

# Stellar Evolution: Birth, Life, and Death of Stars

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# Evolution of stars

- When we talk about stellar evolution we mean on changes that occur in stars as they consume "fuel" , since their birth through their long life, and until they die.
- Understanding the evolution of stars help astronomers to understand:
  - The nature and future fate of our Sun.
  - The origin of our solar system.
  - How we compare our solar system with other planetary systems
  - If there could be life elsewhere in universe.

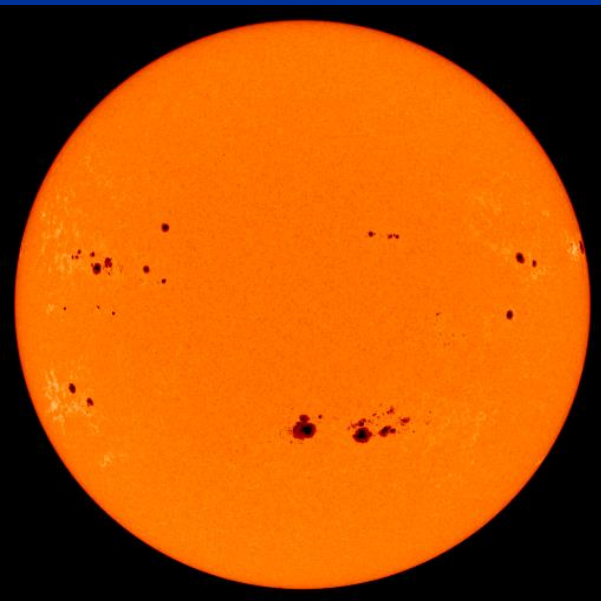


The Ring Nebula, a dying star.  
Source: NASA



# Properties of the Sun: the nearest star and how astronomers measure them – important!

- **Distance:**  $1.5 \times 10^{11}$  m, reflecting radar waves from Mercury and Venus
- **Mass:**  $2 \times 10^{30}$  kg, measuring the movement of the planets that rotate around the Sun
- **Diameter:**  $1.4 \times 10^9$  m, from the apparent diameter (angle) of the Sun and its distance
- **Power:**  $4 \times 10^{26}$  W, from the distance and the measured power from Earth
- **Chemical composition:** 98% hydrogen and helium, studying its spectrum.



The Sun.  
Source: NASA SOHO Satellite



# Properties of stars – distant suns and how astronomers measure them – important!

- **Distance:** from the parallax, or from the apparent brightness if the power is known.
- **Power:** from the distance and apparent brightness
- **Surface temperature:** From the color or spectrum
- **Radius:** From the power and surface temperature
- **Mass:** Using the observations of binary stars
- **Chemical composition:** from stellar spectra



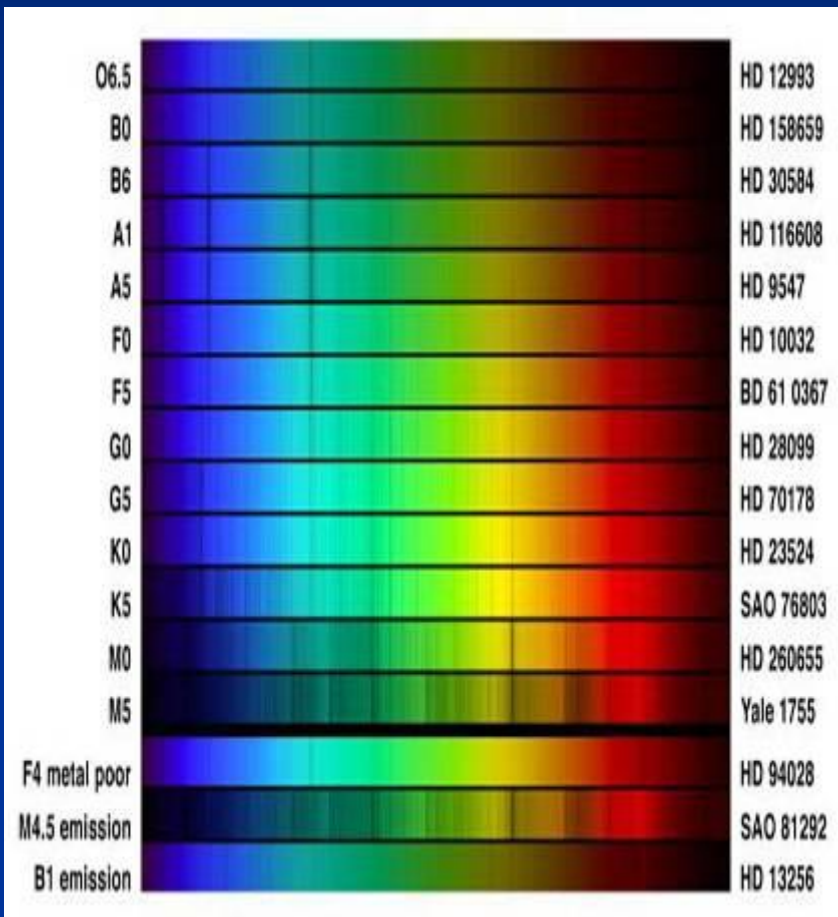
Orion Constellation.

Source: Hubble, ESA, Akira Fujii



# The spectra of the stars: starlight, decomposed into colors

- Astronomers learn about astronomical sources by studying the light that they emit
- The spectrum provides information on the composition, temperature, and other properties of stars



*Left: the first 13 spectra of stars with different surface temperatures (the highest on top); the last three spectra were taken from stars with peculiar properties*

Stellar Spectra

Source: US National Optical Astronomy Observatory





# The Hertzsprung-Russell diagram

There is an order in the properties of stars!

- The Hertzsprung-Russell (HR) diagram, shows the power (brightness) as a function of temperature (spectral class); the ordinate "absolute magnitude" is a logarithmic measure of power.
  - Most of the stars lie on the "main sequence": massive stars are hot and have high power (top left), while the small stars have lower masses, are cold and have low power (bottom right)
  - The giant stars lie on the top-right part of the diagram, while the white dwarfs are on the bottom-left

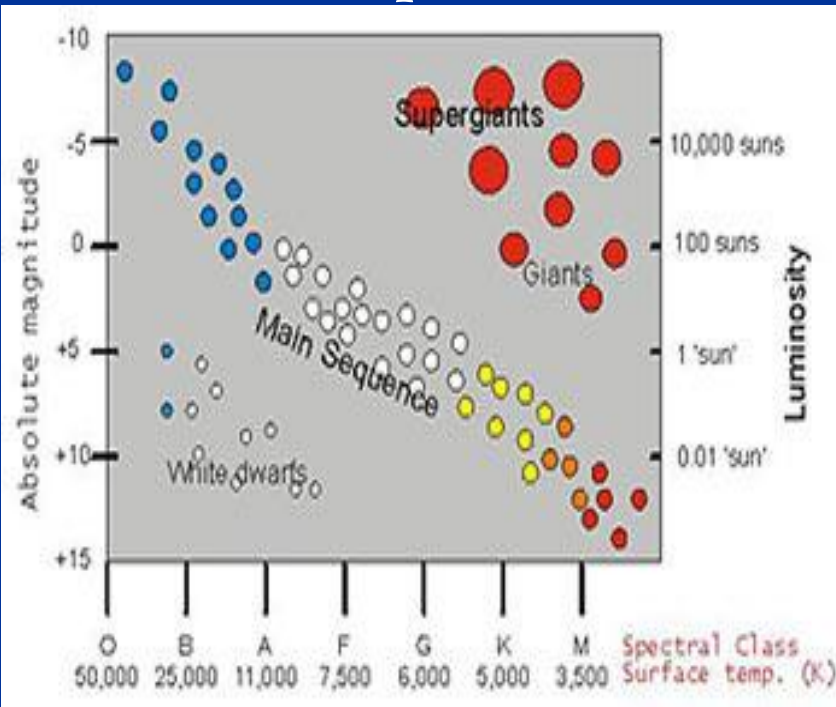
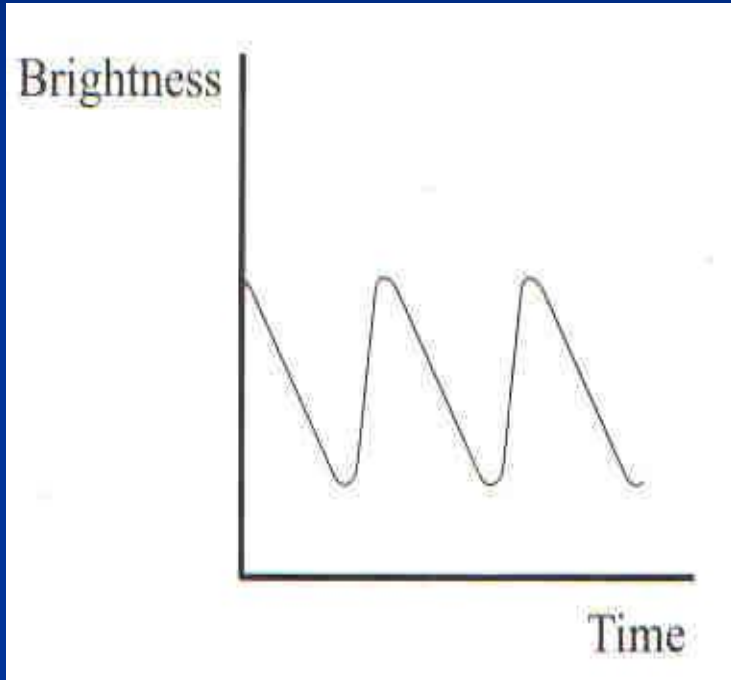


Diagram HR Source: NASA



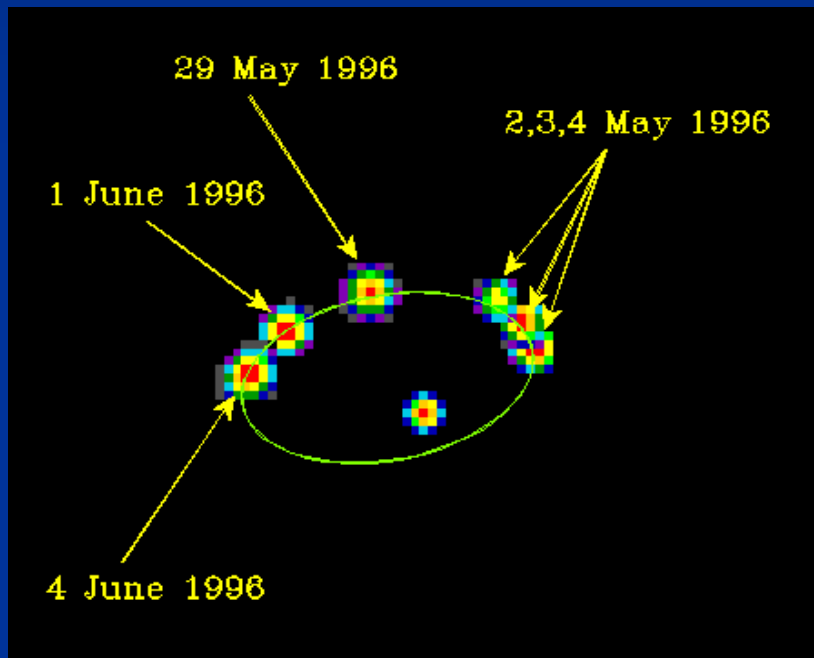
# Variable Stars



Light curve: a graph of brightness vs. time.

- Variable stars are stars that change their brightness with time
- Most of the stars are variable; can vary because they vibrate, shine brightly, erupt or explode, or are eclipsed by a companion star or planet
- Variable stars provide important information about the stellar nature and evolution

# Binary stars (double) and multiple



Orbital movement of Mizar, in Osa Major.  
Source: NPOI Group, USNO, NRL

- Binary stars are pairs of stars that are close together due to gravity, and orbit around themselves. They can be visible directly (as in the image on the left), or detected by their spectra, or an eclipse between the stars.
- They are the most important tool to measure the masses of stars
- Multiple stars are three or more stars that are bonded together due to gravity

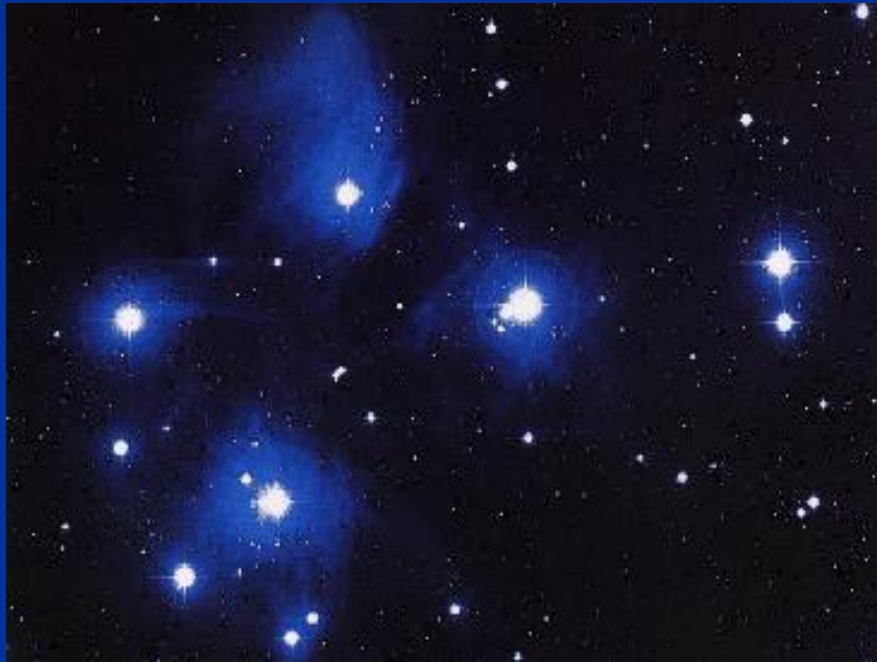




# Star clusters

## "Experiments of nature"

- Star clusters are groups of stars that are close each other due to gravity, and move all together through the space
- They were formed at the same time and place, from the same material, and are at the same distance, only differ in the mass
- Clusters are samples of stars with different masses but with the same age



Open Cluster The Pleiades.  
Source: Mount Wilson Observatory



# What are the Sun and stars made of?



Abundances of chemical elements in the Cosmos:  
birdseed H (90%), rice He (8%),  
beans C, N, and O and a few of  
all the other elements (2%).

- Using spectroscopy and other techniques, astronomers can identify the “prime materials” that stars are made of
- Hydrogen (H) and helium (He) are the most abundant elements, and were formed with the formation of universe
- Heavier elements are million or billion times less abundant. They were formed inside the stars through thermonuclear reactions

1 H																	2 He				
3 Li	4 Be															5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg															13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr				
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe				
55 Cs	56 Ba			72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn			
87 Fr	88 Ra			104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Fl	115 UUp	116 Lv	117 Uus	118 Uuo			
		57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu					
		89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr					



Elements created at the Big Bang



Elements produced by nucleosynthesis, in the core of the stars



Elements produced by supernovas



# The laws of the structure of the stars

- Inside the star, as we go deeper, the pressure increases due to the weight of upper layers.
- According to the laws of gases, temperature and density increase as the pressure increases.
- The energy will flow from the inside hotter part to the outside colder part by radiation and convection.
- If the energy flows out of the star, the star will cool - unless more energy is created inside.
- *The stars are governed by these simple and universal laws of physics*



# Example: Why the Sun does not collapse or contract?



- Inflate a balloon as shown on the left
- The atmospheric pressure is "pushing" the balloon inward. It does not shrink because the gas pressure is "pushing" the balloon outward.
- Inside the Sun, gravity, pushing the material inward, is balanced by the gas pressure.



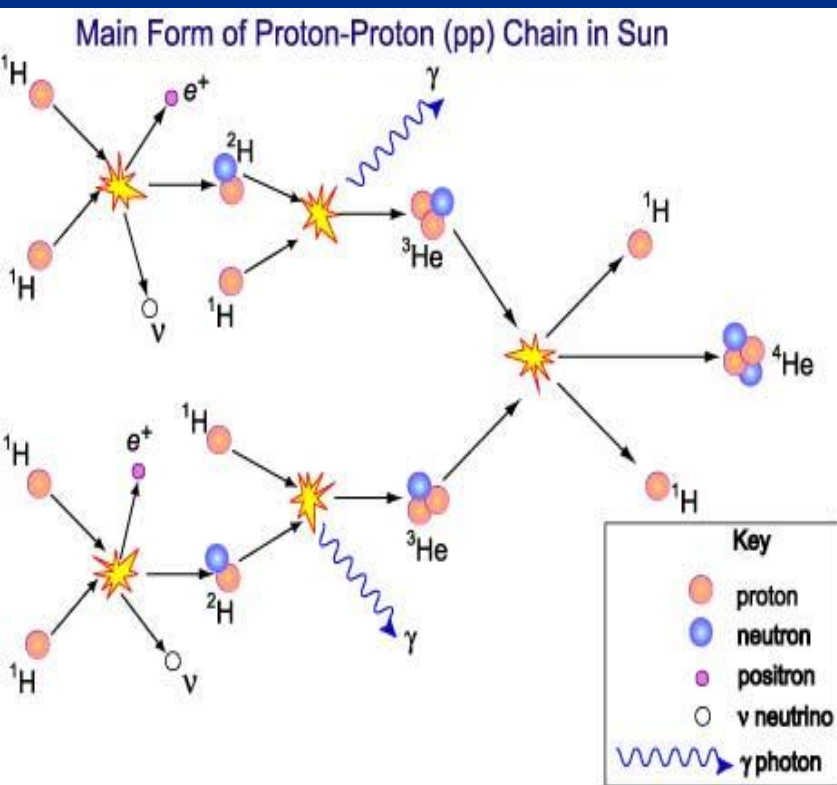
# The energy source of the Sun and stars

- Chemical combustion of gas, oil or carbon?  
This process is so inefficient that bring energy to the Sun for only a few thousand years
- Slow gravitational contraction?  
This could bring energy to the Sun during millions of years, but the Sun is billions years old
- Radioactivity (nuclear fission)?  
Radioactive isotopes are almost non-existent inside the Sun and stars
- Nuclear fusion of light elements into heavier ones?  
**Yes! This is a very efficient process, and light elements such as hydrogen and helium represent 98% of the Sun and stars**



# Proton-Proton chain

is the main process of fusion in the Sun



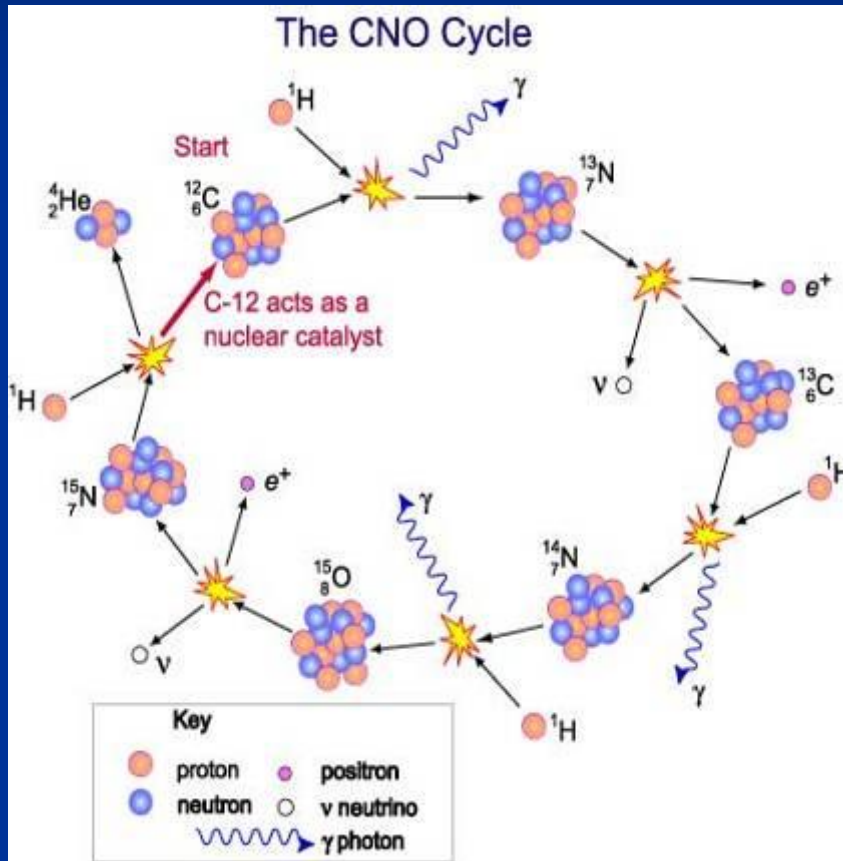
Proton-proton cycle

Source: Australia National Telescope Facility

- At high temperatures and densities, in stars like our Sun, protons (in red) overcome the electrostatic repulsion between them, and form  $^2\text{H}$  (deuterium) and neutrino ( $\nu$ )
- Later, another proton is coupled with deuterium to form  $^3\text{He}$
- Later, the  $^3\text{He}$  nuclei are coupled with each other to form a  $^4\text{He}$  nucleus, releasing two protons.
- Result: 4 protons together to form helium and energy (gamma- and kinetic energy)



# The carbon – nitrogen - oxygen cycle



CNO cycle

Source: Australia National Telescope Facility

- In massive stars, with very hot nucleus, protons (red) can collide with a  $^{12}\text{C}$  (carbon) nucleus (top left)
- This begins a circular sequence of reactions in which finally four protons fuse to form a helium nucleus (top left)
- A  $^{12}\text{C}$  nucleus is recovered again at the end of the cycle, therefore it is not created nor destroyed; it acts as a nuclear catalyst



# Making stellar “models”

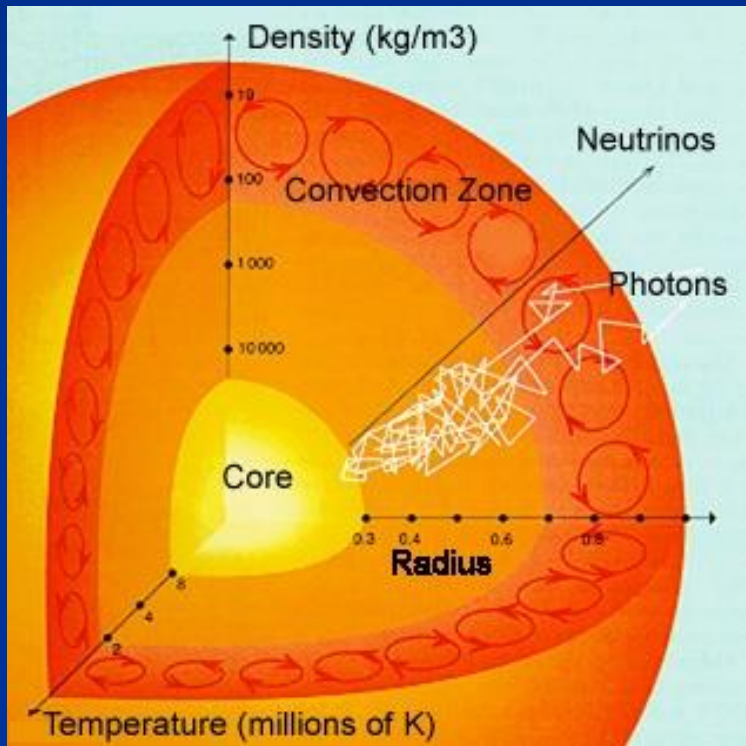


- The laws that describe the stellar structure are expressed in equations, and are resolved by means of a computer
- The computer calculates the temperature, density, pressure, and the power at each point of the Sun or the star. This is called a model
- In the center of the Sun, the density is 150 times higher than the water density, and the temperature is  $\sim 15,000,000$  K!



# In the interior of the Sun

Based on a "model" of the Sun made with computer



Solar model

Source: Institute of Theoretical Physics,  
University of Oslo

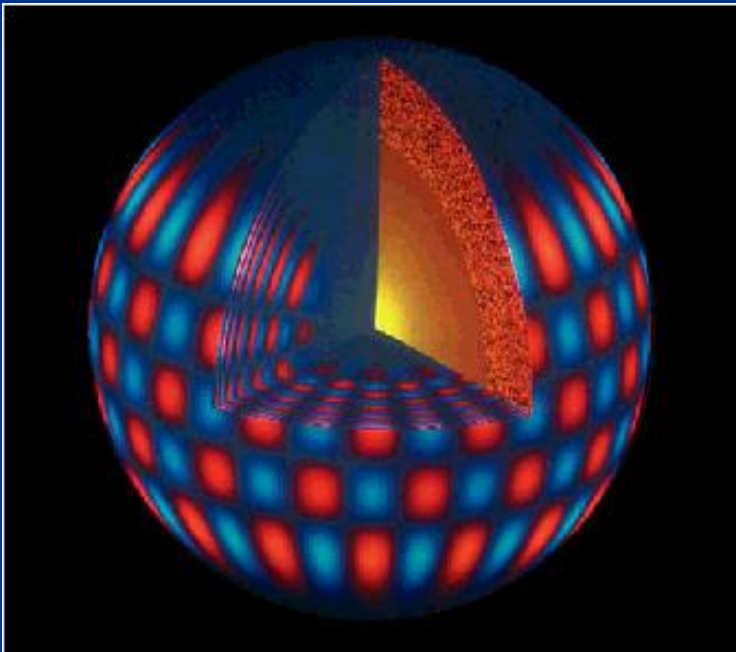
- Inside the hot core, nuclear reactions produce energy by fusing hydrogen into helium
- In the radiative zone, above the nucleus, the energy flows outward through the mechanism of radiation
- In the convective zone, between the radiative area and the surface area, the energy flows outward by convection
- The photosphere, on the surface, is the layer where the star becomes transparent





# Testing helioseismological model

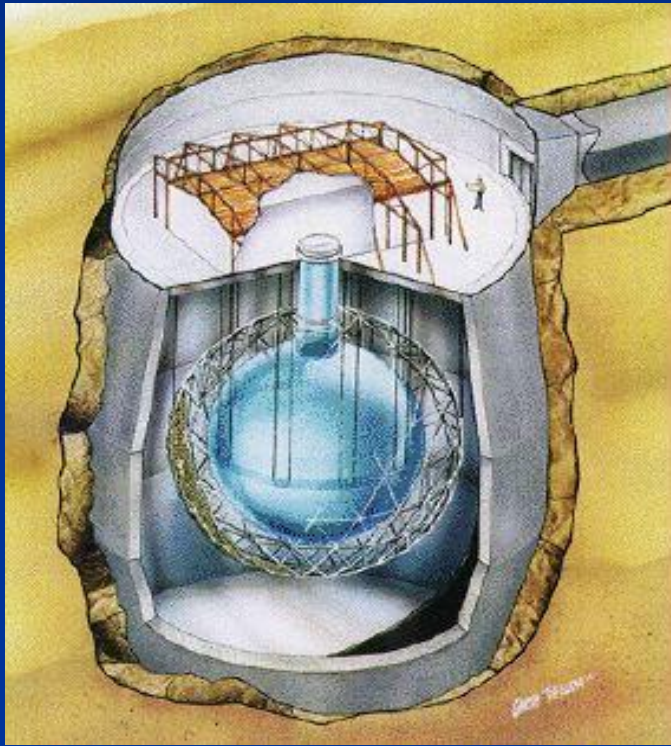
- The Sun vibrates gently in thousands of ways (patterns). One of them is shown in the image on the left
- These vibrations can be observed and we can use them to deduce the internal structure of the Sun, testing therefore the existing models of Sun's structure. This process is known as helioseismology
- Similar vibrations can be observed in other stars: **astroseismology**



Artistic conception of the solar vibration.  
Source: US National Optical Astronomy  
Observatory



# Testing the solar neutrino model



- Nuclear fusion reactions produce elementary particles called neutrinos.
- They have very low mass, and rarely interact with matter.
- Their mass was detected and measured thanks to special observatories, such as the Sudbury Neutrino Observatory (left). The results are consistent with the predictions obtained in models

Observatory of neutrino, Sudbury  
Source: Sudbury Neutrino Observatory



# Duration of the stellar lives

- The duration of the life of a star depends on how much nuclear fuel (hydrogen) it has, and how fast consumes it (power)
- The stars less massive than our Sun are the most common. They have less fuel, but much smaller powers, so they have longer lives
- The stars more massive than the Sun are less common. They have more fuel, but powers much higher, therefore have shorter lives



# How astronomers learn about stellar evolution?

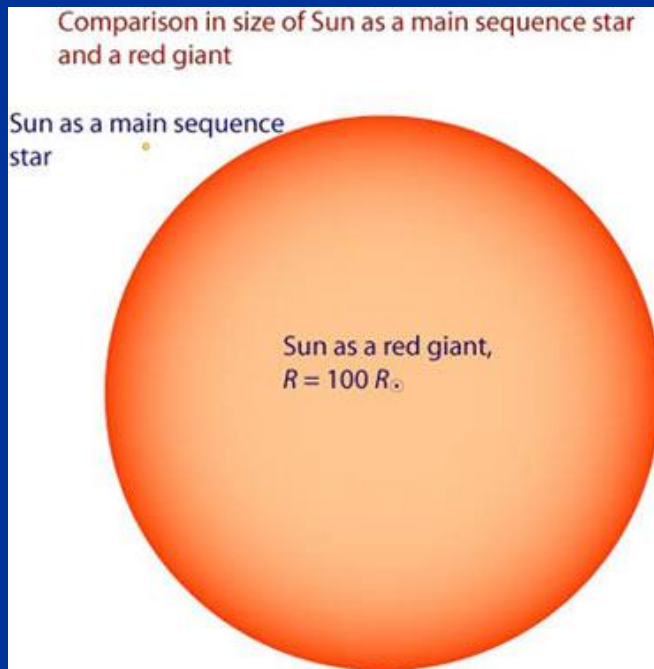
- Observing the stars in various stages of their lives, and putting them in a sequence of logical evolution.
- Making models using computers, using the laws of physics, and accounting the changes in the composition of the stars that occur due to nuclear fusion.
- Studying the stellar clusters and/or groups of stars with different masses, but with the same age.
- Studying the fast and strange phases in stellar lives (e.g. supernovae and novae).
- Through the study of variable pulsating stars, measuring the slow changes in the period of pulsation caused by their evolution.





# The evolution of Sun-like stars

- The Sun-like star does not change much during the first ~90% of its life, as far as it has enough fuel (hydrogen) to continue with thermonuclear reactions. We call it a main sequence star.



- When its fuel, hydrogen, exhausts, it expands into a red giant star.
- Inside the core, the temperatures can increase enough to start to produce the energy through the fusion of helium into carbon.
- When the helium fuel is exhausted, the star again swells into even bigger red giant, hundreds of times bigger than the Sun

Comparison of size: Sun - red giant  
Source: Australia National Telescope Facility





# The death of Sun-like stars



Helix Planetary Nebula.  
Source: NASA

- When the star becomes a red giant, it starts to pulsate (vibrate). We call it Mira star.
- The pulsation causes the separation of the outer layers of the star, producing a beautiful planetary nebula (on the left)
- The core of the star is a dwarf, dense, white, small, and without fuel



# White dwarf

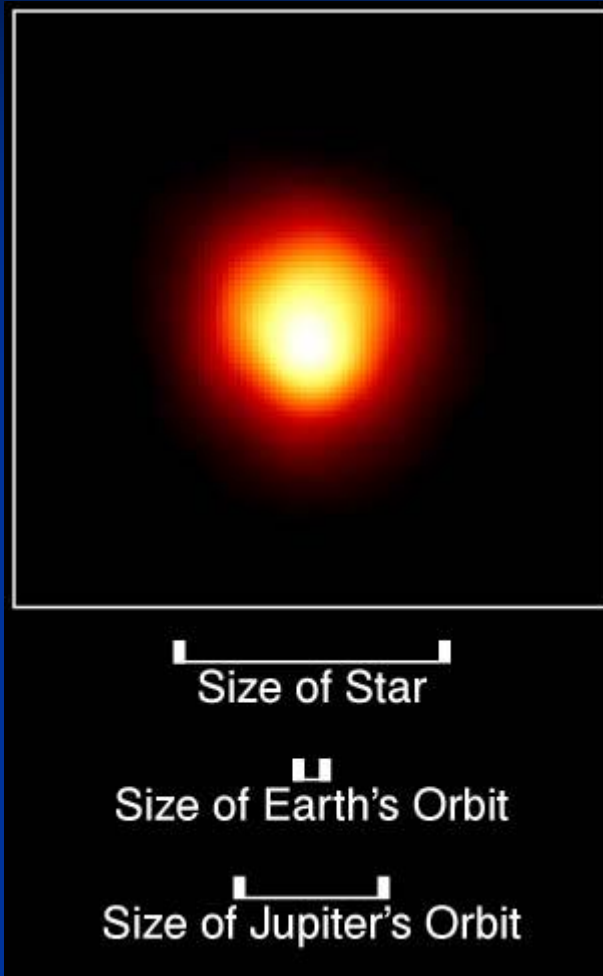


The white dwarf companion (below) of Sirius (above). Source NASA

- A white dwarf represents a dead core of a Sun-like stars.
- A white dwarf star has a mass similar to the Sun, a volume similar to the Earth, and a density million times greater than that of the water.
- In a white dwarf, the centripetal gravitational force is balanced by the external quantum pressure of the electrons in its interior.
- Many nearby stars, including Sirius (left) and Procyon, have white dwarf companions.



# The evolution of a massive star



- Massive stars are rare, powerful and consume their fuel very quickly - in a few million years.
- When they spent their fuel, they swell and become red supergiant stars
- Their core is very hot, enough to produce heavy elements as iron .
- Betelgeuse (left), in Orion constellation, is a bright red supergiant. It is much larger than the Earth's orbit

Betelgeuse.

Source: NASA/ESA/HST



# The death of a massive star

- When the core of a massive star becomes mainly made of iron, it has no more nuclear fuel to continue with fusion and can no longer remain hot.
- Gravity crushes the nucleus in a neutron star, releasing enormous amounts of gravitational energy, and leading the star to an explosion of a supernova (left).
- Supernovae produce elements heavier than iron, and expel these and other elements into the space, elements which will become part of new stars, planets and lives



The Crab nebula, the remnant of an explosion of supernovae observed in 1054 AD. Source: NASA



# Neutron stars



- The stellar cores with masses between 1.5 and 3 times the mass of the Sun collapse and become neutron stars at the end of their stellar lives.
- They have diameters of about 10 km and densities trillions of times bigger than water.
- They are made of neutrons and more exotic particles.
- Young neutron stars rotate rapidly and emit regular pulses of radiation in radio, and are known as pulsars.

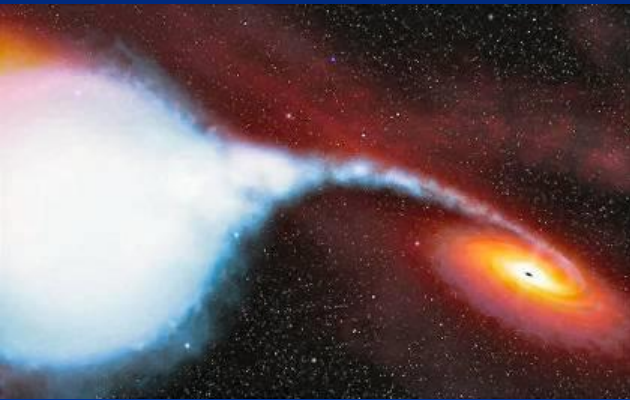
Pulsar, neutron star in the heart of the Crab Nebula The rotational energy that emits energized Nebula.

Source: NASA/ESA/HST





# Black holes



Artistic conception of Cygnus X-1, a visible star (left) with a black hole (right) in a center of accretion disk. Source: NASA.

- A black hole is an astronomical object whose gravity is so strong that nothing can escape from it, not even light.
- The nuclei of the uncommon massive stars (more than 30 times the mass of the Sun) become black holes when their fuel runs out.
- One way of black hole detection: when a visible star is orbiting around it (left).



# Special cases of variable stars

- Many stellar remnants - white dwarfs, black holes or neutron stars - have a normal visible star orbiting around them.
- If the gas from the normal star falls to the stellar remnant, the accretion disk can be formed around it (left).
- When gas falls on the stellar remnant, it can burst, erupt, or explode, which we call a cataclysmic variable star



A pair of normal star (left) and a white dwarf star with an accretion disc stealing gas from the companion (right).  
Source: NASA

# The birth of stars



Orion Nebula  
Source: NASA

- Stars are formed inside the molecular clouds (nebulae), made of cold gas and dust.
- Interstellar dust and gas is about 10% of the matter in our Galaxy.
- The young stars can generally be found inside or near the nebula from which they arose.
- The closest and clear example of a star formation region is the Orion nebula (left), around 1500 light years away from us.



# Interstellar gas

## The gas between the stars

- The interstellar gas (atoms or molecules) can be activated by ultraviolet light coming from a nearby star, producing an emission nebula (left).
- Cold gas between the stars, produces radio waves that can be detected by radio telescopes.



The Orion nebula. The gas is energized by ultraviolet light from the stars in the nebula.

Source: NASA

98% of the interstellar gas is made of hydrogen and helium



# Interstellar dust

## Dust between the stars



M16

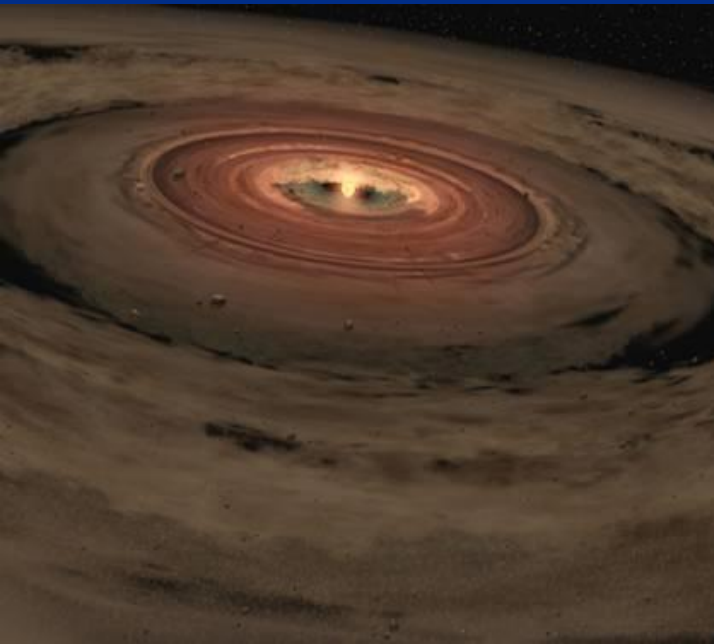
Source: NASA/ESA/HST

- Interstellar dust near the bright stars can be detected in the visible part of spectra
- Dust can block the light from the stars and gas behind (left). The stars are formed in these clouds.
- Only 1% of the material between the stars is dust. The dust particles are a few hundred nm in size, and are mostly silicates or graphite





# Star formation



Artistic conception of a planetary system  
in the formation process.

Source: NASA

- The stars are formed inside the parts of a nebula called nuclei, which are dense or compressed.
- Gravity is responsible for attraction of nuclei.
- The conservation of angular momentum increases the rotation of the nuclei, which become flattened and finally convert into the discs.
- Stars are formed in the center of disks. The planets are formed in the colder, outer parts of the disk.



# Protoplanetary disks: Proplyds

## Planetary systems in the process of formation



Proplyds

Source: NASA/ESA/HST

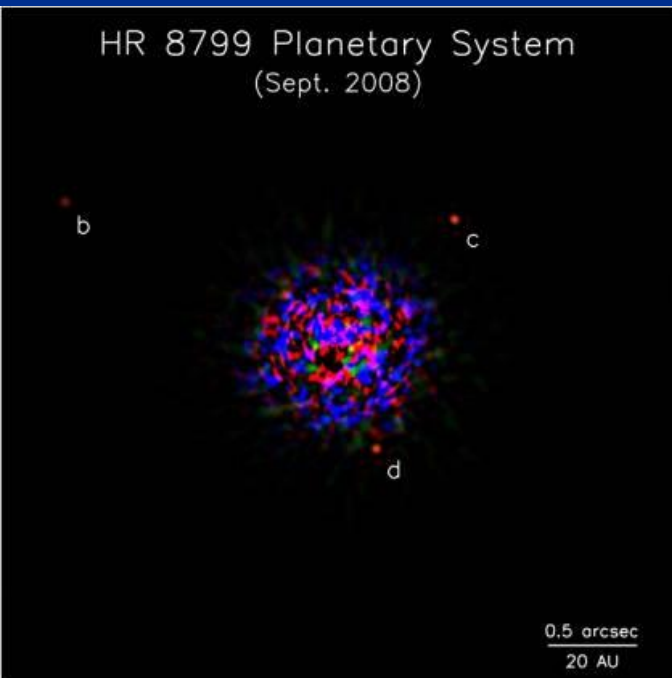
- Protoplanetary disks have been observed in the Orion nebula (left)
- The star can hardly be visible in the center of the disc.
- The disk of dust blocked the light that is behind.
- These and other observations provide a direct evidence of the formation of planetary systems.



# Exoplanets = extrasolar planets

## Planets around other stars

- The exoplanets are usually discovered and studied through gravitational effect they have on the star, or through the light dimming of its star if transit occur.
- Very few have been directly captured (left).
- Unlike the planets in our Solar System, many exoplanets are huge and very close to its star. This allows the astronomers to modify/correct their theories how planetary systems form.



System exoplanet HR 8799

Source: C. Marois et al., NRC Canada



# Final considerations

- “Gravity drives the formation, life and death of stars” [Professor R.L. Bishop]
- The birth of a star explains the origin of our Solar System and other planetary systems.
- The life of the star explains the energy source that makes life on Earth possible.
- The life and death of the stars produce chemical elements heavier than hydrogen, that stars, planets and life are made of.
- During the death of a star, gravity produces the strangest objects in the universe: white dwarfs, neutron stars and black holes.



**Many Thanks  
for your attention !**

