Life Cycle of the Stars

Star Formation

Star Formation

- Stars are formed when **hydrogen** clouds contract due to gravity

$$F = G\frac{m_1 m_2}{r^2}$$

- Gravitational attraction causes the core of the contracting cloud to reach ~ 10, 000 K
- The temperature necessary to fuse two hydrogen nuclei into one helium nucleus
- The helium nucleus has slightly less mass than two hydrogen nuclei
- The difference in mass is the source of a star's energy

$$E=mc^2$$

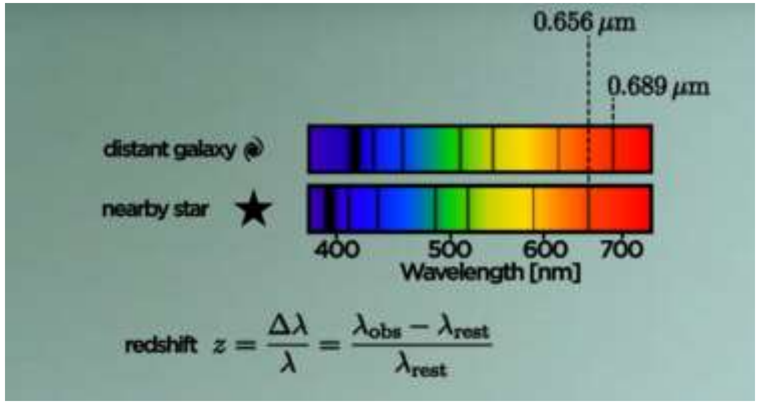
- Great quantities of energy in the form of electromagnetic radiation are released into space

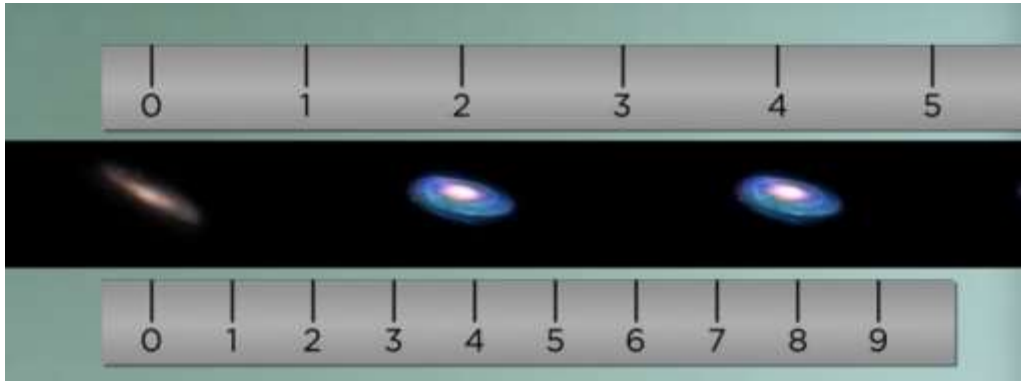
- Where did the hydrogen come from?
- The first stars formed from the hydrogen that was formed after the universe began its expansion
- After the **Big Bang**
- According to the Big Bang theory, the universe is thought to have begun around **13.8 billion years** ago as an infinitesimally small, infinitely hot, infinitely dense, something –
- A **singularity** –that contained all the matter and energy that is in the universe today
- The theory does not address "what came before"
- It describes what came after the beginning

Source of First Stars-Big Bang Theory- Evidence

- which supports the Big Bang theory:
- Galaxies appear to be moving away from us at speeds proportional to their distance
- This is called "**Hubble's Law**," named after **Edwin Hubble** who discovered this phenomenon in 1929
- It is based on doppler effect “**red shift**” of light from distant galaxies
- The spectral emission lines of light are shifted toward the red (longer wavelength) portion of the spectrum
- The wave lengths of photons of light are “stretched” as they move through expanding space

Edwin Hubble (1989-1953)





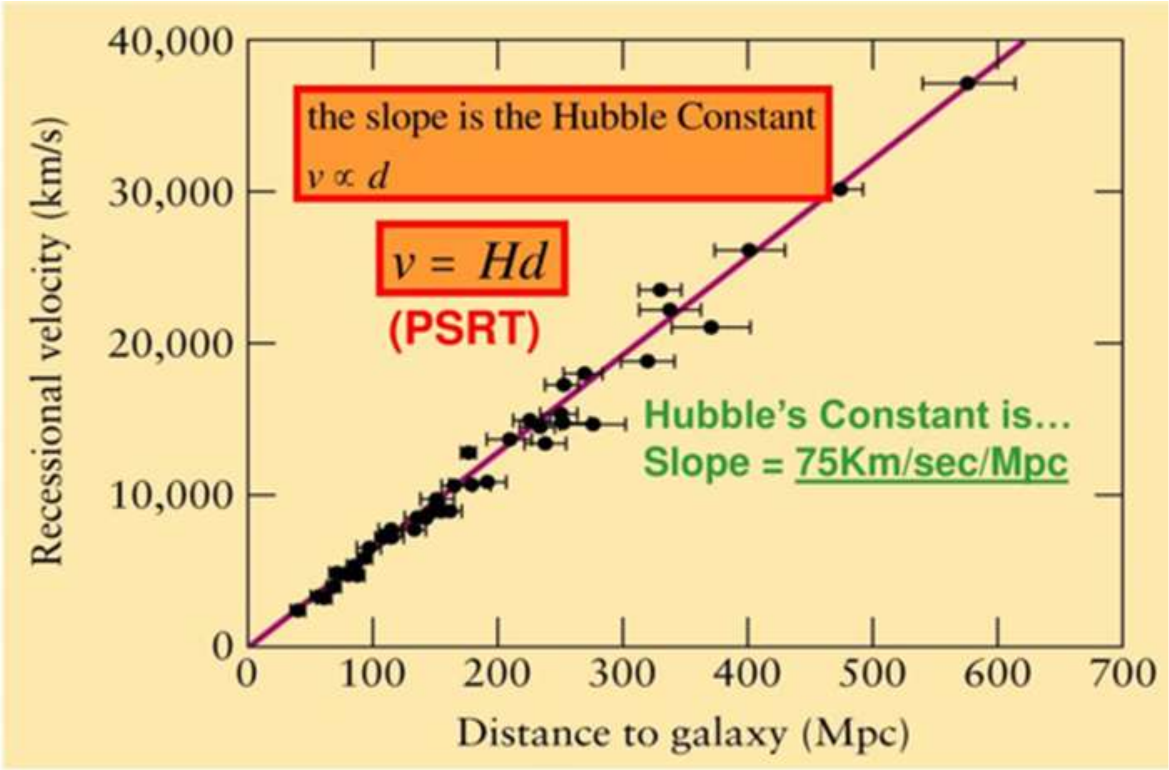
Source of First Stars-Big Bang Theory- Evidence

- Hubble's Law:

$$v = H_0 d$$

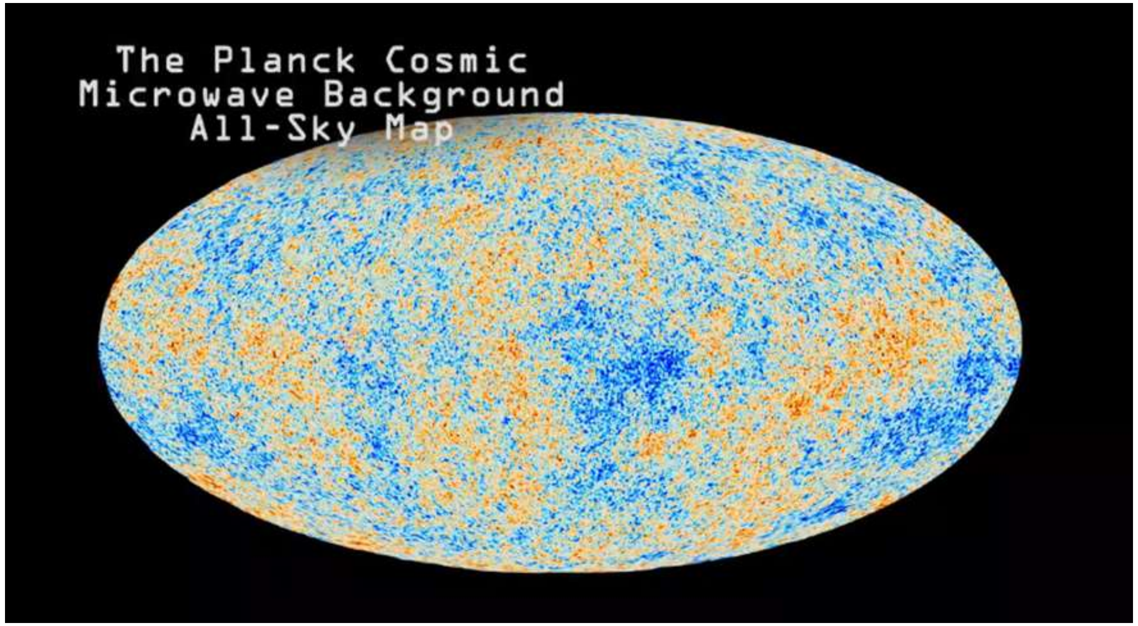
$$v = recessional\ velocity\ of\ galaxy$$
$$H_0 = Hubble\ constant$$
$$d = distance\ to\ galaxy$$

- This observation supports the expansion of the universe and suggests that the universe was once compacted
- It agrees with ramifications of Einstein's theory of relativity
  - **Friedmann** 1922 and **Lemaître** 1927 solutions to the equations of General Relativity for the case of an expanding universe



Source of First Stars-Big Bang Theory- Evidence

- If the universe was initially very, very hot as the Big Bang theory suggests, there should be evidence of this heat
- In 1965, Radio-astronomers **Arno Penzias** and **Robert Wilson** discovered a **Cosmic Microwave Background** radiation (**CMB**) which pervades the observable universe
- Its black body temperature measures **2.725 Kelvin**
- Black body radiation comes from opaque bodies at thermal equilibrium
- The CMB radiation is traveling through transparent space –
- The **expansion of space** has stretched the photon wave lengths from microns to millimeters –the microwave region of the electromagnetic spectrum



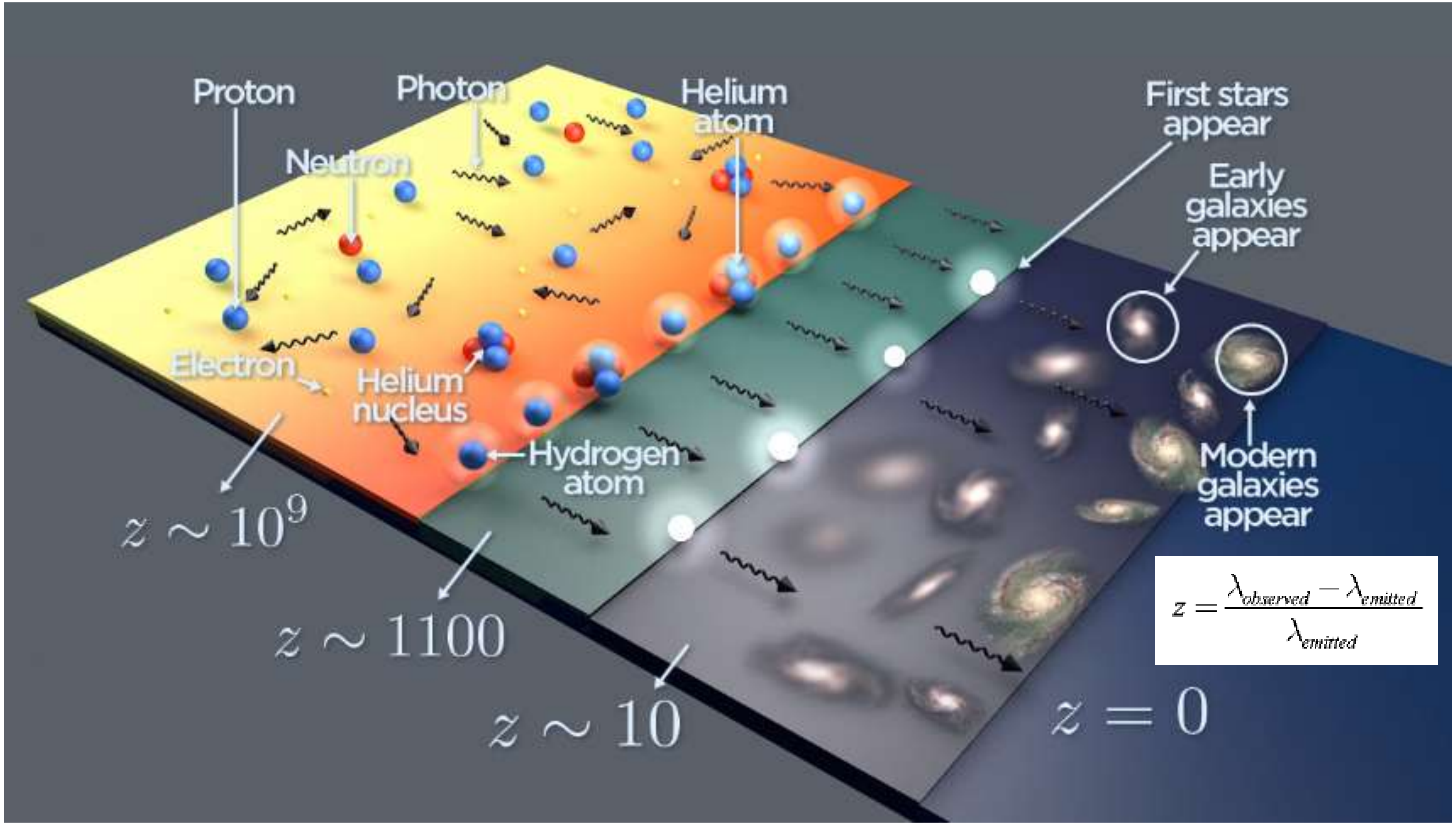
- The abundance of the "light elements" Hydrogen and Helium found in the observable universe also support the Big Bang model

Source of First Stars-Big Bang Theory- Evidence

- The red shift data measures the expansion of space itself
- Galaxies are not traveling faster than the speed of light
- The space in which the galaxies are located is expending so the relative to their “local” space the are not traveling faster than light
- Einstein’s light speed limit is safe

- Space is full of microwave radiation coming from all directions
- It amounts to about 400 photons per cubic centimeter with a spectrum of nearly a perfect black body
- The temperature of this microwave radiation is 2.72548 Kelvin
- Black body radiation comes from optically thick materials in thermal equilibrium
- Photons are constantly randomizing their energies by collisions, absorptions and emissions by charged particles
- The universe is optically transparent-it is not of a uniform temperature

Source of First Stars-Big Bang Theory- Evidence



Source of First Stars-Big Bang Theory-Expansion

- The universe was a tiny hot gaseous plasma consisting of packets of "primal" particles at extremely high energies
- The universe was smaller than the size of a proton
- During this phase physicists believe matter and energy were not separated as they are currently
- The four primary forces of the universe as we know them today were believed to be one united force
- The temperature of the universe was 1 x 10^32 K
- It also began to instantaneously expand and cool extremely fast

- The universe went through an expansionary phase that was faster than the speed of light (space-time is not limited by the speed of light, only objects "within" space-time are)
- In this brief interval of **Inflation**, the "observable" universe expanded by a factor of about 10^70 from being unimaginably smaller than a subatomic particle to about the size of a grapefruit
- That is the equivalent of going from about the size of a grape to the current size of the observable universe in the blink of an eye

Source of First Stars-Big Bang Theory-Expansion

- Inflation was a period of super cooled expansion and the temperature dropped by a factor of 100,000 or so and continued to be cool during this phase
- When Inflation ended the temperature returned to the pre-Inflationary temperature, back up by a factor of 100,000
- This period is called "reheating“
- The universe began its current expansion rate
- The four fundamental forces - gravity, the electromagnetic force, the strong nuclear force, and the weak nuclear force - formed and then separated
- The laws of physics and the four forces of nature began to apply
- Reheating ended at about 10^-10th of a second
- After Inflation, the universe slowed down to the normal "Hubble Rate“ of expansion
- As the universe continued to cool, the nucleons were formed
- This early formation phase is called the **Big Bang Nucleosynthesis** (**BBN**)
- With the temperature falling below 10 billion Kelvin, BBN took place from about ten seconds to about twenty minutes
- Protons, neutrons, electrons-basis of atoms
- The BBN theoretical calculations result in a nuclei abundance of about 75% hydrogen (1 proton nucleus), about 25% helium (2 protons and 2 neutrons in the nucleus), and about 0.01% of deuterium (1 proton and 1 neutron nucleus)

Source of First Stars-Big Bang Theory-Expansion

- Observed hydrogen and helium abundances in early distant galaxies are very consistent with the above theoretical calculations
- It is considered "strong evidence" for the Big Bang Theory
- After the first twenty minutes the universe settled down to a much longer period of expansion and cooling
- High energy radiation (photons) dominated the cosmos
- As the universe continued to cool, more and more matter was created
- Expansion caused radiation to lose more energy than matter so that after a while, matter (nuclei) particles exceeded massless particles (photons)

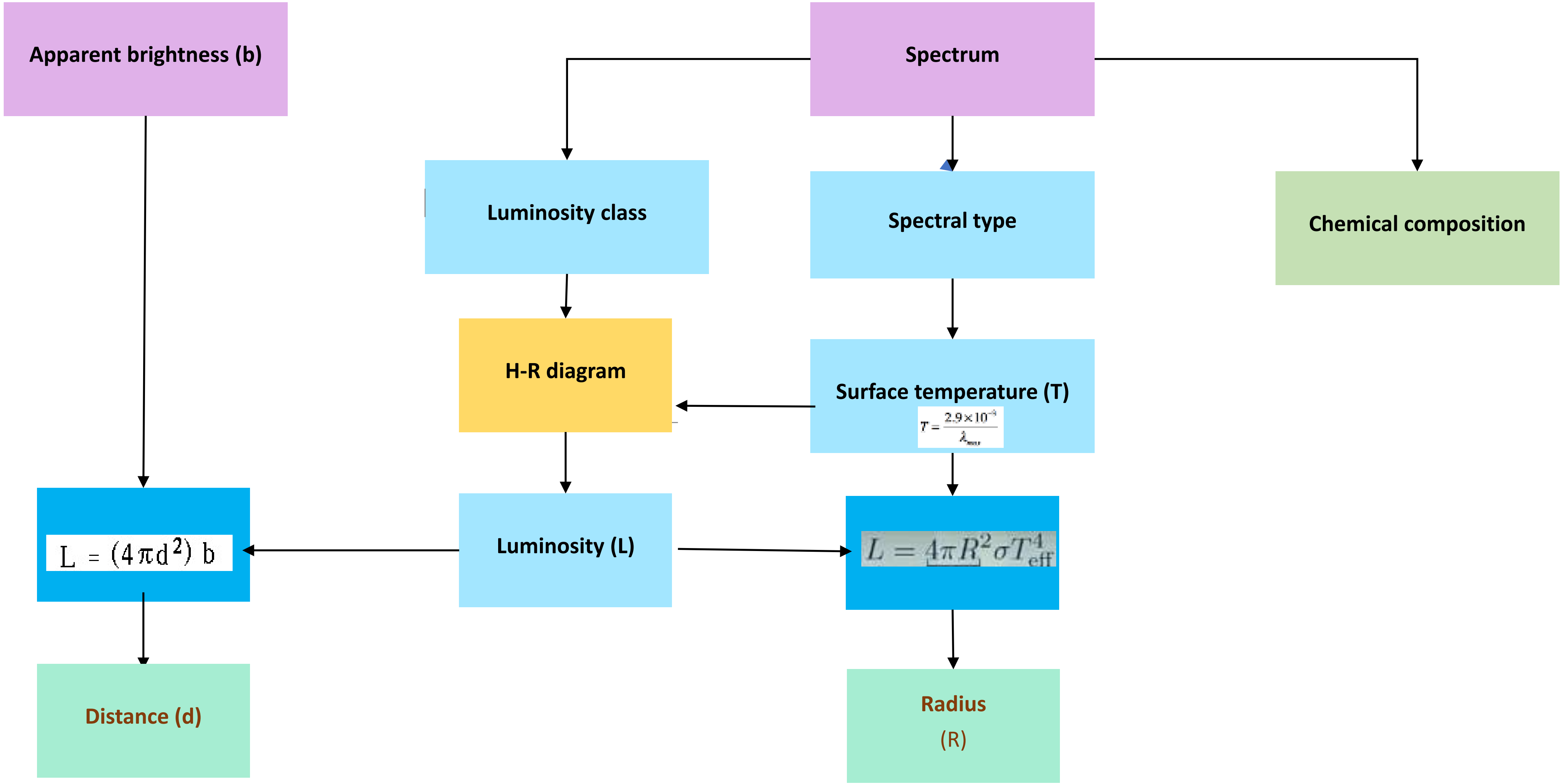
- About 70,000 years after the Big Bang, radiation and matter were about equal in density, shortly thereafter matter began to dominate
- For the next 310,000 years the universe continued to expand and cool, but was still fiery hot and dark
- Any visible light was immediately scattered by collisions with the ubiquitous electrons and protons
- It contained only the simplest elements, mostly hydrogen and helium ions
- As the universe cooled further, the electrons (with a negative charge) begin to get captured by the ions (with a positive charge) forming atoms (electrically neutral)
- This process happened relatively fast and is known as "recombination“
- The first bits of structure began to form

Source of First Stars-Big Bang Theory- First Generation

- The small clumps of matter grew in size as their gravity attracted other nearby matter
- At about 380,000 years of cooling, light (photons) began to travel through the spaces between the atoms which now "bond" the electrons in their orbits
- The universe had become transparent
- The first early radiation that could freely travel was the **CMB**, the remnants of which we can detect in the current universe 13.8 billion years later
- 380,000 years is the earliest point in time we can ever look back and "**see**" because everything before that was part of the dark ages

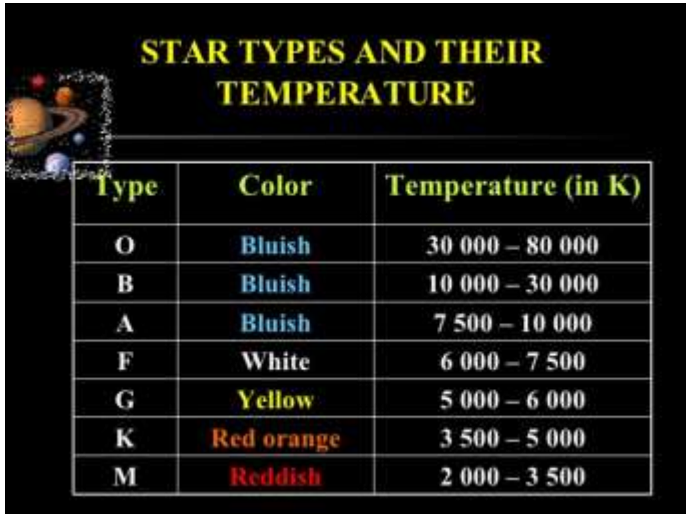
- It is thought that this pure hydrogen/helium mix allowed the first stars to grow much more massive than stars can get today
- It's believed that they could have gathered together several hundred solar masses
- The most massive star that can form today is thought to only be about 150 solar masses
- This **first generation** of stars probably lasted just a million years or so, and then detonated as supernovae
- Creating heavier elements that are spread out into space
- The **Sun** is a third-generation star

Finding Properties of a Distant Star



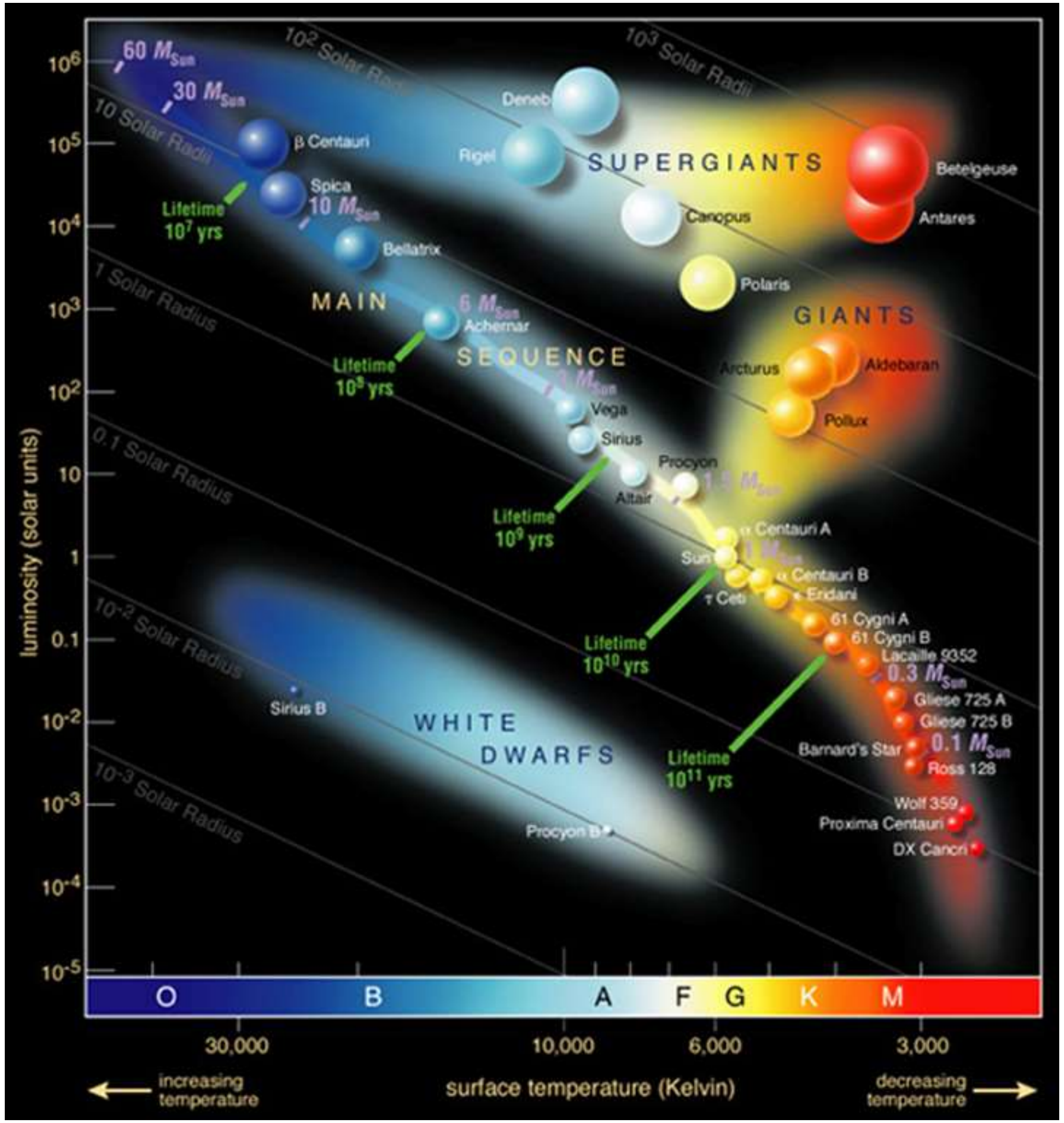
Star Formation-Main Sequence Stars

- The **H-R diagram** shows that stars are **not randomly distributed** as far as their luminosities and effective temperatures are concerned
- They can be arranged in groups:
  - The Main Sequence
  - White Dwarfs
  - Giants
  - Super Giants



STAR TYPES AND THEIR TEMPERATURE

Type	Color	Temperature (in K)
O	Bluish	30 000 – 80 000
B	Bluish	10 000 – 30 000
A	Bluish	7 500 – 10 000
F	White	6 000 – 7 500
G	Yellow	5 000 – 6 000
K	Red orange	3 500 – 5 000
M	Reddish	2 000 – 3 500



Star Formation-Main Sequence Stars

- Stars form inside relatively dense concentrations of interstellar gas and dust known as **molecular clouds** or **dark nebulas**
- These regions are extremely cold (temperature about 10 to 20K, just above absolute zero)
- At these temperatures, gases become molecular meaning that atoms bind together
- Interstellar gas clouds are mostly hydrogen and helium
- The deep cold also causes the gas to clump to high densities
- When the density reaches a certain point, stars form
- Since the regions are dense, they are opaque to visible light and are known as dark nebula

The Eagle Nebula is part of a molecular cloud with a diameter of about 20 light years.

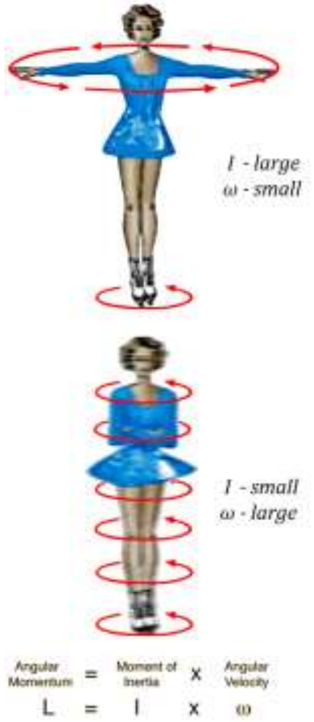
Star Formation-Conservation of Angular Momentum-Stars' Rotation

- Since they don't shine by optical light, IR and radio telescopes are used to investigate them
- Star formation begins when the denser parts of the cloud core collapse under their own weight/gravity
- These cores typically have masses around 10^4 solar masses in the form of gas and dust
- The cores are denser than the outer cloud, so they collapse first
- As the cores collapse, they fragment into clumps around 0.1 parsecs in size and 10 to 50 solar masses in mass
- These clumps then form into protostars and the whole process takes about 10 millions years

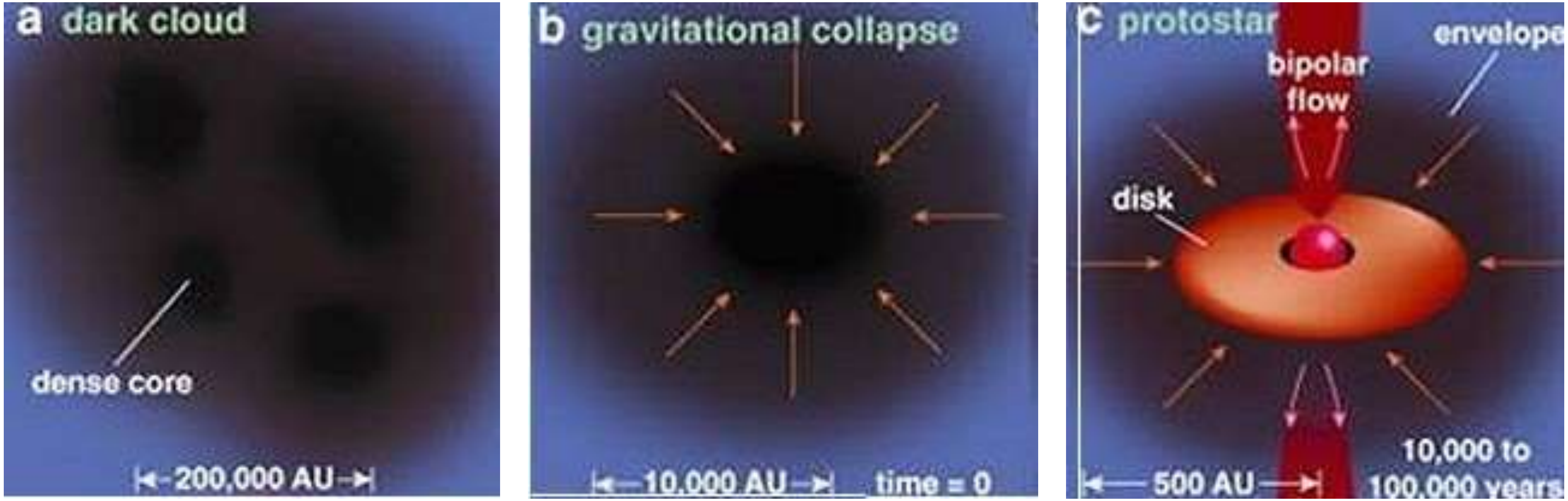
- Large clouds of gas are rotating slowly
  - Large radius
- Gravity causes gas clouds to shrink
  - Smaller radius
- Angular momentum of shrinking gas

  cloud is conserved
  - Stays constant
- Mass stays the same
- Angular momentum = I x ω

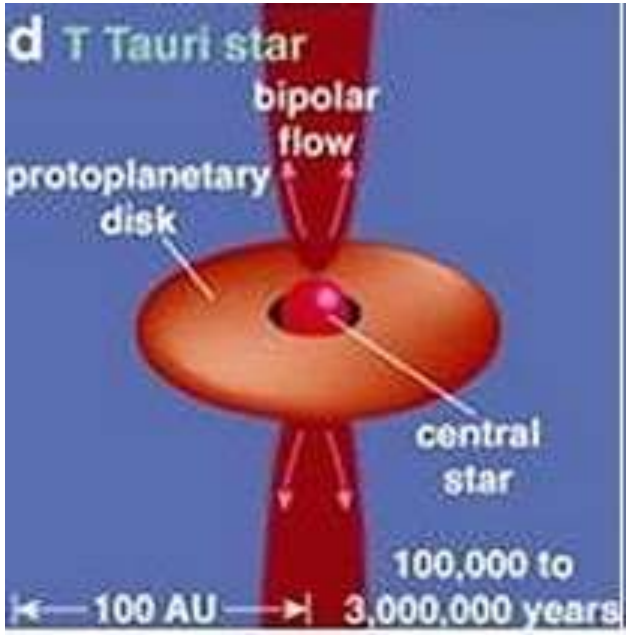
  (Moment of Inertia x Angular Velocity)
- As gas cloud shrinks to form a sphere its rotation its angular velocity ,rotational speed increases

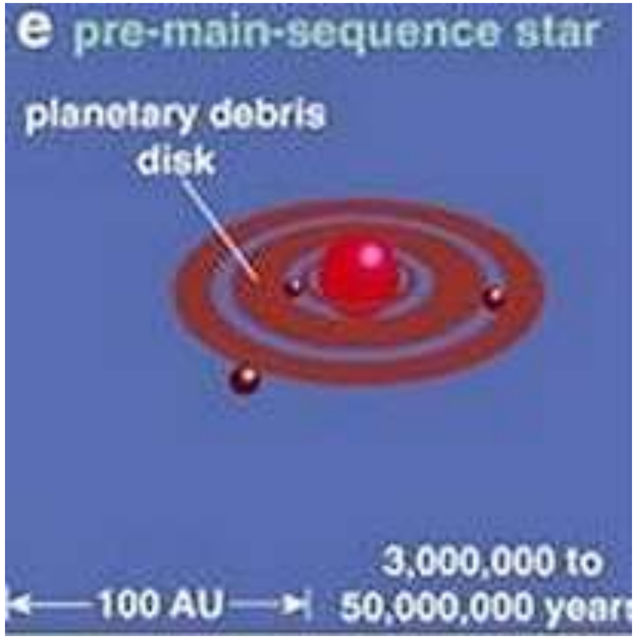


Star Formation-Main Sequence Stars

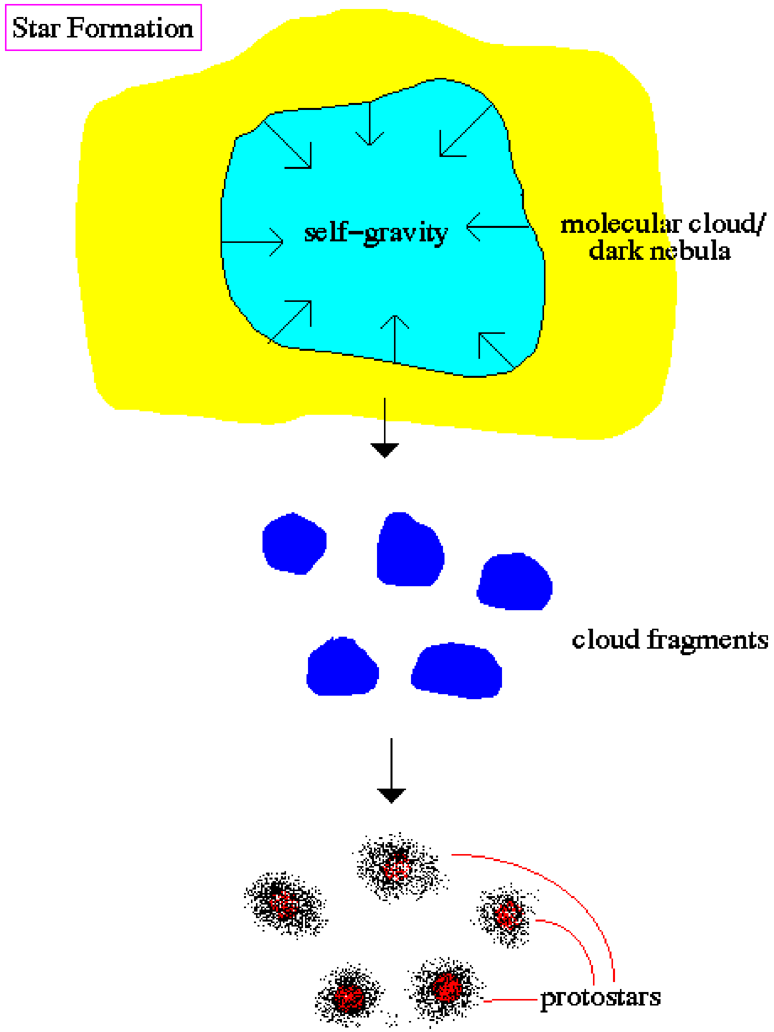


Star Formation-Main Sequence Stars





Star Formation-Main Sequence Stars



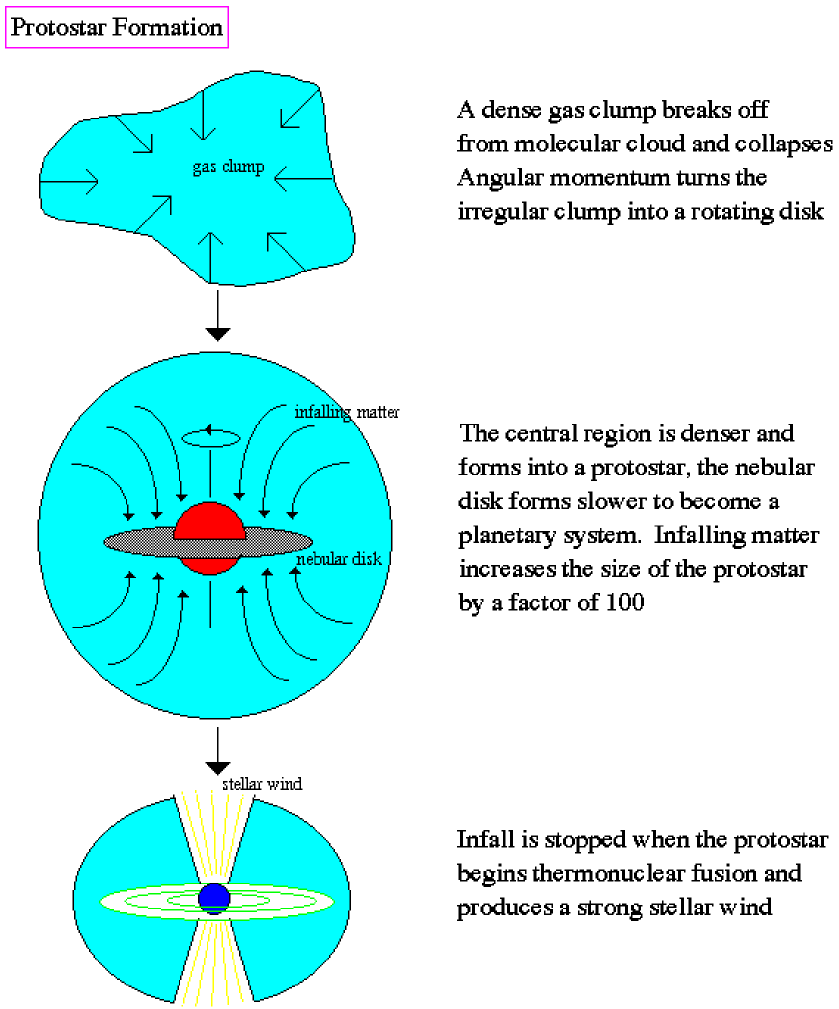
- How do we know this is happening if it takes so long and is hidden from view in dark clouds?
- Most of these cloud cores have IR sources, evidence of energy from collapsing protostars (potential energy converted to kinetic energy)
- Also, where we find young stars we find them surrounded by clouds of gas, the leftover dark molecular clouds
- And they occur in clusters, groups of stars that form from the same cloud core

Star Formation-Main Sequence Stars-Protostars

- Once a clump has broken free from the other parts of the cloud core, it has its own unique gravity and identity and we call it a **protostar**
- As the protostar forms, loose gas falls into its center
- The infalling gas releases kinetic energy in the form of heat and the temperature and pressure in the center of the protostar goes up
- As its temperature approaches thousands of degrees, it becomes an IR source
- Several candidate protostars have been found by the **Hubble Space Telescope** in the Orion Nebula
- The **Orion Nebula** spans about 24 light-years across and is part of the much larger Orion Molecular Cloud Complex
- The nebula is some 1,350 light-years away from Earth in the constellation of Orion

Orion Nebula

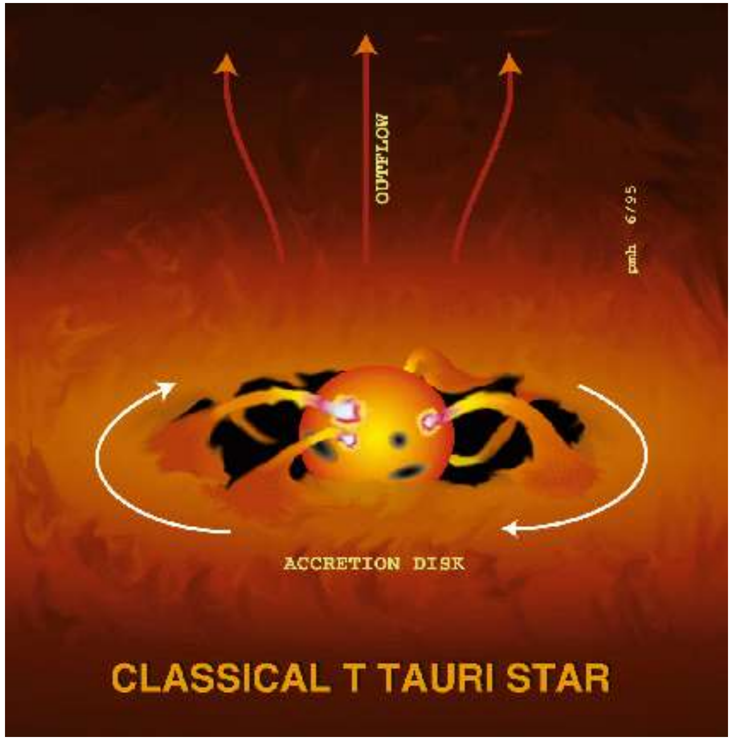
Star Formation-Main Sequence Stars-Protostars



- During the initial collapse, the clump is transparent to radiation and the collapse proceeds fairly quickly
- As the clump becomes more dense, it becomes opaque-photons do not pass through
- Escaping IR radiation is trapped, and the temperature and pressure in the center begin to increase
- At some point, the pressure stops the in-fall of more gas into the core and the object becomes stable as a protostar
- The protostar, at first, only has about 1% of its final mass
- But the envelope of the star continues to grow as infalling material is accreted-by gravity
- After a few million years, thermonuclear **fusion** begins in its core, then a strong stellar wind is produced which stops the in-fall of new mass
- The protostar is now considered a young star since its mass is fixed, and its future evolution is now set

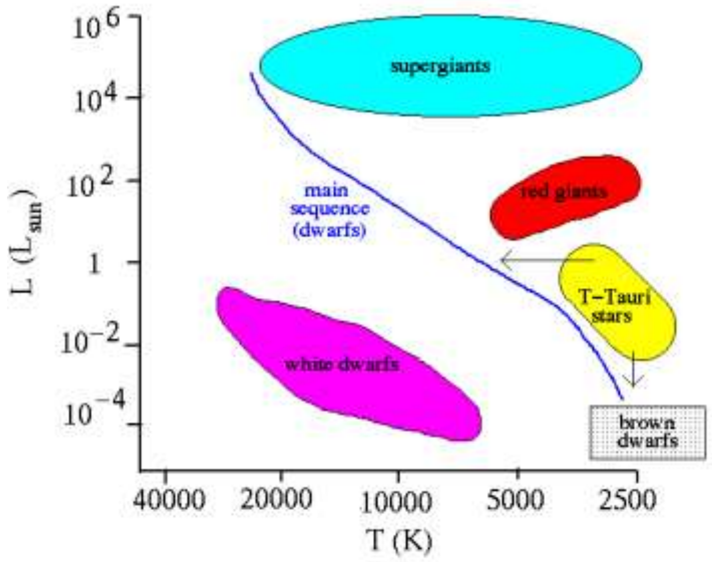
Star Formation-Main Sequence Stars-T-Tauri Stars

- Once a **protostar** has become a hydrogen-burning star, a strong stellar wind forms, usually along the axis of rotation
- Thus, many young stars have a bipolar outflow, a flow of gas out the poles of the star
- This is a feature which is easily seen by radio telescopes
- This early phase in the life of a star is called the **T-Tauri** phase
- One consequence of this collapse is that young T-Tauri stars are usually surrounded by massive, opaque, circumstellar disks
- These disks gradually accrete onto the stellar surface, and thereby radiate energy both from the disk (infrared wavelengths), and from the position where material falls onto the star at (optical and ultraviolet wavelengths)



Star Formation-Main Sequence Stars-T-Tauri Stars

- A fraction of the material accreted onto the star is ejected perpendicular to the disk plane in a stellar jet
- The outflow relieves the build-up of angular momentum as material spirals down onto the central star through the accretion disk
- The circumstellar disk eventually dissipates- probably when planets begin to form
- Young stars also have dark spots on their surfaces which are analogous to sunspots but cover a much larger fraction of the surface area of the star
- The T-Tauri phase is when a star has:
    - Vigorous surface activity (flares, eruptions)
    - Strong stellar winds
    - Variable and irregular light curves
- A star in the T-Tauri phase can lose up to 50% of its mass before settling down as a main sequence star, thus we call them pre-main sequence stars



- The arrows indicate how the T-Tauri stars will evolve onto the main sequence
- They begin their lives as slightly cool stars, then heat up and become bluer and slightly fainter, depending on their initial mass
- Very massive young stars are born so rapidly that they just appear on the main sequence with such a short T-Tauri phase that they are never observed

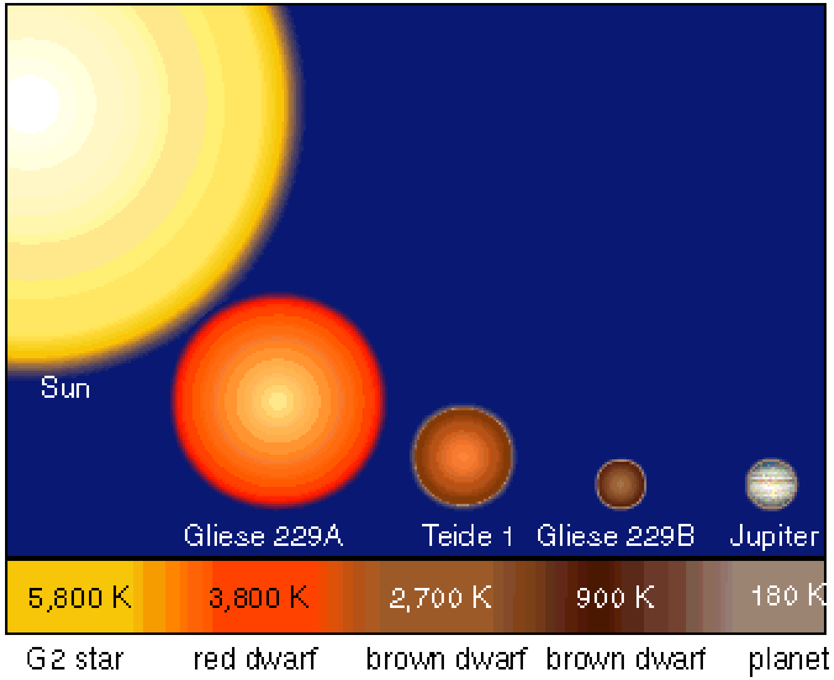
Star Formation-Main Sequence Stars-Brown Dwarfs

- If a protostar forms with a mass less than 0.08 solar masses, its internal temperature never reaches a value high enough for thermonuclear fusion to begin (10E7 K)
- This failed star is called a **brown dwarf**, halfway between a planet (like **Jupiter**) and a star
- A star shines because of the thermonuclear reactions in its core, which release enormous amounts of energy by fusing hydrogen into helium
- And because core temperature rises with gravitational pressure, the star must have a minimum mass:
  - About 75 times the mass of the planet Jupiter
  - About 8 percent of the mass of our sun

- The brown dwarf 2MASSWJ 1207334−393254 as seen in a photo taken by the Very Large Telescope at the European Southern Observatory, Cerro Paranal, Chile
- The brown dwarf has a mass 25 times that of Jupiter and a surface temperature of 2,400 K
- **Sun's** surface temperature is 5,800 K
- Orbiting the brown dwarf at a distance of 8.3 billion is a planet (lower left) that has a mass five times that of Jupiter and a surface temperature of 1,250 K

Star Formation-Main Sequence Stars-Brown Dwarfs

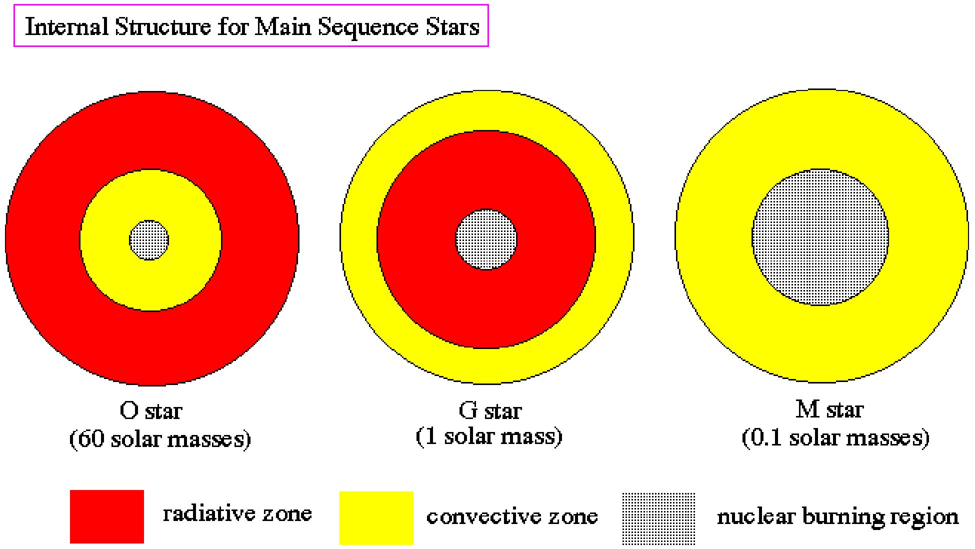
- Relative sizes and effective surface temperatures of two recently discovered brown dwarfs -- **Teide 1** and **Gliese** 229B -- compared to a yellow dwarf star (the **Sun**), a red dwarf (**Gliese** 229A) and the planet **Jupiter**, reveal the transitional qualities of these objects
- Brown dwarfs lack sufficient mass (about 80 Jupiters) required to ignite the fusion of hydrogen in their cores, and thus never become true stars
- The smallest true stars (red dwarfs) may have cool atmospheric temperatures (less than 4,000 degrees Kelvin) making it difficult for astronomers to distinguish them from brown dwarfs
- Giant planets (such as Jupiter) may be much less massive than brown dwarfs, but are about the same diameter, and may contain many of the same molecules in their atmospheres



- The challenge for astronomers searching for brown dwarfs is to distinguish between these objects at interstellar distances

Star Formation-Main Sequence Stars

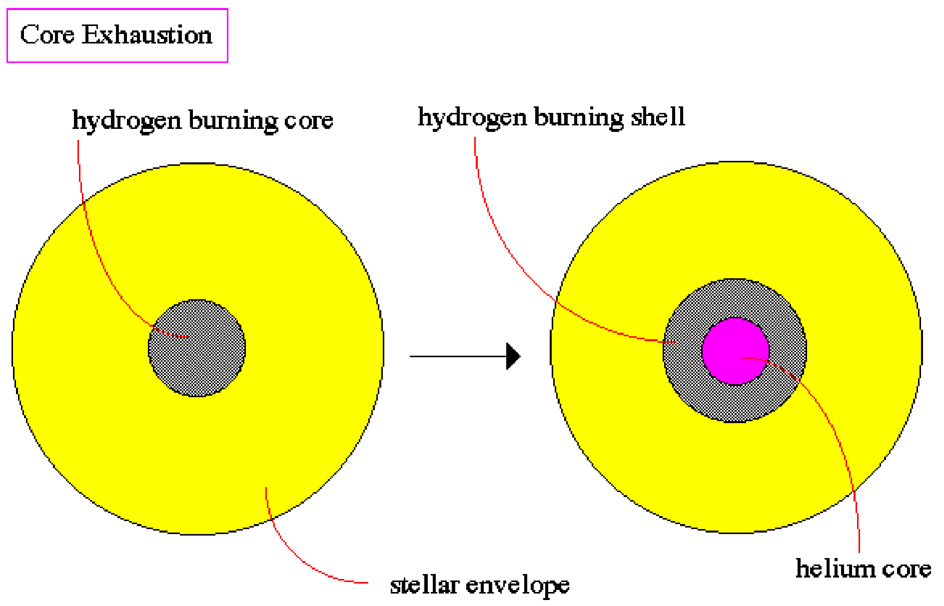
- Once a protostar starts burning hydrogen in its core, it quickly passes through the **T-Tauri** stage (in a few million years) and becomes a **main sequence** star where its total mass determines all its structural properties
- The three divisions in a star's interior are:
  - The nuclear burning core
  - The convective zone
  - The radiative zone
- Energy, in the form of **gamma-rays**, is generated solely in the nuclear burning core
- Energy is transferred towards the surface either in a **radiative** manner or **convection** depending on which is more efficient at the temperatures, densities and opacities



- The interior of three stellar types are shown
- Note that an **O** star is about 15 larger than a **G** star, and a **M** star is about 1/10 the size of a **G** star, this scale is shown below the interiors

Star Formation-Main Sequence Stars

- The nuclear burning regions takes up a larger percentage of the stellar interior as one goes to low mass stars
- High mass stars have a very small core surrounded by a large envelope
- The energy released from the stellar core heats the stellar interior producing the pressure that holds a star up against gravity-hydrostatic equilibrium
- Stars do not fade out when they have burned (fused) all their core hydrogen
- But fusion converts hydrogen into helium
- The star's core does not become empty, it fills with "**helium ash**"



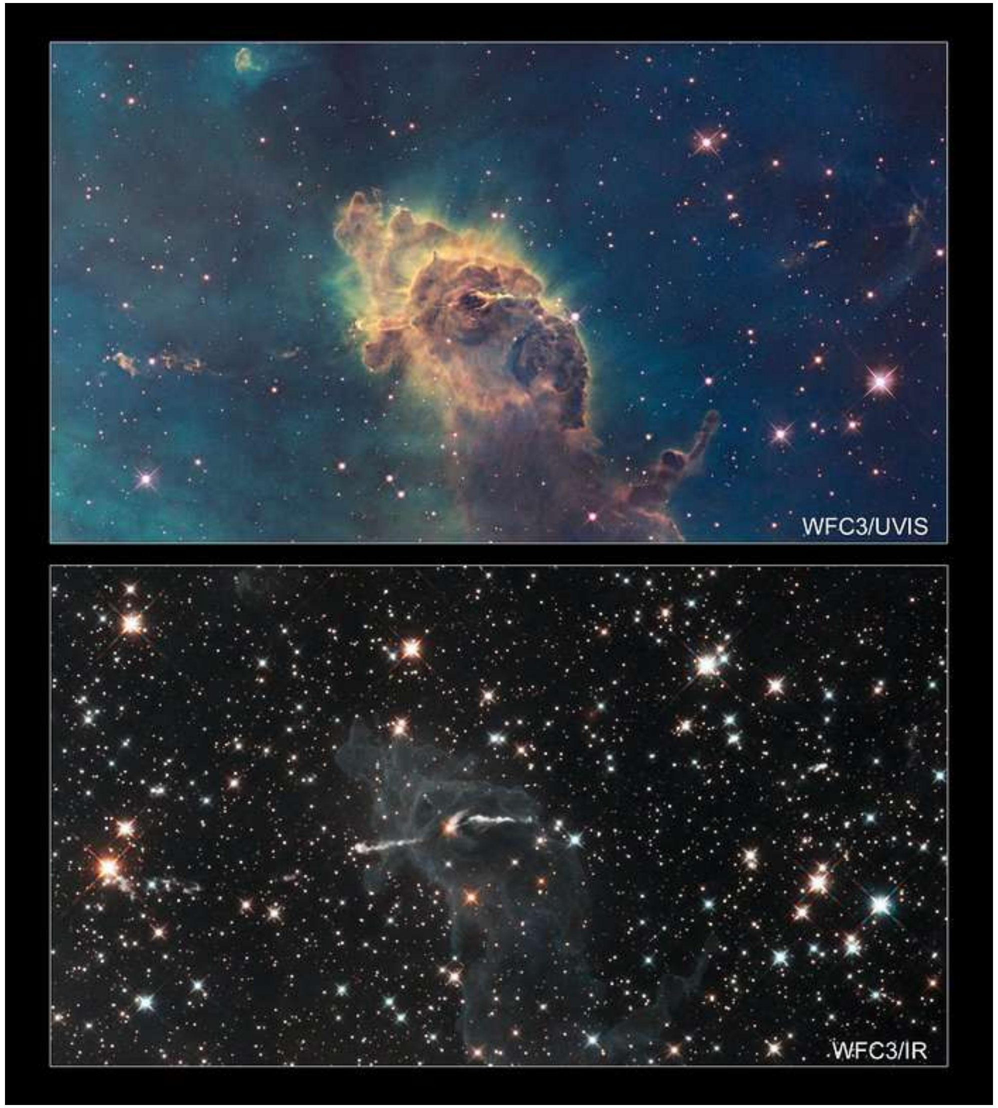
- As the helium ash builds up, energy generation stops in the core
- The hydrogen fusion process moves outward into a shell surrounding the hot helium core

Star Formation-Main Sequence Stars

- **Hubble Space Telescope** view of the **Orion Nebula**
- The Orion Nebula is 1,500 light-years away, the nearest star-forming region to Earth
- The Orion Nebula is a picture book of star formation, from the massive, young stars that are shaping the nebula to the pillars of dense gas that may be the homes of budding stars
- The bright central region is the home of the four heftiest stars in the nebula
- The stars are called the **Trapezium** because they are arranged in a trapezoid pattern
- Ultraviolet light unleashed by these stars is carving a cavity in the nebula and disrupting the growth of hundreds of smaller stars

Star Formation-Main Sequence Stars

- Star birth always seems to take place in dusty environments, where Hubble's infrared capabilities have been necessary
- Dust clouds scatter visible light, but let infrared light through unimpeded, meaning infrared observations are often the only way to see young stars
- Images of the Carina Nebula (7500 light years away) made in visible light show dense clouds of dust and gas
- Images of the same region in infrared make the dust fade, leaving just a faint outline of its location
- Details not seen at visible wavelengths are uncovered in near-infrared light
- The young stars forming inside the cloud are suddenly revealed



Next session

Life and death of stars