The Formation of Stars

Stars form from the clouds of gas and dust in the ISM.

This HST image shows young stars being formed inside its dusty nebula. This particular star cluster is in the nearby Small Magellanic Cloud. Strong stellar winds are hollowing out a cocoon inside the nebula.

Stars exist because of the persistent pull of gravity and the interplay between the effects of pressure, density and temperature.

To understand how stars form, we first have to understand the physics of gases.

A Beginner's Guide to How Gases Work

Properties of gases:

1) Temperature: A measure of how much energy is contained in the gas, most often in K. Higher temperatures mean the gas has more energy, so the atoms will be moving faster.

2) Density: A measure of how many atoms are packed into a certain volume. E.g. atoms per cubic cm (atoms/cm^3). Higher densities imply atoms are more crammed in.

3) Pressure: As gas atoms move around, they will bump into each other and the sides of any container they are in. This exerts a force which we measure over a given area (e.g. the sides of the container) and this is the pressure.

What happens if we change one of the properties of a gas?

Increase the temperature: If we heat up a gas filled ballon we are injecting energy into the system. This makes the atoms move around faster so the pressure will increase. In the case of a balloon, the container is not rigid, so the balloon will get larger (the volume will increase).

Reduce the volume: If we compress a gas we are forcing the same number of atoms to be in a smaller volume, this means the density increases. Cramming more atoms into a smaller space also heats the gas up so the temperature increases.

Some practical examples:

1) A squash ball heats up during the game as it is repeatedly compressed by the blow of the racket.
2) Put your finger over the end of a bicycle pump and compress the air – you can feel it heat up.
3) Air bubbles in clay expand and can burst when pottery is fired.

Where Do Stars Form?

Stars form from the gas in the ISM, but they need sites of high density. As we saw in chapter 10, the highest densities are found in molecular clouds.

In these dense clouds, stars form by the gradual attraction of gravity to form dense gas cores. In order to achieve this, the contracting gas needs to overcome four forces:

1) Thermal energy in the cloud. Even at temperatures as low as 10K, the average hydrogen molecule travels at 800 mph. This exerts a pressure which will cause the gas cloud to drift apart.

2) Magnetic fields. Charged (not neutral) particles are affected by magnetic fields (like the solar wind causing aurora). This acts like a spring, again resisting collapse.

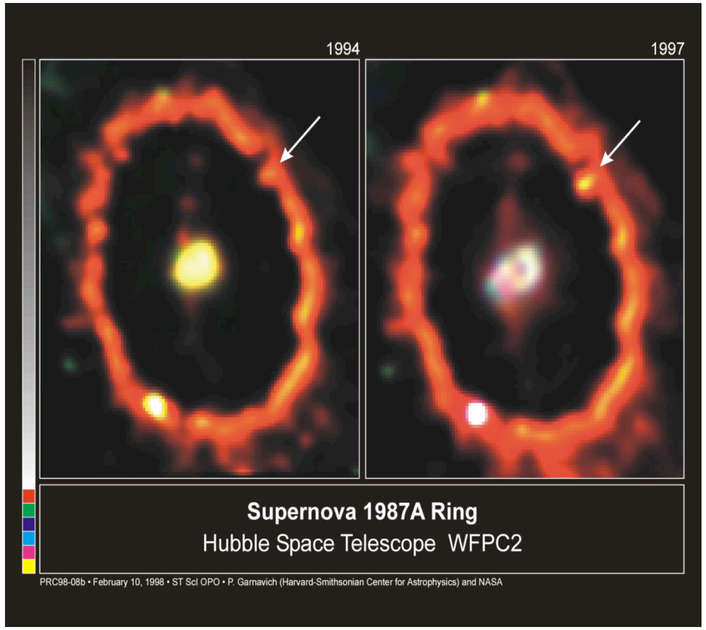
3) Rotation. As a gas cloud collapses, it will spin more rapidly (think of the ice skater). Spinning fast will tend to fling a gas cloud apart.

4) Turbulence. The random motions in the cloud, as well as the twisted filaments and currents we've seen to be common in nebulae, also resist gravitational collapse.

Shock Waves Trigger Star Formation

Given all the forces that resist collapse, the molecular cloud needs a “kick” to get star formation going. This kick comes in the form of a shock wave from one of 4 places:

1) Supernova explosions. A nearby supernova can shock the surrounding ISM setting up density ripples. This image shows the expanding shock wave from SN1987A as it lights the surrounding gas.



2) Nearby star formation. Stars breed stars; young stars ionize the surrounding gas which drives a weak shock into the surrounding ISM

3) Collision of molecular clouds. Collisions of clouds compress the gas and can trigger star formation

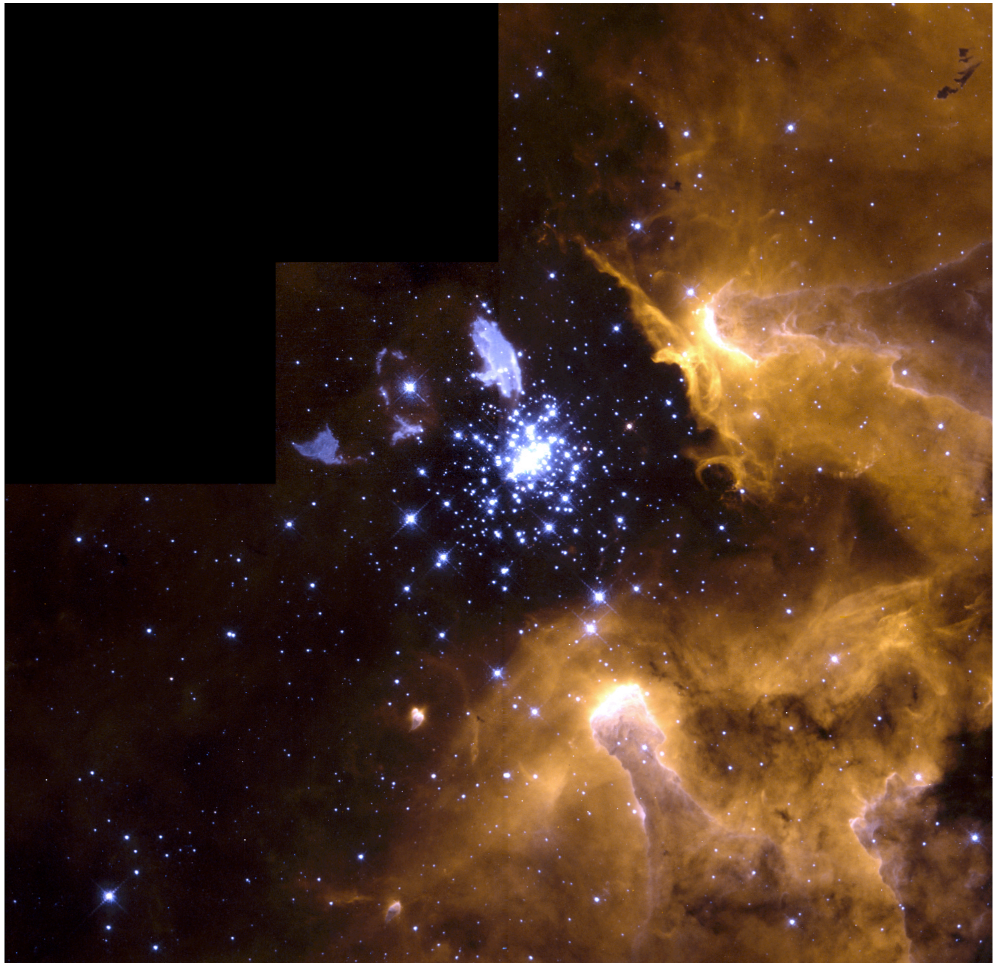
4) Shocks due to spiral arms. It is thought that galaxies like the Milky Way have spiral arms because of large scale shock waves. Therefore, a molecular cloud travelling through a spiral arm could be shocked.

Formation of a Protostar

Shock waves trigger fragmentation in a molecular cloud and individual protostars start to form. Gravity causes the small cores to collapse. The atoms fall towards the centre of the cloud, this is called free-fall contraction.

As we have seen, compressing a gas heats it up, so during gravitational collapse, the thermal energy increases. The process of heating increases the pressure which resists further collapse. Only if a would-be protostar has enough mass does the gravity win.

Eventually, the thermal energy (heat) produced during gravitational contraction is sufficient to ignite reactions in the core of the protostar and begin its life cycle.



In this picture of NGC 3603 we see Bok Globules (top right), the glowing pillars of gas inside which stars are forming and the hot, blue star cluster that has carved a

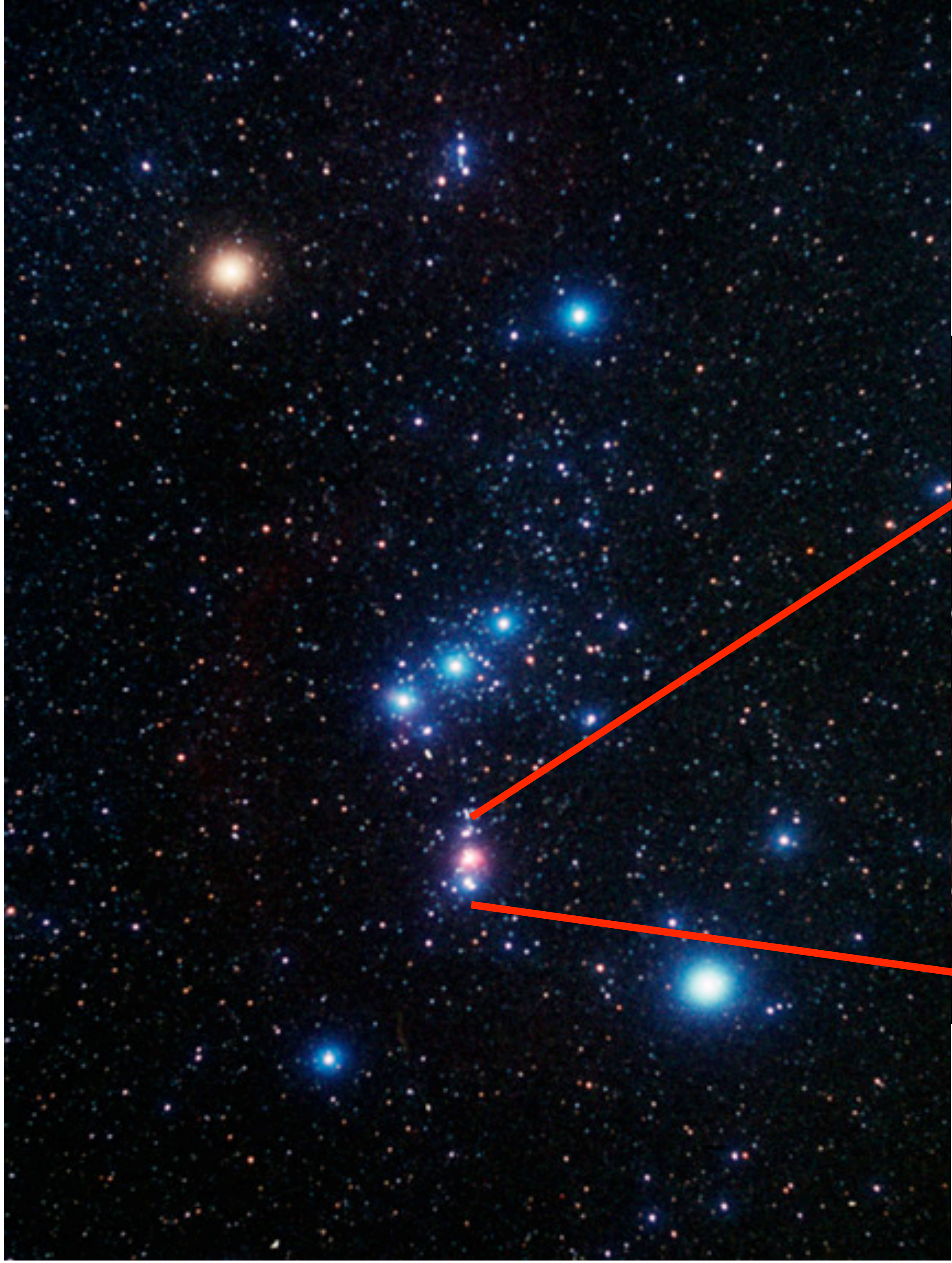
Protostellar Disks

The molecular cloud from which a protostar forms has angular momentum (physics speak for it is spinning). As the protostar collapses the spinning causes the cloud to flatten and form a disk with the protostellar core in the middle.

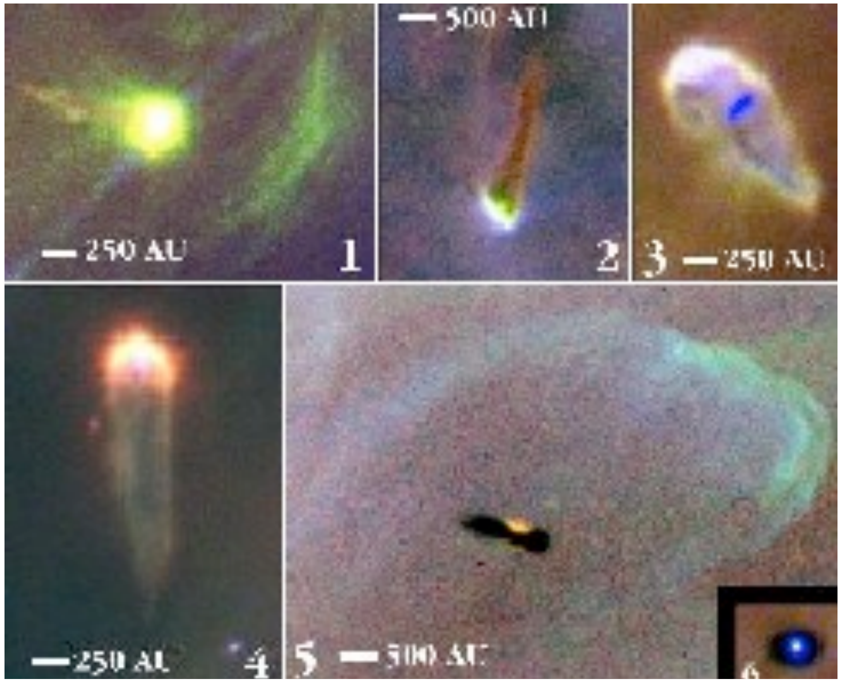
Therefore, the protostar is actually forming inside a disk of dust and gas. Although this disk “spins up” as it collapses, collisions cause atoms to lose angular momentum and they fall to the centre. When the protostar finally lights up, it is cocooned in a cradle of dust and gas so that it is hard to see.

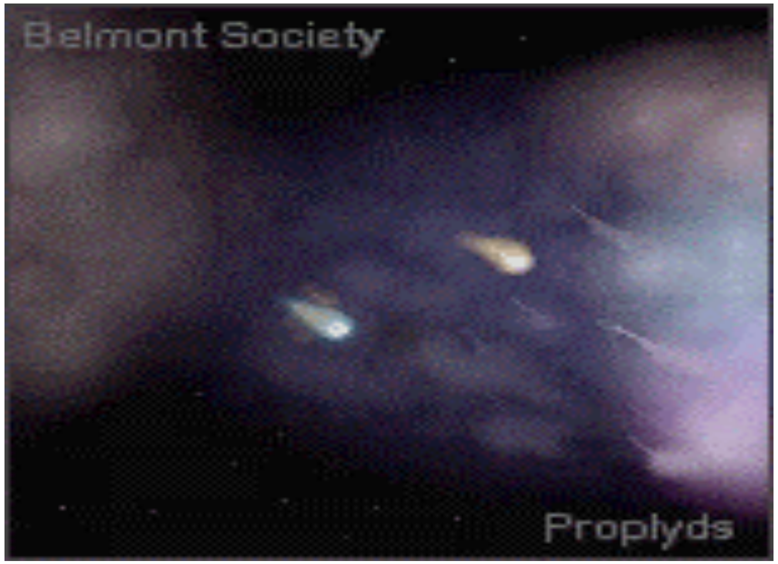
When the star is hot enough, it will blow away this cocoon and it will become visible. Excellent examples of proto-stars with disks are seen in the Orion nebula

The Trapezium in Orion
is one example of an
active star-forming region

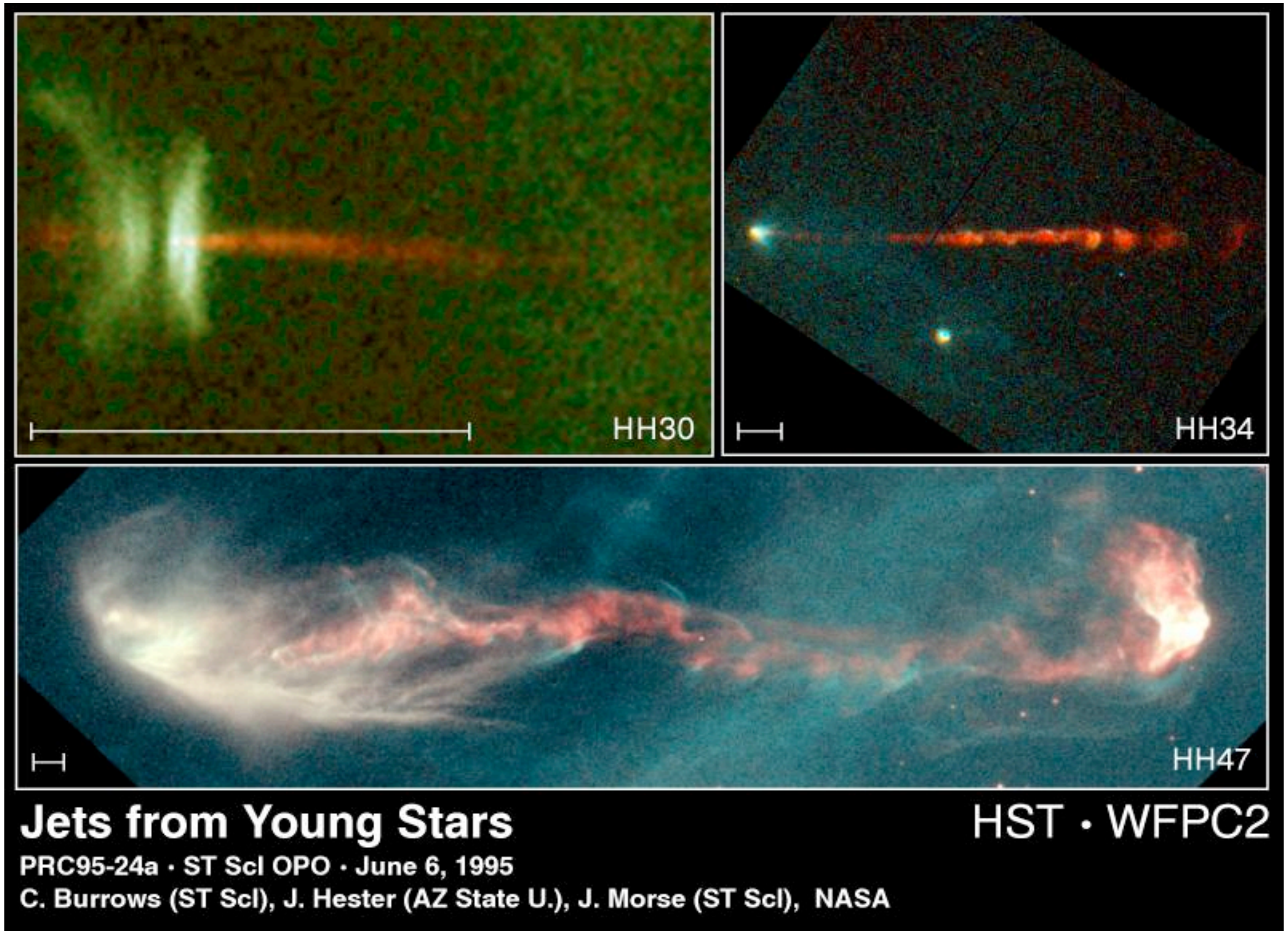


Proplyds in Orion show many signs of newly forming stars: disks, dust cocoons etc., and they are being shaped by the winds from nearby, newly formed stars.



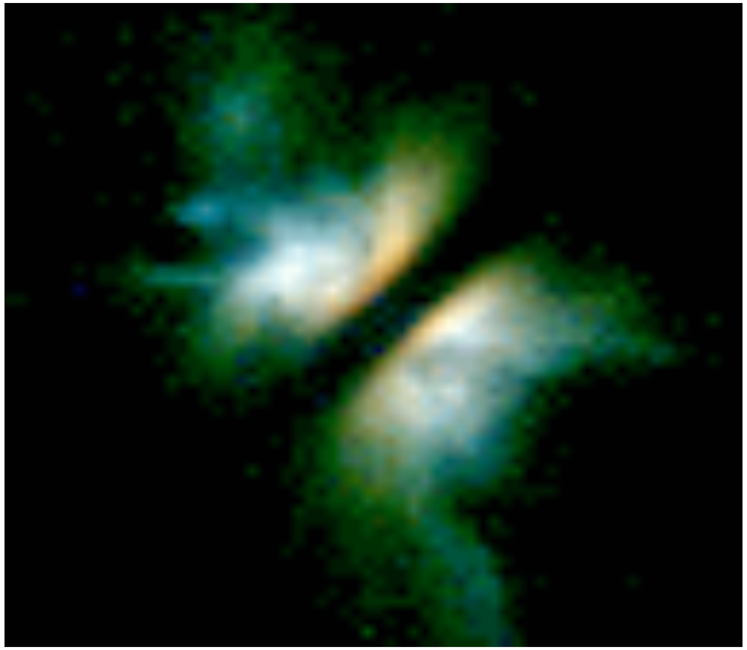


This picture shows disks and jets from young stars. The disks are left over from the birth cloud. The jets are caused by interactions between the infalling material in the disk and the spinning star. These are known as Herbig-Haro (or HH) objects. Jets are important because they transfer away angular momentum.



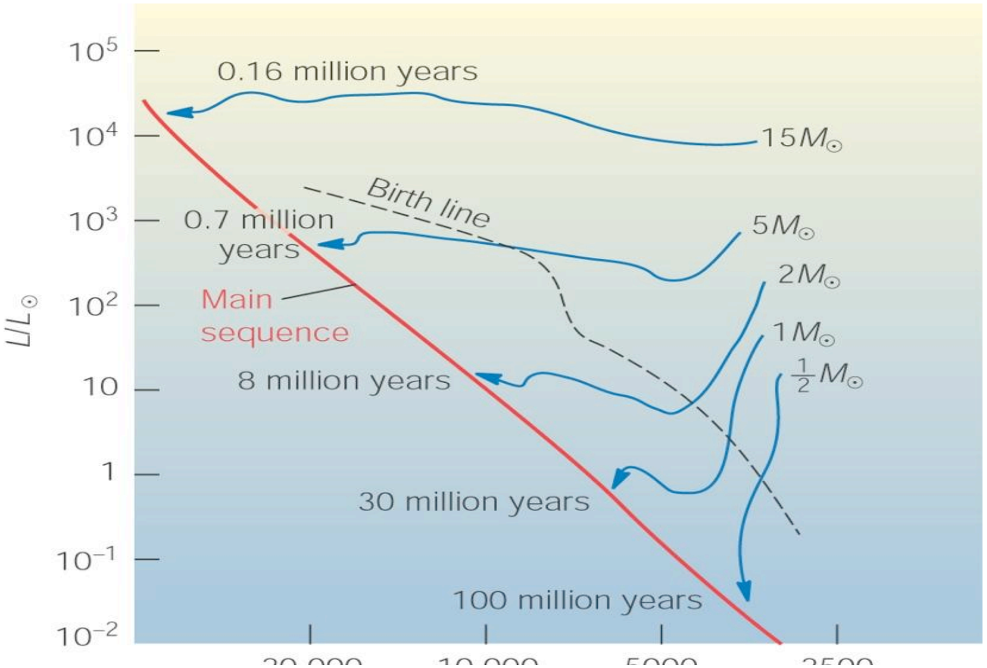
The jets cause shock waves (bow shocks) as they interact with the surrounding ISM. The disks around protostars are eventually where planets may form.

T Tauri Stars



Like HH objects, T Tauri stars (named after the first example discovered in the constellation of Taurus) are often found near the sites of star formation.

T Tauri stars are characterised by being embedded in dust clouds, sometimes with a dust disk around them. The fluctuate in brightness very rapidly and can have large Doppler velocities associated with them.



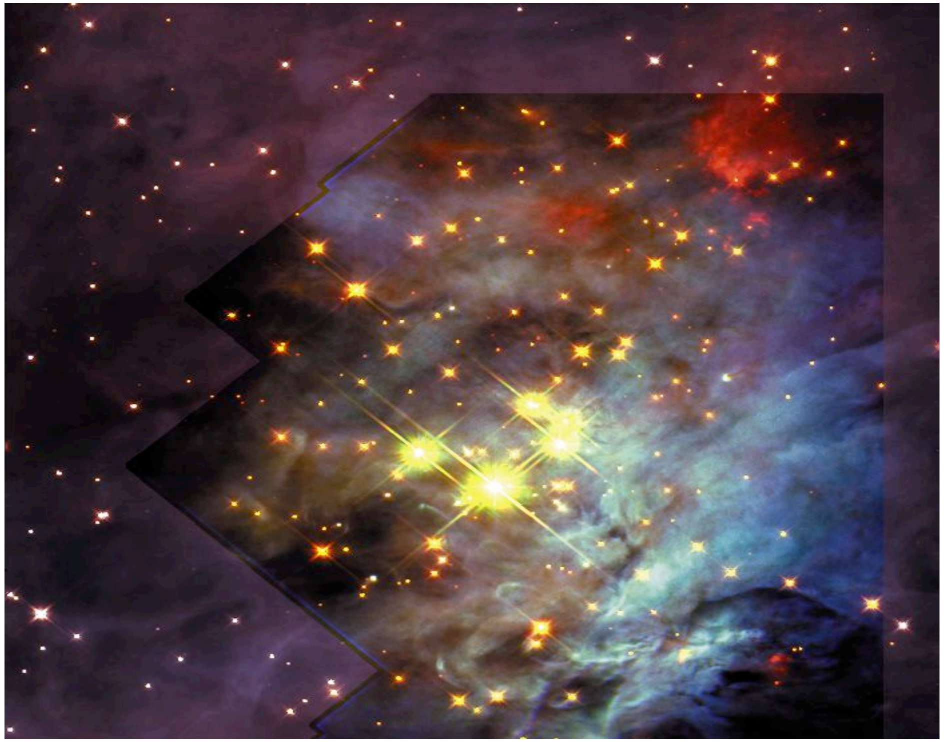
These stars also occur near the birth line on the HR diagram and are therefore interpreted as being young stars that are just blowing away their birth cloud

The birth line is the location on the HR diagram where a star first 'appears' once it has shed its dust cocoon. More massive stars contract faster and reach the birth line quicker than low mass stars.

Star Clusters and Associations

Associations of stars are loose groups that are not bound by gravity. Stars in associations eventually wander away from each other. Therefore, we only ever see young stars in associations. Star clusters are more compact and are bound by gravity. Most young clusters are only loosely bound and are called open clusters.

Associations are usually named via the type of star they contain e.g. an O association contains O stars.



The pleiades (AKA M45 or Seven Sisters) is a naked eye open cluster.

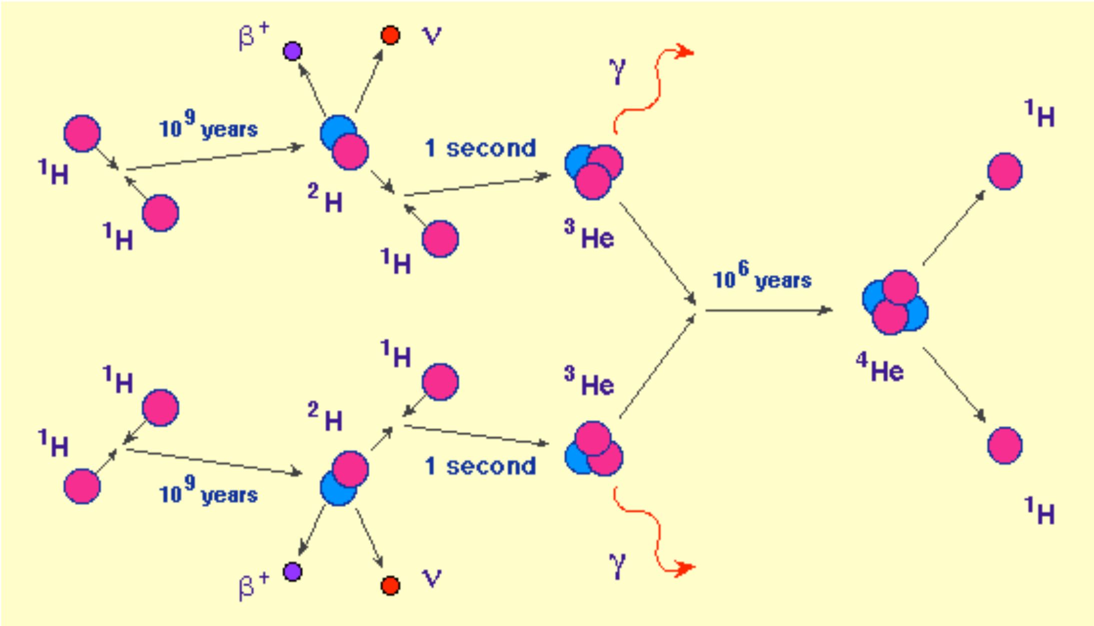
The Trapezium is another famous open cluster in Orion.

From what we have learned about the early process of star formation, we can summarise how to identify the signatures of stellar birth:

- Bok globules, which are only 1 lyr or so in diamater are the first stage of formation. These dusty molecular clouds are best observed in the infrared.
- Associations of young stars that are not gravitationally bound must be being observed early in their lifetimes
- The presence of T Tauri stars and Herbig Haro objects which are often most noticeable in the IR because they are shrouded in dust.
- Nebulae are lit up from within by hot young stars which will eventually drive away the leftover gas and dust.
- Finally, indirect evidence comes from the detection of massive stars. These are short-lived so must have formed recently.

Great Balls of Fire: Sources of Stellar Energy

We have already seen the proton-proton (p-p) chain reaction at work in the sun:



- $_1H^1 + {}_1H^1$ ===> $_1H^2 + e^+ + \nu$
  Hydrogen — Deuterium+positron+neutrino
- $_1H^1 + {}_1H^2$ ===> $_2He^3 + \gamma$
  H + Deuterium — Helium-3 + Photon
- $_2He^3 + {}_2He^3$ ===> $_2He^4 + {}_1H^1 + {}_1H^1$
  Helium-3 — Helium-4 + Hydrogen
  Plus ENERGY

This is the most basic of nuclear reactions in stars since it only requires protons and no more complex nuclei. A minimum temperature of 10 million K is required to start this reaction, because the thermal energy of the protons must be large enough to overcome the charge (coulomb) potential which repels them.

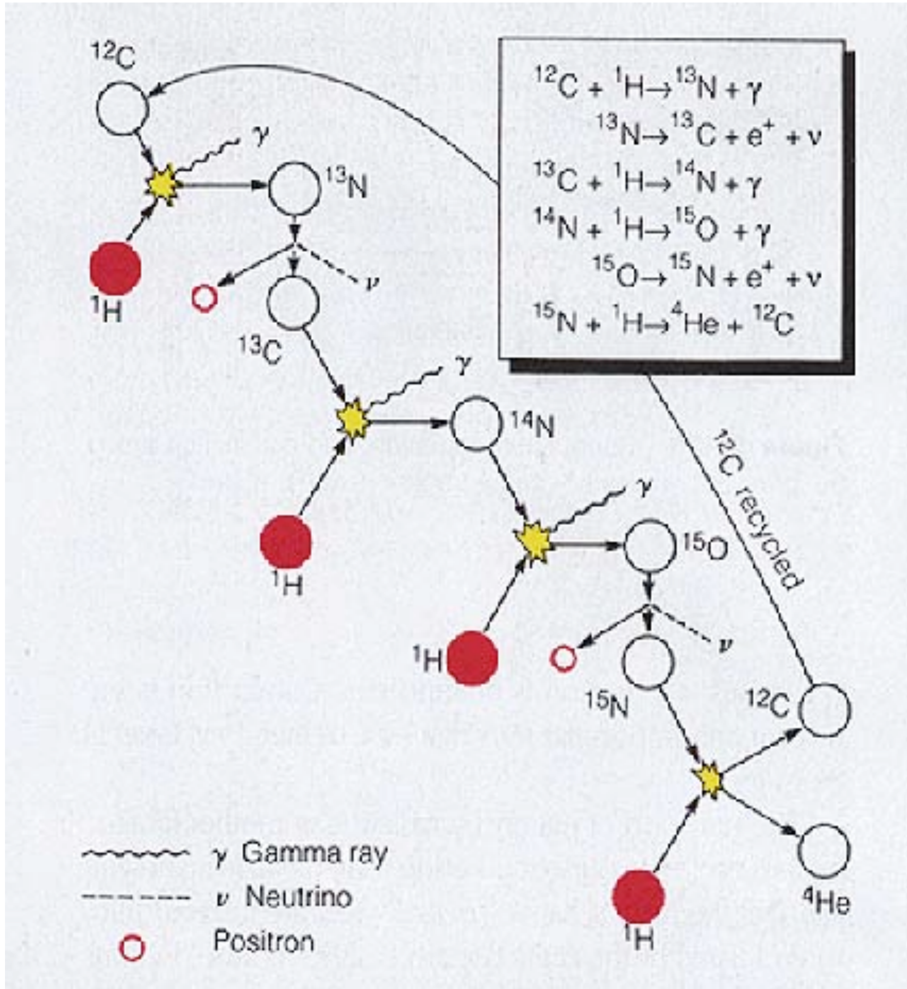
The p-p chain, however, is not very efficient at producing energy

The CNO (Carbon-Nitrogen-Oxygen) Cycle

A much more efficient way to fuse H into He is via the CNO cycle. This cycle uses a carbon atom as a catalyst but the carbon atom is not actually used up.

One important difference between the CNO cycle and the p-p chain is the coulomb barrier that the initial phase has to overcome. In the CNO cycle, this barrier is much larger than the p-p chain because the C has 6 protons.

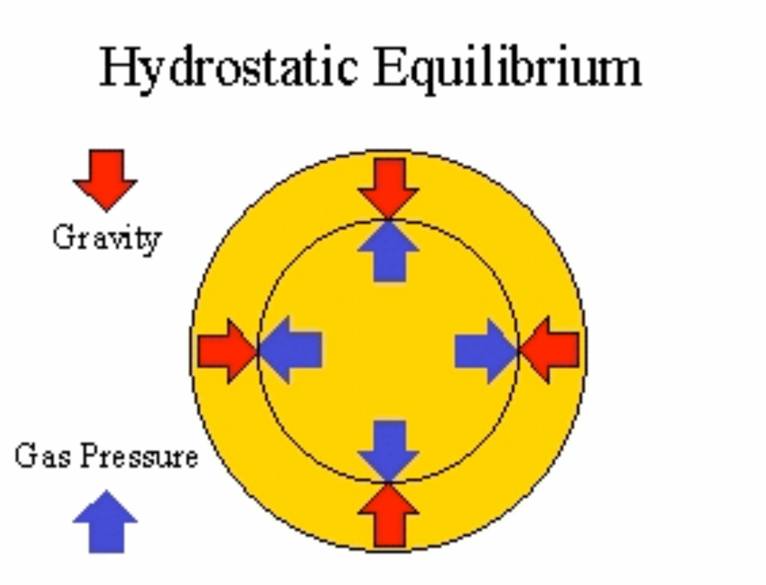
The temperature required to start the CNO cycle is therefore higher than for the p-p chain (>16 million K). This reaction can take place in stars more massive than 1 solar mass (remember that massive stars are hotter).



Stars with core temperatures < 16 million K produce most of their energy via the p-p chain, whereas hotter stars benefit from the CNO cycle. Both these

Hydrostatic Equilibrium

This is one of the most important physical concepts in stellar astronomy, because the fine balance between thermal/radiation pressure and gravity are the main source of supoort in a star. The modulation of these forces also drives all the phases of stellar evolution



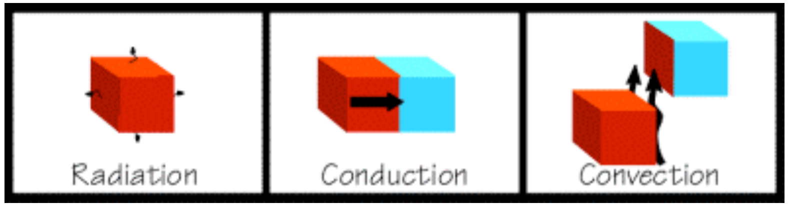
The concept is straightforward. Nuclear reactions in the star's core produce heat, which must be transported away (remember heat always flows from hotter to cooler regions, in this case, to the outer layers of the star). The pressure created by the hot gas must balance exactly the force of gravity if the star is to remain stable. These forces are strongest towards the centre of the star and weak near the surface

What Supports Stellar Structure?

Stellar support is a fine balance between the inward tug of gravity and the outward push of thermal energy and photons. This is called hydrostatic equilibrium and we'll re-visit this concept later.

The thermal energy produced in star's core and its transport to the outer layers is essential in regulating a star's structure.

Thermal energy can be moved around via 3 processes: conduction, convection and radiation



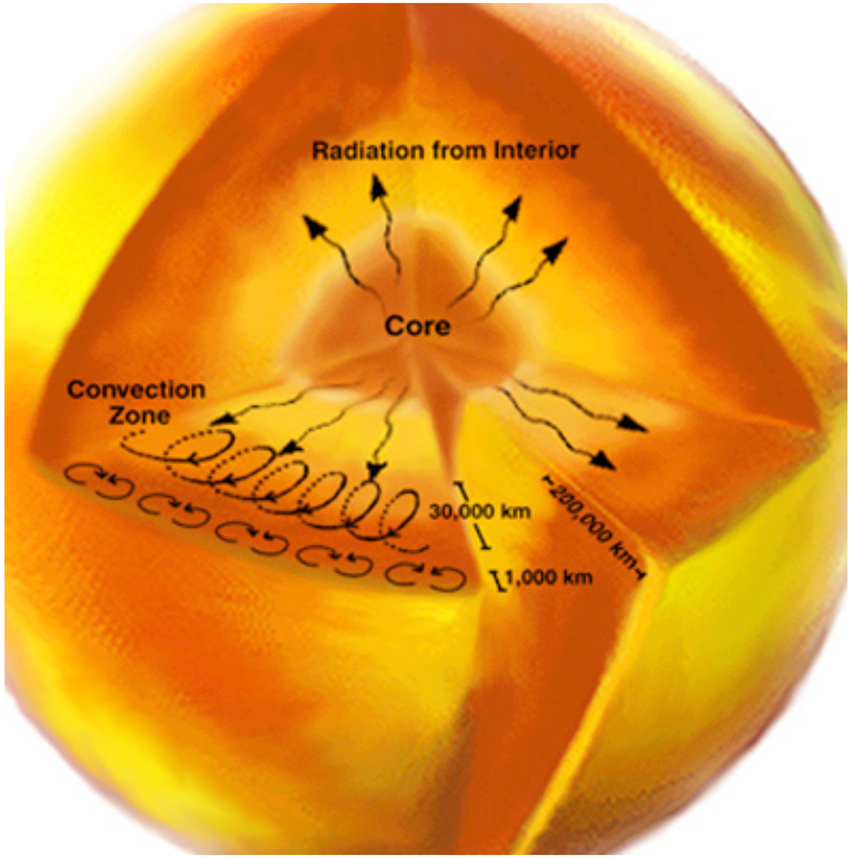
Conduction: heat is transferred by the vibration of particles in close contact. E.g. heating along a metal bar.

Convection: heat is transferred by the movement of particles from a warm to a cold environment. E.g. air currents on a warm day

Radiation: heat is transferred by photons. E.g. sunlight. Note that this is the only mechanism that can transfer thermal energy in a vacuum.

Structure of the Sun

Convection and radiation are the 2 most important mechanisms in a star (conduction is most important in solids).



Different sized stars will have different internal structures. Sun-like stars have convective envelopes around an inner radiative zone.

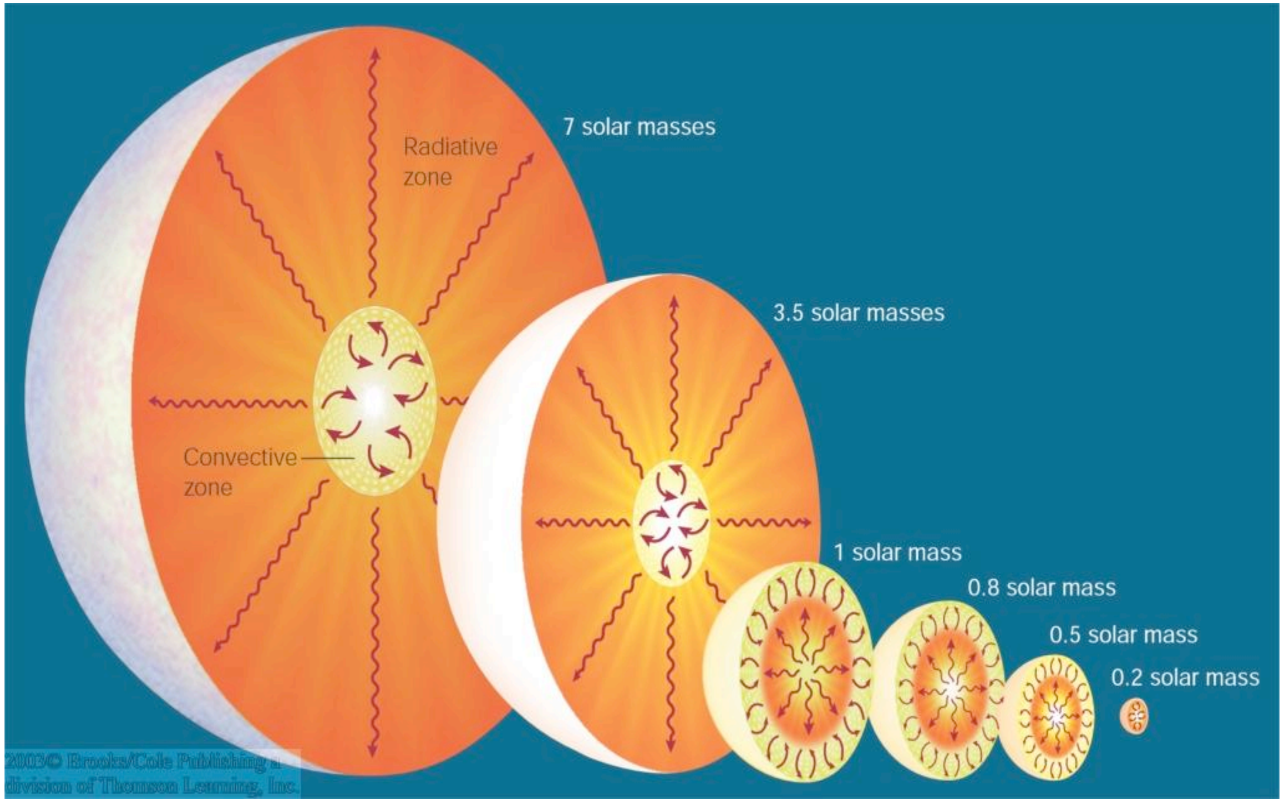
Radiation is only efficient in hot, low density gas, otherwise the photons can not move freely and collide with other particles. We say that radiation requires a low opacity.

Convection dominates in the cooler, more opaque outer layers of the sun. Convection also drives mixing in these layers.

Structure of Other Stars

Not all stars transport energy in the same way as the sun (i.e. with a large internal radiative zone and an outer convective envelope.

Higher mass stars have higher temperatures in their cores, so more of of the energy comes from the CNO cycle (recall that the balance between the CNO cycle and the p-p chain is very temperature sensitive). The increased temperatures and energy production in the cores of stars with >3.5 solar masses can not efficiently radiate away all its energy.



The centres of massive stars therefore rely on convection and have outer radiative zones. Low mass stars (<0.4 solar masses) are almost all convection cooled, because the low temperatures increase the opacity such that radiation is inefficient.

In summary: Radiation is not efficient in the centres of massive stars because it can't transport energy fast enough from the core. Radiation is also inefficient in the outer layers of smaller stars because the cool gas is too opaque.