Structure of the Sun

Core... 0 ～ 160,000 km

Energy is generated by nuclear fusion.
T ： 15,800,000 K （center）

Radiative zone... 160,000 km ～ 500,000 km

Energy is transported by radiation.

Convection zone... 500,000 km ～ 700,000 km

Energy is transported by convection.

Photosphere... 0 ～ 500 km (solar surface = 0 km)

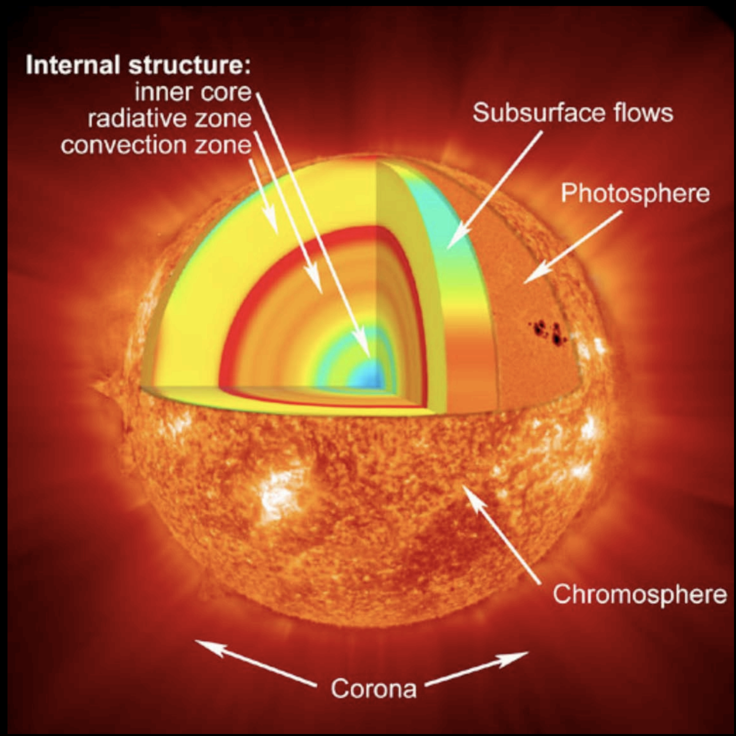
Observed in visible light (solar surface)
T ： 6000 K

Chromosphere... 500 km ～ 2000 km

Temperature-reversed region
T ： 10,000 K

Corona... 2500 km ～

Hot and low-density region
T ≥ 1,000,000 K



SOHO (ESA & NASA)

Modeling of the Solar Interior

Solar interior (below the photosphere**)... invisible with electromagnetic waves**

(transparent against neutrinos & acoustic-gravity waves)

↓

Theoretical modeling based on physical laws is required to investigate the internal structure of the Sun.

→ This is done using **stellar evolution theory** combined with observed data of the solar surface (photosphere).

Stellar evolution theory...

describes how the internal structure of a star develops with time

Assumptions (in the case of the Sun)**:**

1) **Spherically symmetric** (solar rotation, global convective flow, and solar magnetic field are neglected)

2) **Chemical composition:** $X(t) + Y(t) + Z(t) = 1\ ,\ Z(t) = 0.017\ \text{(constant)}$

Fractional abundance: X... hydrogen, Y... helium, Z... other heavy elements

This is the value observed at solar surface.
This is a typical value for population I stars.

3) **Mixing length** (l_{mix}) is introduced to describe the convection zone.

Important parameter values... estimated from the present state of the Sun**:**

1) **Initial helium abundance**... $Y_0 = Y(t=0) \simeq 0.25$ according to the present Sun's luminosity

2) **Ratio of mixing length to pressure scale height (convection zone)**...

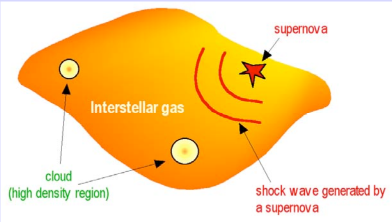
$$\alpha \equiv \frac{l_{mix}}{H_p} \simeq 1$$ according to the present Sun's radius

Protostar evolution

How is a star born?

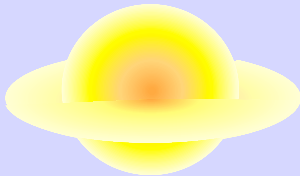
Pre-main-sequence stellar evolution

1) Initial cloud collapse



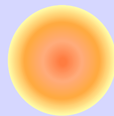
Disturbances produced by, for example, a supernova locally form a high-density cloud in interstellar medium, which then starts to collapse by self gravity.

2) Accretion & dynamic contraction



Interstellar gas in the vicinity of a collapsing cloud continuously accumulates on it (**accretion**) and the cloud rapidly contracts.

3) Slow contraction



After the accretion, the central cloud slowly contracts as a whole (**quasi-static contraction**). During this phase, gravitational energy is converted into thermal and radiative energy (becomes hotter and brighter).

1) Initial cloud collapse (~ $3\times10^{7}\ yr$)

The distribution of density in interstellar medium is subject to disturbances via, for example, a shock wave produced by a supernova.

↓

These disturbances locally form a high-density cloud which starts to collapse when the Jeans condition is satisfied (gravitational contraction wins gas pressure repulsion):

$$\frac{G\,m_c}{r_c} > \frac{R\,T}{\mu}$$

G: gravitational constant

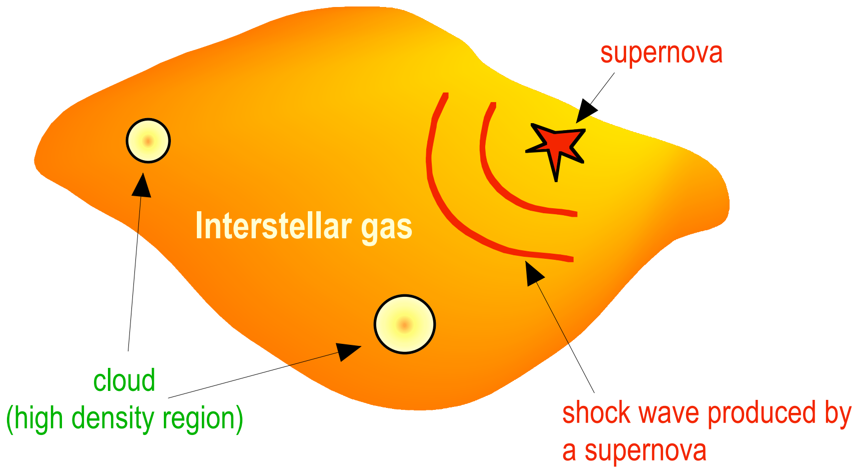
R: gas constant

r_c: radius of a cloud

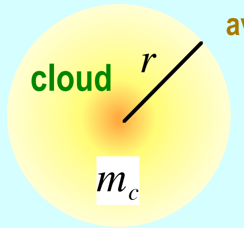
m_c: mass of a cloud

T: temperature of a cloud

μ: mean molecular weight of a cloud



Jeans condition



average density of a cloud:

$$\rho \sim \frac{m_c}{\frac{4}{3}\pi r_c^3} \Rightarrow r_c \sim \left(\frac{3\,m_c}{4\pi\rho}\right)^{\frac{1}{3}}$$

$$\frac{G\,m_c}{r_c} > \frac{R\,T}{\mu} \longrightarrow m_c > \left(\frac{3}{4\pi}\right)^{\frac{1}{2}}\left(\frac{R}{G\,\mu}\right)^{\frac{3}{2}} T^{\frac{3}{2}}\rho^{-\frac{1}{2}}$$

As collapse goes on (density increases), the lower limit of m_c decreases, so collapse is facilitated (positive feedback... **collapse instability**)

Typical time scale of the collapse... **free-fall time:** $t_{ff} \sim \frac{1}{\sqrt{G\,\rho}}$

typical density of interstellar gas... 10^{-23} g cm^{-3}
=> $t_{ff} \sim 3\times10^{7}\ yr$