59 ms pulsar in an elliptical 8 hour orbit with another neutron star (not pulsing).





from Hulse & Taylor (1975)

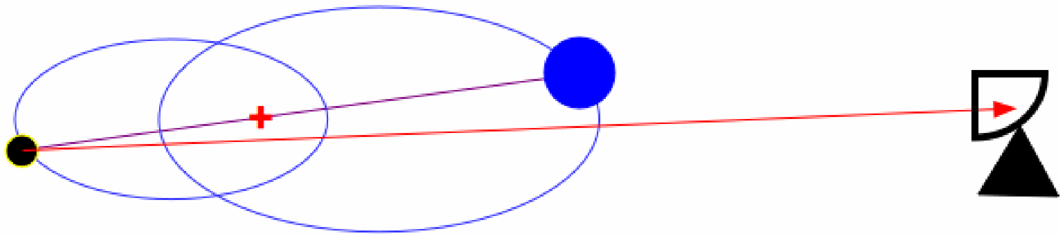
PSR J0737–3039A and B

- In 2004, the first double pulsar was discovered: a binary where both neutron stars are pulsars. The binary consists of a pulsar with a spin-period of 23 ms – the millisecond pulsar – orbiting a 2.8 s pulsar in a 2.4 h orbit ($a \sim R_\odot$)). The mean orbital velocity is about 0.1% of the speed of light. Furthermore, the orbit is almost exactly edge-on, so both pulsars are actually eclipsed each orbit.
- The millisecond pulsar must have initially been the more massive star; the slower pulsar resulted from the *second* supernova, so is much younger than the other. The chance of finding such a binary is remote, since both pulsars have to be pointing in our direction and the younger pulsar must still be alive.

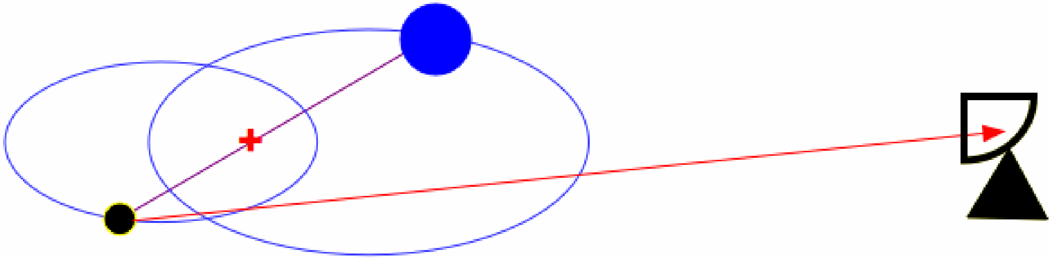
PSR J0737–3039A and B

- These binary systems make exquisite laboratories for testing General Relativity in the strong field; the advance of periastron, the decay of the orbit due to gravitational waves, and the Shapiro delay in the pulse arrival times due to the gravitational field of the companion.

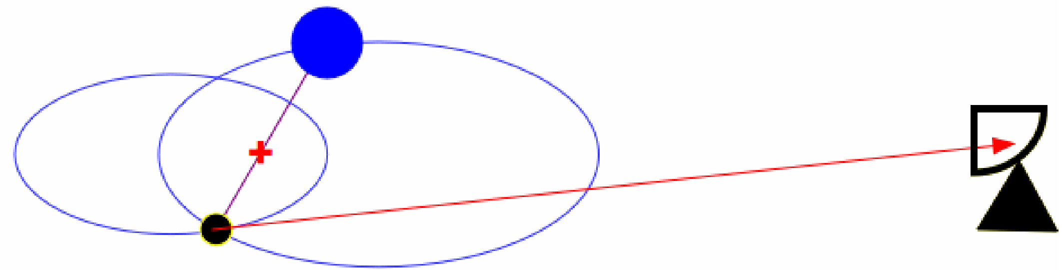
Shapiro delay



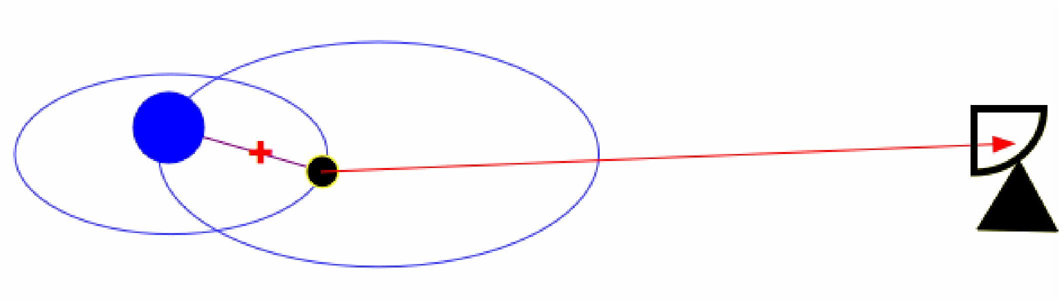
Shapiro delay



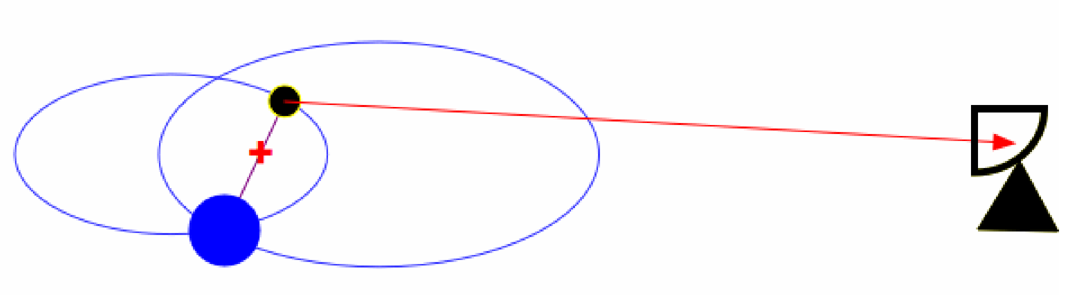
Shapiro delay



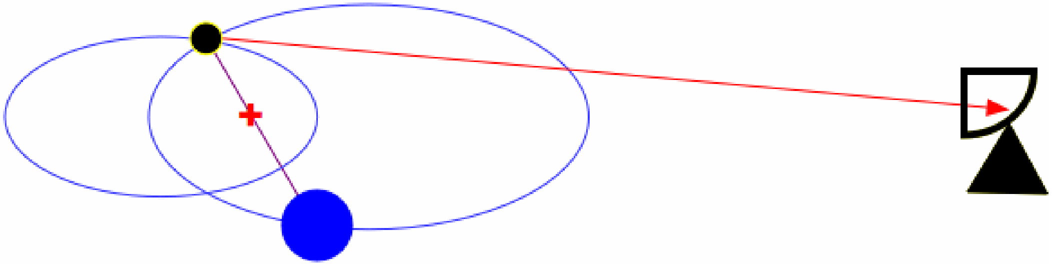
Shapiro delay



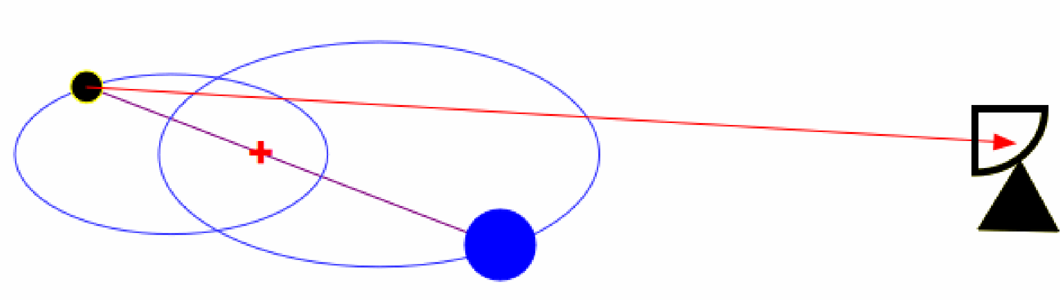
Shapiro delay



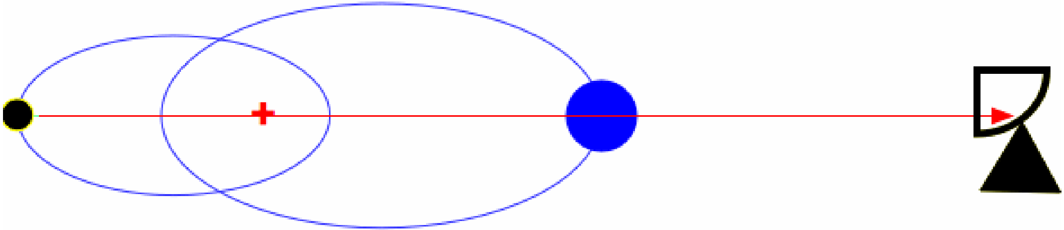
Shapiro delay



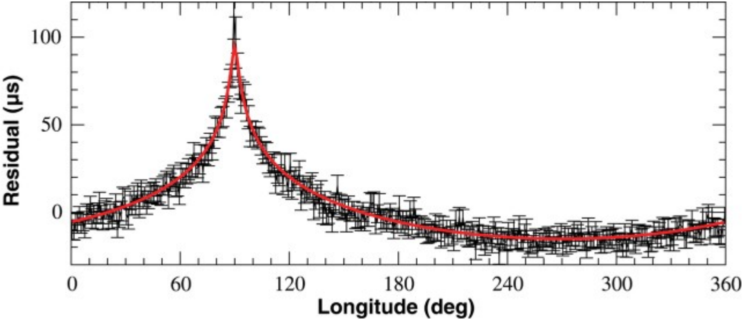
Shapiro delay



Shapiro delay



Shapiro delay



Measurement of the Shapiro delay for the double pulsar PSR J0737–3039A.

That's all, folks!

- This is the last ordinary lecture for this module.
- Lab 4: exploring Roche lobes is on Friday *(also from 10am–12pm today)*. Unfortunately, the room bookings were messed up so we don't have the Learning Studio. Tutors will be **HERE** for you to work on your own laptop. Better to go to SNH4003 today if you can.
- The last lecture (next Tuesday) is an Advanced-only lecture; I will talk about modern research questions involving binaries, particularly Type Ia supernovae and the binaries found using LIGO. Everyone is welcome.
- Checkpoints for lab 4 are due in next Friday: leave at the Student office or under my door. All lab solutions are will be up shortly.
- There will be a review session during Stuvac.