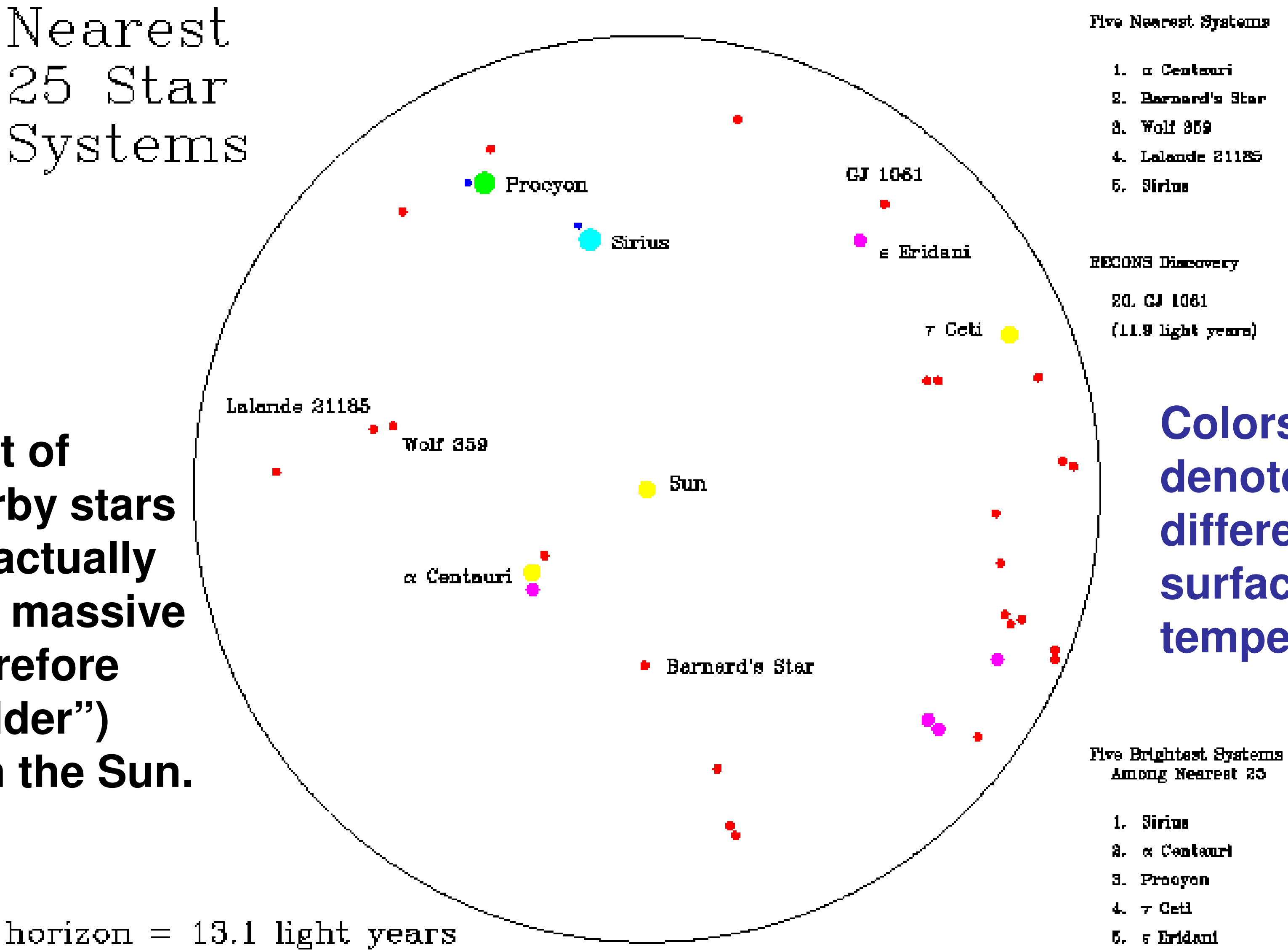
宇宙物質的回收與再生：恆星與星際物質

辜品高
師大地科系
中研院天文所

http://www.chara.gsu.edu/~thenry/RECONS/map25.html



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

Colors denote different surface temperature.

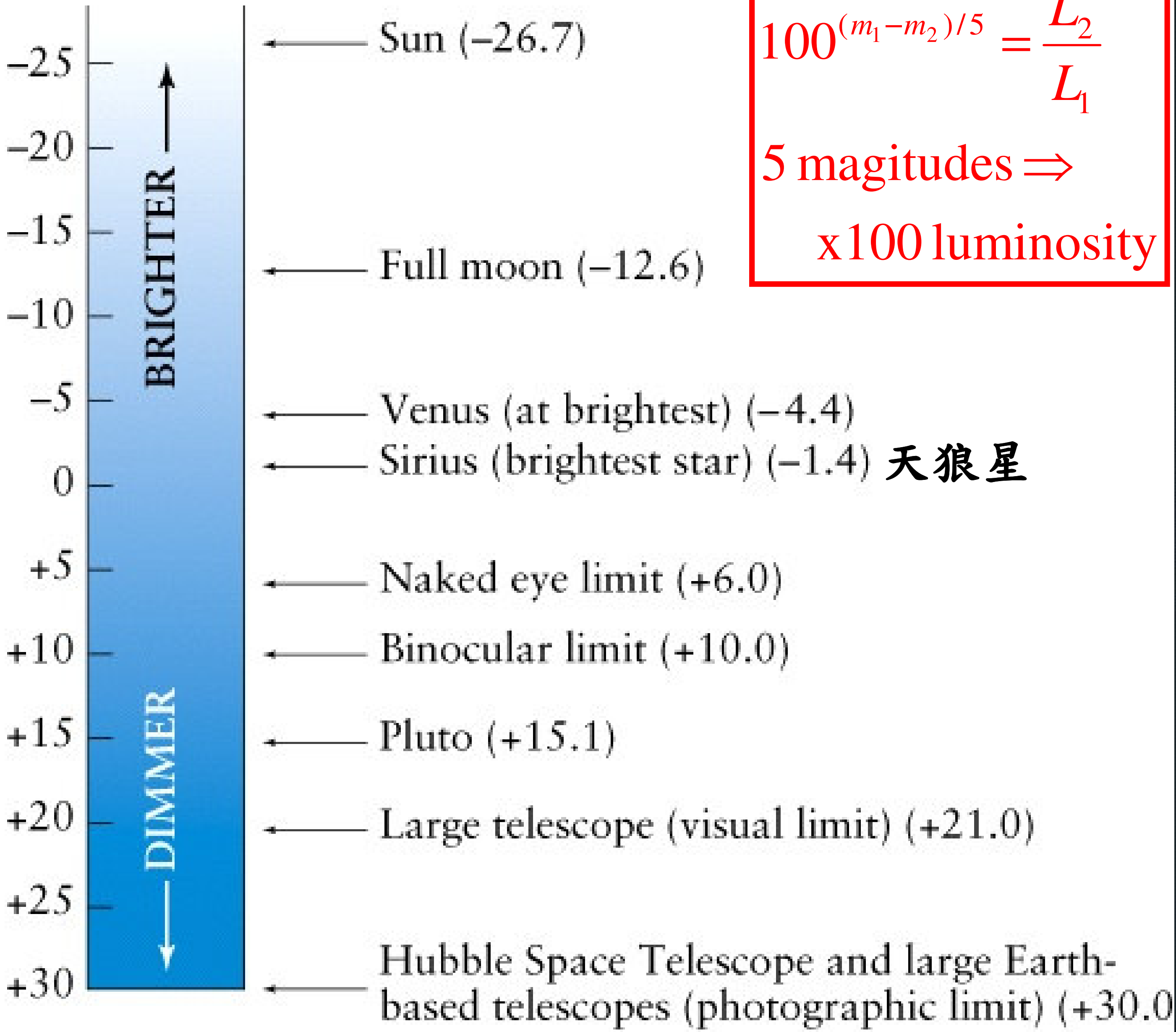
Stellar Magnitude (星等)

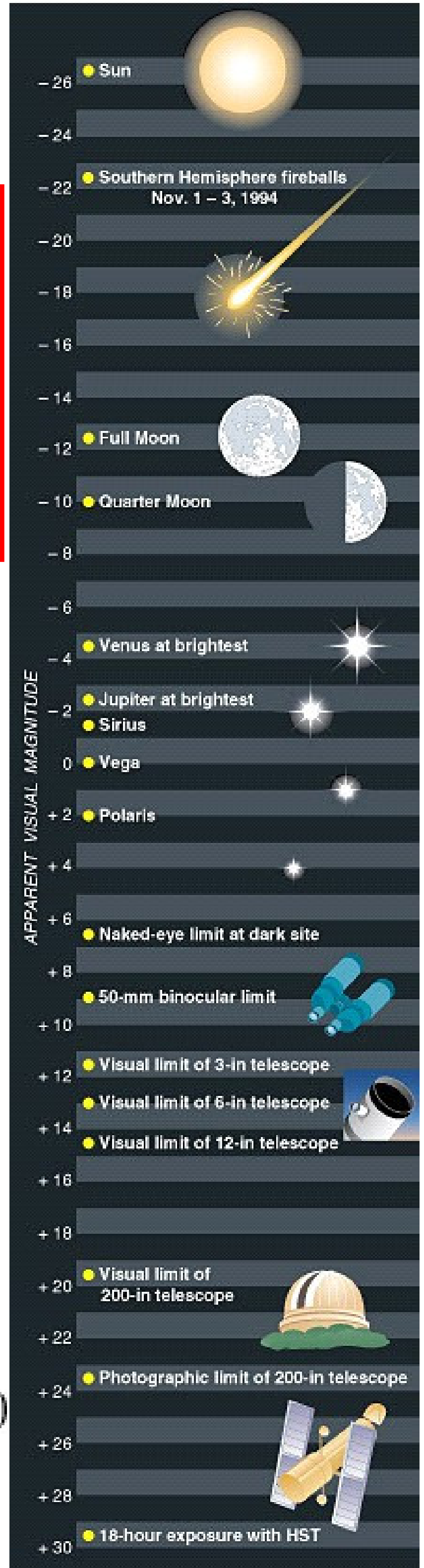
http://calgary.rasc.ca/stellarmagnitudes.htm

$$100^{(m_1-m_2)/5}=\frac{L_2}{L_1}$$

5 magitudes ⇒

x100 luminosity





note

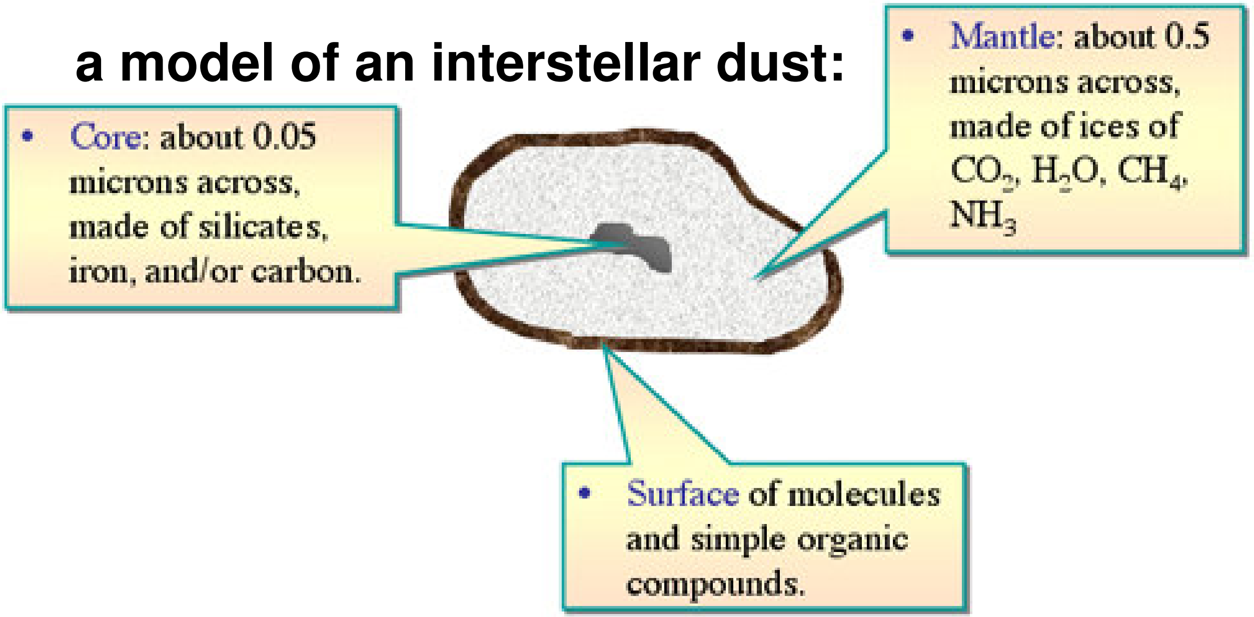
The values of stellar magnitudes shown in the previous slide are so-called "apparent visual magnitudes" (視星等). In other words, they do not indicate their intrinsic luminosity (i.e. "absolute magnitude" 絕對星等) because an intrinsically more luminous star might look dimmer due to its longer distance from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



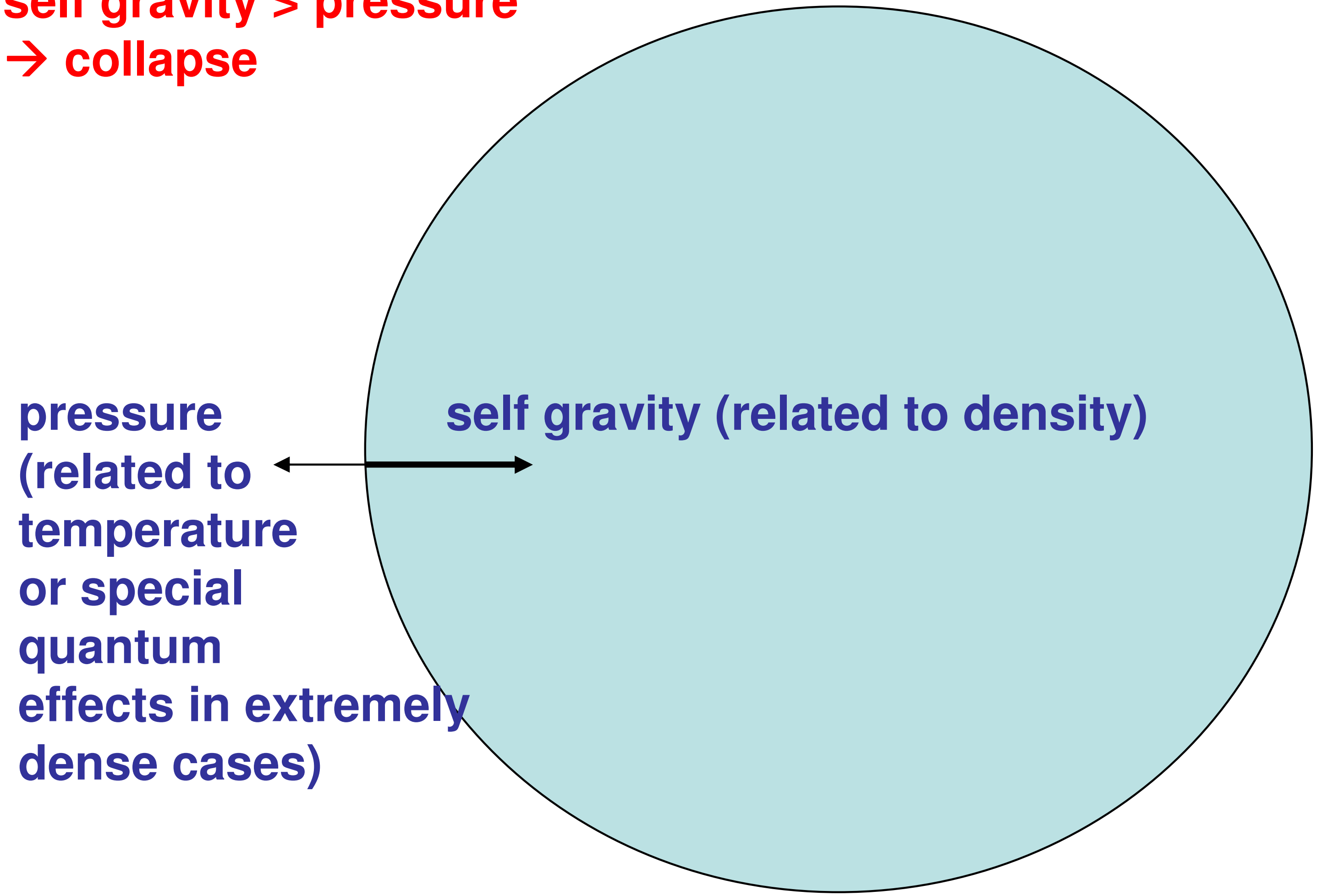
http://cosmos.swin.edu.au/lookup.html?e=dustgrain

note

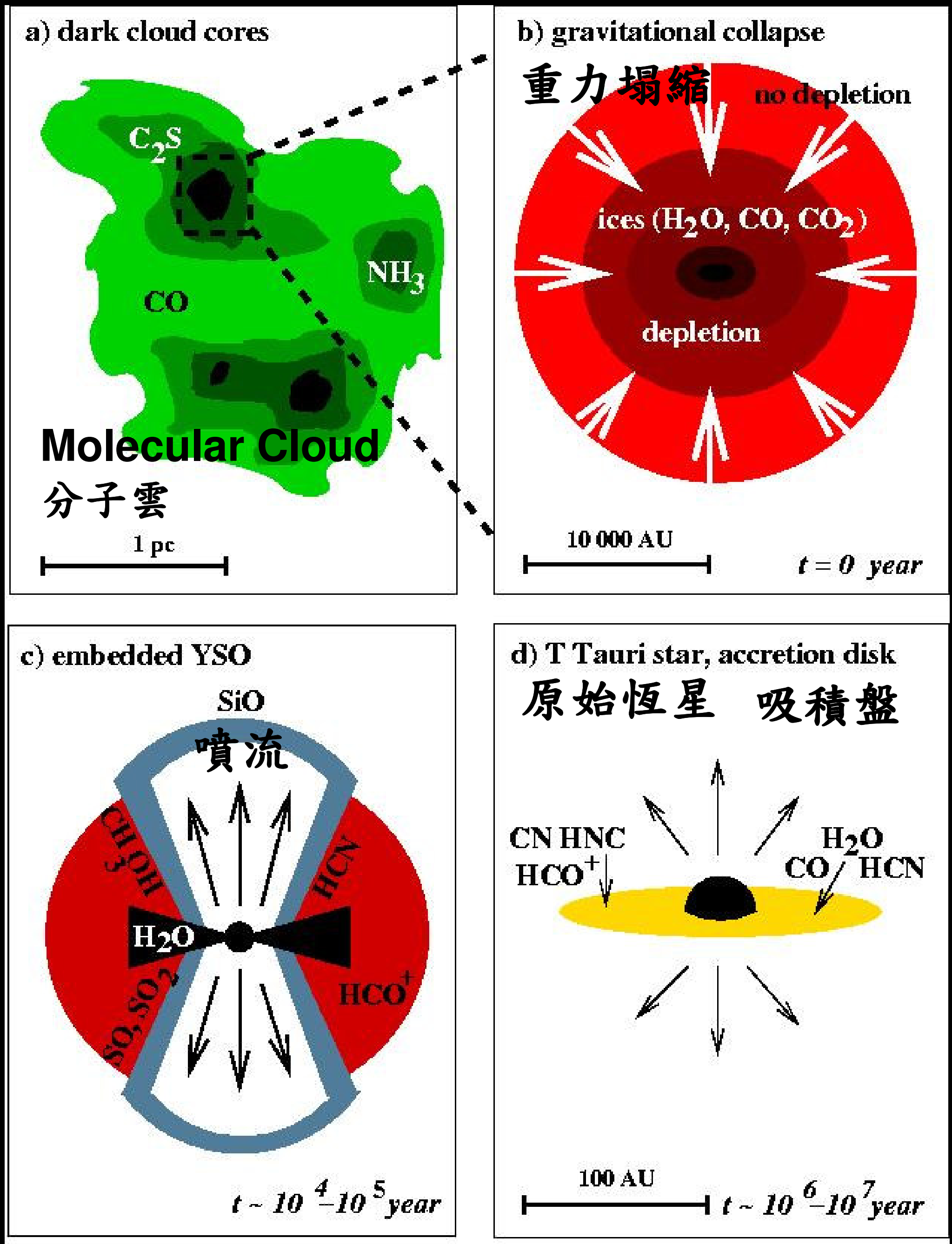
Speaking of ices in astronomy, it does not imply water ice only, but sometimes is referred to dry ice 乾冰 (CO_2), ammonia ice 阿摩尼亞冰 (NH_3), and methane ice 甲烷冰 (CH_4) because they are all abundant in the interstellar medium (of course, they are still far less than H and He gases) and may be frozen into a solid form under an extremely cold condition. We would learn more about this when we talk about the atmospheres of different planets.

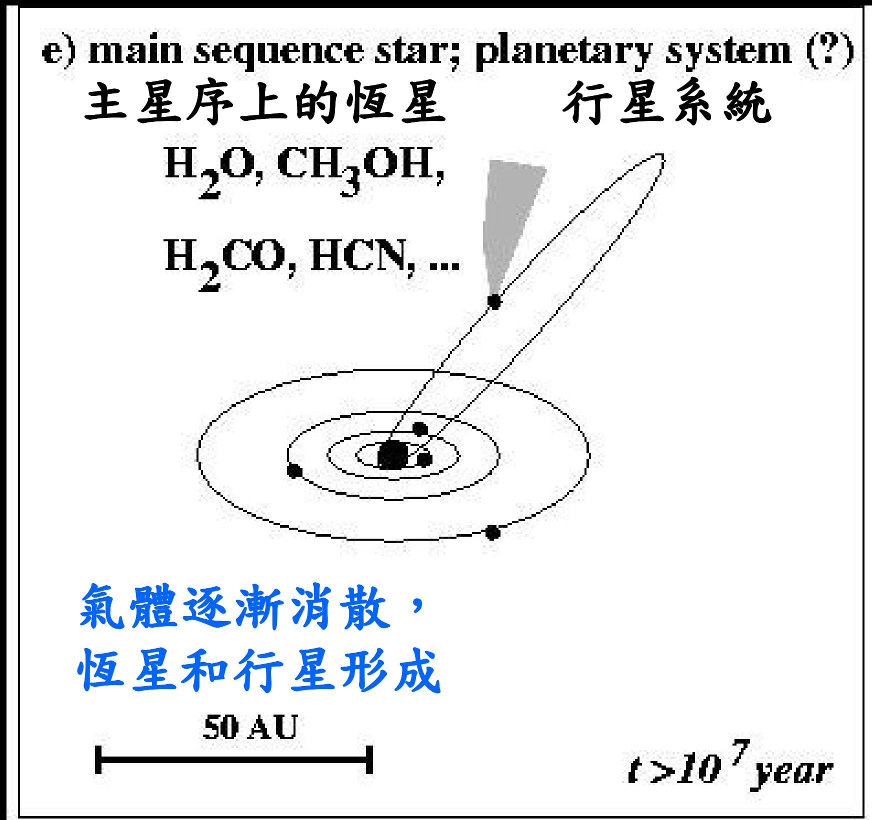
Gravitational Collapse (重力塌縮)

self gravity > pressure
→ collapse



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).

note

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 原始恆星盤) forms to feed the gas into the central proto-star (原始恆星). 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

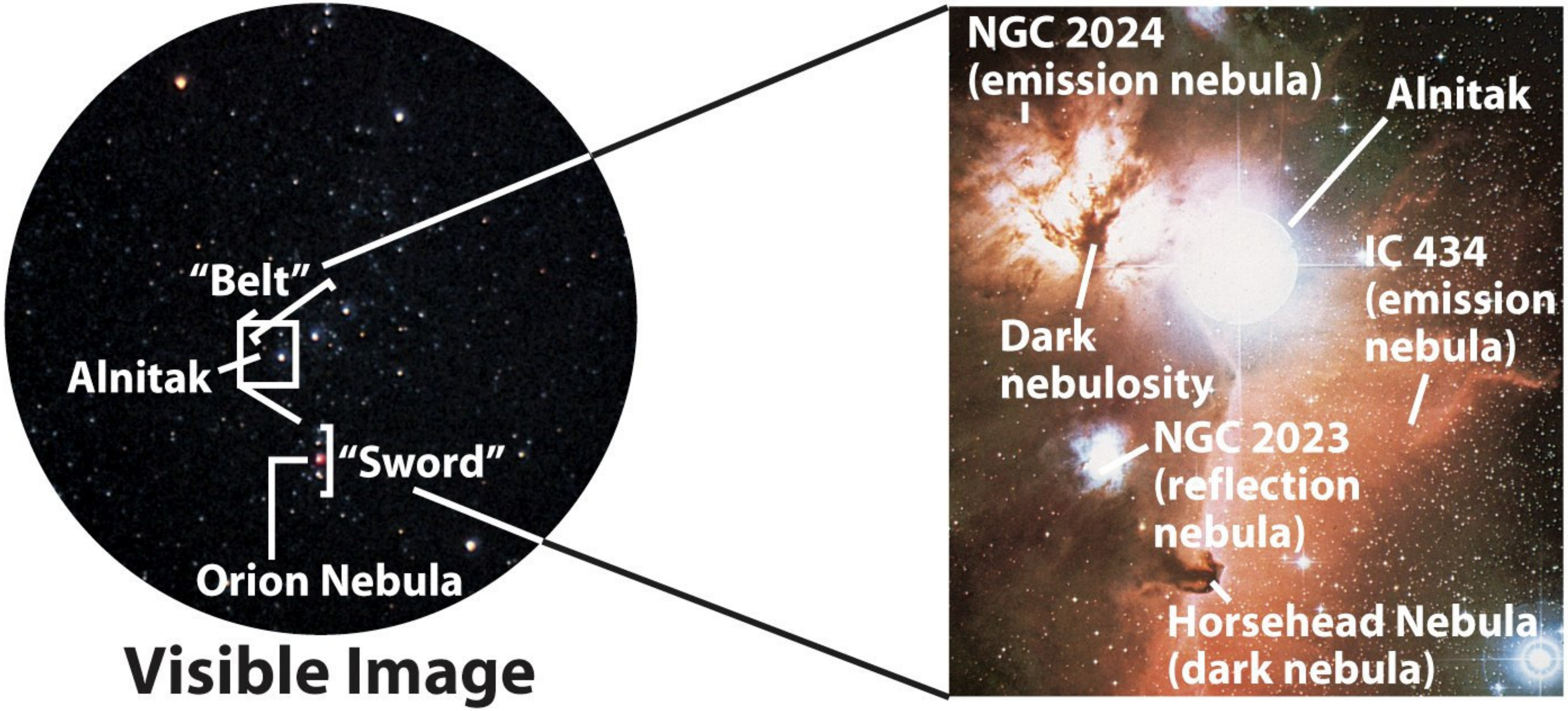


Figure 12-5bc
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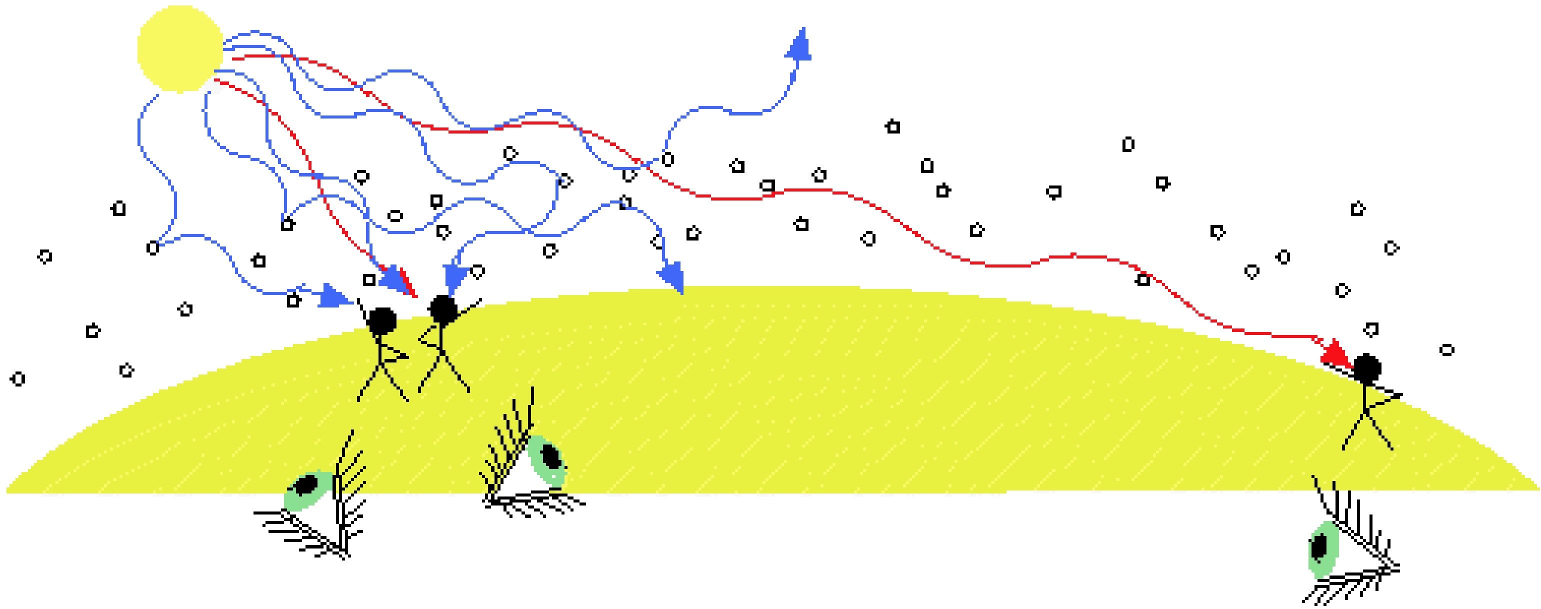
Nebula (星雲)

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)?

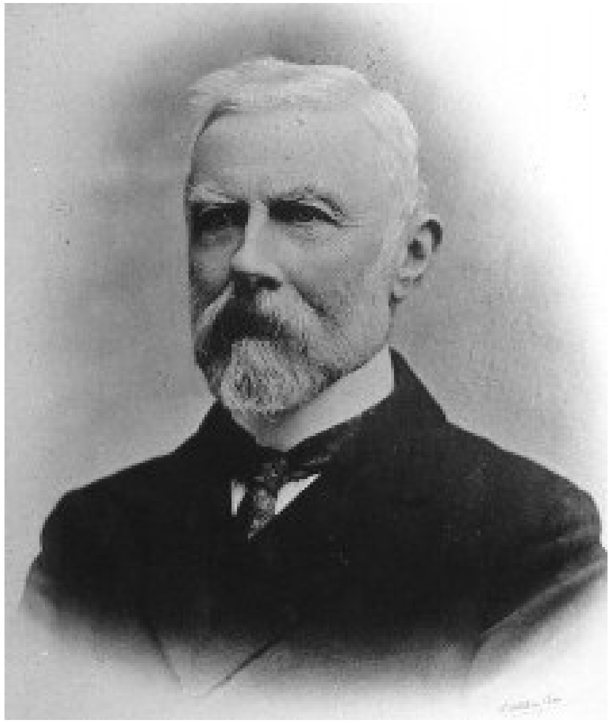


Blue light scatters more than red light. When the Sun is high in the sky you will see all of the colors if you look right at the Sun. But looking in other directions, you will see just the blue colors because some of the blue sunlight will be scattered back to you. When the Sun is near the horizon, the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

http://www.astronomynotes.com/telescop/s12.htm

天體目錄

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/



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/

Horse head Nebula

Multiple wavelength investigation!

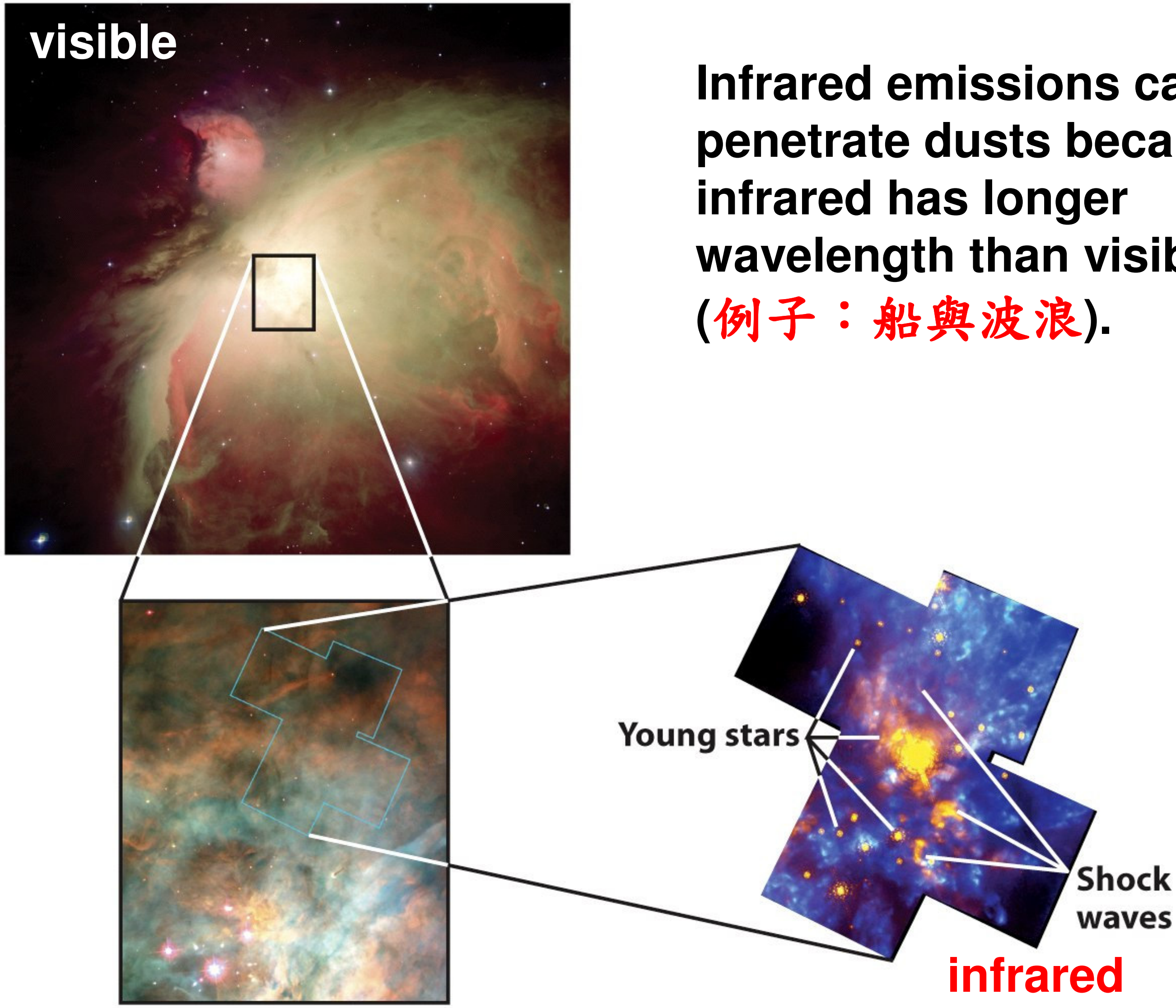
Alnitak

Near-infrared light from stars penetrate dusts

light from cold dusts
Shown in mid-infrared

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/ir_tutorial/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).

Figure 12-16
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note

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 (ie 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

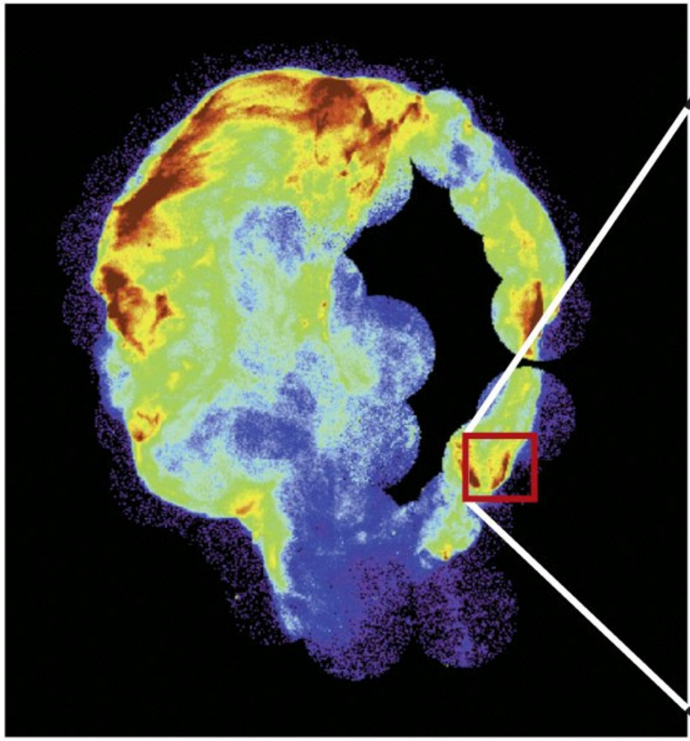
note

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”.

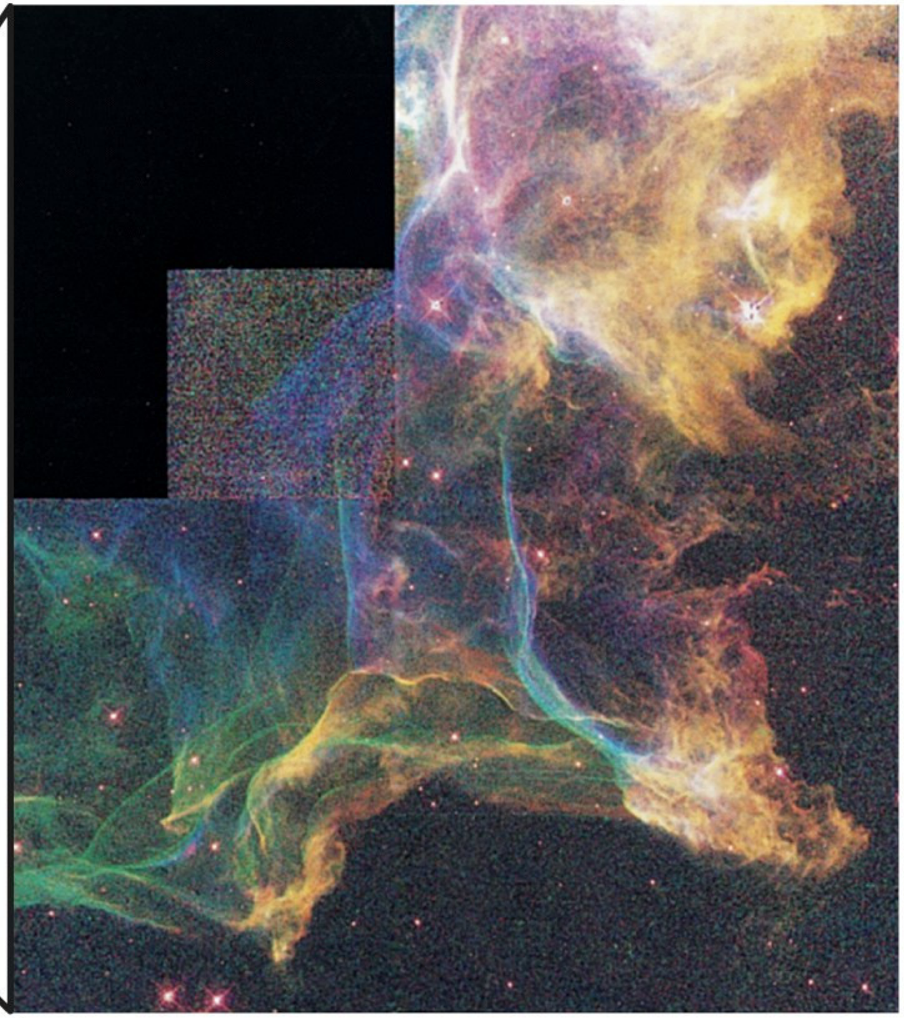
The animation you saw in class (previous slide) shows liquid water condensed from the compressed air in front of the supersonic fighter. That is, the supersonic fighter sweeps and hence compresses the air in front of it. A shock wave forms. The shock wave causes water vapors within the compressed air 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



a **X-ray image**



b **optical image by HST**

Figure 12-7
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supernova → shocks in interstellar medium →Compress gas → gas contracts by gravity → stars form in cluster

Making stars: triggered by OB stars

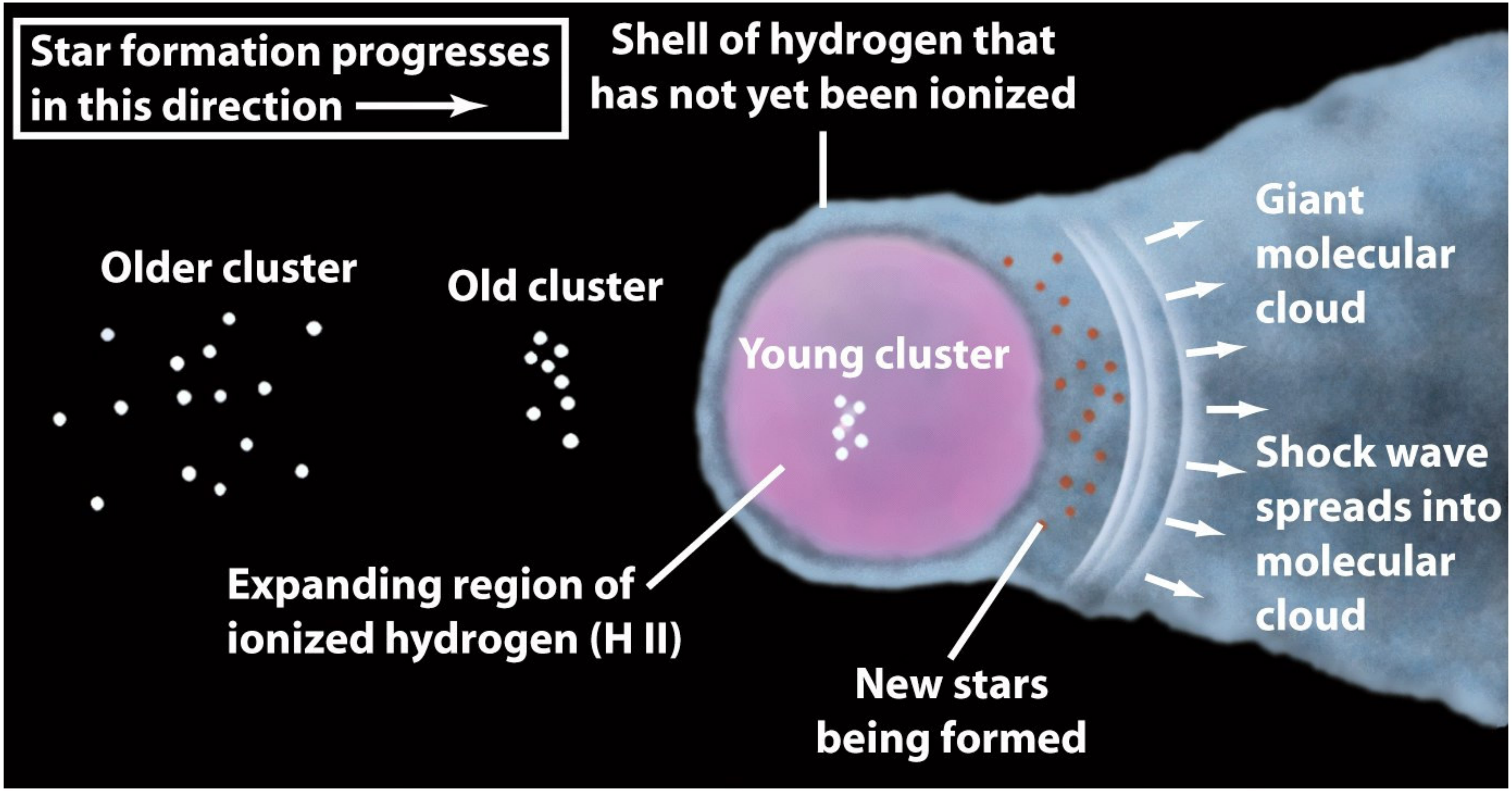

Figure 12-17a
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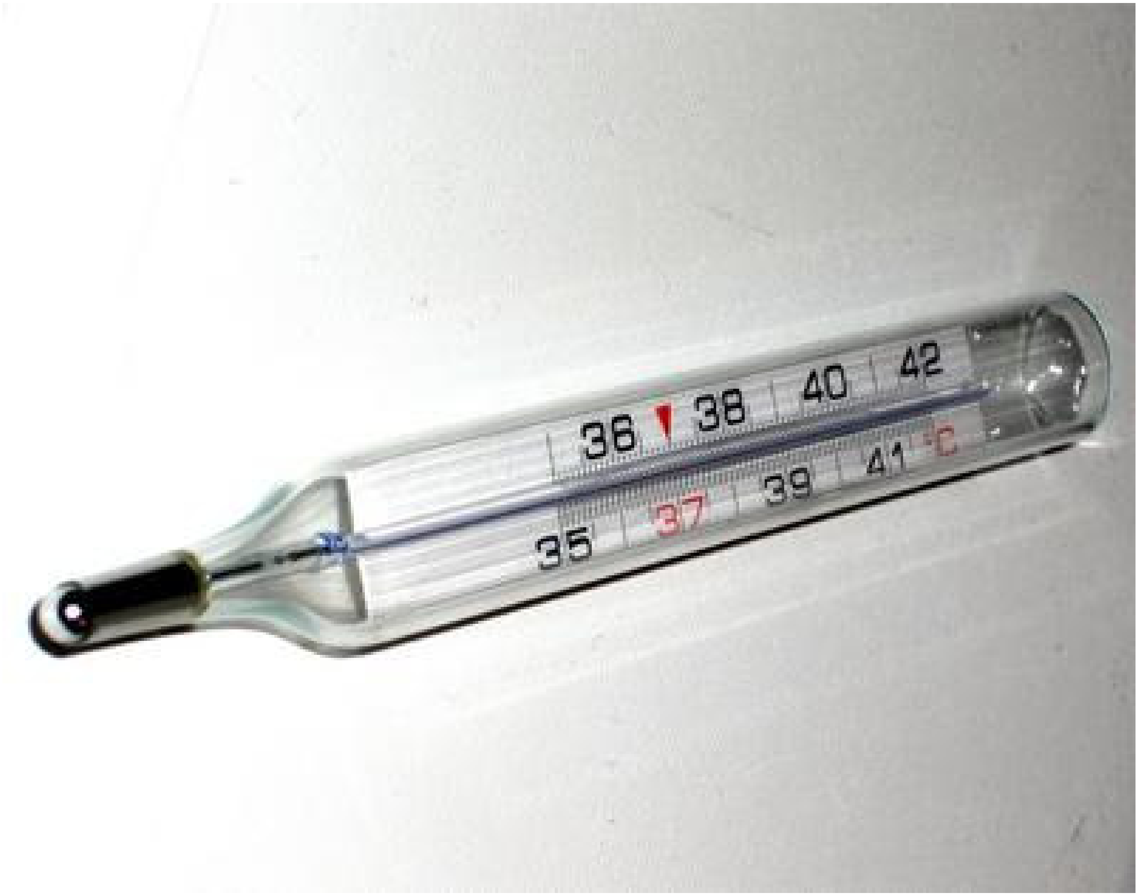
熱水使玻璃杯破裂

Thermal Expansion



note

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 薔薇星雲):

OB stars → UV radiation → expanding hot gas → shock compression → gravitational collapse → stars form in cluster

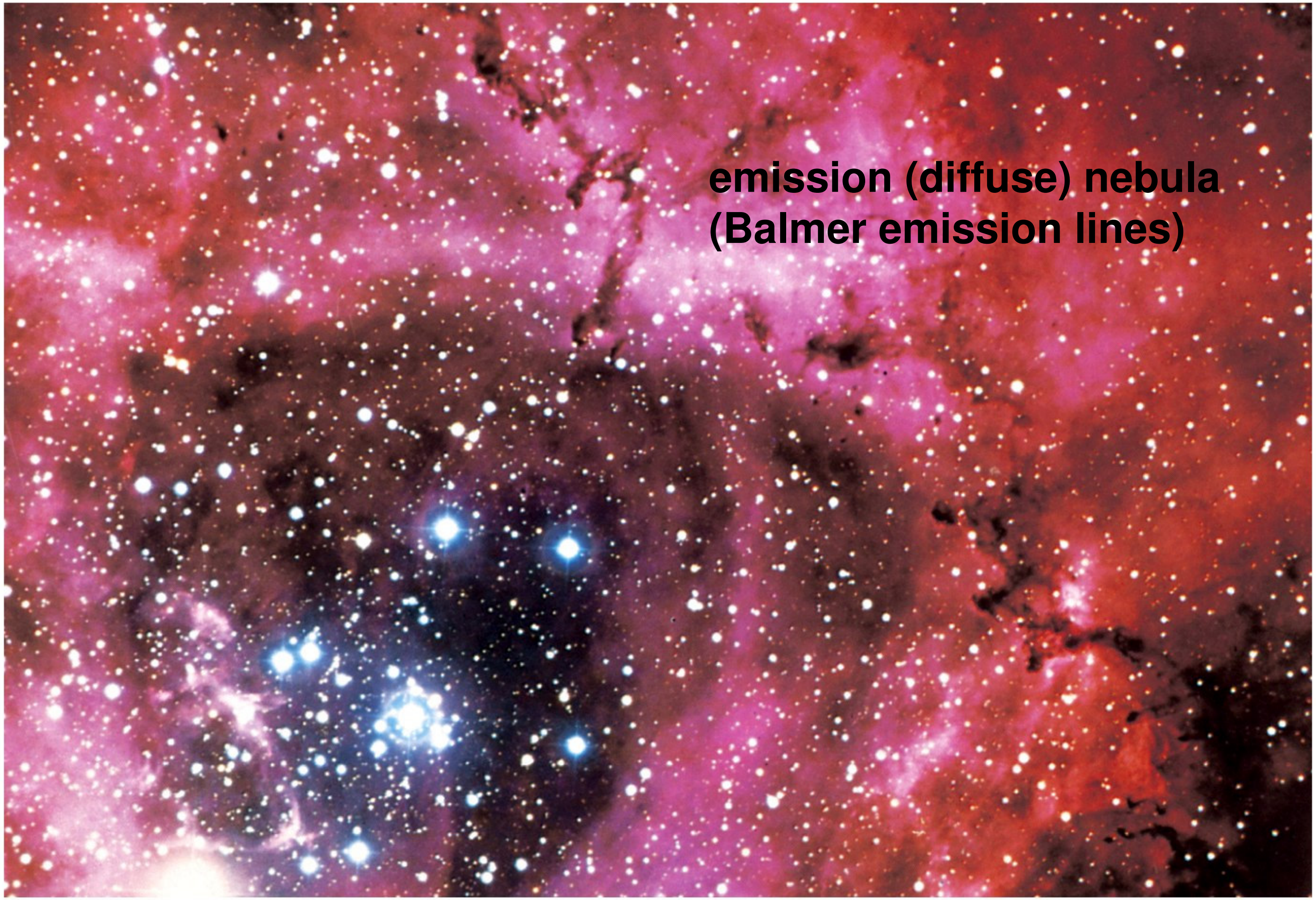


Figure 12-8
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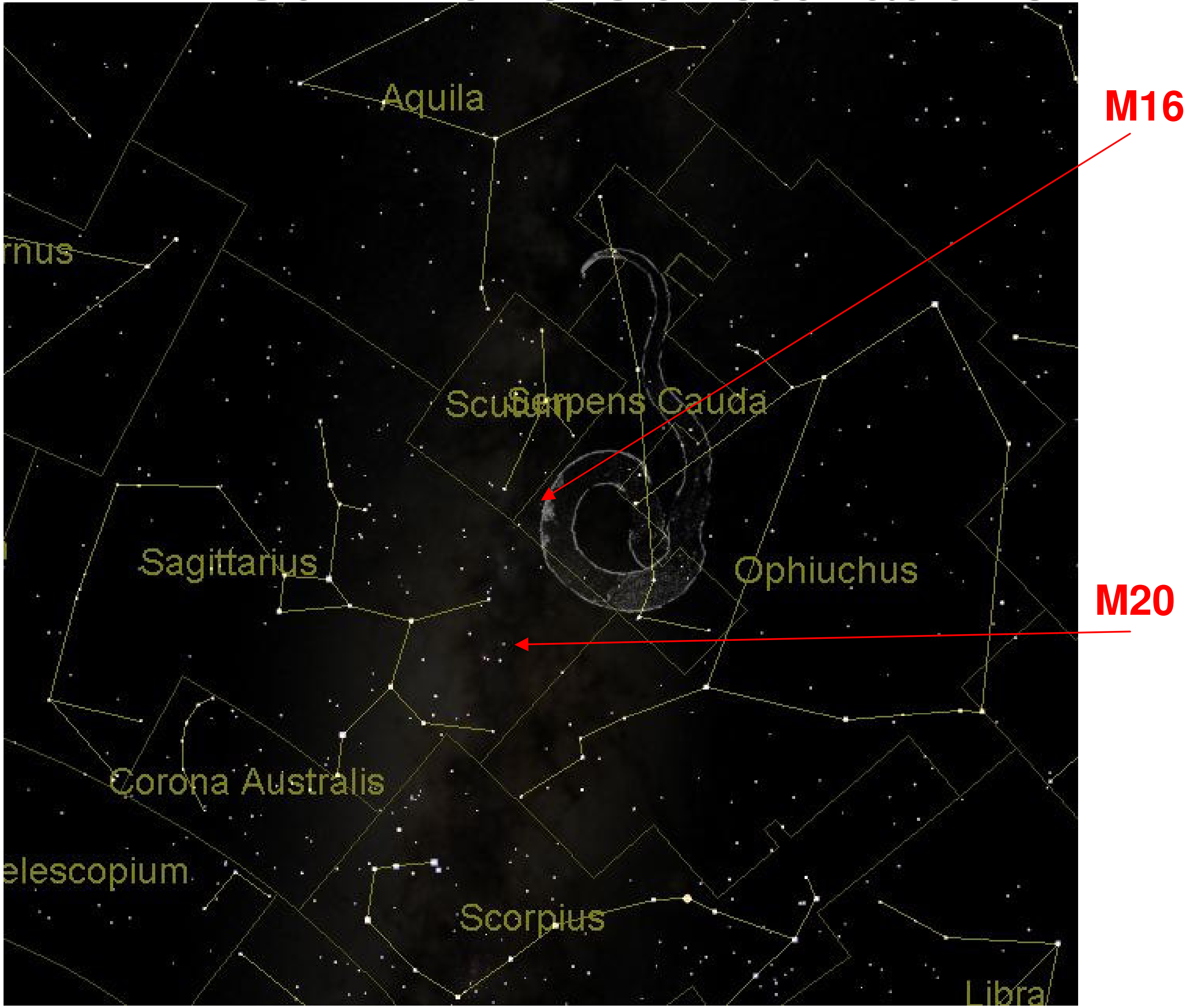
Summer's Constellations



Star forming region: dust, gas, & evaporation!

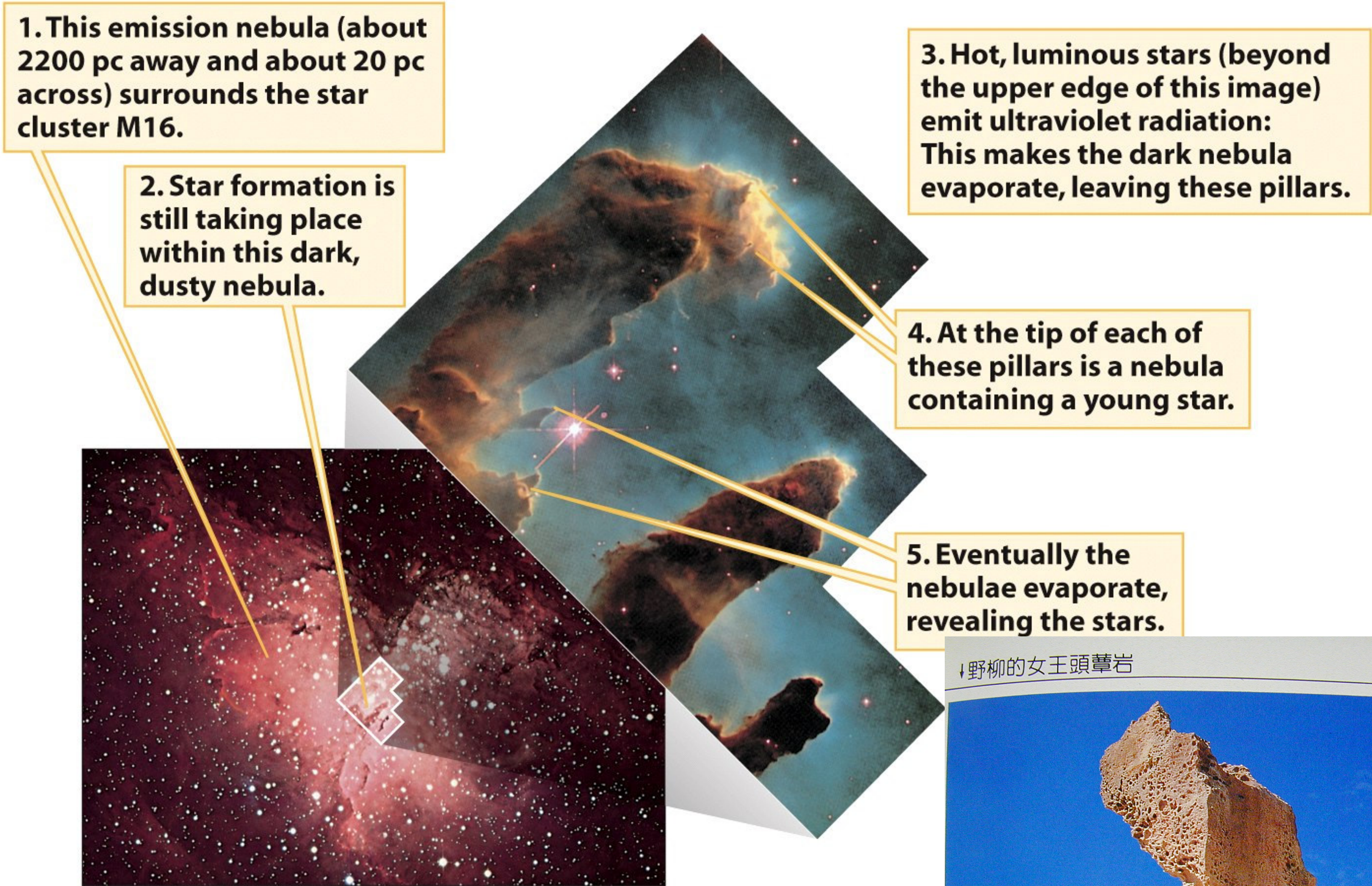


Figure 12-15
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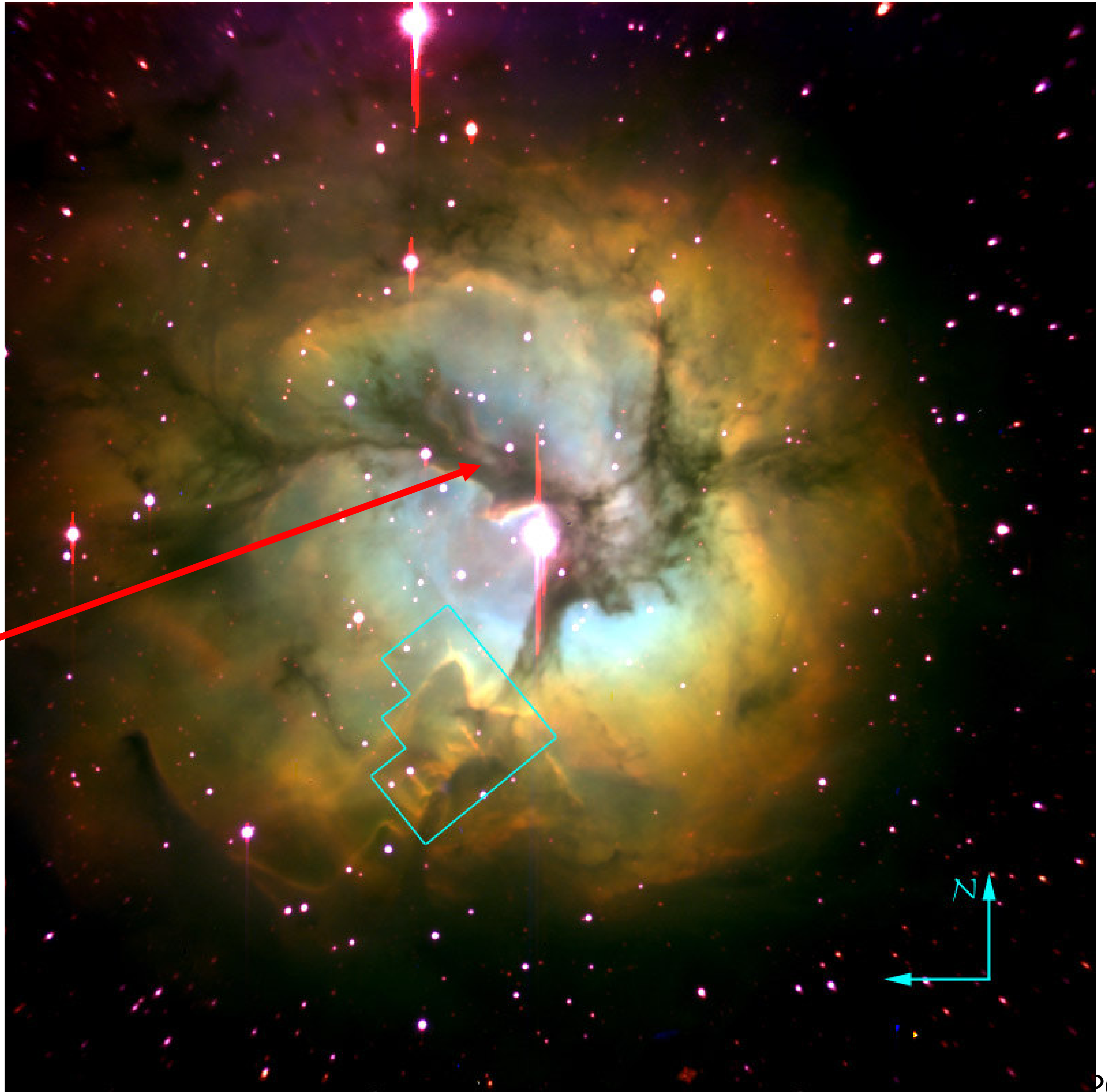
Eagle Nebula (M16)

斷頭危機 ☹
風化

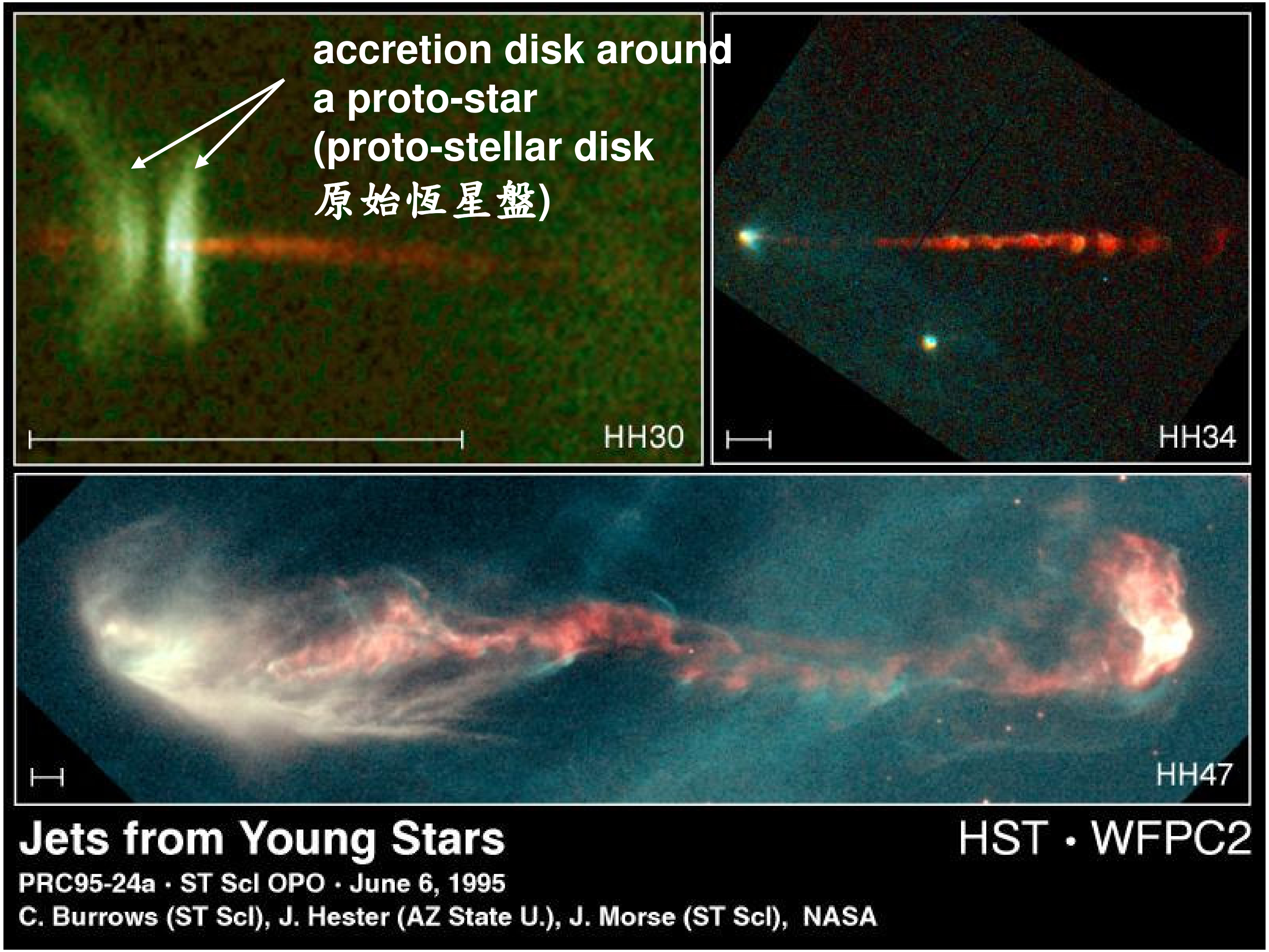
Trifid Nebula (M20)

人馬座 三裂星雲

dust



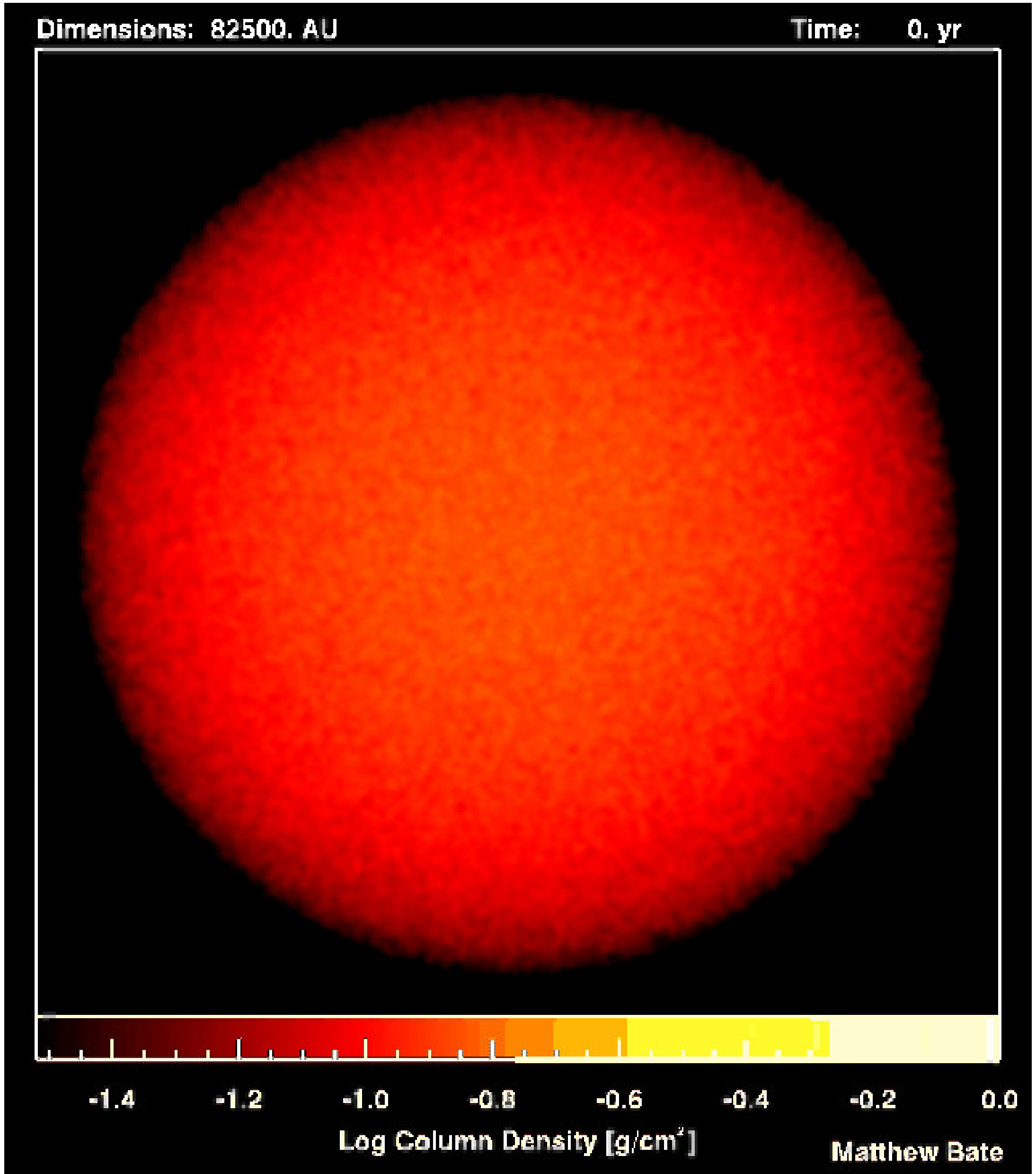
Accretion Disks & Jets (吸積盤和噴流)



Formation of Stars in a turbulent cloud

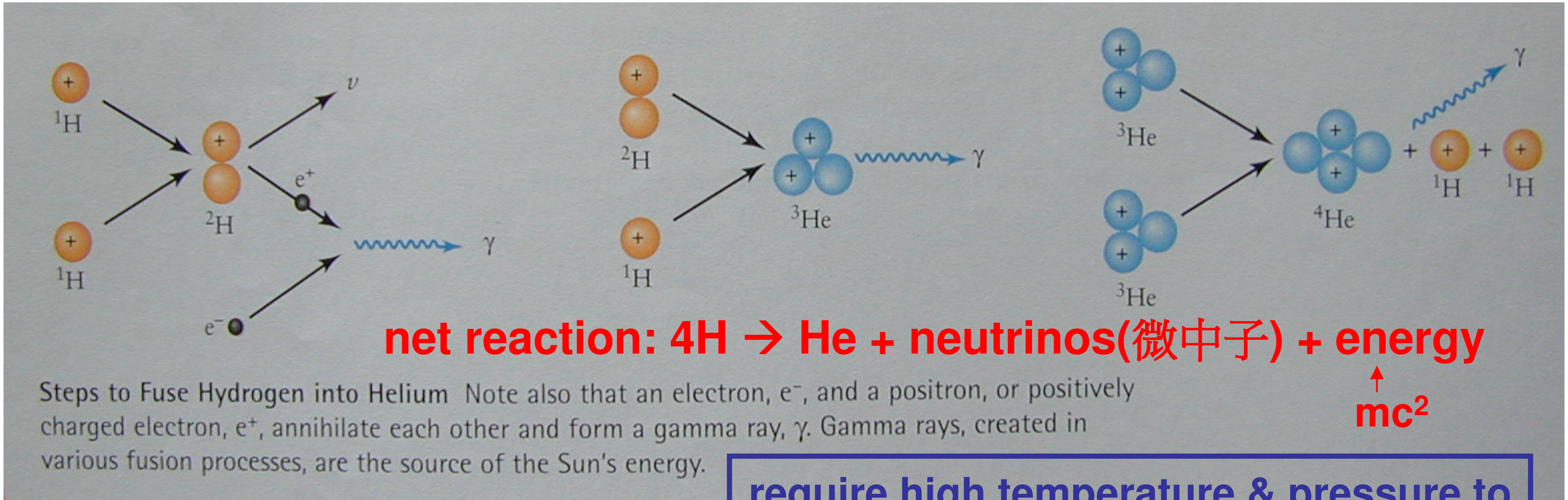
http://www.ukaff.ac.uk/starcluster/

Key words:
turbulence
gravitational collapse
proto-stellar disks
mulitple-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.

Nuclear Fusion (核融合)



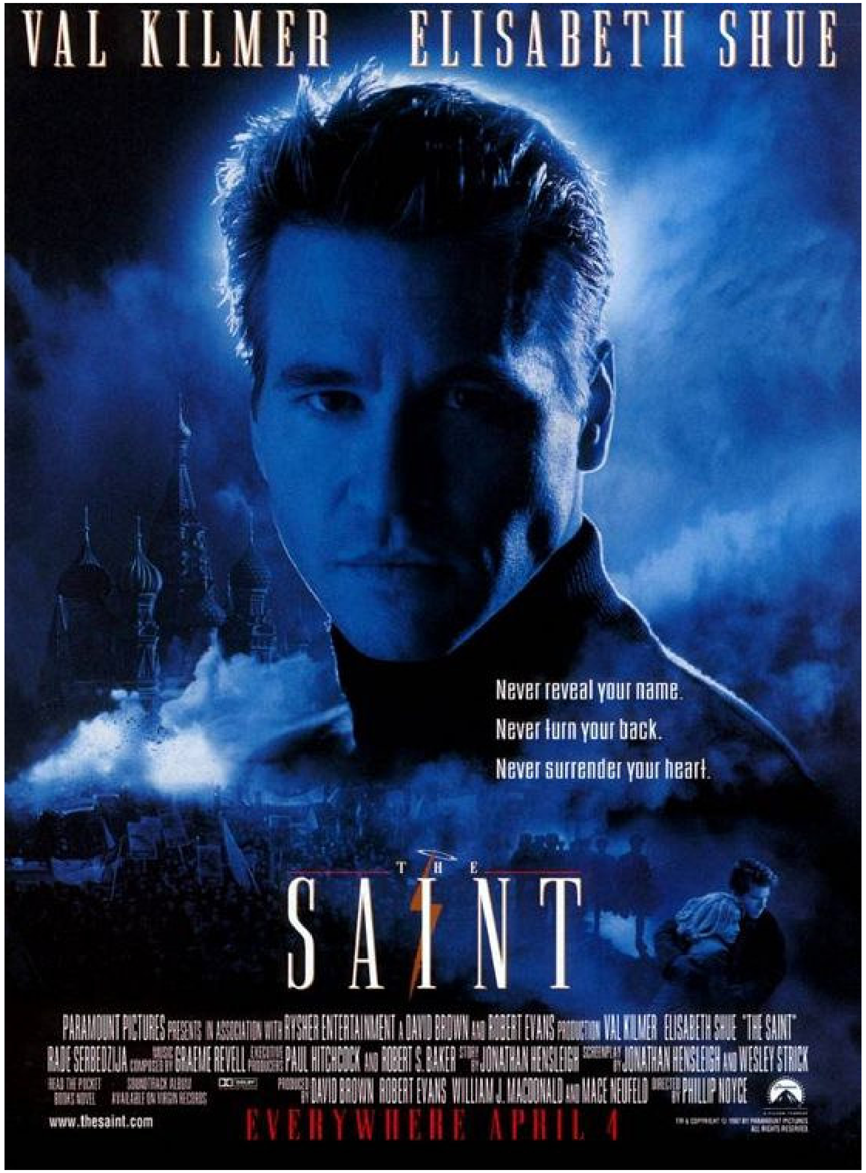
net reaction: 4H → He + neutrinos(微中子) + energy

↑ **mc^2**

require high temperature & pressure to overcome the electric force

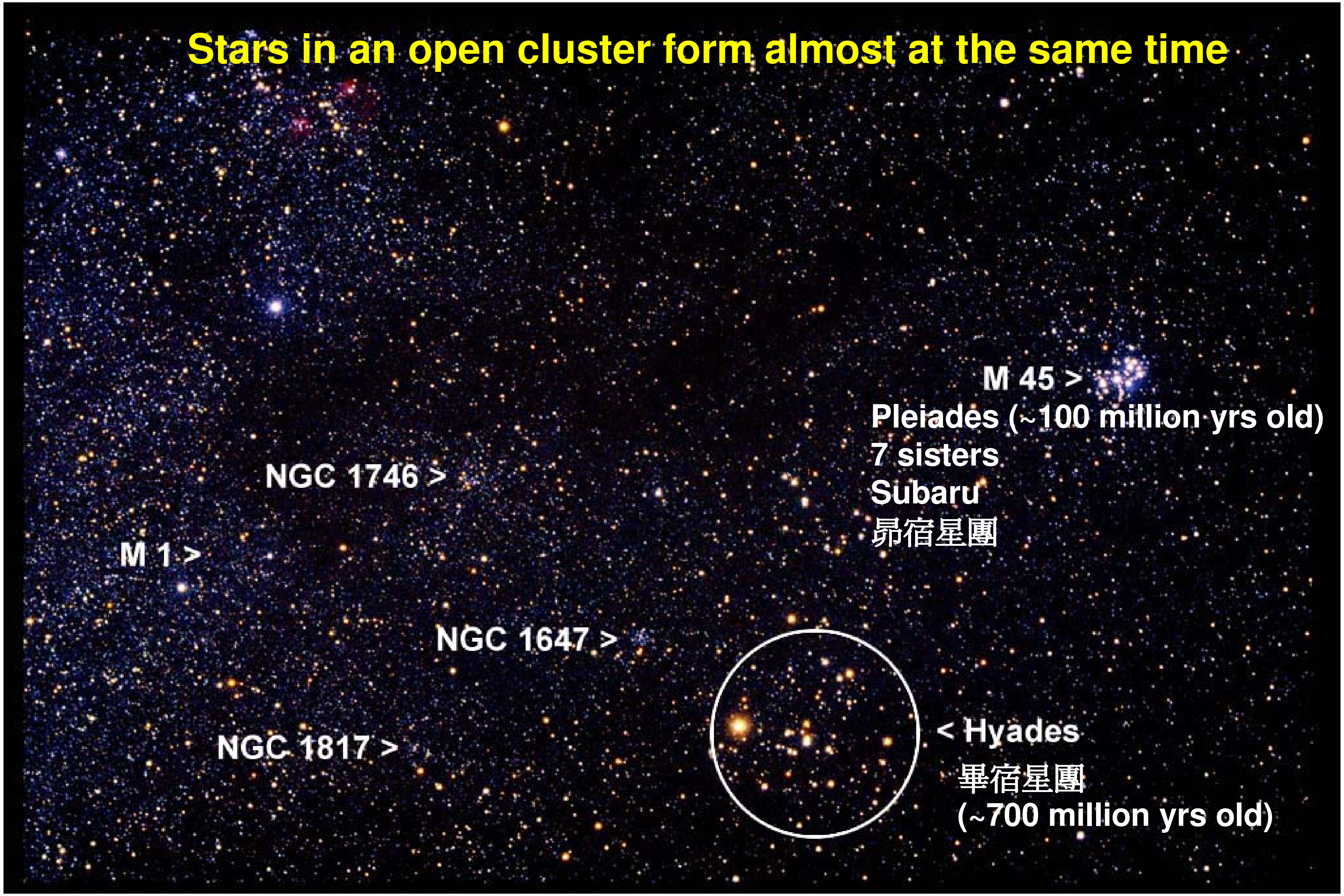
Remark (search for new energy source): unlike the energy generated by nuclear fission (核分裂), nuclear fusion does not produce nuclear waste. Physicists have been working hard to generate and sustain the nuclear power through nuclear fusion, but there has never been any success so far ☹

There is no cold fusion



室溫下的核融合？

young open clusters (疏散星團) in Taurus



Why is the Sun so "lonely"?

- Stars form in (open) cluster → what's wrong with the Sun (or other "field" stars) in the past?
- Number of open clusters is decreased with age → 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

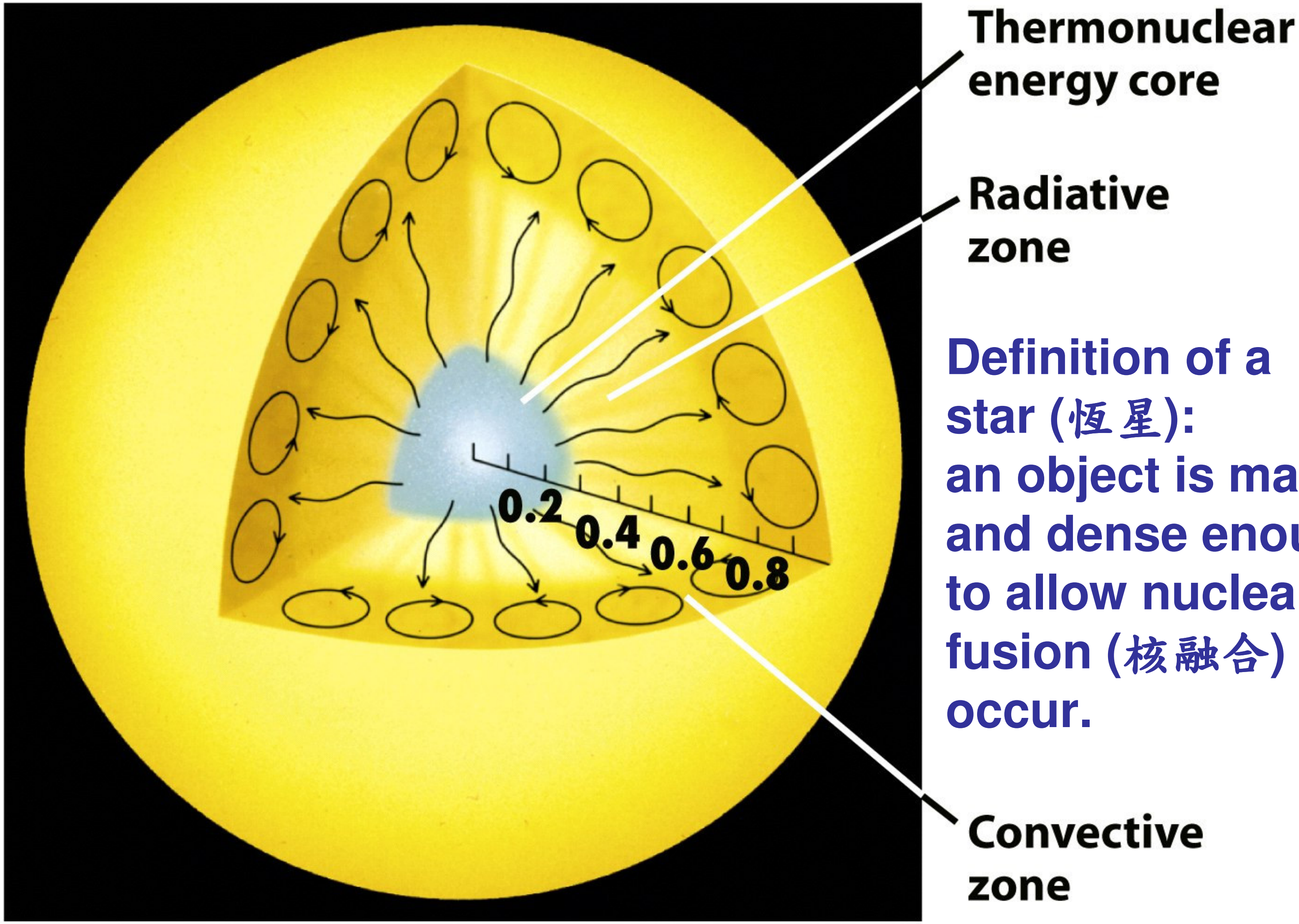


Figure 10-21a
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Definition of a star (恆星): an object is massive and dense enough to allow nuclear fusion (核融合) to occur.

note

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

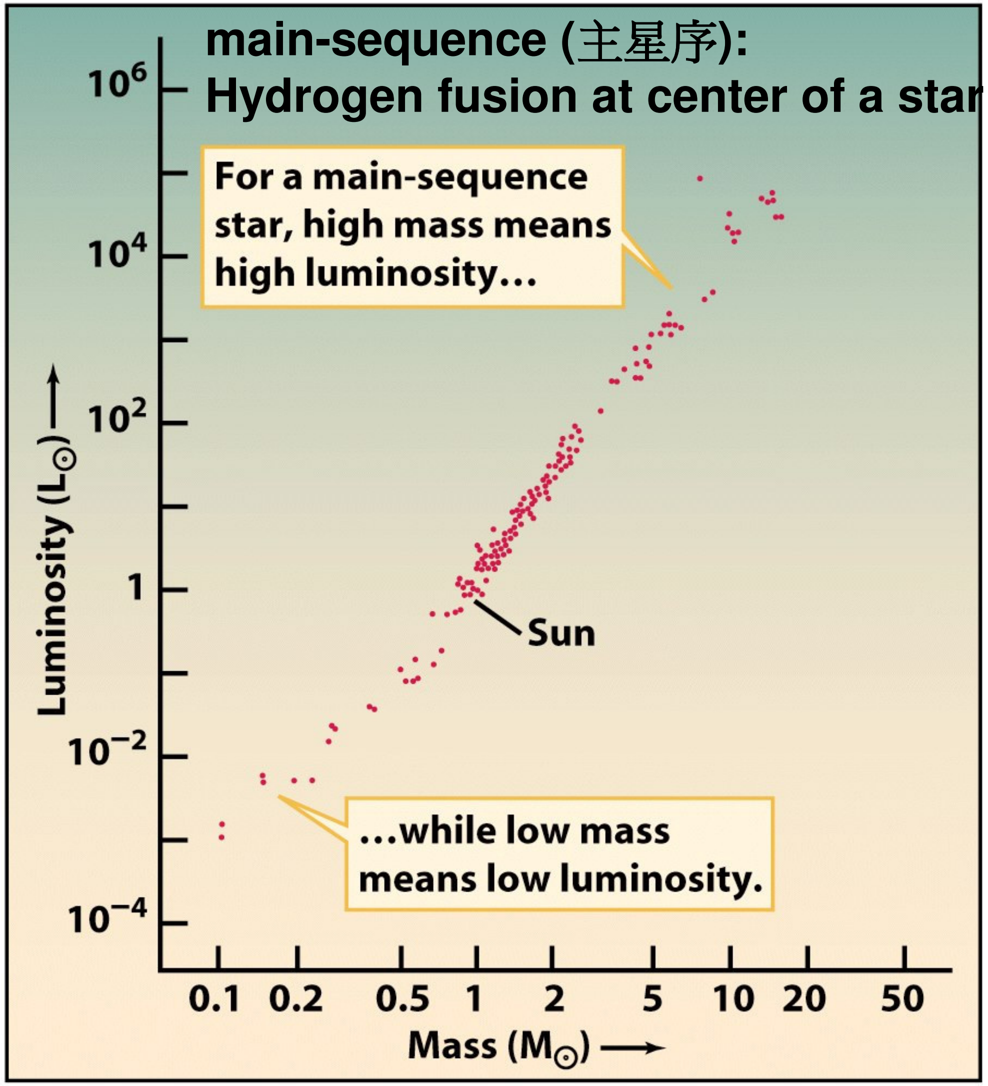

Figure 11-12a
Discovering the Universe, Seventh Edition

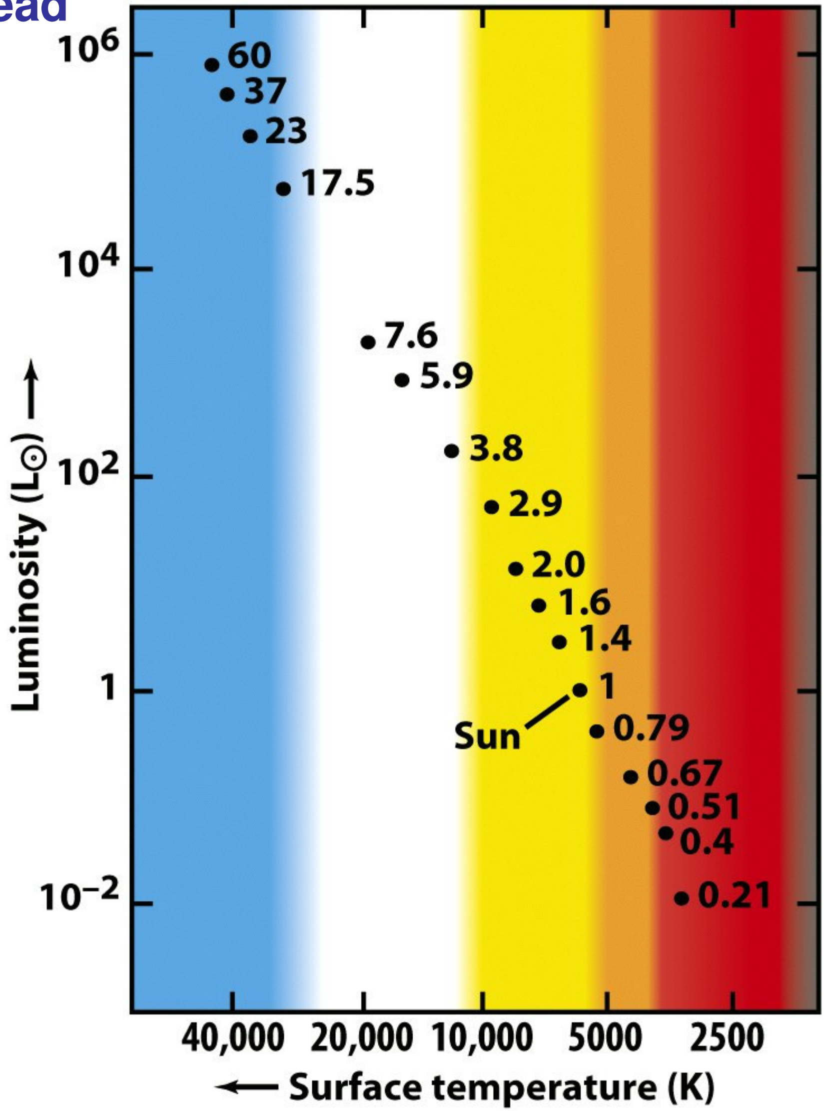

Figure 11-12b
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Temperature & Color

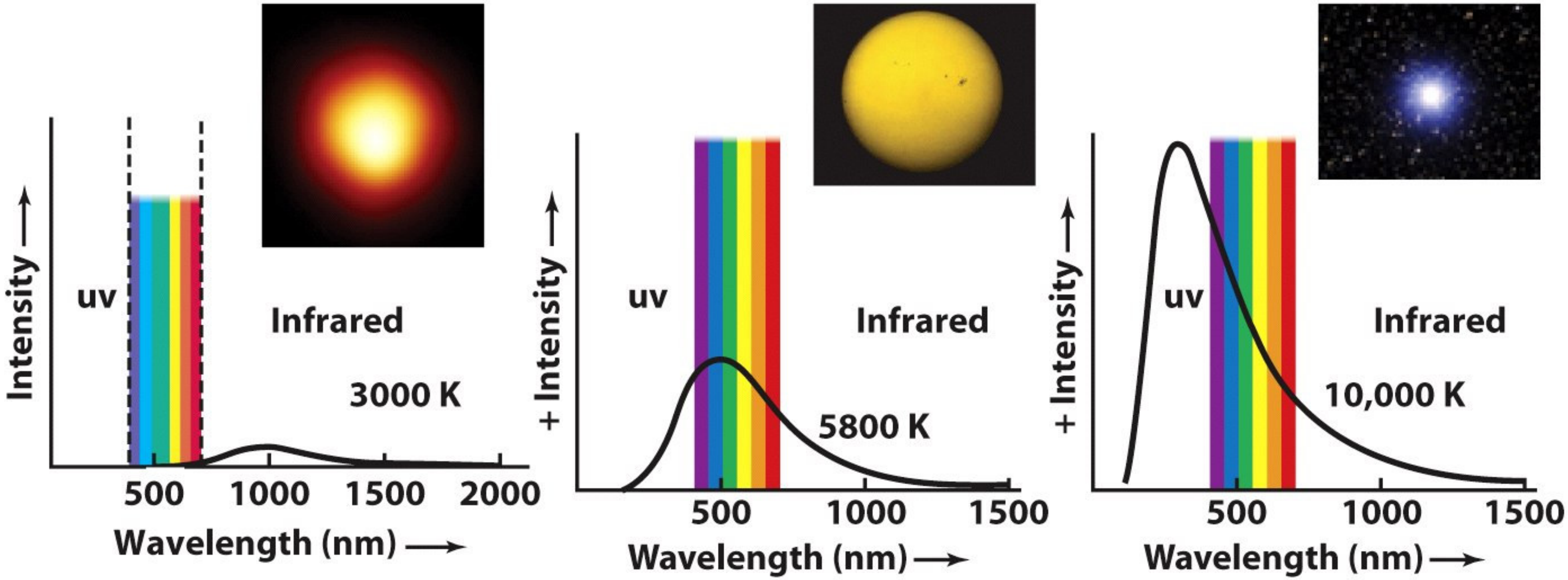

Figure 11-4b
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Main-Sequence Lifetimes

Evolution depends on mass.

TABLE 12-1 Main-Sequence Lifetimes

Mass ($M_{\odot}$)	Surface temperature (K)	Luminosity ($L_{\odot}$)	Time on main sequence (10^6 yrs)	Spectral class
25	35,000	80,000	3	O
15	30,000	10,000	15	B
3	11,000	60	500	A
1.5	7000	5	3,000	F
1.0 (Sun)	6000	1	10,000	G
0.75	5000	0.5	15,000	K
0.50	4000	0.03	200,000	M

Table 12-1
Discovering the Universe, Seventh Edition

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.

} 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.

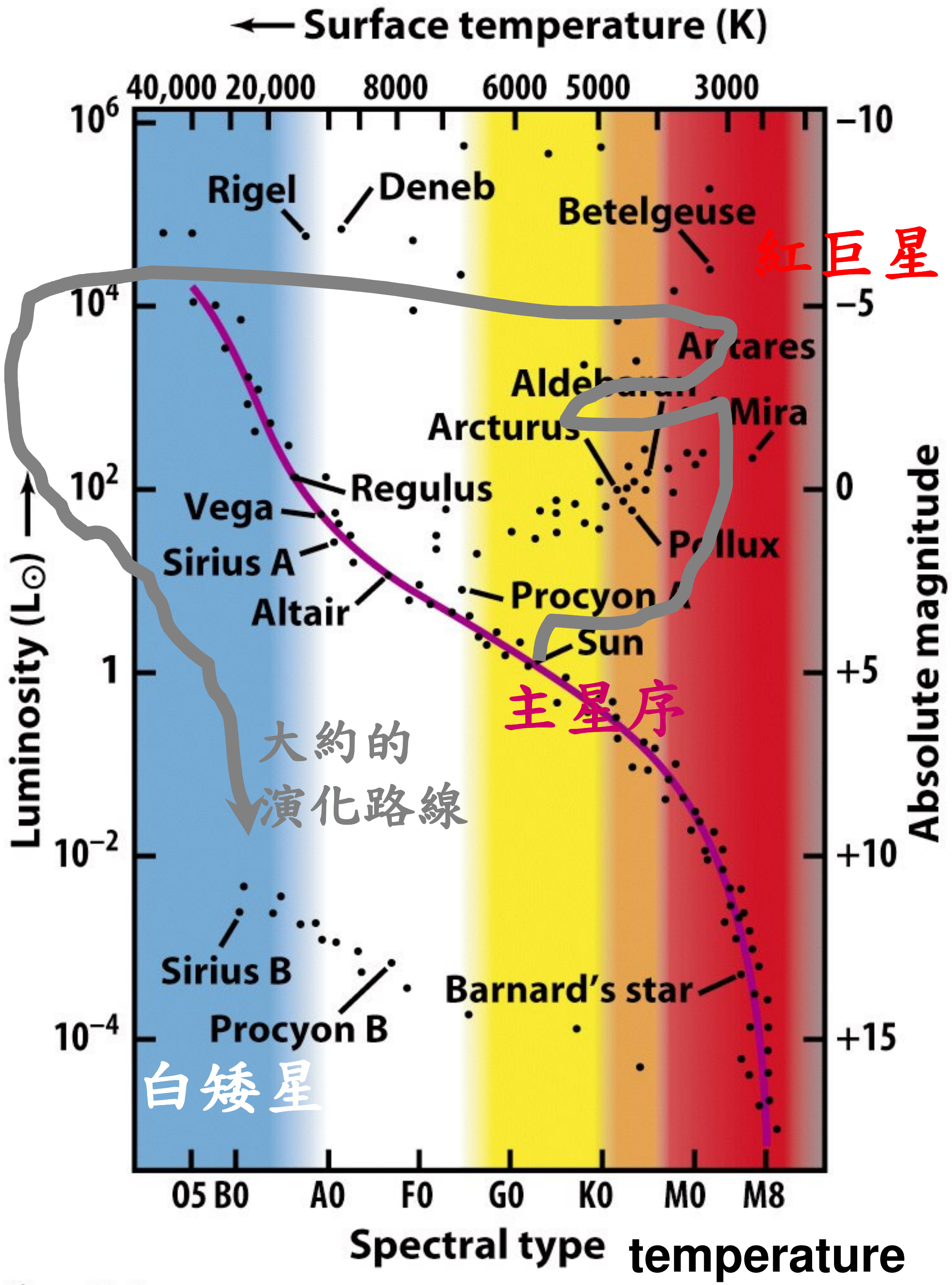

Figure 11-7
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Horizontal Branch & Asymptotic Giant Branch

Horizontal branch: He fusing in the core
3He → C +energy; He + C → O + energy

Asymptotic Giant branch: core collapses (no fusion) but outer layer expands (shell He fusing)

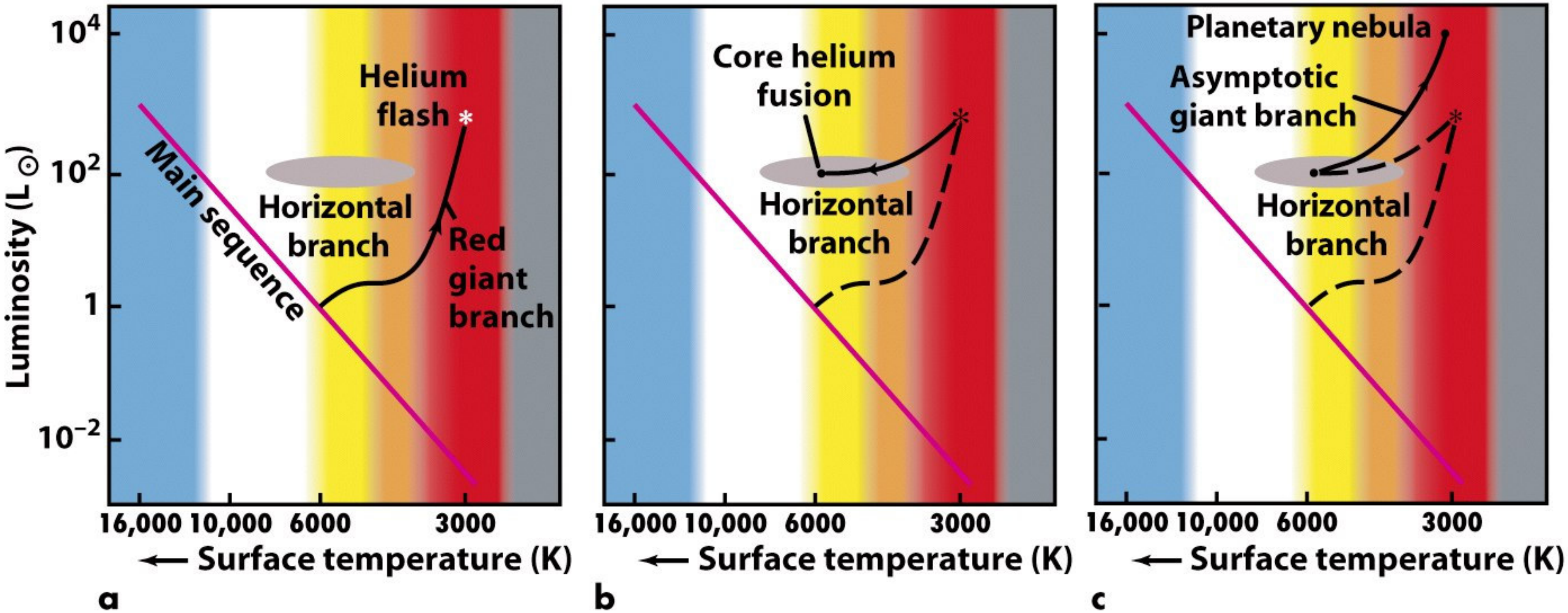

Figure 13-1
Discovering the Universe, Seventh Edition

note

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

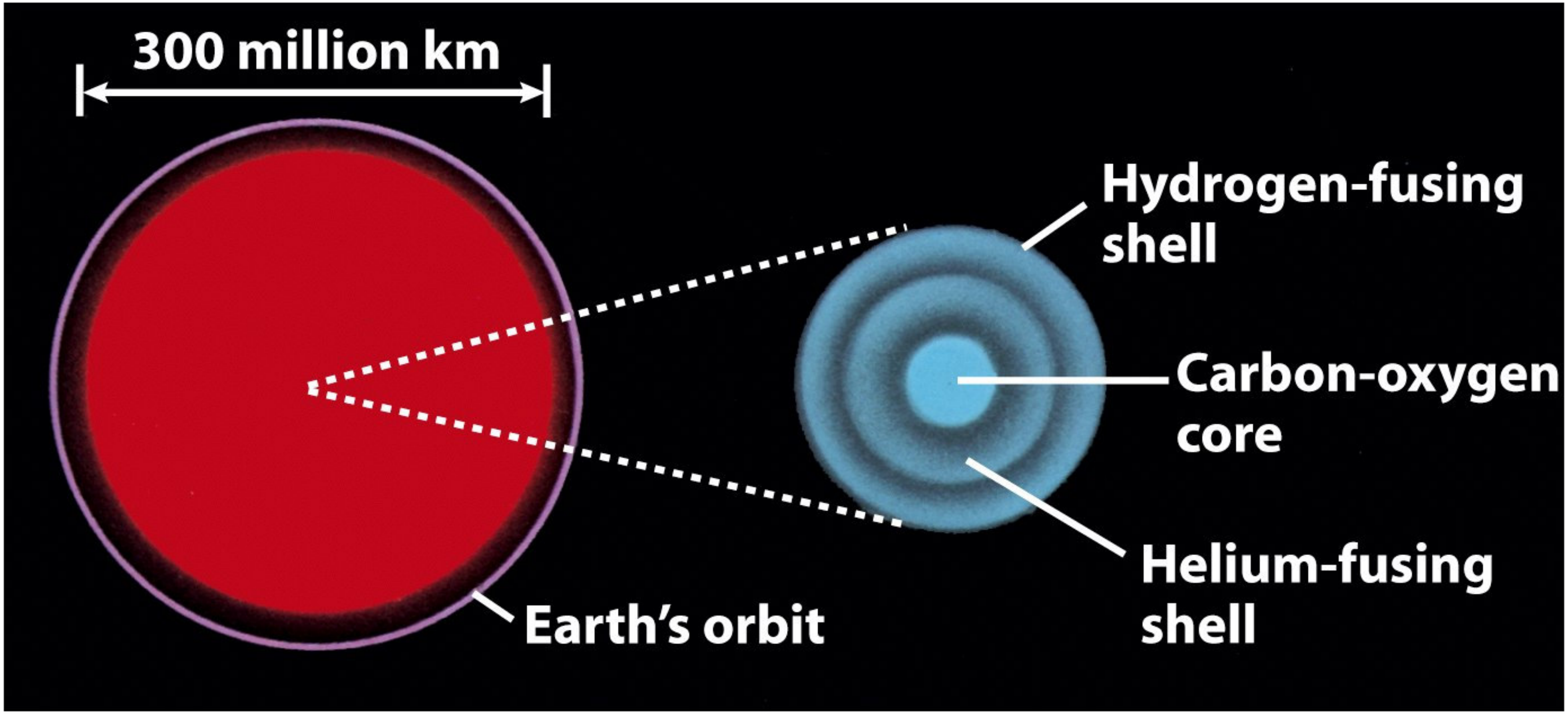

Figure 13-2
Discovering the Universe, Seventh Edition

We are all star dusts!

Planetary nebulae: fate of low mass stars

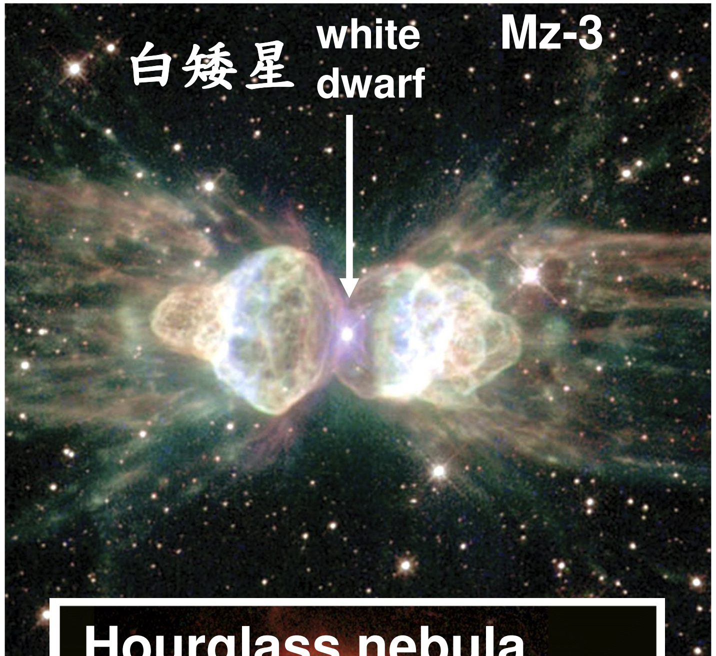

Figure
Discover
© 2006 V

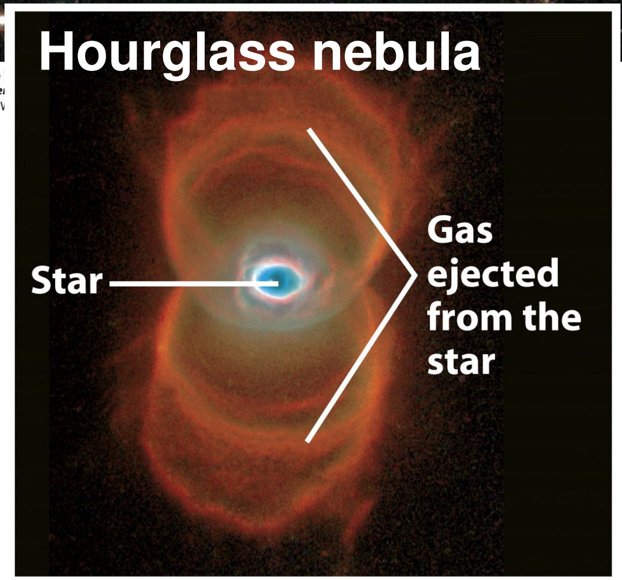

Figure 13-5c
Discovering the Universe, Seventh Edition
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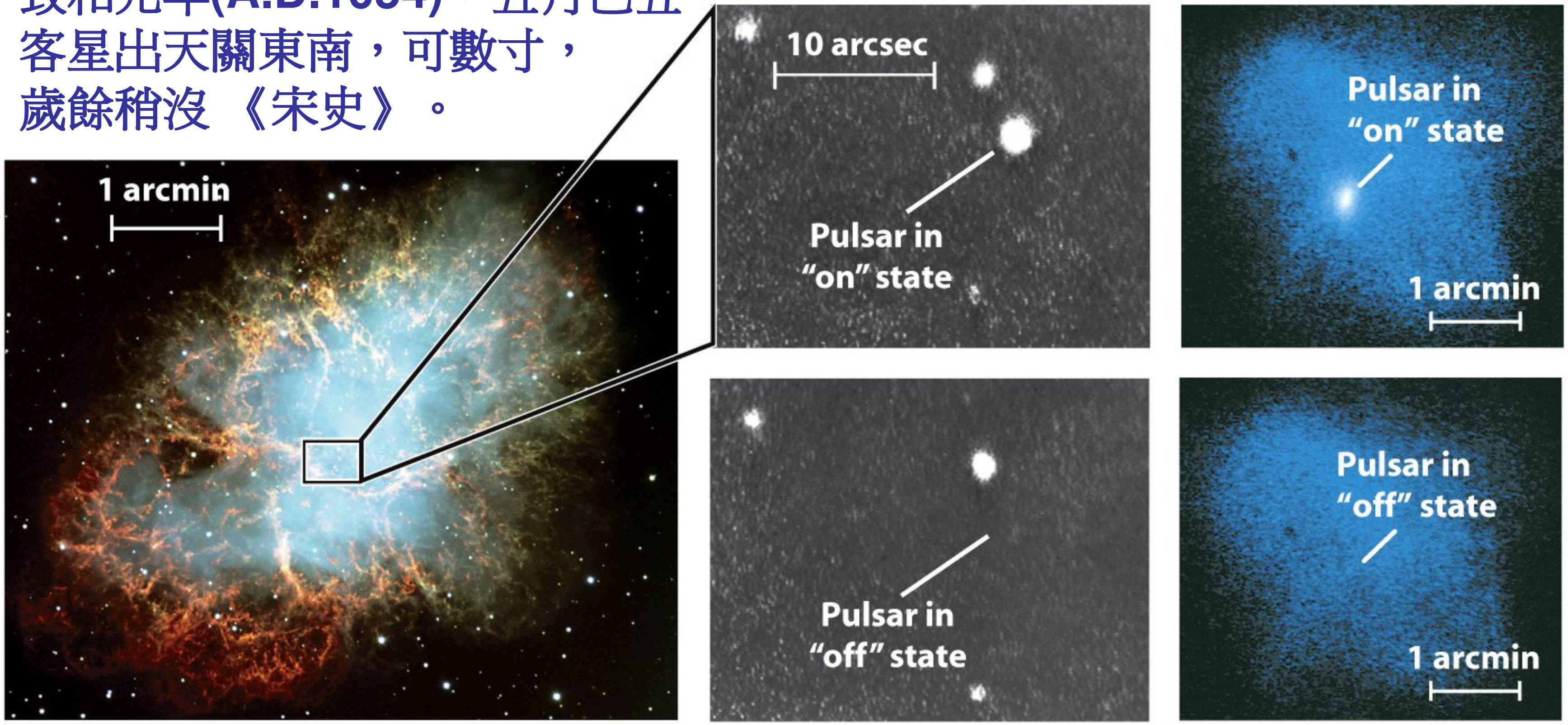
note

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)，五月己丑，
客星出天關東南，可數寸，
歲餘稍沒 《宋史》。



The Crab Nebula 蟹狀星雲 (M1) | The Crab pulsar in visible light | The Crab pulsar in X rays

Figure 13-18b
Discovering the Universe, Seventh Edition

Pulsar (脈衝星) was thought to be a signal from an advanced alien civilization ☺

- as bright as the Milky Way
- once per century in our galaxy

Summary I: star formation

- 什麼是星際物質(interstellar medium)？
- 如何可以造成重力塌縮(gravitational collapse)？
- 什麼是原始恆星(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)

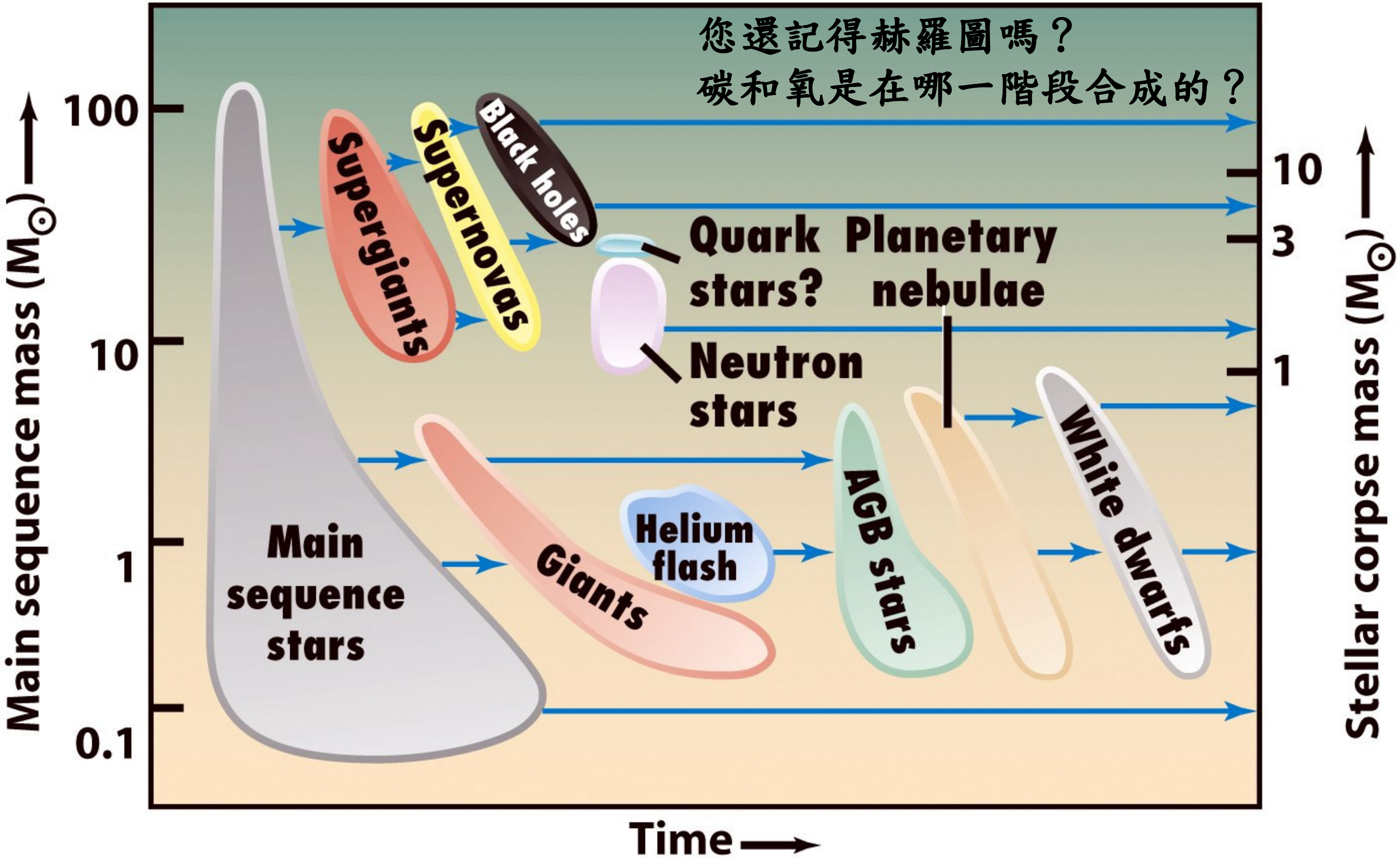


Figure 13-27a
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Cosmic Cycle

Ehrenfreund & Charnley 2000