宇宙物質的回收與再生：恆星與星際物質

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Most of nearby stars are actually less massive (therefore “redder”) than the Sun.

Colors denote different surface temperature.

horizon = 13.1 light years
Stellar Magnitude (星等)

http://calgary.rasc.ca/stellarmagnitudes.htm

\[ 100^{\left( m_1 - m_2 \right) / 5} = \frac{L_2}{L_1} \]

5 magnitudes ⇒ x100 luminosity

Sun (-26.7)
- Full moon (-12.6)
- Venus (at brightest) (-4.4)
- Sirius (brightest star) (-1.4)
- Naked eye limit (+6.0)
- Binocular limit (+10.0)
- Pluto (+15.1)
- Large telescope (visual limit) (+21.0)
- Hubble Space Telescope and large Earth-based telescopes (photographic limit) (+30.0)
note

The values of stellar magnitudes shown in the previous slide are so-called “apparent visual magnitudes” (視星等). In other words, they do not indicate their intrinsic luminosity (i.e. “absolute magnitude” 絕對星等) because an intrinsically more luminous star might look dimmer due to its longer distance from us.

Remember that some “stars” appear extremely bright but do not twinkle in the night sky. They are actually the reflected light from the planets in the Solar System.
Interstellar Medium (星際物質)

- contents: the gas and dust distributed between stars (not truly vacuum)
- interstellar dust: micron-size solid grains
- interstellar gas: 75% H + 25% He + heavier elements (in different forms: atomic, molecular, and ionized)
- structure: clumpy (number density ≈ 0.01-10^5 per cm^3 c.f. 10^{19} per cm^3 on the ground of the Earth) and turbulent (supersonic!)

a model of an interstellar dust:

Speaking of ices in astronomy, it does not imply water ice only, but sometimes is referred to dry ice 乾冰 (CO2), ammonia ice 阿摩尼亞 冰 (NH3), and methane ice 甲烷 冰 (CH4) because they are all abundant in the interstellar medium (of course, they are still far less than H and He gases) and may be frozen into a solid form under an extremely cold condition. We would learn more about this when we talk about the atmospheres of different planets.
Gravitational Collapse (重力塌縮)

self gravity > pressure
→ collapse

self gravity (related to density)

pressure (related to temperature or special quantum effects in extremely dense cases)
Scenario of Star & Planet formation

A star is made of gas → star formation needs gas → a star forming region is full of dense gas and dust (原料).
In our daily life, we are aware of the gravity from the Earth other than from anything else. In astronomy, the space scale and therefore the mass that is involved is so large that gravity plays an important role everywhere.

The important concept of star formation is that gas needs to be gathered together. As a result, the gas becomes so dense (so-called molecular cloud 分子雲) that the gravitational pull of the cloud itself dominates its own pressure. Gravitational collapse ensues and then many stars form in the gas cloud. This is why stars form in cluster.

During the collapse to form stars, a number of processes occur: jet (噴流) as a gas outflow from the star forming region, and an accretion disk (吸積盤 or called a “proto-stellar disk 原始恒星盤) forms to feed the gas into the central proto-star (原始恒星). A proto-star grows until the accretion disk finally disappears. A proto-star will become a star once nuclear fusion starts to occur at its center.
Star forming regions: dust & gas

Nebula (星雲)
1. star formation: emission (發射星雲；氫被激發而放出紅色), reflection(反射星雲，氫如大氣般散射而呈藍光), dark(暗星雲；塵埃擋住背景的輻射而呈黑暗) 注意：這些分類是就可見光而言
2. dying (evolved) stars: planetary(行星狀星雲)
Why is the sky blue (scattering 散射)?

Blue light scatters more than red light. When the Sun is high in the sky you will see all of the colors if you look right at the Sun. But looking in other directions, you will see just the blue colors because some of the blue sunlight will be scattered back to you. When the Sun is near the horizon, the blue sunlight is scattered away leaving only the red and orange sunlight—the Sun appears red.

http://www.astronomynotes.com/telescop/s12.htm
Charles Messier (1730-1817) compiled a list of approximately 100 diffuse objects (nebulae, star clusters, galaxies) that were difficult to distinguish from comets through the telescopes of the day. [http://www.seds.org/messier/](http://www.seds.org/messier/)

John L. E. Dreyer (1852-1926) compiled a catalogue of deep sky objects including the data from Herschel. This so-called “New General Catalogue” (known as NGC) contains nearly 8000 objects. [http://www.ngcic.org/](http://www.ngcic.org/)
Horse head Nebula

Multiple wavelength investigation!

Visible (courtesy of Howard McCallon), near-infrared (2MASS), and mid-infrared (ISO) view of the Horsehead Nebula. Image assembled by Robert Hurt.

http://coolcosmos.ipac.caltech.edu/cosmic_classroom/irTutorial/irregions.html
Star forming region: Orion Nebula

Infrared emissions can penetrate dusts because infrared has longer wavelength than visible.

(例子：船與波浪).
Unlike visible light, infrared can penetrate interstellar dusts to reveal the star forming region embedded inside the dusts. The main reason is that interstellar dusts are very small; they are only micron-size which is comparable to the wavelength of infrared radiation but is larger than the wavelength of visible light. To visualize how this works, you may think of the “船與波浪” analogy. When we sail a boat and encounter incoming ripples (water waves), the boat can block the ripples if the wavelength of the ripples (i.e., the distance between two adjacent peaks of the ripple) is much smaller than our boat. However, if the wavelength of the ripple is comparable to the size of our boat, our boat would move up and down together with the “large” ripple and at the same time, the ripple still moves forward without being blocked by our boat.
Shock wave (衝擊波) → Compression
note

Grasping air by your hands seems like a “mission impossible”. However, if your hand can move faster than the speed of sound, the air in front of your hand does not have enough time to escape and therefore is accumulated to become denser. The dense air forms in front of a supersonic motion of an obstacle (your hand in this case) is a phenomenon called a “shock wave”.

The animation you saw in class (previous slide) shows liquid water condensed from the compressed air in front of the supersonic fighter. That is, the supersonic fighter sweeps and hence compresses the air in front of it. A shock wave forms. The shock wave causes water vapors within the compressed air to get closer and therefore bond together, resulting in the formation of liquid water. Note that the fighter flies very low, so the liquid water condensed from the air is not due to low temperature at a high altitude.
Making Stars: triggered by a supernova

Cygnus loop: supernova occurred 20000 years ago.
Size is about 120 ly

X-ray image

Supernova → shocks in interstellar medium
→ Compress gas → gas contracts by gravity
→ Stars form in cluster

Figure 12-7
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Making stars: triggered by OB stars

Star formation progresses in this direction

Shell of hydrogen that has not yet been ionized

Older cluster
Old cluster

Expanding region of ionized hydrogen (H II)

Young cluster

New stars being formed

Giant molecular cloud
Shock wave spreads into molecular cloud

Figure 12-17a
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Thermal Expansion
A supernova 超新星 (an explosion of a dying massive star) or the thermal expansion of gas driven by the intense radiation from a group of OB stars (ie massive stars) can act like a supersonic fighter. They sweep and compress the interstellar medium, generating shock waves. The compressed interstellar gas may become dense enough to collapse gravitationally against its own pressure. Consequently, stars form within the shock waves.
Monoceros (麒麟座)

NGC2237 Rosette nebula
Making stars: triggered by OB stars

Rosette Nebula (NGC 2237 蕃薇星雲):
OB stars → UV radiation → expanding hot gas → shock compression → gravitational collapse → stars form in cluster

emission (diffuse) nebula
(Balmer emission lines)
Summer’s Constellations

- M16
- M20
Star forming region: dust, gas, & evaporation!

1. This emission nebula (about 2200 pc away and about 20 pc across) surrounds the star cluster M16.

2. Star formation is still taking place within this dark, dusty nebula.

3. Hot, luminous stars (beyond the upper edge of this image) emit ultraviolet radiation: This makes the dark nebula evaporate, leaving these pillars.

4. At the tip of each of these pillars is a nebula containing a young star.

5. Eventually the nebulae evaporate, revealing the stars.

Eagle Nebula (M16)
Trifid Nebula (M20)

人馬座三裂星雲

dust
Accretion Disks & Jets

Accretion disk around a proto-star (proto-stellar disk)

Jets from Young Stars

PRC95-24a · ST ScI OPO · June 6, 1995
C. Burrows (ST ScI), J. Hester (AZ State U.), J. Morse (ST ScI), NASA
Formation of Stars in a turbulent cloud

http://www.ukaff.ac.uk/starcluster/

Key words:
turbulence
gravitational collapse
proto-stellar disks
multiple-star systems
stellar cluster
ejection of stars

A proto-stellar disk will disappear and the proto-star will continue to contract until it becomes a main-sequence star, i.e. hydrogen starts to fuse into helium at the center.
Remark: unlike the energy generated by nuclear fission, nuclear fusion does not produce nuclear waste. Physicists have been working hard to generate and sustain the nuclear power through nuclear fusion, but there has never been any success so far.
There is no cold fusion

室温下的核融合？
young open clusters (疏散星團) in Taurus

Stars in an open cluster form almost at the same time

- NGC 1746
- M 1
- NGC 1647
- M 45
- Pleiades (~100 million yrs old)
- 7 sisters
- Subaru
- < Hyades
- 畢宿星團
- (~700 million yrs old)
Why is the Sun so “lonely”?

• Stars form in (open) cluster $\rightarrow$ what’s wrong with the Sun (or other “field” stars) in the past?

• Number of open clusters is decreased with age $\rightarrow$ most of open clusters disperse as they age (probably due to an evaporation process)

• The Sun used to be one member of an open cluster (supposedly).
The Sun as an example of a star

Definition of a star: an object is massive and dense enough to allow nuclear fusion to occur.

- Thermonuclear energy core
- Radiative zone
- Convective zone
A hot gas can cool by two means: radiation 輻射 and convection 對流. Radiation is a process in which light (electromagnetic waves) carries energy away from a hot region to a cold region. So the hot region is losing energy through this process but no gas flow is involved. Convection is a different cooling process in which hot gas is lighter and hence rises against gravity just like a hot balloon. In other words, there is a gas flow to bring energy from a hot region to a cold region.
Stellar Mass, Color, & Luminosity

notice that mass spread vs luminosity spread

main-sequence (主星序):
Hydrogen fusion at center of a star

For a main-sequence star, high mass means high luminosity...

…while low mass means low luminosity.
Figure 11-4b
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Main-Sequence Lifetimes

Evolution depends on mass.

<table>
<thead>
<tr>
<th>Mass ($M_\odot$)</th>
<th>Surface temperature (K)</th>
<th>Luminosity ($L_\odot$)</th>
<th>Time on main sequence ($10^6$ yrs)</th>
<th>Spectral class</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>35,000</td>
<td>80,000</td>
<td>3</td>
<td>O</td>
</tr>
<tr>
<td>1.5</td>
<td>30,000</td>
<td>10,000</td>
<td>15</td>
<td>B</td>
</tr>
<tr>
<td>1.0 (Sun)</td>
<td>11,000</td>
<td>60</td>
<td>500</td>
<td>A</td>
</tr>
<tr>
<td>0.75</td>
<td>7000</td>
<td>5</td>
<td>3,000</td>
<td>F</td>
</tr>
<tr>
<td>0.50</td>
<td>6000</td>
<td>1</td>
<td>10,000</td>
<td>G</td>
</tr>
<tr>
<td></td>
<td>5000</td>
<td>0.5</td>
<td>15,000</td>
<td>K</td>
</tr>
<tr>
<td></td>
<td>4000</td>
<td>0.03</td>
<td>200,000</td>
<td>M</td>
</tr>
</tbody>
</table>

Due to extremely high luminosity, high-mass stars are using up their fuel (ie fusing 4 hydrogen to one Helium) more quickly than low-mass stars. This is why massive stars are short-lived.

Table 12-1
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longer than the current age of the Universe!
Hertzprung-Russell Diagram (赫羅圖)

Tells us about the evolution of a star, a nuclear process depending on the stellar mass (see the previous slide to know the mass)!

Please note that the huge spread of stellar luminosity.
Horizontal Branch & Asymptotic Giant Branch

**Horizontal branch:** He fusing in the core

\[ 3\text{He} \rightarrow \text{C} + \text{energy}; \text{He} + \text{C} \rightarrow \text{O} + \text{energy} \]

**Asymptotic Giant branch:**
core collapses (no fusion) but outer layer expands (shell He fusing)
You don’t need to know the very much details (such as horizontal branch & asymptotic branch) about the stellar evolution on the Hertzprung-Russell diagram (赫羅圖). But you should know a rough picture for a life of a star on the Hertzprung-Russell diagram:
proto-star in a proto-stellar disk with jets
→ main-sequence star 主星序星 (making Helium)
→ red giant star 紅巨星 (making carbon, oxygen, or other heavier elements)
→ planetary nebula 行星狀星雲 (fate of less massive stars) or supernova 超新星 (fate of more massive stars)
→ a dense stellar core: white dwarf 白矮星 or neutron star 中子星 or black hole 黑洞

We will focus on the final stage of a star (ie white dwarf, neutron star, and black hole) in one of the next lectures.
Supergiant & Element Factory

Very strong stellar wind due to low gravity & high luminosity

We are all star dusts!
Planetary nebulae: fate of low mass stars

Planetary nebulae in our universe are short-lived. Therefore, we can conclude that these nebulae must be a common end stage in stellar evolution. All stars, no matter how massive, are destined to die as planetary nebulae.

The Hourglass Nebula

The Hourglass Nebula is a region in the constellation Cassiopeia. This nebula is visible even in small telescopes. The cloud, or nebulosity, found in the constellation Cassiopeia, is the result of the hot blue star at its center and the radial texture in the gas, suggesting outward motion.

The dense gas that produces planetary nebulae involves two stellar winds. First, the gas is ejected from the outer layers of the star in a slow wind of low-excitation gas that is not visible. Once the hot interior of the red giant is exposed, it ejects a high-speed wind that overtakes and compresses the slow wind, much like a snowplow. Ultraviolet radiation from the hot central star excites the gas, causing it to glow like a giant neon sign.

We see a planetary nebula when the last wind compresses the slow wind.
A star like our Sun will convert hydrogen to helium and then to heavier elements such as carbon and oxygen at its center. At this stage, the star will inflate to a huge size and become a supergiant. The stellar surface now is far from the stellar center and therefore experiences very small gravitational pull. The gas on the surface can then easily escape and forms strong stellar winds. The heavy elements such as carbon and oxygen manufactured at the stellar center can be brought away by the winds to the interstellar space where new stars and/or planets may form. This is why stars are element factories and we are all star dusts. Soon after the supergiant phase, the star loses lots of gas and becomes a planetary nebula, leaving a very dense, hot stellar core at the center. This dense core is a white dwarf.
Supernova 超新星: fate of high mass stars

致和元年(A.D.1054)，五月已丑，客星出天關東南，可數寸，歲餘稍沒 《宋史》。

Figure 13-18b
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- as bright as the Milky Way
- once per century in our galaxy

Pulsar (脈衝星) was thought to be a signal from an advanced alien civilization 😊
Summary I: star formation

• 什么是星際物質(interstellar medium)？
• 如何可以造成重力塌縮(gravitational collapse)？
• 什么是原始恆星(proto-star)的噴流(jet)？
• 星雲(nebula: emission, reflection, dark, and planetary)和恆星形成演化有關嗎？
• 疏散星團(open cluster)和恆星形成有關嗎？
• 如何透視星際塵埃？
• 恆星的定義為何？
Summary II (stellar evolution depends on mass)
Cosmic Cycle

Ehrenfreund & Charnley 2000