1 Star Formation

When Gravity Rules!

1.0.1 Giant Molecular Clouds

- Typically 50 parsecs in diameter
- Cold $\sim 10\,\mathrm{K}$
- Molecular velocity - for one molecule of mass m

$$\begin{aligned} Kinetic\ energy &= \frac{3}{2}kT \\ \frac{1}{2}mv^2 &= \frac{3}{2}kT \end{aligned}$$

$k = 1.3806568 \times 10^{-23}\,\mathrm{J\,K^{-1}}$ = Boltzmann constant

Average molecular velocity for $10\,\mathrm{K} \sim 350\,\mathrm{m/s}$

Temperature is one factor that determines whether a cloud will collapse into stars.

- May contain $100,000$ solar masses

Three factors that may resist contraction of the cloud

1. Molecular velocity - for one molecule of mass m

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   $k = 1.3806568 \times 10^{-23}\,\mathrm{J\,K^{-1}}$ = Boltzmann constant

   Average molecular velocity for $10\,\mathrm{K} \sim 350\,\mathrm{m/s}$

   (a) Interstellar magnetic field - deflects ions and electrons

2. Acts like an internal spring
3. Rotation - Conservation of angular momentum

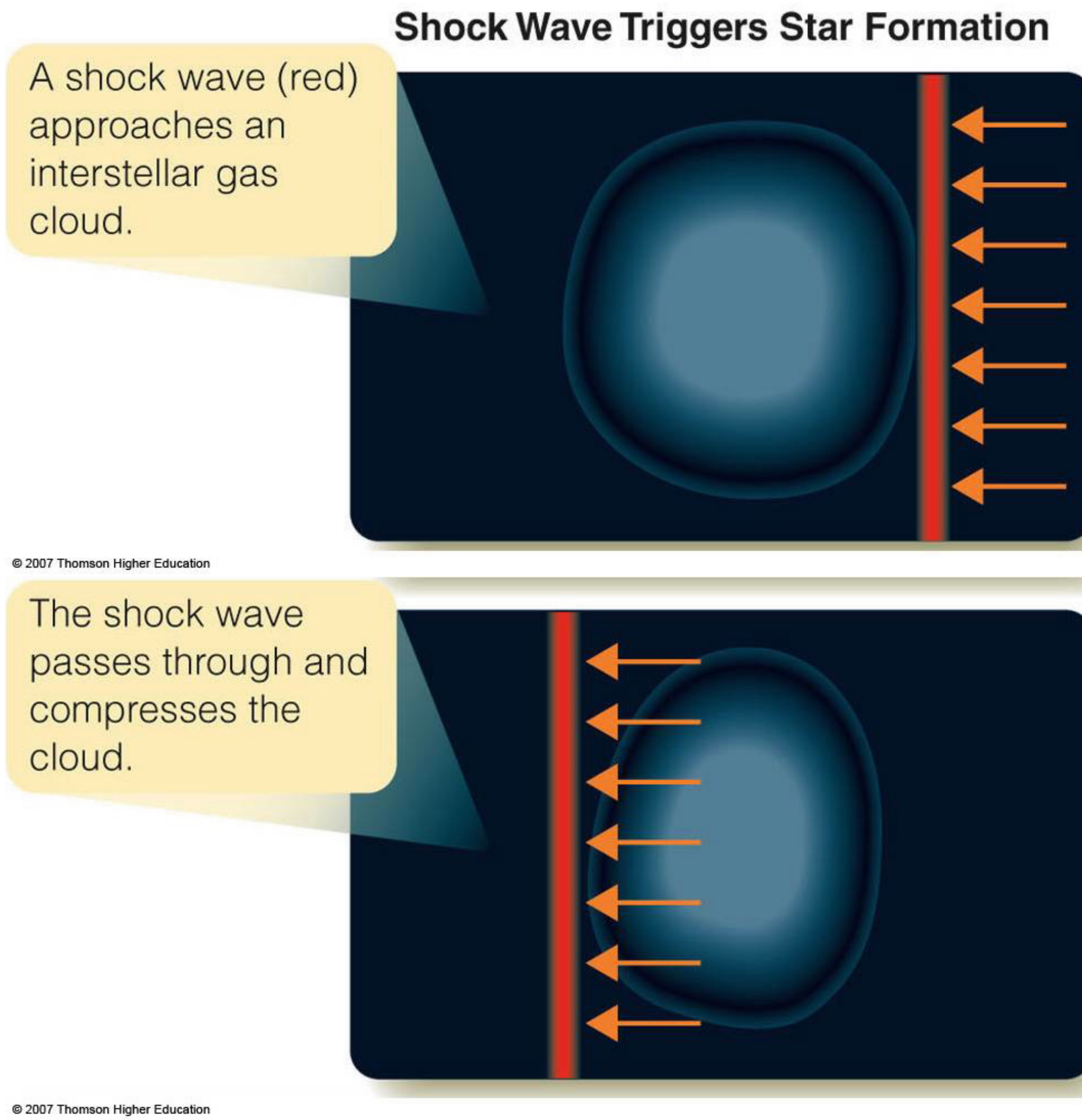
   Fast rotations can resist contraction

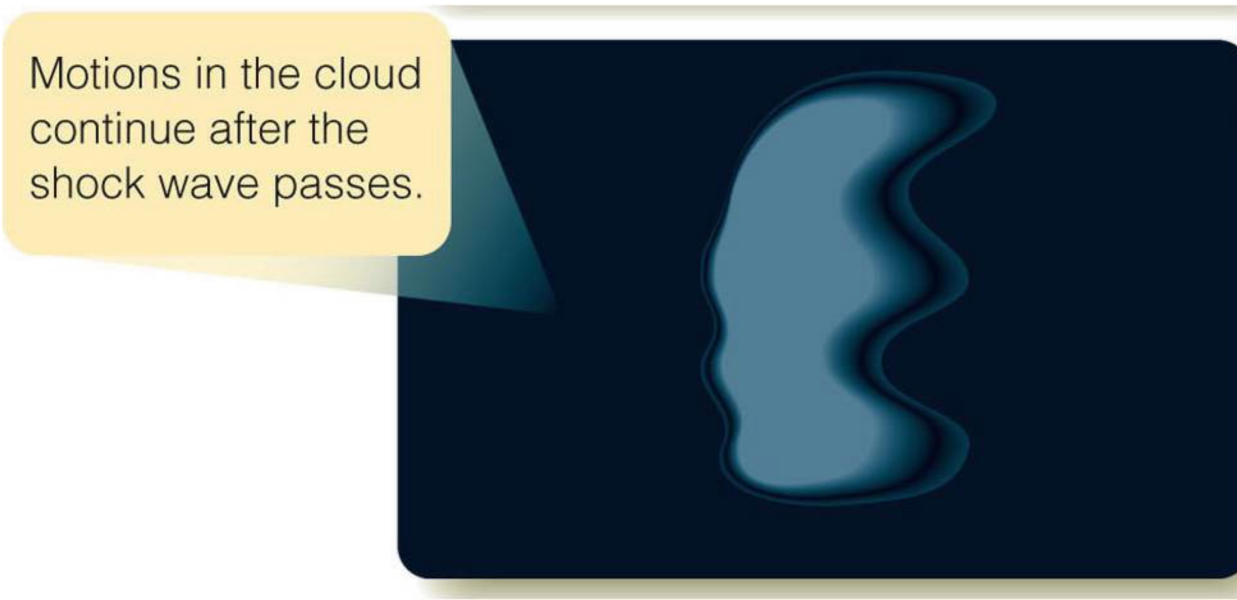
   Fragmentation of the cloud can produce binaries

1.0.2 Triggers for star formation -4 processes

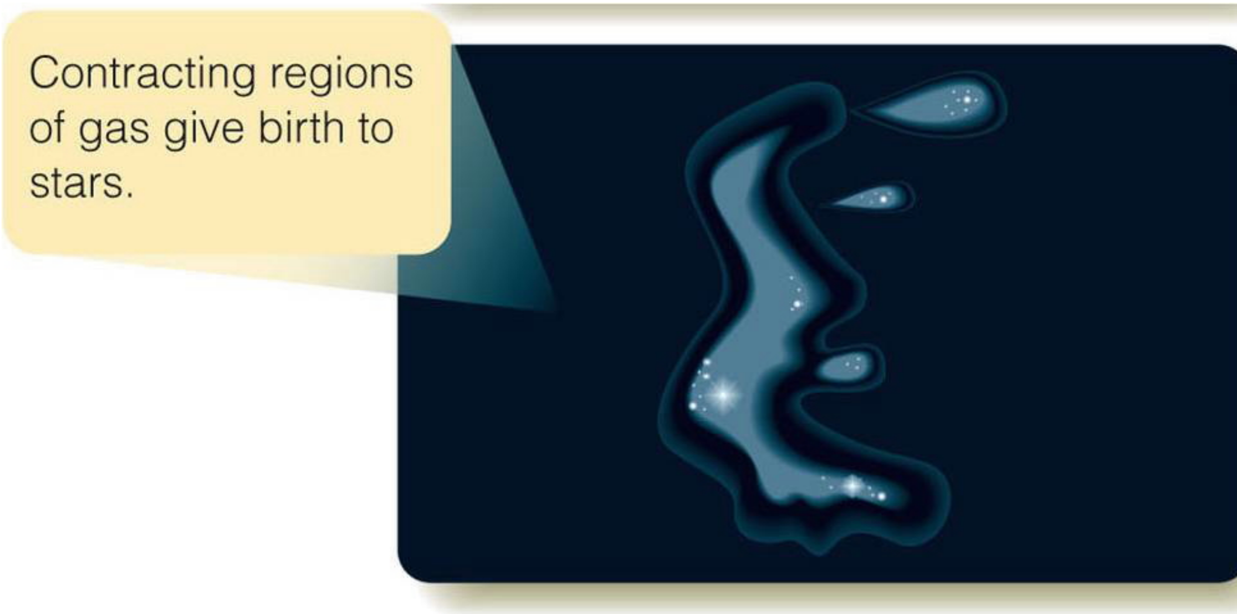
Molecular clouds do not contract all be themselves

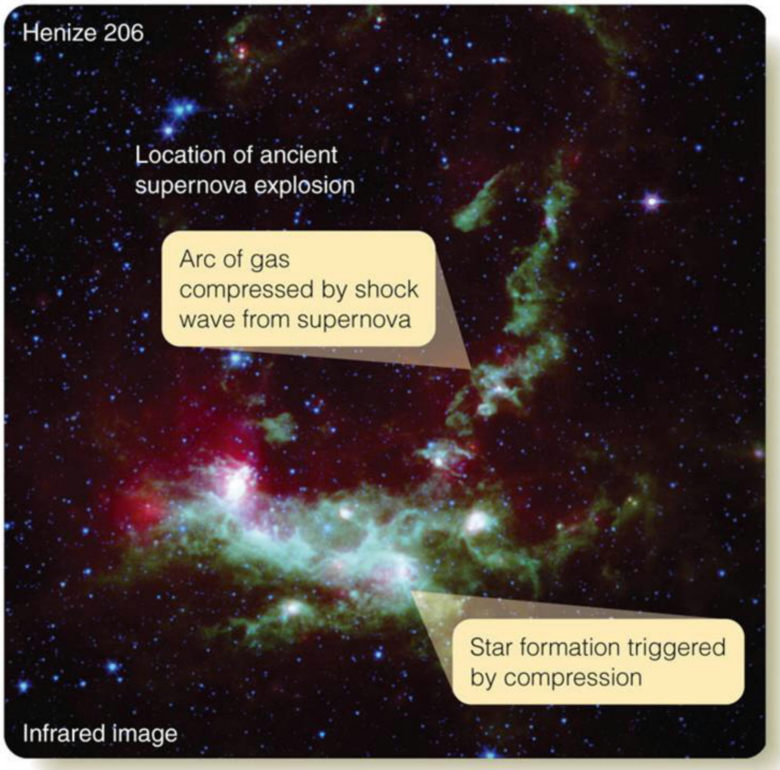
- Supernovea explosions




Motions in the cloud continue after the shock wave passes.

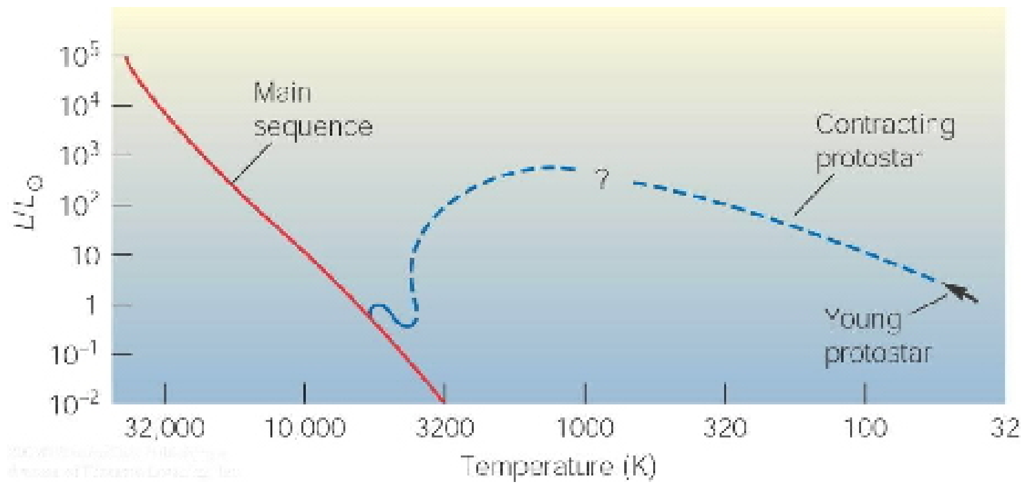

The densest parts of the cloud become gravitationally unstable.


Contracting regions of gas give birth to stars.

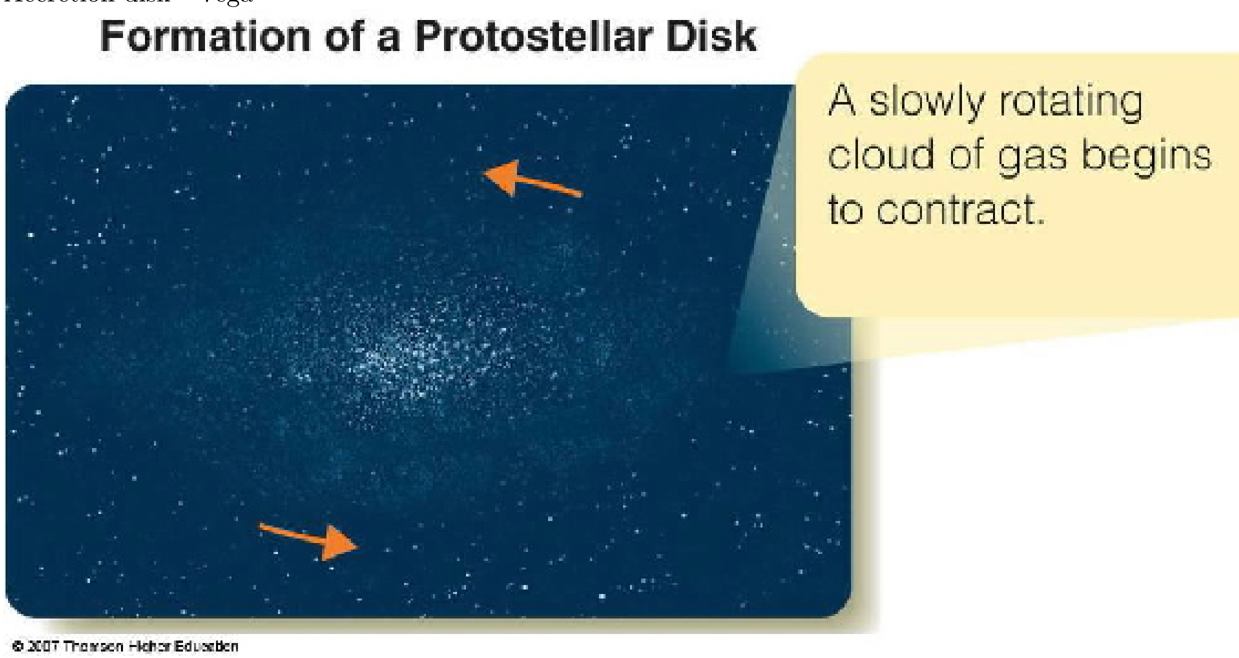


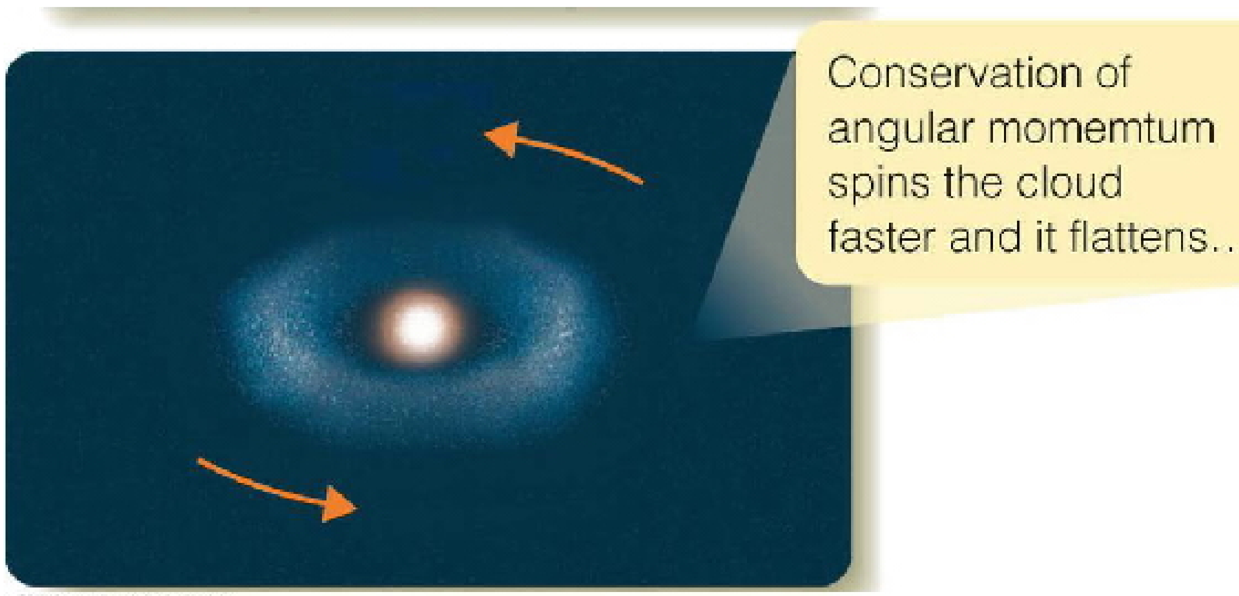
- Ignition of nearby hot stars
- Colliding molecular clouds
- Spiral pattern in the Milky Way

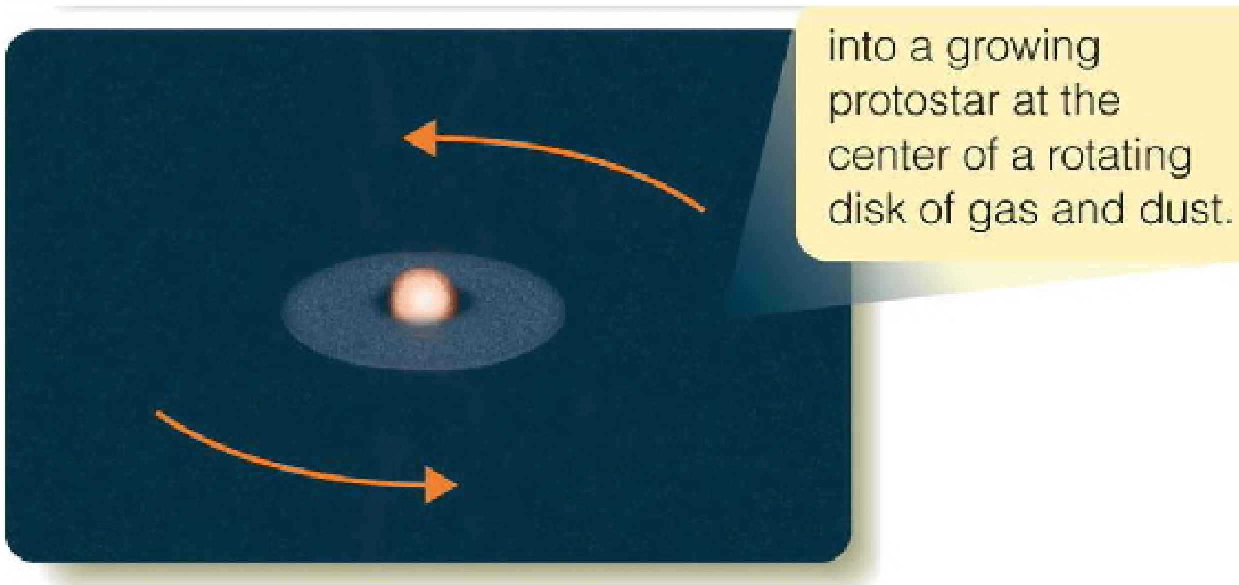
Process Collapse of the molecular cloud
Contraction and heating
Protostar stage
HR Diagram



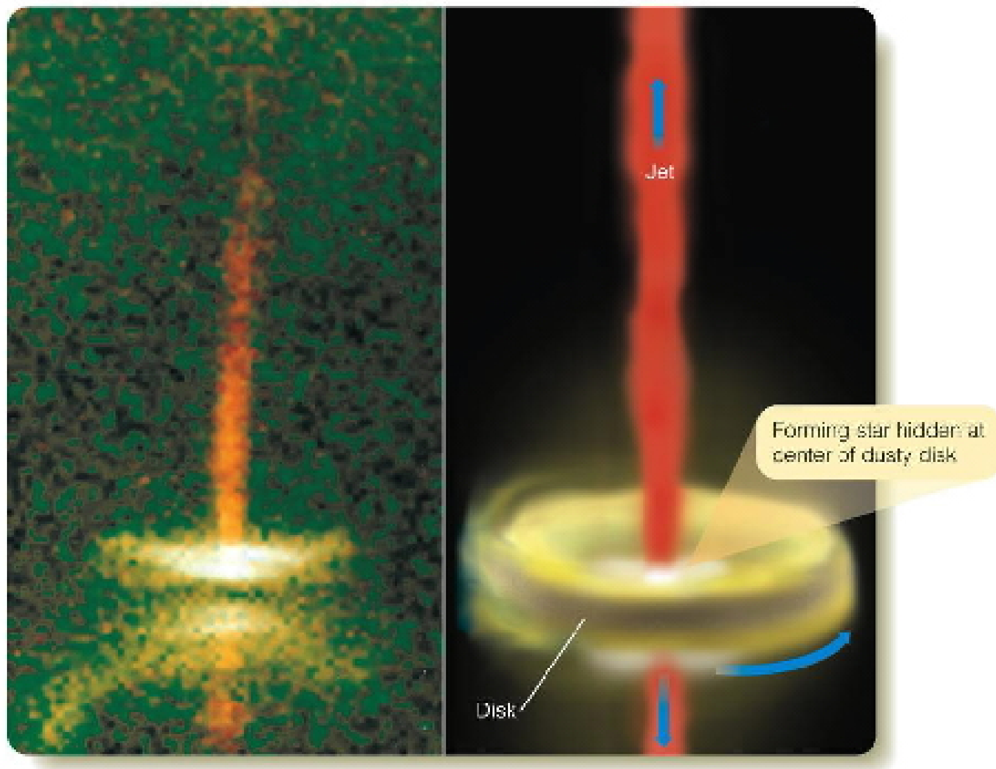
Accretion disk - Vega



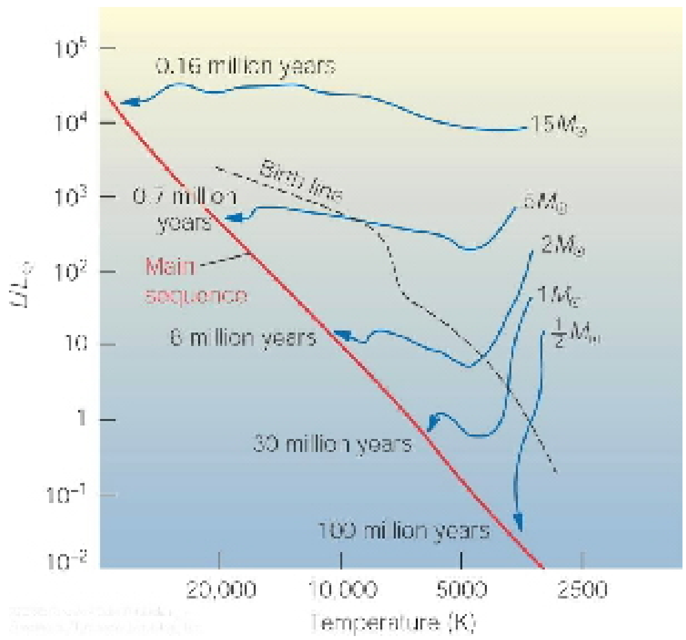




Bipolar flows

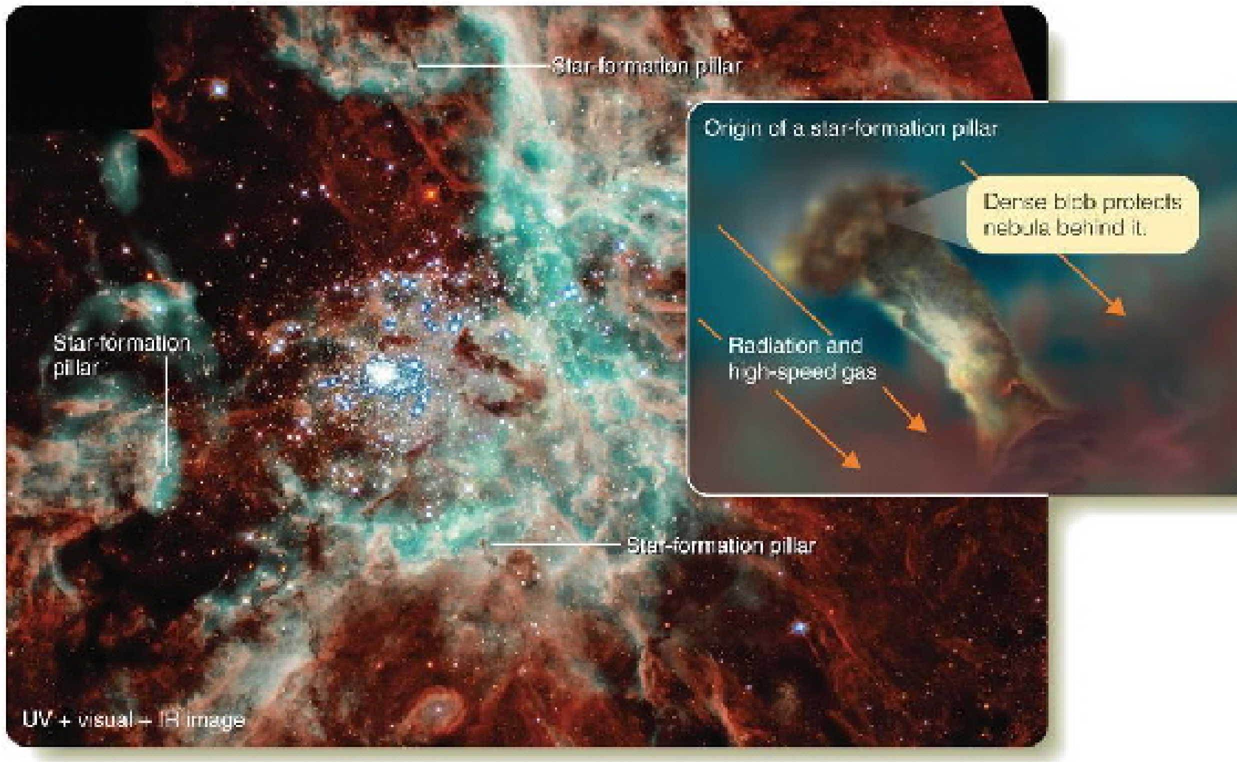


Thermonuclear Fusion - Birth line, time to reach main sequence

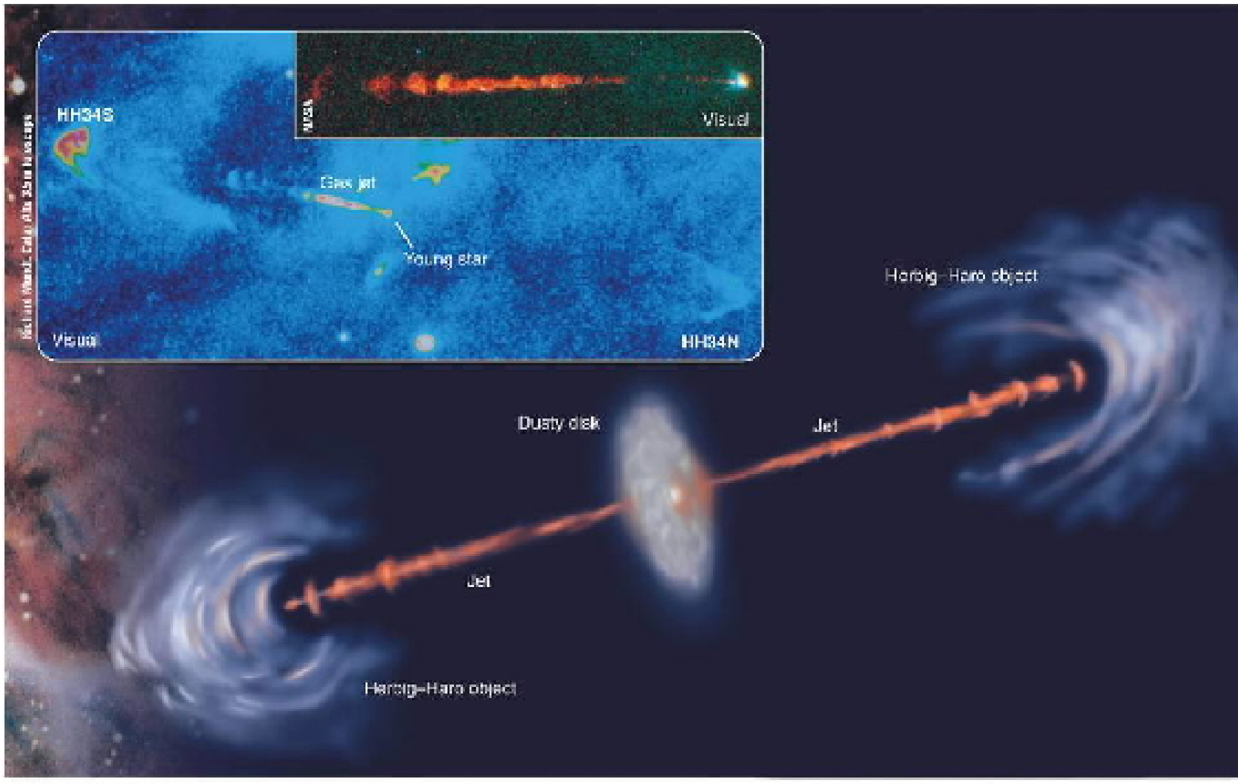


0.16 million years
$15 M_\odot$
Birth line
0.7 million years
$5 M_\odot$
$2 M_\odot$
Main sequence
$1 M_\odot$
$\frac{1}{2} M_\odot$
6 million years
30 million years
100 million years
$L/L_\odot$
10^5
10^4
10^3
10^2
10
1
10^{-1}
10^{-2}
20,000
10,000
5000
2500
Temperature (K)

Cocoon



T-Tauri stars − young stars emerging from their cocoons − variables
Herbig-Haro Objects - biploar flows interacting with the intersellar medium



1.1 Stellar Energy

How do stars generate energy? Chemical processes can not account for the energy of Sun

1930 - discovery of the neutron

Thermonuclear Fusion Four hydrogen nuclei come together at very high speed to form one helium nucleus in a 3 step process

In the process, a little bit of mass is converted to energy

$$E = m_o c^2$$

4 hydrogen nuclei	=	6.693×10^{-27} kg
1 helium nuclei	=	6.645×10^{-27} kg
difference in mass	=	0.048×10^{-27} kg

The amount of energy generated in this one reaction is

$$E = m_o c^2 = \left(0.048 \times 10^{-27}\,\text{kg}\right)\left(3 \times 10^8\,\text{m/s}\right)^2 = 0.048 \times 10^{-11}\,\text{J}$$

This by itself is not very much. Sun must have a lot of reactions each second, approximately 10^{38} reactions per second. This means Sun must convert 5 million tons of mass directly into energy every second.

The temperture at the core of Sun is about 15 million kelvins

The 3 step process goes like this

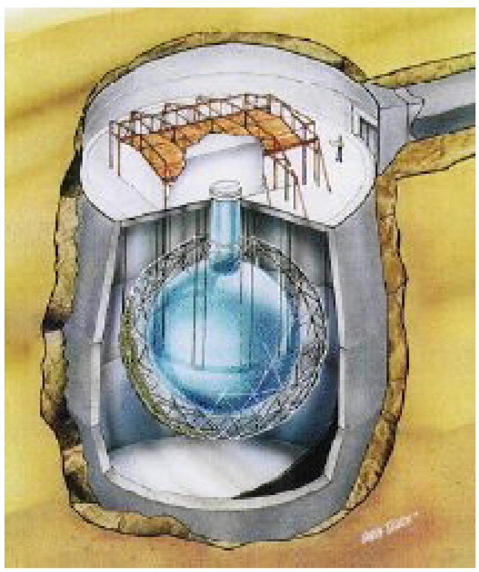
$$\begin{array}{lll} {}^1_1H +{}^1_1 H & \longrightarrow & {}^2_1H + e^+ + \nu \\ {}^2_1H +{}^1_1 H & \longrightarrow & {}^3_2He + \gamma \\ {}^3_2He +{}^3_2 He & \longrightarrow & {}^4_2He +{}^1_1 H +{}^1_1 H \end{array}$$

The neutrino, ν, is in the same family as the electron.

The positively charge electron, e^+, is the anti-matter component of the normal electron. A very elusive particle, doesn't react with matter.

The energy released occurs in the second step, γ.

Solar Neutrino Observatories Sudbury, Ontario, Canada



Contains $1,000$ tonnes of heavy water, ${}^2_1H_2O$, with an added 2 tonnes of high purity table salt, $NaCl$.

> In a presentation Sunday, September 7, 2003, at TAUP 2003, a major scientific conference in Seattle, Washington, new measurements are reported that strongly confirm the original SNO results announced in 2001 and 2002 that solved the "Solar Neutrino Problem" and go much further in establishing the properties of neutrinos that cause them to change from one type to another in transit to the Earth from the Sun. "We have moved to a precision phase

> of the measurements," says Queen's University Professor Art McDonald, SNO Project Director through the first two phases of the project. "These measurements are essential to define a new theory of elementary particles required to explain finite neutrino masses and their ability to change types. Some of the simplest proposed theories have already been ruled out."

and

> The observations in recent years that neutrinos change from one type to another, implying that they have mass, has led to great interest in the scientific community. These new findings require a modification of the most basic theories for elementary particles and have provided a strong confirmation that our theories of energy generation in the Sun are very accurate. New experiments to provide further information on neutrino properties and the origin of the Dark Matter in the Universe are being developed. These include projects that could be sited in the new SNOLAB being developed near the SNO underground site. Such measurements could provide insight into fundamental questions such as why our Universe is composed of matter rather than anti-matter. The answers to such questions require a further understanding of elementary particle theory and further insight into the evolution of the Universe.

Background Information on the Sudbury Neutrino Observatory
The Sudbury Neutrino Observatory is a unique neutrino telescope, the size of a ten-storey building, two kilometers underground in Inco's Creighton Mine near Sudbury, Ontario, planned, constructed and operated by a 100-member team of scientists from Canada, the United States and the United Kingdom. Through its use of heavy water, the SNO detector provides new ways to detect neutrinos from the sun and other astrophysical objects and measure their properties.

For many years, the number of solar neutrinos measured by other underground detectors has been found to be smaller than expected from theories of energy generation in the sun. This had led scientists to infer that either the understanding of the Sun is incomplete, or that the neutrinos are changing from one type to another in transit from the core of the Sun.

Stellar lives Hydrogen fusion lasts 90% of the star's lifetime.
Stars that are fusing hydrogen in their cores are called main sequence stars.

Other fusion reactions that can occur in stars CNO cycle - Mass of star must be at least $1.1 M_{\odot}$, with core temperatures hotter than 16 million kelvins.

Triple alpha process - fuses helium into carbon.

1.1.1 Stellar Structure

Hydrostatic equilibrium

Pressure - Temperature thermostat
2 forces - directed opposite but equal in magnitude
Gravity pulls material inward
Flow of energy outward pushes the layers outward

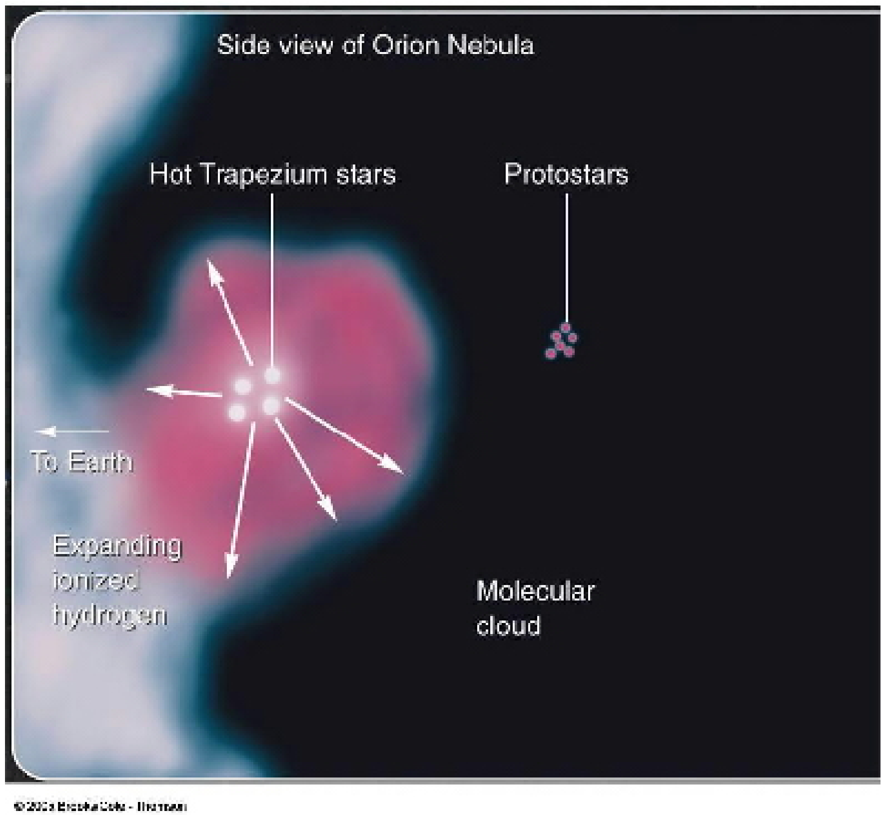
Heat Transfer Mechanisms Core - Radiation Zone - Convective Zone - photosphere

1.1.2 Sites where stars are forming

Orion Nebula

Star formation started near the west shoulder of Orion around 12 million years ago. The stars in the belt formed about 8 million years ago and the stars in the Trapezium are only a few million years old. Northwest to Southeast.

A few million years ago, the stars in the Trapezium were contracting protostars within a moleculur cloud. As thermonuclear fusion began in their cores, radiation pressure pushed on the remaining cloud triggering more star formation. As the temperatures in the star increased more ultraviolet light was emitted that ionized the cloud and halted star formation nearby.


Side view of Orion Nebula
Hot Trapezium stars
Protostars
To Earth
Expanding
ionized
hydrogen
Molecular
cloud

Eagle nebula