Theoretical Astrophysics I: Physics of Sun and Stars
Lecture 12: Binary, Variable stars, and Supernovae

Petri Käpylä Ivan Milić

pkapyla,milic@leibniz-kis.de

Institut für Sonnenphysik - KIS, Freiburg

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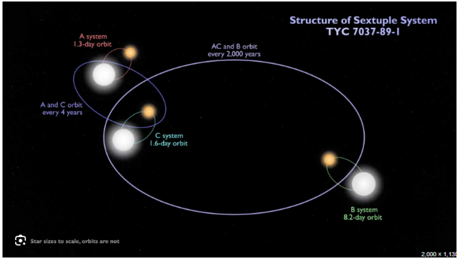
Recap

- We have understood the structure (and a bit of evolution of the stars) though the power of 1-D models.
- There we have assumed that the stars are isolated, and spherically symmetric.
- We have also assumed that the processes in them act extremely slowly.
- We allowed for some, miniscule oscillations that allowed us to perform helio/astroseismology.
- In real life, things are much different...

Departures from ideal approximations

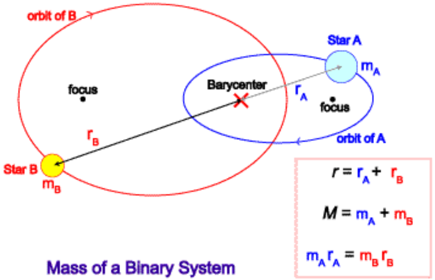
- Stars are not born alone, and they do not evolve alone. 85% of all the stars are in the binary systems.
- Some stars are highly assymetric, either because of fast rotation or strong magnetic fields (or both!)
- Some exhibit strong, periodic changes, and can change their brightness substantially with period of order of hours or days.
- ...explode and completely change their structure (and eject the material in the interstellar space!)



Credits: NASA

Binary stars

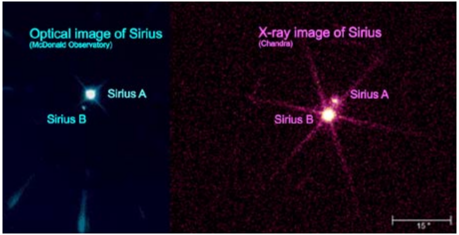
- We will focus on systems of two stars, even though there can be more than one.
- Note: we are **not** talking about stellar clusters now.
- Binary star is a system of two stars that are gravitationally bound to each other.
- They revolve around the center of the mass of the system.



Credits: Australia Telescope National Facility

Visual Binaries

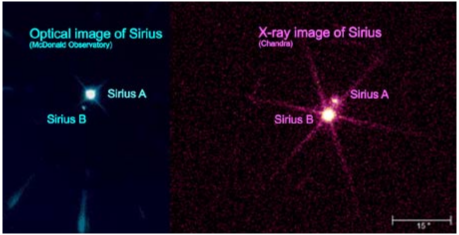
- Binary star is a system of two stars that are gravitationally bound to each other.
- Sometimes their movement can be detected directly - through the change in the apparent position of the stars on the sky - **astrometric methods**
- These stars are often called visual binaries.
- To the right we see Sirius, which is in fact a binary star.



Credits: NASA/SAO/CXC/MacDonald Observatory

Visual Binaries

- We did not immediately discover both. In 1844 Bessel detected that Sirius has a companion, through the change in its proper motion.
- In 1915 we observed the spectrum of Sirius B and concluded it is a white dwarf, of the size of the Earth and mass approximately $M_{\odot}$
- The orbit of the system is very eccentric ($e = 0.6$).
- Sirius A is an A class star (hehe), with temperature around 10 000 K and mass equal to 2 $M_{\odot}$.



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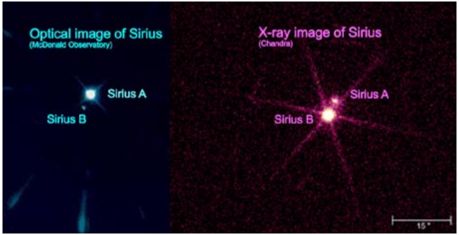
Sirius

- Sirius A is an A class star with temperature around 10 000 K and mass equal to 2 $M_\odot$.
- Sirius B and concluded is white dwarf, of the size of the Earth and mass approximately $M_\odot$
- Is there something here that does not fit?



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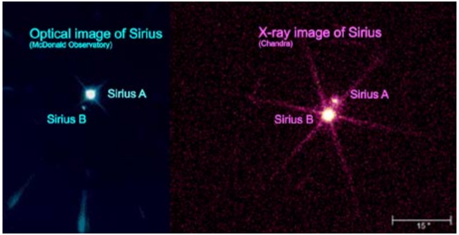
Sirius

- Sirius A is an A class star with temperature around 10 000 K and mass equal to 2 $M_{\odot}$.
- Sirius B and concluded is white dwarf, of the size of the Earth and mass approximately $M_{\odot}$
- Is there something here that does not fit? - How is less masive star a white dwarf and the more massive one still on the main sequence?



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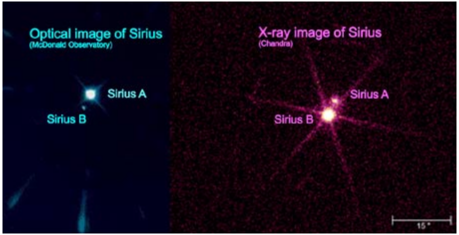
- Sirius B and concluded is white dwarf, of the size of the Earth and mass approximately $M_\odot$
- Is there something here that does not fit? - How is less masive star a white dwarf and the more massive one still on the main sequence?
- Sirius B must have lost a big part of its mass through the evolution.
- How do we know these stellar masses?



Credits: NASA/SAO/CXC/MacDonald Observatory

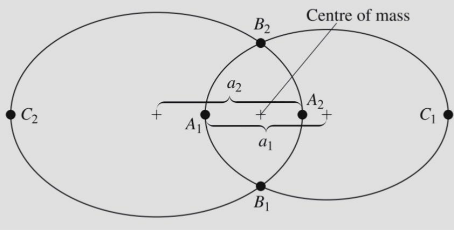
Visual binaries - mass determination

- Observing systems like this one is crucial for measuring stellar masses.
- **First** we measure the period of the system.
- **Then** we can use Kepler's third law:

$$\frac{(a1 + a2)^3}{T^2} = \frac{G(M_1 + M_2)}{4\pi^2} \tag{1}$$

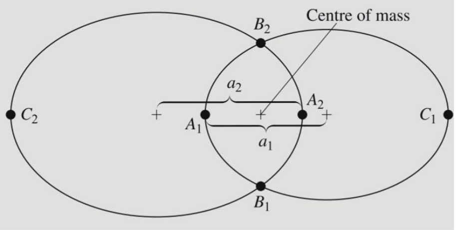
- To find the mass of the system. Then, we can find individual masses from:

$$M_1 a_1 = M_2 a_2 \tag{2}$$



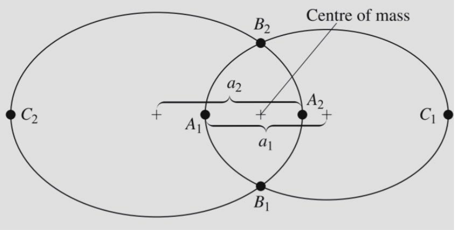
Visual binaries - mass determination

- What did we have to measure to perform this?



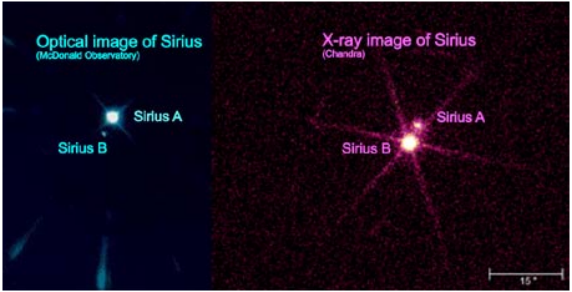
Visual binaries - mass determination

- What did we have to measure to perform this?
- Period of the system
- Orbits of both of the stars.
- We also needed the orbit to be in the plane of the sky.
- We need to be a bit fortunate for this to happen!
- **But, it allows us to directly measure stellar masses and test our models!**



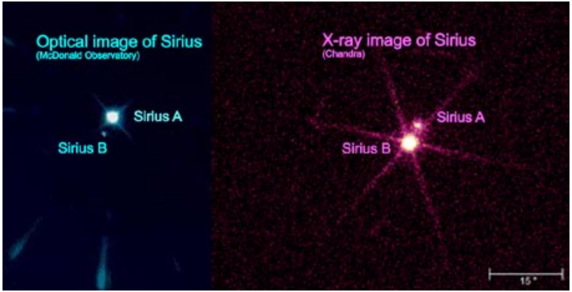
One more question on Sirius

- How come that Sirius A is brighter in optical wavelengths and Sirius B is brigther in X ray?



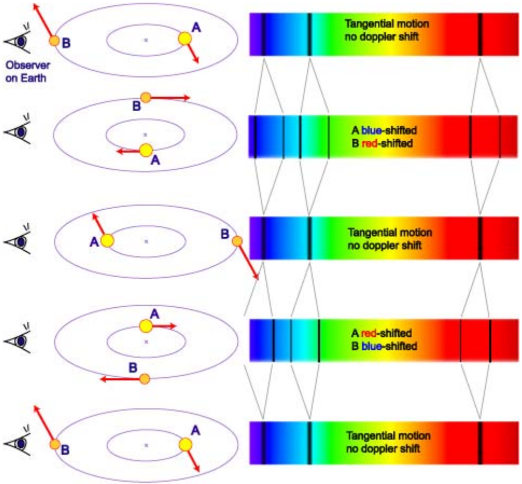
One more question on Sirius

- How come that Sirius A is brighter in optical wavelengths and Sirius B is brigther in X ray?
- $L_\nu \approx B_\nu 4\pi R^2$
- Sirius B is smaller but **much hotter**.
- Because of non-linearity of Planck function. It can still be brighter in X domain but not in the optical.



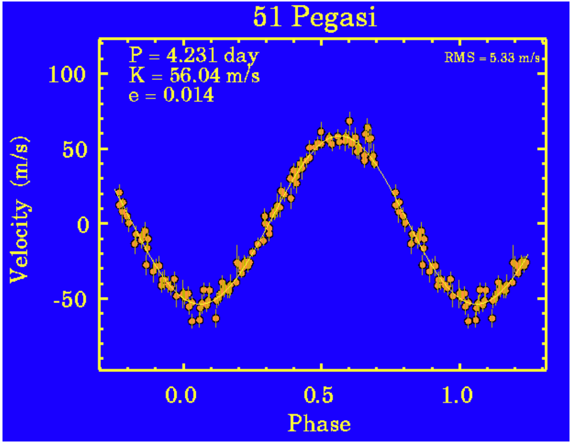
Spectroscopic binaries

- If we take the spectrum of the binary star, we will see spectral lines shifting to red and blue.
- This allows us to infer the line-of-sight velocity of these stars:
- $v_{los} = \frac{\lambda - \lambda_0}{\lambda_0} c$
- Today we can measure these velocities down to **one meter per second**. (E.g. famous HARPS spectrograph).



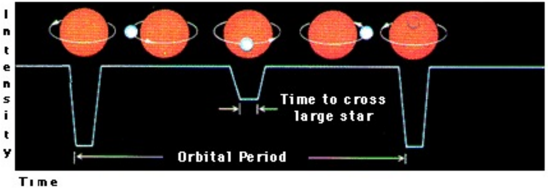
Spectroscopic binaries and exoplanets

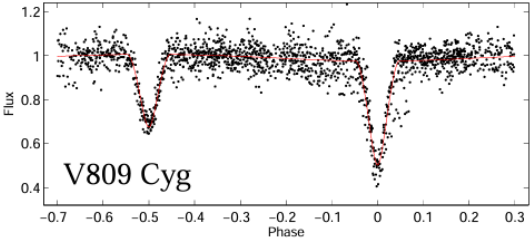
- Sometimes we can only see the spectrum of one component, but we can still detect the shifts.
- That still gives us some information about the other component.
- The problem is always the inclination of the system w.r.t us.
- Similar technique is used to detect exoplanets.
- What is the relative velocity of the Sun due to influence of the Earth?



Eclipsing binaries

- If it happens that the orbit of the system coincides with line of sight, we can see the stars eclipse each other.
- Here we can learn something even if we cannot directly see them separately.
- What can we learn?





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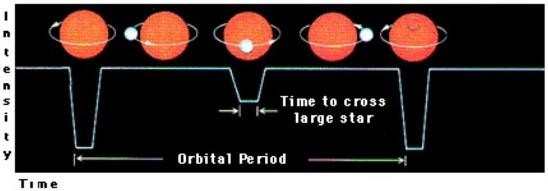
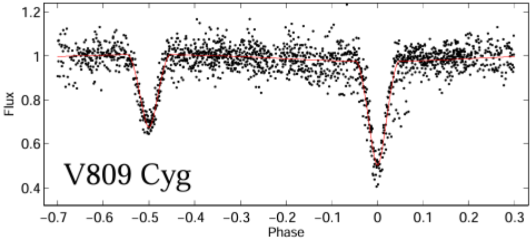
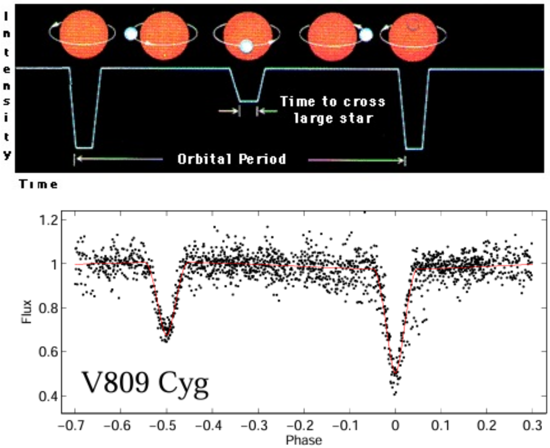




Eclipsing binaries

- Here we can learn something even if we cannot directly see them separately.
- What can we learn?
- The depths of transits and the maximum of brigthness allow us to infer the magnitudes of the components.
- Duration of transits $\rightarrow$ sizes of the components.
- Shape of the transit and the time difference between primary and secondary transit $\rightarrow$ shape and the orientation of the orbit.



Exoplanet transits

- This is similar to how exoplanet transits work.
- Except, of course, planets are much smaller than the stars :-)
- Several space missions and ground based telescopes have been developed to study exoplanet transits.
- For example Kepler space telescope.
- What can you conclude from the lightcurve to the right? (Use blackboard)

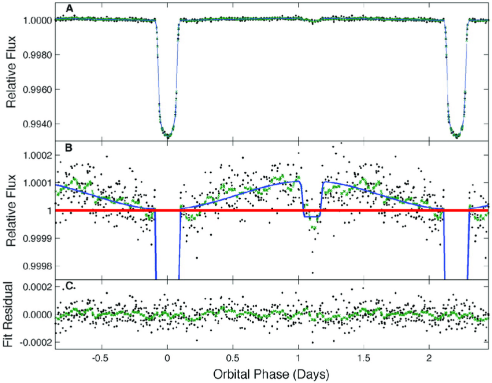
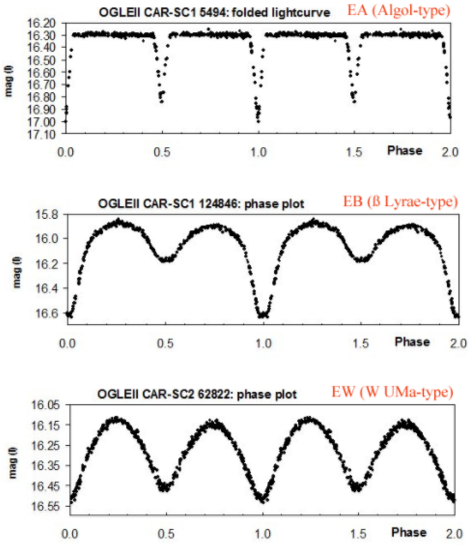


Figure: Hat P7-b lightcurve. From Borucki et al. 2011

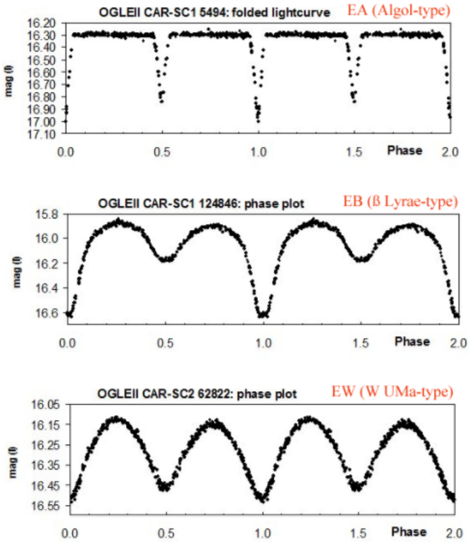
Eclipsing binaries

- Now, what about these lightcurves to the right?



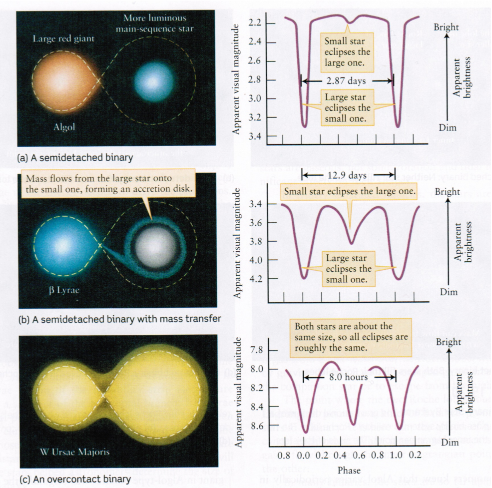
Close binaries

- Now, what about this lightcurve to the right?
- Close binary systems are binary stars where the components are so close to each other that they physically pertub each other's shape.
- The stars are sometimes in contact - with the mass flow from one to the other.
- Obviously, these stars are not perfect, 1D spherically symmetric!



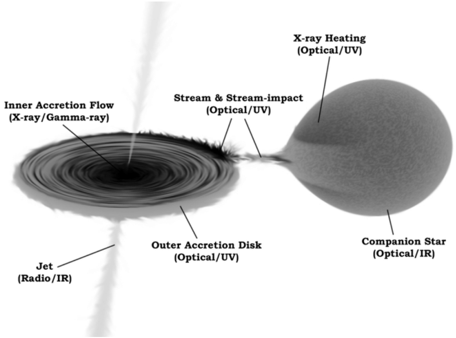
Close binaries

- Modeling and understand curves of close (interacting) binaries requires detailed understanding of their shapes and corresponding distortions of their atmospheres.
- One often introduces bright or dark spots on the stellar surface.
- Inferring the properties of these objects is done through the light curve fitting where we fit the model of the system to the lightcurves (often recorded in different filters).
- If you want to know more about this, sign up for WS 2024 ("Remote sensing" course).



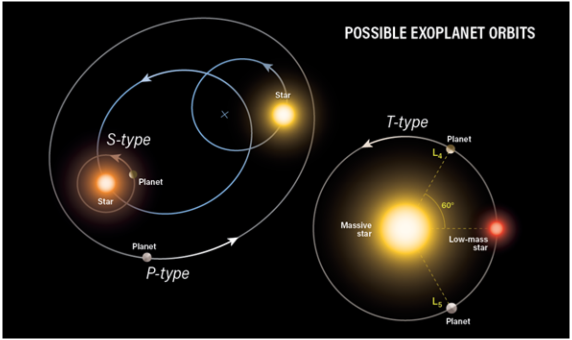
Close binaries

- Sometimes there is even an accretion disk around one of the components.
- The accretion disk itself can heat up significantly due to “friction” and reach very high temperatures, thus emitting substantially in X-domain.
- If you want to know more about this, sign up for WS 2024 (“Remote sensing” course).



How come we are not in a binary star system?

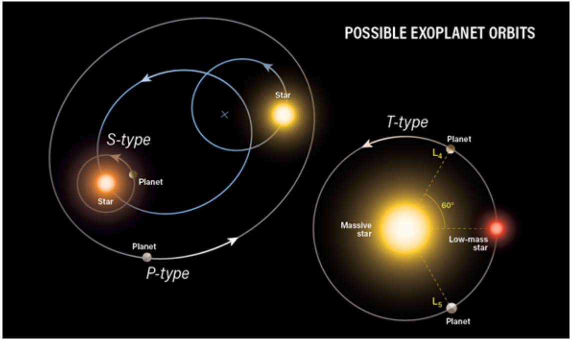
- If 85% of the stars are in the binary systems, how come we are living in the system with a single star?



Credits: ESA

How come we are not in a binary star system?

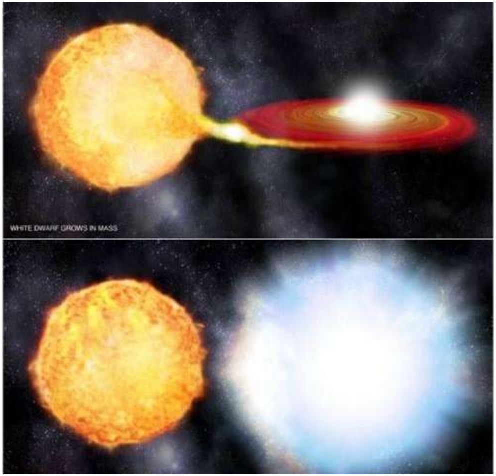
- If 85% of the stars are in the binary systems, how come we are living in the system with a single star?
- In multiple star system the planet would suffer large variations of irradiance.
- These would make temperature very unstable (can you estimate?).
- Which would, probably, severly hamper chances of developing life.



Credits: ESA

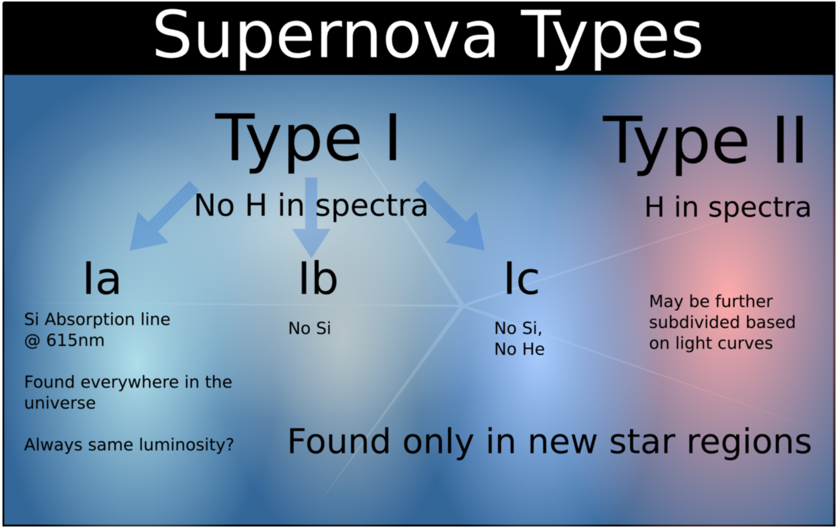
Stellar evolution in close binary systems

- When the star evolves and expands (e.g. red giant phase), the Roche lobe will overflow.
- The material will flow onto the other (less massive) star, accelerating her evolution.
- The whole story can happen again... Second component overflows, dumping material onto the white dwarf.
- Sometimes this material ignites in the TN reactions, creating a **Type Ia Supernova!**.

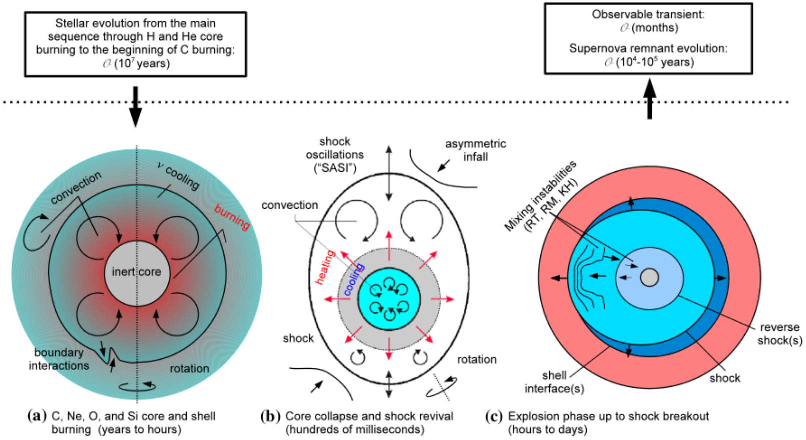


Credits: NASA/CXC/M. Weiss

Supernovae classification



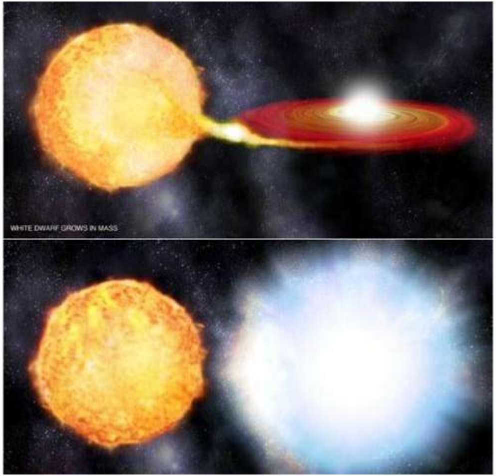
Supernovae classification. Credits:Stanford University



Hydrodynamics of a core-collapse supernova. Credits: Müller, 2020

SNe type 1a - Standard candles

- **Standard candle** - an object whose absolute magnitude (luminosity) we know with a high accuracy.
- SNe type1a are standard candles because they ignite when an exact mass is reached.
- They are also bright - making them suitable for distance measurement.
- There is still a number of uncertainties (chemical composition, interstellar absorption...)



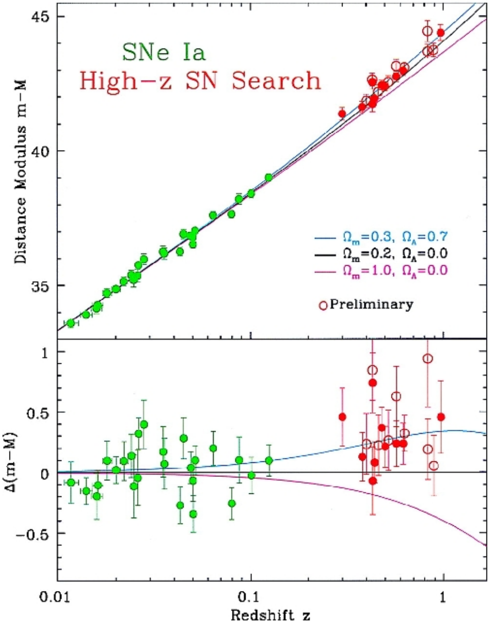
Credits: NASA/CXC/M. Weiss

SNe type 1a - Standard candles

- **Standard candle** - an object whose absolute magnitude (luminosity) we know with a high accuracy.

$$m = M - 5 + 5\log d \qquad (3)$$

- By observing a swath of supernovae, supernova cosmology project managed to map the geometry of spacetime and infer that the universe expands with some acceleration.
- Nobel prize 2011.



Hubble diagram from supernova cosmology

How did this story start?

- Edwin Hubble observed variable stars in other "nebulae" and measured distance to them.
- He also used measurements of radial velocity made by Vesto Slipher to construct a simple Hubble diagram.
- The relationship between the distance and velocity implied that universe is expanding.
- This is consistent with a solution of Einstein's equations.

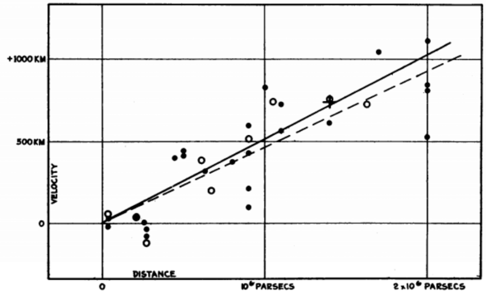


FIGURE 1
Velocity-Distance Relation among Extra-Galactic Nebulae.

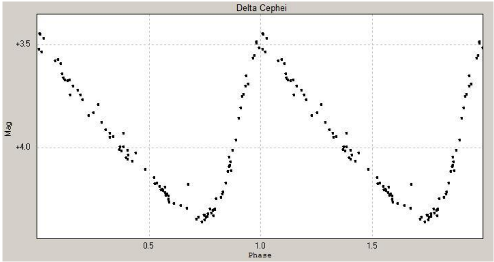
Original Hubble diagram from 1924

How did Hubble measure distances?

- He used another type of standard candles - Cepheid variable stars.
- Around that time, Henrietta Swan Leavitt established the connection between the **mean absolute brightness and the period** of these variable stars.

$$< M_V > = -2.11 \log 10P - 0.6 \quad (4)$$

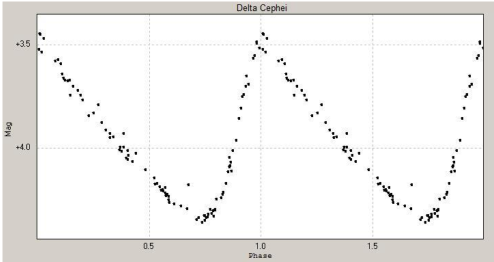
- Measuring the period **immediately** gives us the absolute magnitude.
- And then, as always: $m = M - 5 + 5 \log d$



Lightcurve of delta cephei

Why does the brightness of Cepheid vary?

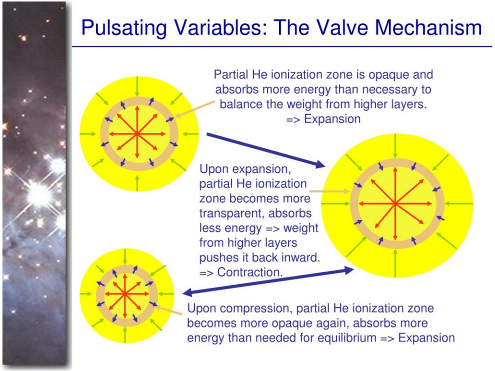
- Cepheids are kind of pulsating stars.
- Their brightness changes substantially. How come? Does the energy production change?



Lightcurve of delta cephei

Kappa (κ) mechanism

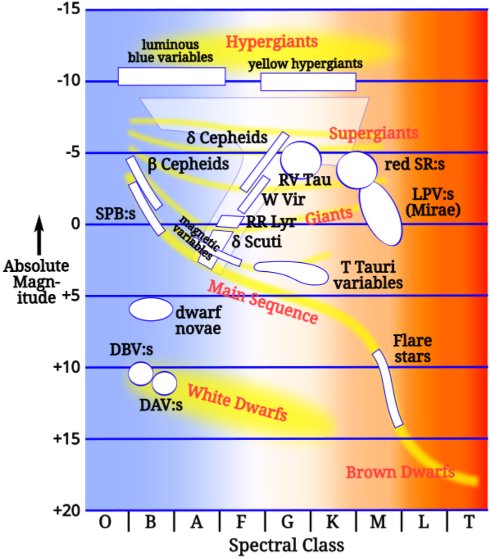
- We have seen that opacity is an essential ingredient of stellar structure.
- In cepheids, the structure is such that the star constantly goes between states where Helium is once and twice ionized.
- This causes substantial changes in opacity, and thus structure.
- Pulsations ensue. There is, obviously, a lot of open question.



Cepheid pulsations

Other variable stars

- There are different kinds of Cepheids (type I, type II)
- Also, RR Lyrae stars
- And δ Scuti variable stars.
- All these are important for understanding specific phases in stellar evolution but also as standard candles.



Cepheid pulsations

That's all folks!

- This was a story about stars that significantly depart from what we have been discussing so far.
- A lot of research, both theoretical and observational is revolving around these phenomena.
- If you are interested in future reading - let us know! We will also post some review articles.
- This is also the end of our course:
- Next hands on: solving HW2
- Next class: test exam
- **Exam, 30th of June, 10:00**