Chapter 7 Birth of stars

7.1 Interstellar medium (ISM)

The dominant component is hydrogen gas (75% by mass) in various forms: Neutral atomic hydrogen (H I), ionized hydrogen (H II), molecular hydrogen (H_2). Helium makes up most of the remaining mass (24%), a trace of heavier elements like carbon, oxygen, silicon are detected too.[1]

When we observe a remote star, two phomenona might be observed. ***Interstellar extinction*** refers to a situation that distant stars appear fainter than it would be if space were perfectly transparent. The absorption and scattering of star light by the dust in the interstellar medium (ISM) modify the distance modulus equation to $\boxed{m_\lambda - M_\lambda = 5\log r - 5 + A_\lambda}$, where m_λ and M_λ are, respectively, the apparent magnitude and the absolute magnitude of the star, and *r* is the distance measured in *pc*, and $A_\lambda > 0$ is the wavelength-dependent interstellar extinction. If A_λ is large enough, the star becomes too faint to be seen by naked eyes.

In addition, the light from remote stars is reddened as it passes through the interstellar medium because the blue component of their starlight is scattered or absorbed by interstellar dust. It is called ***interstellar reddening.*** (Fig. 7-1) In cases where the dust particle is small (a particle size smaller than 1/10 λ), the extinction coefficient α is given by [2]

$$\alpha = A\frac{N}{\lambda^4},$$

where A is a constant. The proof is out of scope. Note that the extinction coefficient is proportional to the number of ISM particles per unit volume *N* and inversely proportional to λ^4. Thus, the amount of extinction decreases with increasing wavelengths (in UV, visible and IR bands). (Fig. 7-2) The same effect causes the blueness of the sky and the redness of the sunset.

[1] Besides the funny names such as H I (instead of H) and H II (instead of H^+), astronomers also use the word "metal" to denote an element other than hydrogen and helium.

[2] Jackson, J.D., *Classical Electrodynamics* (Singapore: John Wiley & Sons, 1990), pp.422-423.

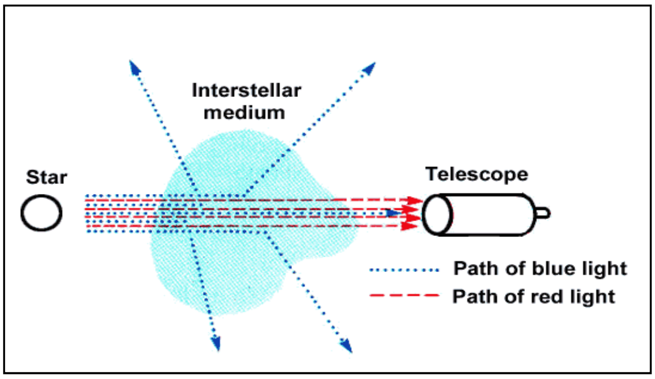

Fig. 7-1: Interstellar reddening of starlight.

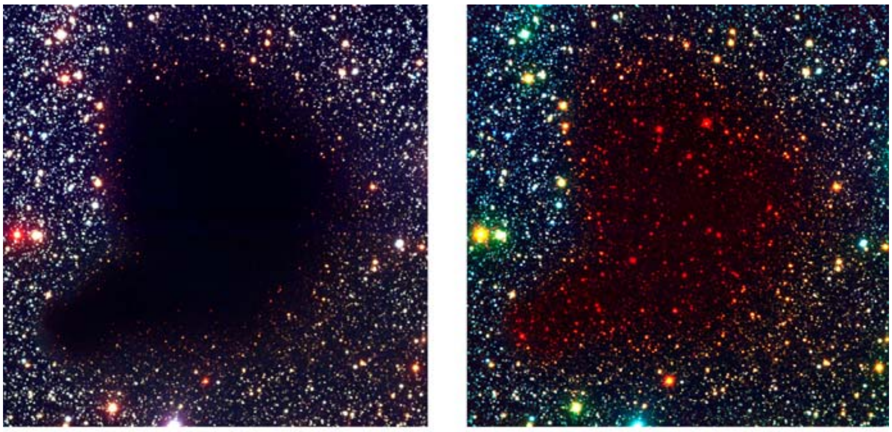

Fig. 7-2: Tri-color composite images of the Barnard 68 cloud. It is completely dark in the mostly visible-light image on the left, while numerous stars can be clearly seen in the mostly infrared photo on the right. (Note: B-band centres at ~450nm, V-band at ~550nm, I-band at ~810nm, and K-band at ~2000nm.) (Image: ESO)

Here, some terminologies in stellar astronomy are introduced. The average density of interstellar medium is very low – about a few particles per cubic cm. However, the interstellar medium is not evenly distributed in our universe. Clouds of interstellar medium with *higher density* are called **nebulae**.

Emission nebulae, or H II regions, are composed primarily of ionized hydrogen atoms, which are *ionized* by UV radiation from nearby hot stars. The hydrogen ions re-emit mostly red light when they *recapture* electrons, so emission nebulae appear red in colour (Fig. 7-3, mainly upper half). The temperature is about 10,000 K and mass about 100 - 10,000 solar masses. Because this mass is spread over a huge volume that is light-years across, the density is quite low, only about 100 - 1,000 atoms per cubic centimetre. [3]

[3] For comparison, the air we breathe on the Earth's surface is about 10^{19} atoms/cm^3).

Reflection nebulae are colder dust clouds which are usually blue (Fig. 7-3, lower left corner). Short wavelength (blue) light from nearby bright star(s) is scattered and reflected by dust gains, whereas more long-wavelength (red) light gets through the dust without scattering (Fig. 7-1). If the condition is right, the blue scattered light is the dominated emission in the nebulae.

Dark nebulae are think high-density dust clouds. The extinction is so strong that they appear to be dark (Fig. 7-3, the Horsehead Nebula). Since UV radiation from stars is shielded, the hydrogen molecules (H_2) inside the cloud can exist without undergoing dissociation. Hydrogen molecules are however quite difficult to detect because they do not have emission or absorption lines in visible or radio band. Nevertheless, scientists use radio telescopes to have identified nearly 100 particles such as hydrogen (21 cm), carbon monoxide (2.6 mm), carbon, and cyanide ion.

Fig. 7-3: Three types of nebulae. The Horsehead Nebula (with width ~0.5 pc) in Orion is a dark nebula, which blocks the red light of an emission nebula at the back. At the lower left, a reflection nebula forms around a bright star. (Image: Jean-Charles Cuillandre (Canada-France-Hawaii Telescope) / Giovanni Anselmi (Coelum))

Bok globule is relatively small (<1 pc), high density (10^4 to 10^9 particles/cm^3) and very massive (10-100 solar masses). It resembles the inner core of a dark nebula with the outer, less dense portions stripped away. Many of them contain infrared sources at the centres where may be possible star formation sites. (See the section of "The Formation of Stars" below)

Giant molecular clouds are typically very huge, spanning over 15 to 100 pc and containing up to a million solar masses. They may contain bright H II regions excited by hot stars, and low-temperature (~15 K) regions with high density (~10^8 particles cm^{-3}). The Horsehead Nebula in Fig. 7.3 is a small part of the Orion Molecular Cloud Complex.

7.2 The Formation of Stars

A cloud tends to contract due to the *gravitational force* among the particles. On the other hand, the random *thermal motions* of the particles provide pressure support which tends to expand the cloud. Turbulence and rotational motions of particles provide further support to resist contraction.

The **Virial Theorem** theorem providers a condition for equilibrium of a gravitationally bound system: $2K + U = 0$, where K and U are, respectively, the kinetic energy and the gravitational energy of an equilibrium cloud. The derivation of the theorem is found in $\mathscr{Box}\ 8.1$.

Observation evidences show that most clouds in the sky ar*e not* dense enough to contract by their own gravity. Star formation is usually triggered by some shock waves. Possible sources of shock waves are: exploding stars at their final stage of evolution such as supernovae; radiation pressure coming from neighbouring stars; collision between molecular clouds or galaxies (Fig. 7-4); and density waves generated by galactic rotations.

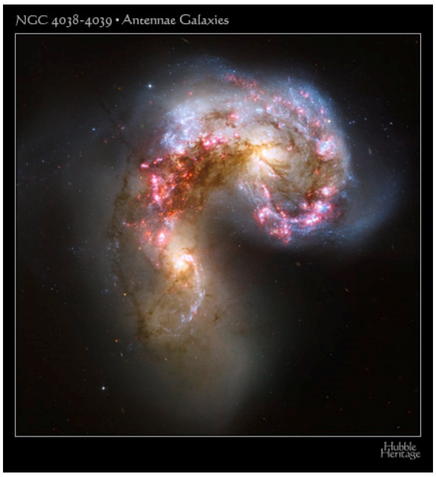

Fig. 7-4: A pair of merging galaxies, collectively known as the Antennae galaxies. The collision has triggered a lot of star-forming activities. (Image: NASA, ESA, and the Hubble Heritage Team (STScI/AURA)-ESA/Hubble Collaboration)

Shock waves could trigger fragment formation. (Fig. 7-5) If the contracting cloud is too large such as mass > 100 solar masses, it becomes unstable during contraction. It would fragment into smaller pieces, and each might form a new star. The group of young stars, called **cluster** (星團), forms at about the same time.

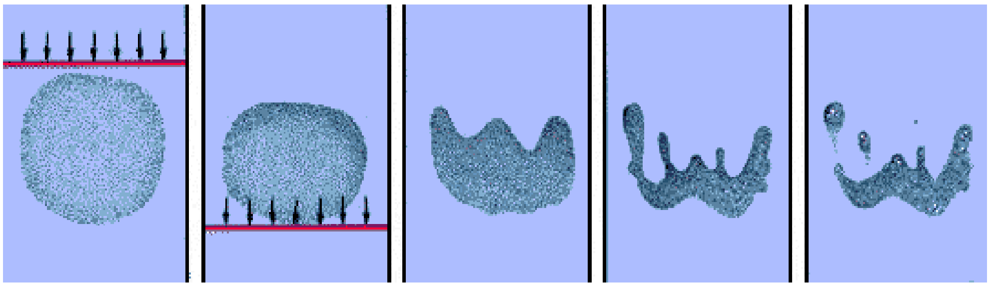

Fig. 7-5: Shock waves cause fragments of a molecular cloud, and some fragments may further collapse and form individual stars.

Once the gravity overcomes the supporting forces, the cloud starts to contract. In this initial free-fall phase, the density is low enough that the gravitational potential released radiates effectively from the cloud. The temperature is almost constant, and the collapse is isothermal. As the cloud contracts, the density increases. Collisions among particles are more often, and the temperature and pressure increase gradually.

Protostar (原恒星) is the core of collapsing cloud which is hot enough to emit infrared radiation, yet not hot enough to ignite nuclear fusion. It enters the upper-right area of the **Hertzsprung-Russell diagram** (赫羅圖). The protostar is at the centre of the collapsing cloud, and is enveloped by cocoons, which are colder and lower-density clouds. The surrounding clouds absorb light from the protostar (inner region), and re-radiates the energy as infrared radiation. Therefore, the infrared sources signal the sites of star formation. Due to the net angular momentum of the collapsing cloud, a rotationally supported circumstellar disk is formed around the protostar. The structure is also known as a **protoplanetary disk** because planets are believed to be formed by condensation and accretion in the disk. (Fig. 7-6)

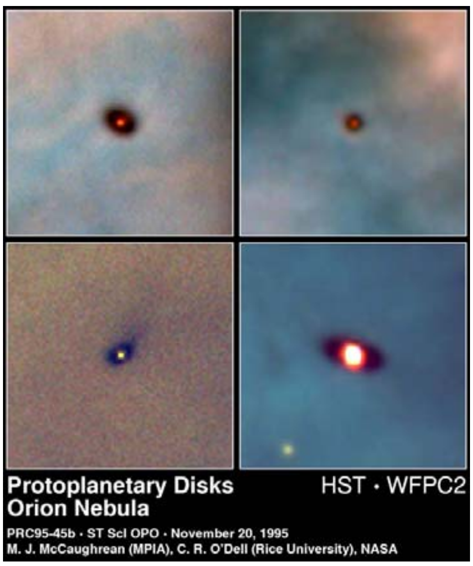

Fig. 7-6: The protoplanetary disks show the star formation regions in the Orion nubula.

At this stage, the luminosity of the protostar may vary significantly and irregularly with time. Those objects are known as T Tauri stars. Star formation process could also produce outflow of gas. The gaseous jets ejected along the axes of disks could reach a long distance from the object. (Fig. 7-7)

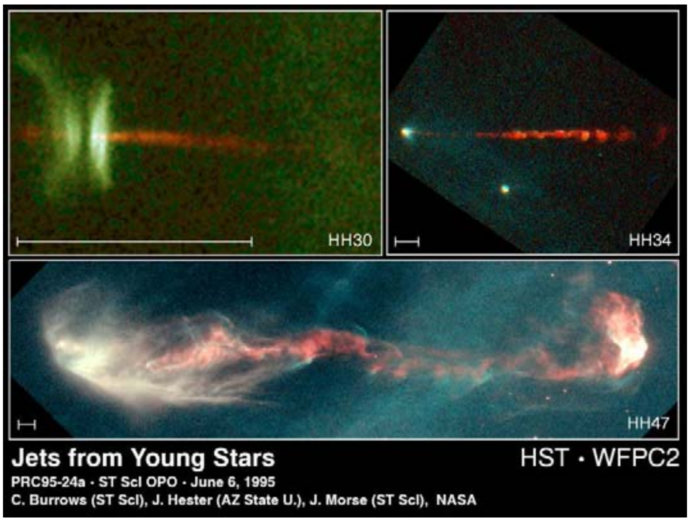

Fig. 7-7: The Hubble Space Telescope images of gaseous jets from three newly forming stars. The scale in each of the three panels indicates a distance of 1000 AU.

Radiations from the increasing hot protostar eventually vaporizes and clears the cocoon, and the protostar becomes visible. It is now at the **birth-line** on the H-R diagram (the dotted line in Fig. 7-8). The time taken for a main-sequence star to form depends on the mass. In general, massive protostars collapse faster due to the stronger gravity. When the central temperature becomes higher than 10^7 K, nuclear fusion is ignited at the core. A lot more energy is generated, and the temperature rises further. On the H-R diagram, the star moves to the left (hotter). When the thermal pressure and radiation pressure finally balance the gravity, the collapse ceases and the star becomes stable. The star now resides on the **main sequence**, on which it will keep shining for a long time.

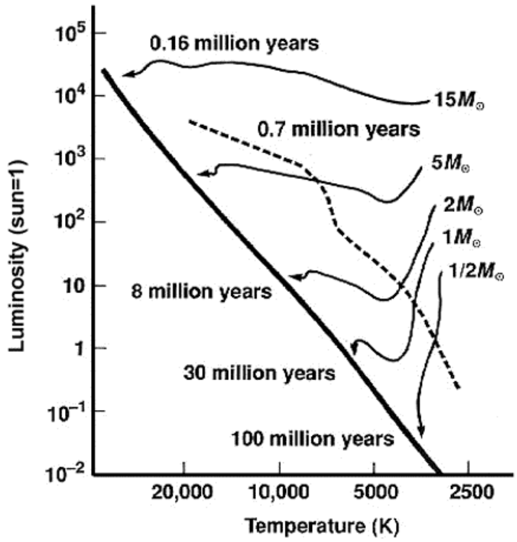

Fig. 7-8: The paths of the protostars entering the main sequence in the H-R diagram. A more massive protostar has stronger gravity and thus faster contraction. The dashed line is the birth line, where the protostars become visible as they clear the surrounding clouds.

However, not all the protostars will evolve into the main sequence:

- Below the lower mass limit (the protostar's mass is too small, $< 0.08\ M_\odot$), the centre of a protostar is *not hot* and *dense* enough to ignite nuclear fusion (at least not the main type of nuclear fusion in star). The object never reaches the main sequence. It is known as a **brown dwarf** (棕矮星), which emits infrared radiation and cools slowly.
- Above the upper mass limit (the protostar's mass $\gtrsim 100\ M_\odot$), the massive large cloud is gravitationally unstable,[4] and will likely fragment to pieces of smaller masses.[5]

[4] The Jeans Instability happens when the self gravity at a certain length scale overcomes the thermal pressure.

[5] In some cases, the massive protostar does form a massive star with mass beyond 100 $M_\odot$. The most massive star on record is the 265-solar-mass blue R136a1 (see http://www.eso.org/public/news/eso1030/). Those massive stars are *not* classified as main-sequence stars for various reasons. They also evolve differently compared to main-sequence stars.