The Nature of Stars 恆星的性質

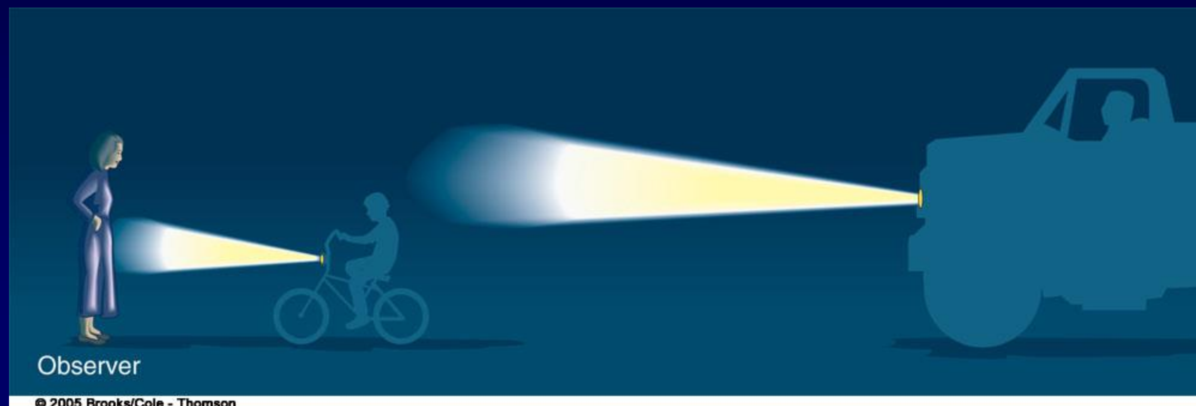
本章學習重點

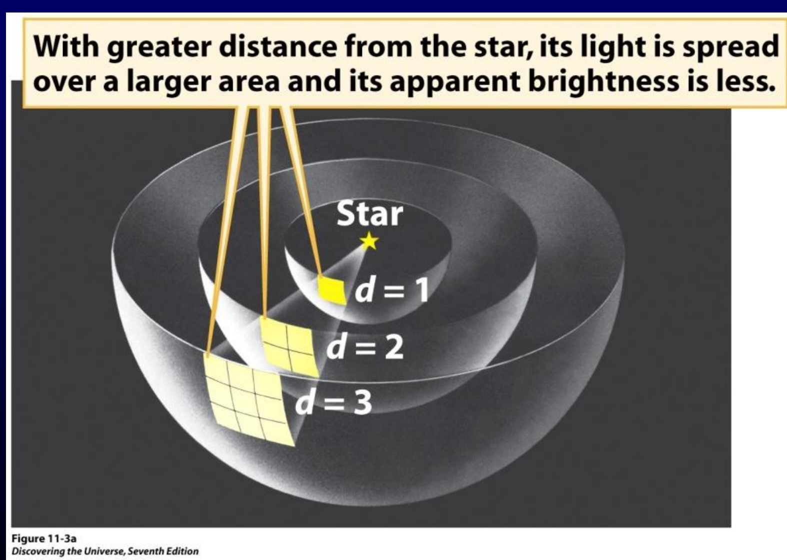
- 如何測量恆星的**距離**
- 如何測量恆星的**亮度**與**光度**（這兩個差別何在？）
- 如何表達亮度與光度（單位）
- 如何估計恆星的表面**溫度**
- 如何得知恆星的化學**成分**
- 如何估計恆星的大小、質量

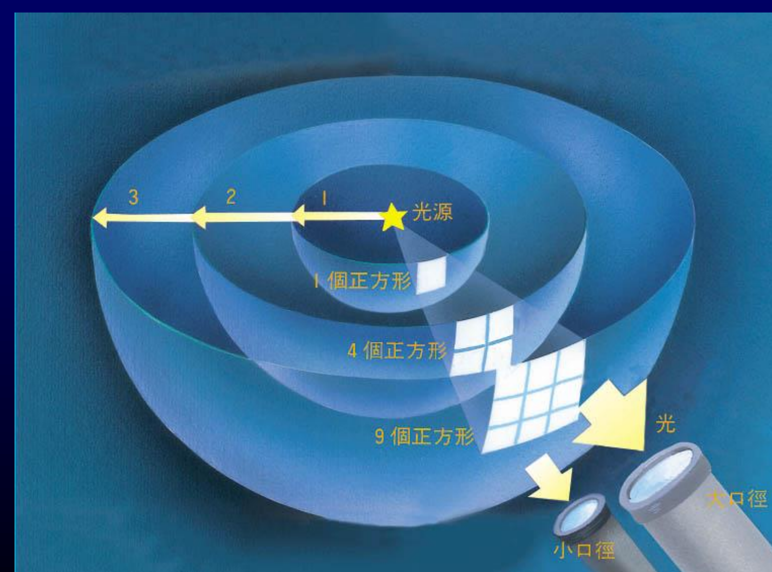
恆星的亮度 (brightness)

星星看起來的**亮度** ＝ 實際**光度** ＋ **距離**

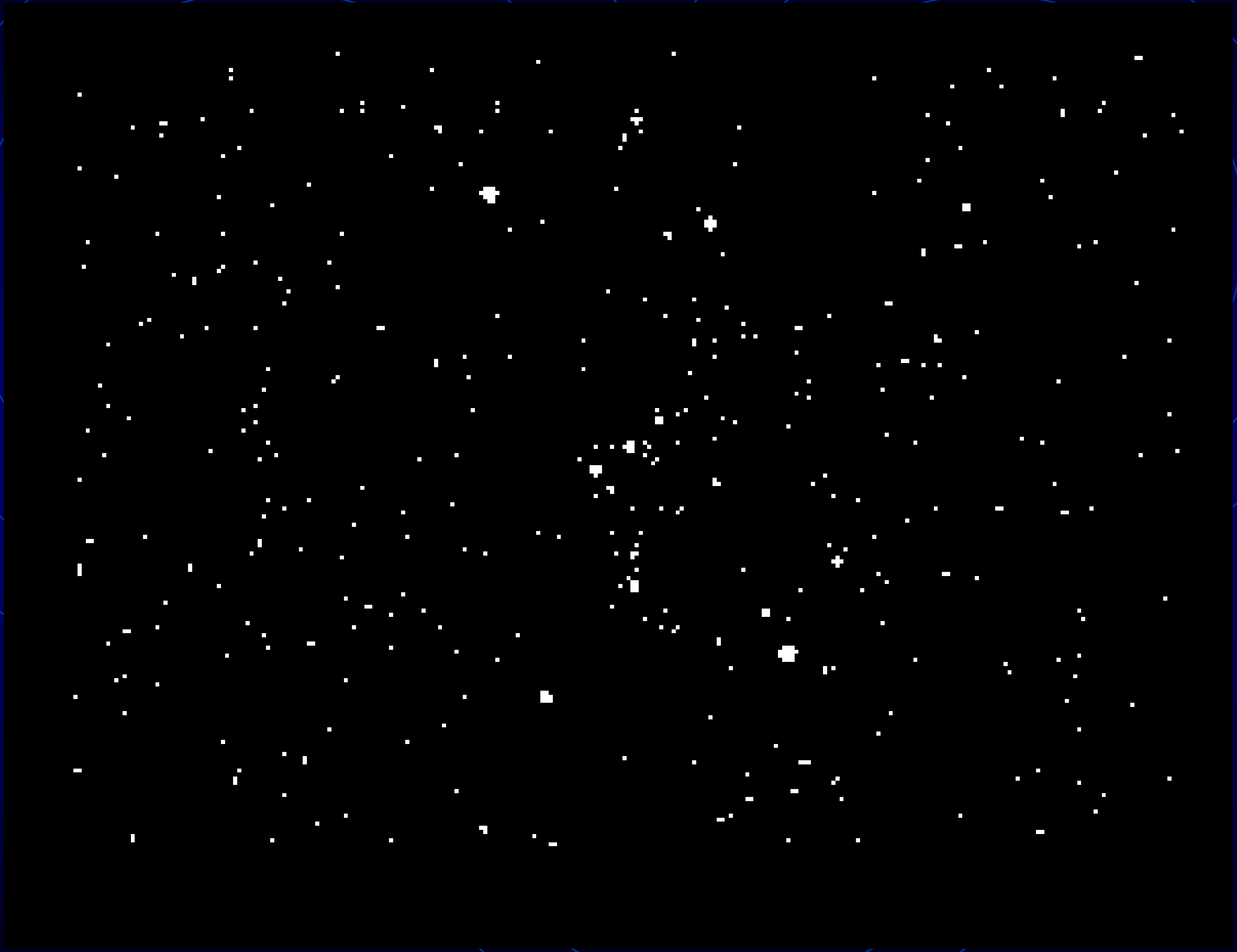
One over
distance squared







Orion from +7.0 to 2.0 mag sky



http://www.darksky.org/infoshts/is120.html

- **視星等 (apparent magnitude)** 表示天體「看起來」的亮度。**天體看起來越明亮，，其星等數字越小**。例如 1 等星比 2 等星亮；19 等星比 30 等星明亮（很多）
- 1 等星比 6 等星亮 **100 倍整**，也就是**差一個星等，亮度差約 2.51 倍**。 $\sqrt[5]{100} \approx 2.512$
- 裸眼能見最暗約6等星，全天空共 5000～6000顆星，任一時刻天空出現最多 2000～3000顆。
- 使用雙筒望遠鏡，集光面積比瞳孔大，可以看到10等星，全天空約10,000顆（**集光能力 ∝ 面積＝口徑^2**）

天體	視星等
太陽	-26.8
天狼星	-1.5
織女星	0.0
參宿四	0.4

- 兩顆星亮度**比**與星等**差**的關係

$$m_1 - m_2 = 2.5 \log b_2/b_1$$

Q1: 三等星的亮度和一等星如何相比？

Q2: 天狼星的視星等為 -1.5，它有顆伴星稱為 Sirius B，其亮度是天狼星的萬分之一（哪些性質決定恆星的亮度呢？），試估計天狼B星的視星等。

Q3: 假設一般人瞳孔直徑約 7 mm，試估計要用多大的望遠鏡，可以用肉眼觀測 12 等星。

Q4: 假設使用大型望遠鏡仔細觀測該12等星，發現它其實是由兩顆星所組成，亮度比為3比1，試算這兩顆星各自的星等。

Q1: 三等星的亮度和一等星如何相比？

A: $(2.512)^2 \cong (2.5)^2 \cong 6.25 \cong$ 6 times fainter

Q2: 天狼星的視星等為 -1.5，它有顆伴星稱為 Sirius B，其亮度是天狼星的萬分之一，試估計天狼B星的視星等。

A: 100 times of flux → 5 mag difference, so 10,000 times fainter → 10 mag larger, ∴ Sirius B has m = -1.5 + 10 = 8.5 mag

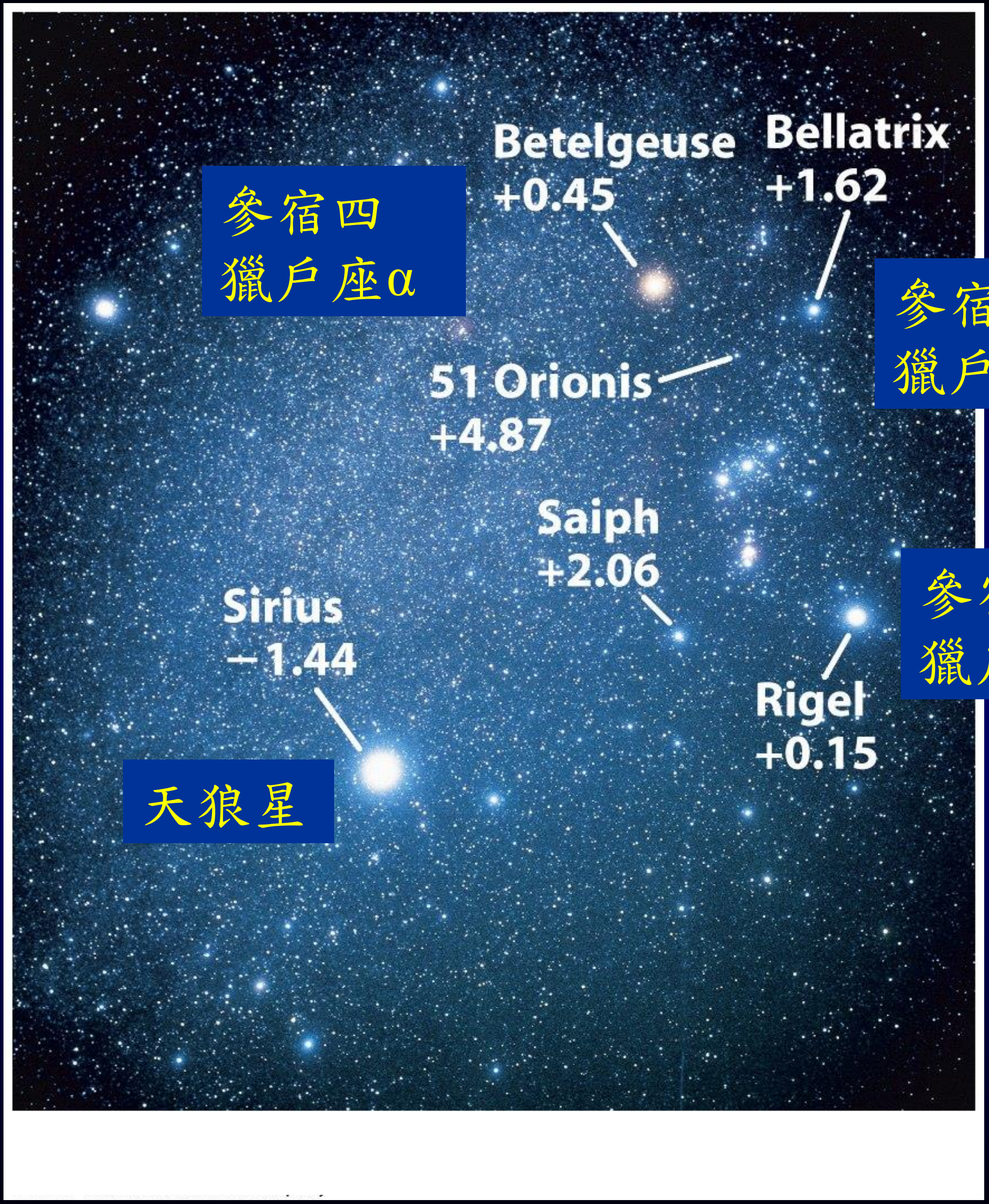
Q3: 假設一般人瞳孔直徑約 7 mm，試估計要用多大口徑的望遠鏡，可以用肉眼直接觀測 12 等星。

A: naked eye limit = 6 mag, so 12 mag is $(2.5)^6 \cong 250$ times fainter ∴ telescope aperture should be > 7 mm x 16 = 110 mm

Q4: 假設使用大型望遠鏡仔細觀測該12等星，發現它其實是由兩顆星所組成，亮度比為3比1，試算這兩顆星各自的視星等。

A: $b_1/b_2 = 3/1$, so $(b_1+b_2)/b_2=4/1$, $m_{1+2} - m_2 = 2.5 \log \frac{1}{4} \cong -1.5$
∴ $m_2 = 12 + 1.5 = 13.5$ mag; likewise $m_1 = 12 + 0.3 = 12.3$ mag

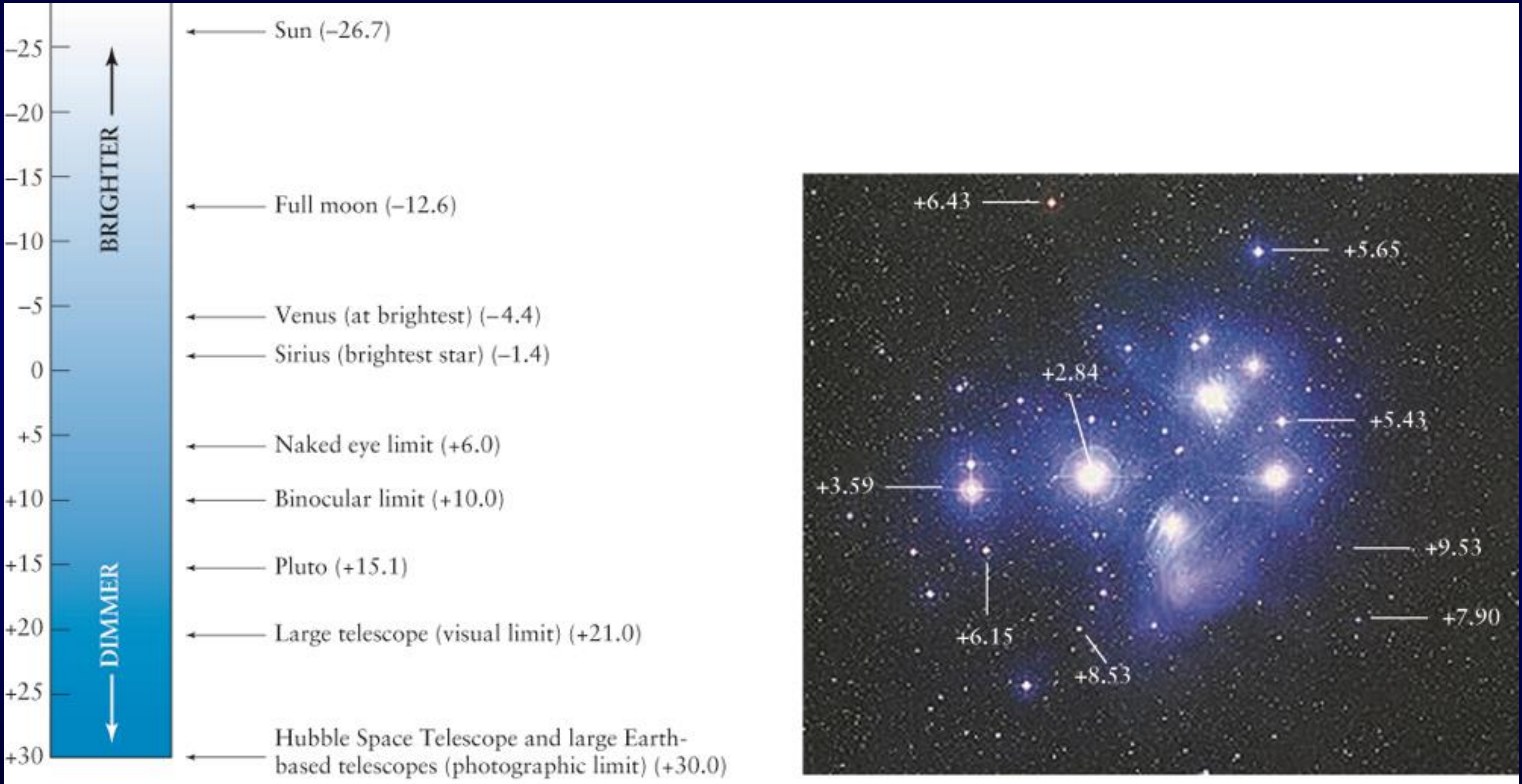
星球看起來的亮度



獵戶座 = Orion

獵戶座（的）α星
= α Orionis
= α Ori

星球的視星等



(a) Some apparent magnitudes

(b) Apparent magnitudes of stars in the Pleiades

Introduction to Astronomy

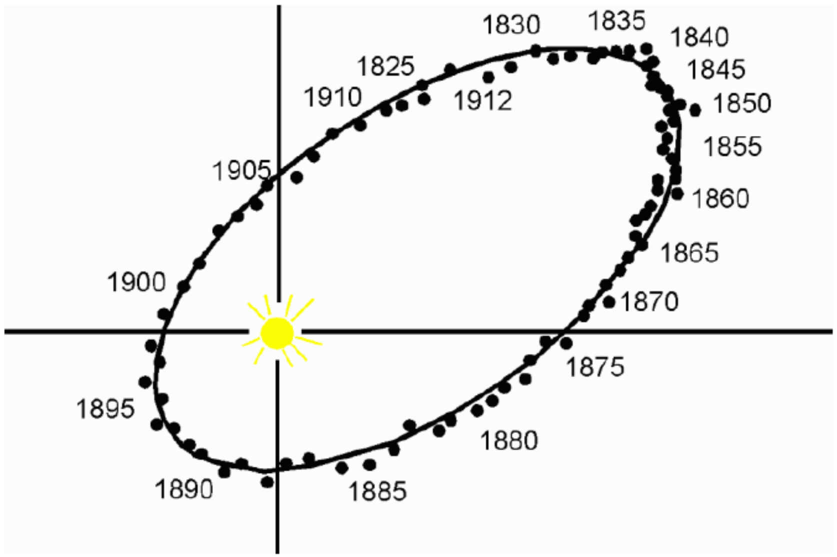
HW150312

due in one week

1. (a) Estimate how many kilograms of hydrogen the Sun has consumed over the past 4.56 billion years, and estimate the amount of mass that the Sun has lost as a result. Assume that the Sun's luminosity has remained the same during the time. (b) In fact, however, the Sun's luminosity when it first formed was only about 70% of its present value (the "*faint young sun paradox*"). With this in mind, explain whether your answers are an overestimate or an underestimate.

2. How far away is a star that has a proper motion of 0.08 arcseconds per year and a tangential velocity (proper motion) of 40 km/s? For a star at this distance, what would its tangential velocity have to be in order for it to exhibit the same proper motion as Barnard's star?

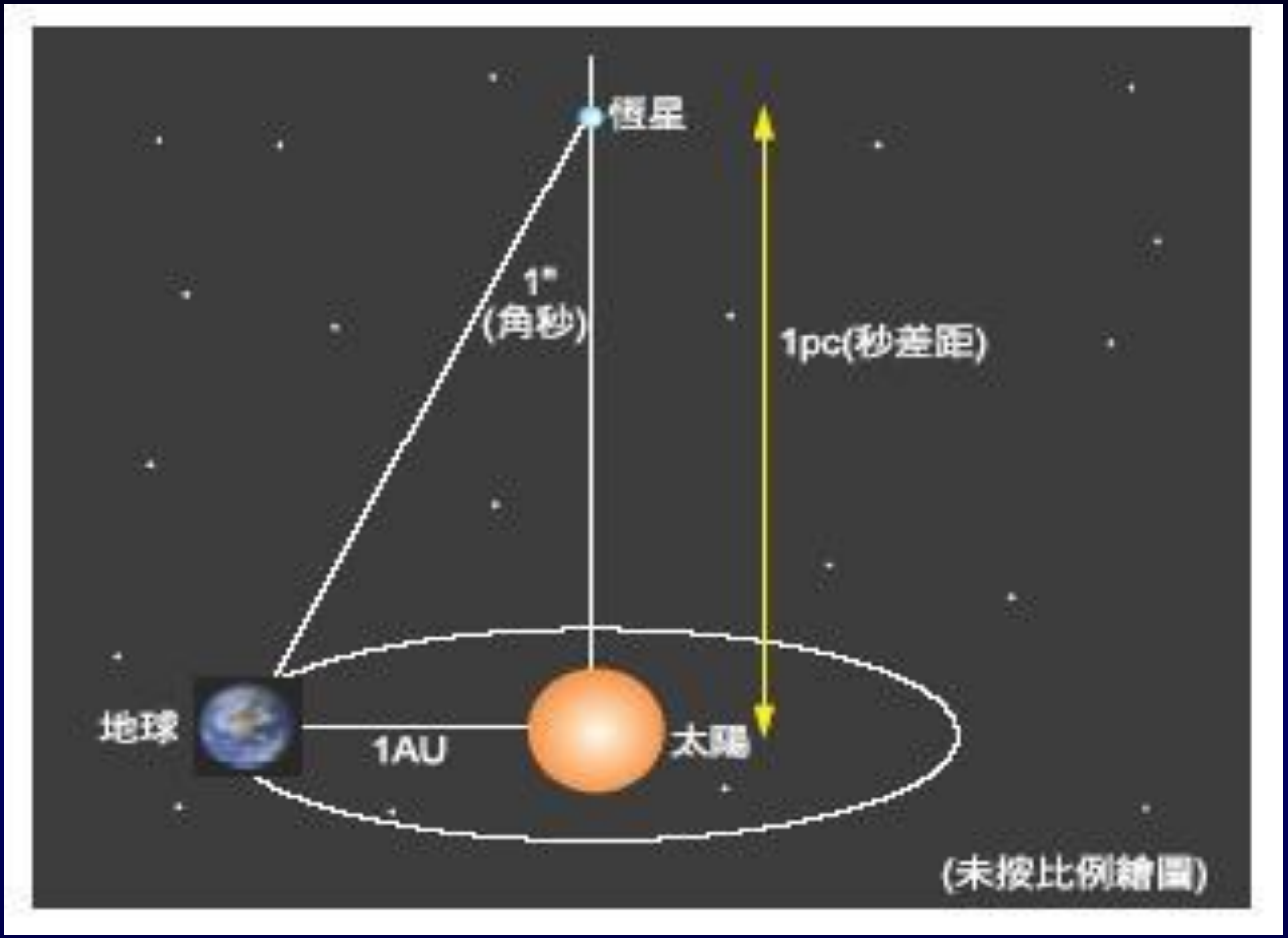
3. The visual binary 70 Ophiuchi has a period of 87.7 years. The parallax of 70 Ophiuchi is 0.2 arcseconds, and the apparent length of the semimajor axis as seen through a telescope is 4.5 arcsec. (a) What is the distance to 70 Ophiuchi in parsecs? (b) What is the actual length of the semimajor axis in AU? (c) What is the sum of the masses of the two stars in solar masses?



4. Search the World Wide Web for information about *Gaia*, a European Space Agency (ESA) spacecraft meant to extend the work carried out by *Hipparcos*. What is the status of *Gaia*? What is the main mission of *Gaia*? How does it compare to *Hipparcos* in terms of performance? What other types of research is it supposed to carry out?

5. A star is measured to have m_V=10.00. It is later resolved to be a binary with a brightness ratio of 2. What is the apparent magnitude of each binary component? If the system is at a distance of 100 pc. What is the absolute magnitude of each star?

3/26（週四）停課
3/31（週二）10：00 補課



註：1 pc ≅ 3.26 ly（光年）

當距離為1秒差距（pc)
時，1 AU的張角為1角秒

- 把星星放在同一距離，比較它們的視星等，就能夠比較它們的光度強弱。
- **光度 (luminosity)** 是實際發光的能力 (Watts)
- 同一距離 ≡ 10 pc

- 假想星星位於 d= 10 pc 處，其**視星等 (m)** 定義為**絕對星等 (M, absolute magnitude)**

$$m - M = 5 \log d - 5$$

derivation

Note: $m = M$ when d =10 pc

Q: 太陽的視星等約為 m = −27，試估計太陽的絕對星等 (M)。

Q: 太陽的視星等約為 m = -27，試估計太陽的絕對星等 (M)。

$$m - M = 5 \log d - 5$$

A: m = -27 mag, and d = 1 AU = $(206265)^{-1}$ pc

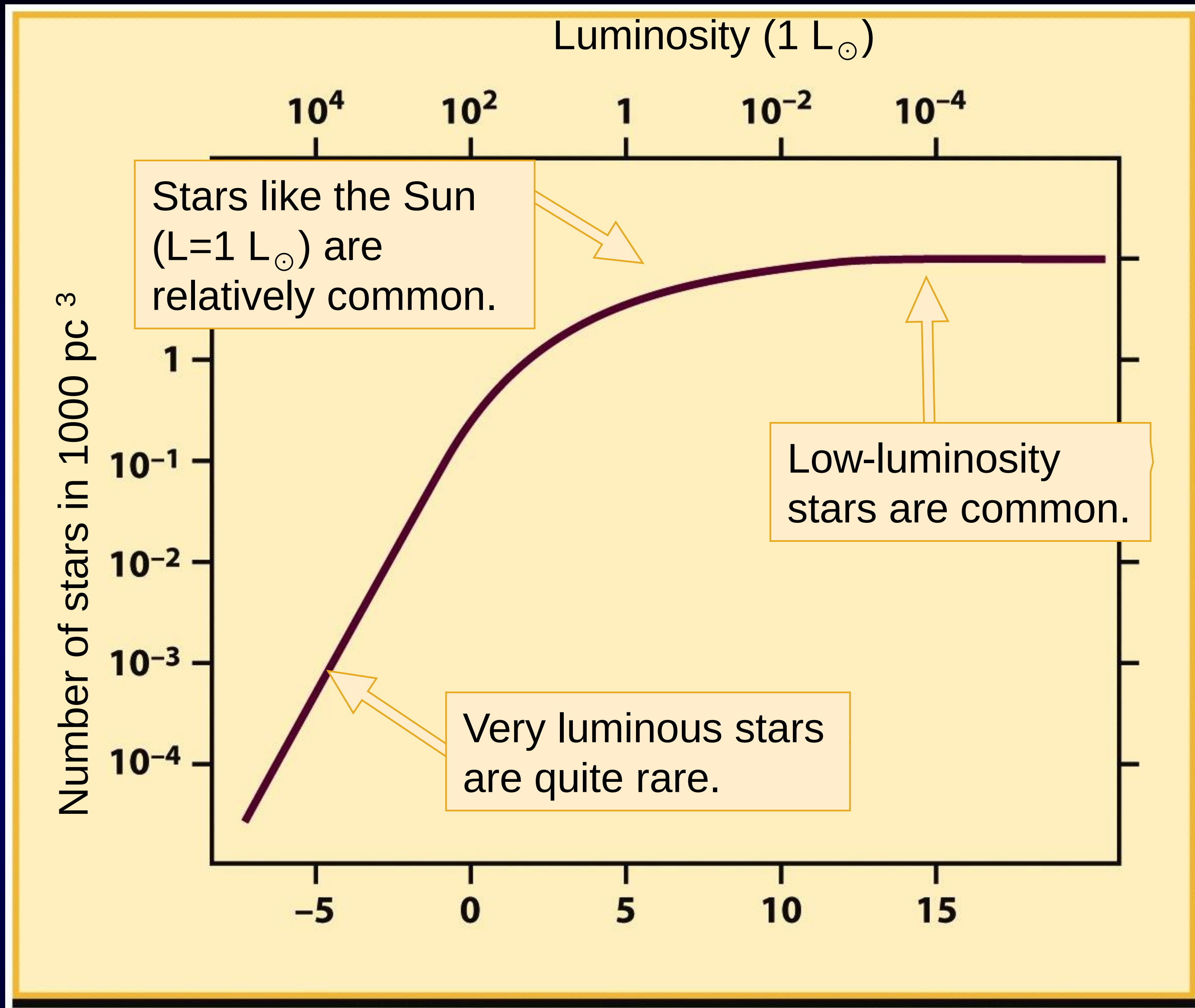
→ 5 log d – 5 ≅ -31.6, ∴ M ≅ 4.6 mag

Q: ε (Epsilon) Eridani is 3.23 pc from Earth. As seen from Earth, the star appears only 6.73 x 10^{-13} as bright as then Sun. Estimate the luminosity of εEridani compared with that of the Sun.

A: $L/L_{\odot} = (d/d_{\odot})^{2}\,(b/b_{\odot})$

3.23 pc = 3.23 x 206265 AU/pc = 6.66 x 10^{5} AU

→ $L/L_{\odot} = (6.66 \times 10^{5})^{2}\,(6.73 \times 10^{-13}) = 0.30$



光度弱的恆星個數多得多

Inverse-Square Law

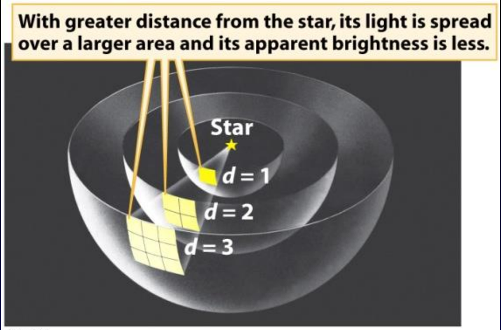


Figure 11-3a
Discovering the Universe, Seventh Edition

- *b*: apparent brightness, in W/m^2
- *L*: a star's luminosity, in W
- *d*: distance to the star, in meters

$$b = \frac{L}{4\pi d^2}$$

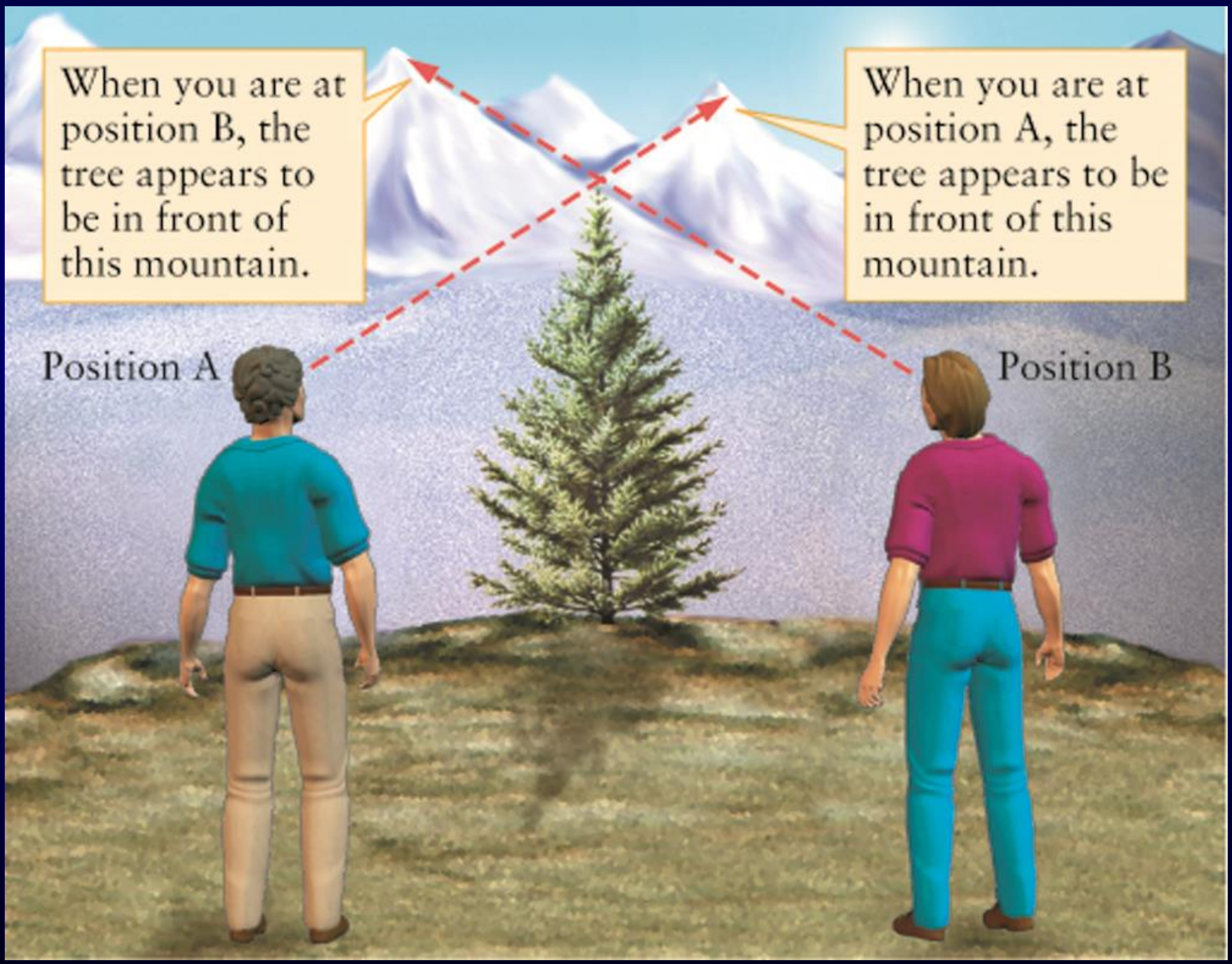
- For the Sun,

$$b_\odot = \frac{3.90 \times 10^{26}\,\mathrm{W}}{4\pi(1.50 \times 10^{11}\,\mathrm{m})^2} = 1370\,\mathrm{W\,m^{-2}}$$

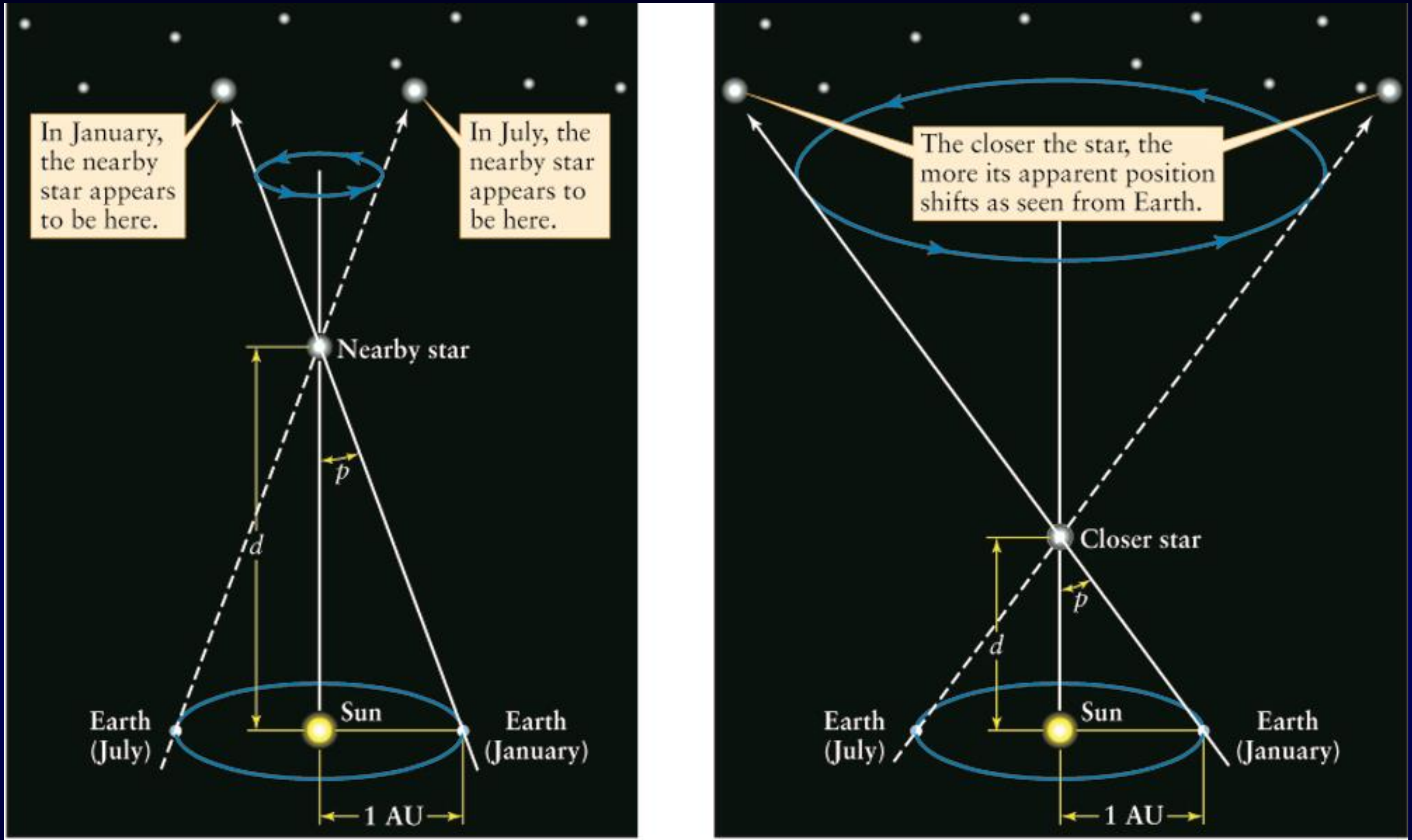
This is called the Earth's **Solar Constant**.

恆星的距離

視差現象 (parallax)



相對於遙遠的物體，近距離的東西在不同地方觀測，看起來相對位置似乎會改變



(a) Parallax of a nearby star
(b) Parallax of an even closer star

$$d \text{ (pc)} = 1/p \text{ (arcsec)}$$

Distance Determination by Parallax

- 例如夜空最亮的天狼星，其周年視差角 (annual parallax) 為0.38角秒，因此天狼星距離我們約2.6 pc，相當於 8.6光年

- 受到大氣擾動以及儀器精確度的限制，利用 parallax 方法，大約可以估計 < 1 kpc 天體的距離

- 太空觀測（尤其比AU更長的基線）可以有效提高精確度

估計恆星的基本性質

視差法 → 距離 → 看起來的亮度 → 實際光度

恆星是發光氣體，顏色 → 表面溫度
→ 每塊面積發光能力 → 總面積 → 直徑

恆星處於靜力平衡狀態 向外熱壓力vs 向內重力

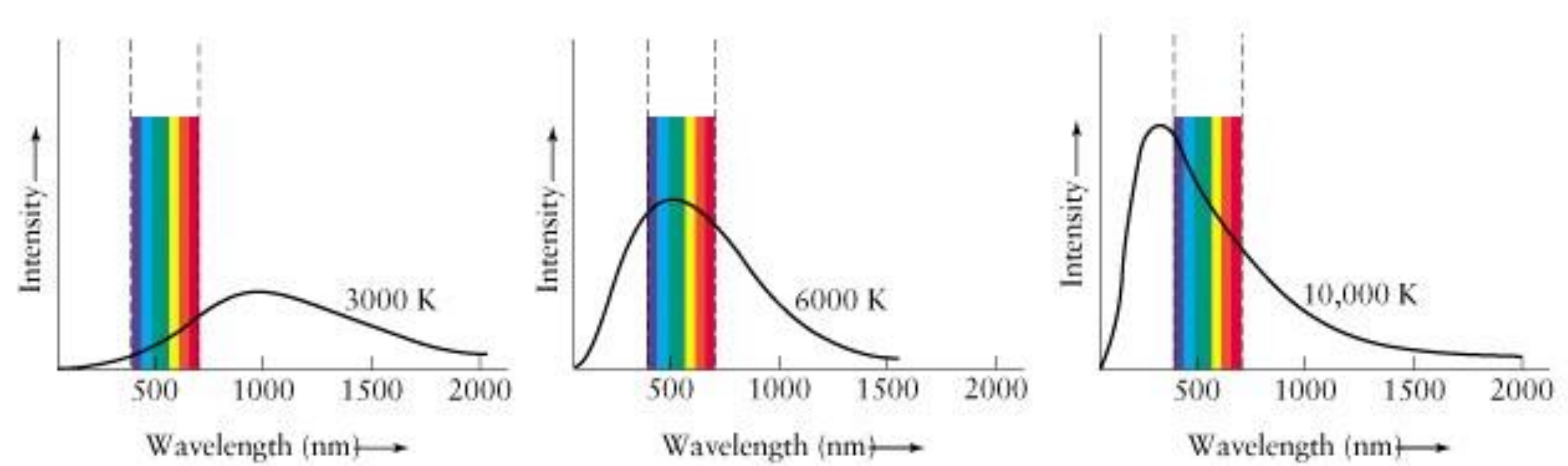
質量大 → 萬有引力強
←→ 核心溫度高、壓力大
→ 核子反應快 → 發光強 → 表面溫度高

∴ 恆星 表面溫度↑→ 光度↑

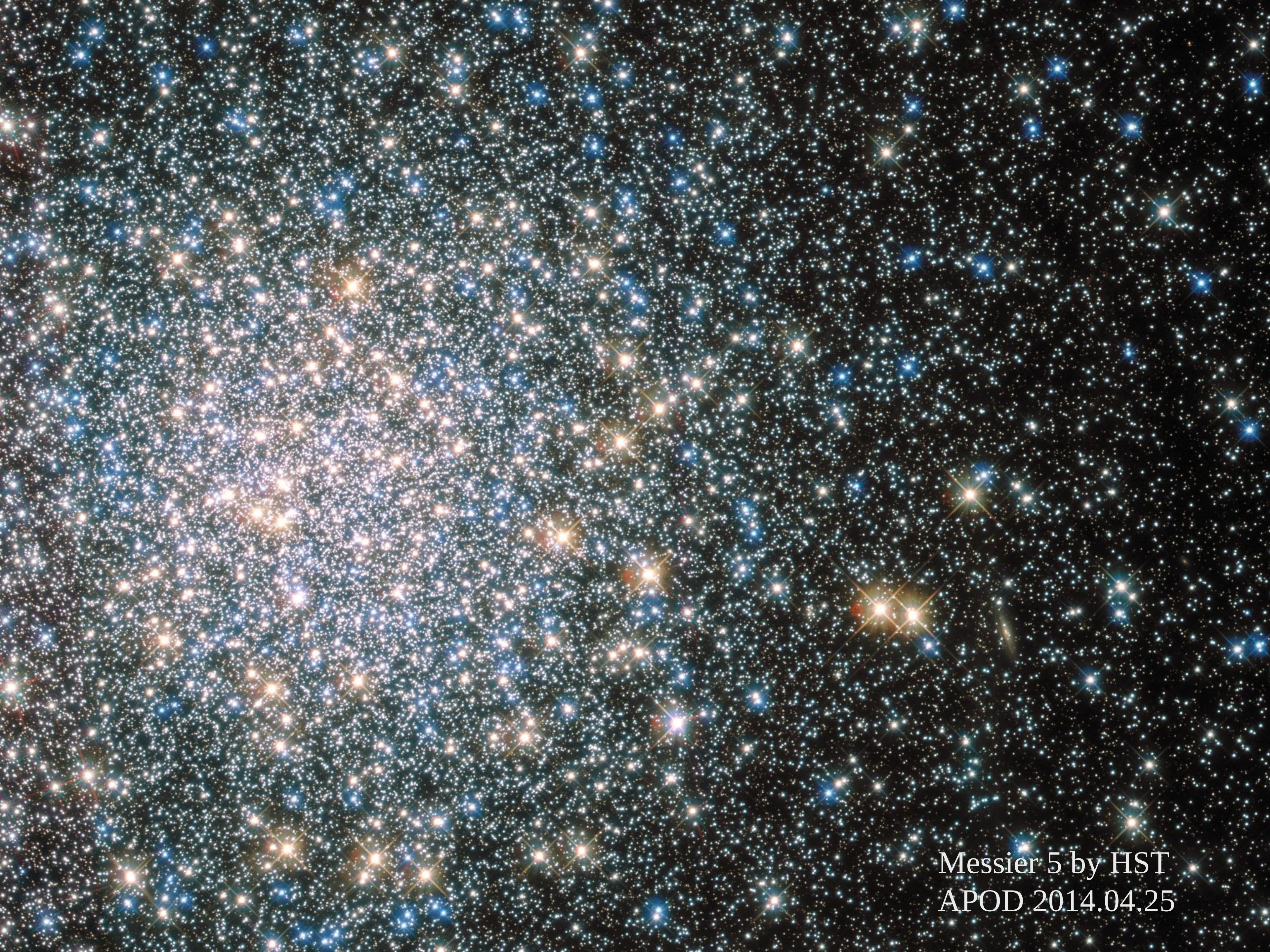
輻射體溫度高 → 放出較多能量高的光
例如X射線、紫外光、藍光等
（這些電磁波頻率比較快）

輻射體溫度低 → 放出頻率低（也就是波長比較長）的輻射，例如紅光、紅外線、微波等

天文學習慣上以紅表示低溫、藍或白表示高溫

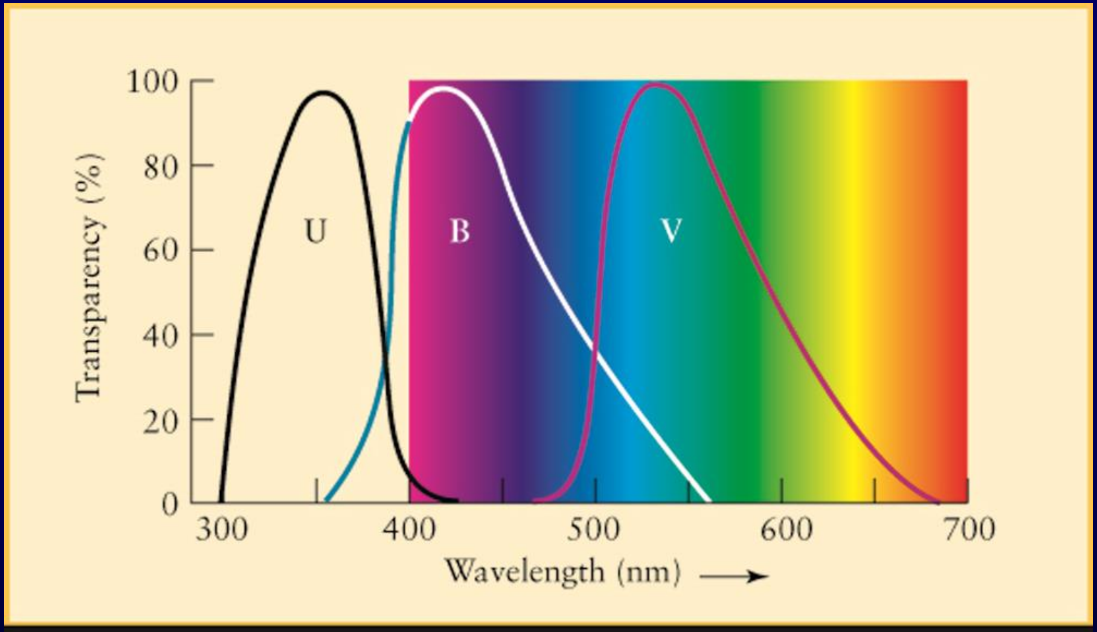


a This star looks red
b This star looks yellow-white
c This star looks blue-white

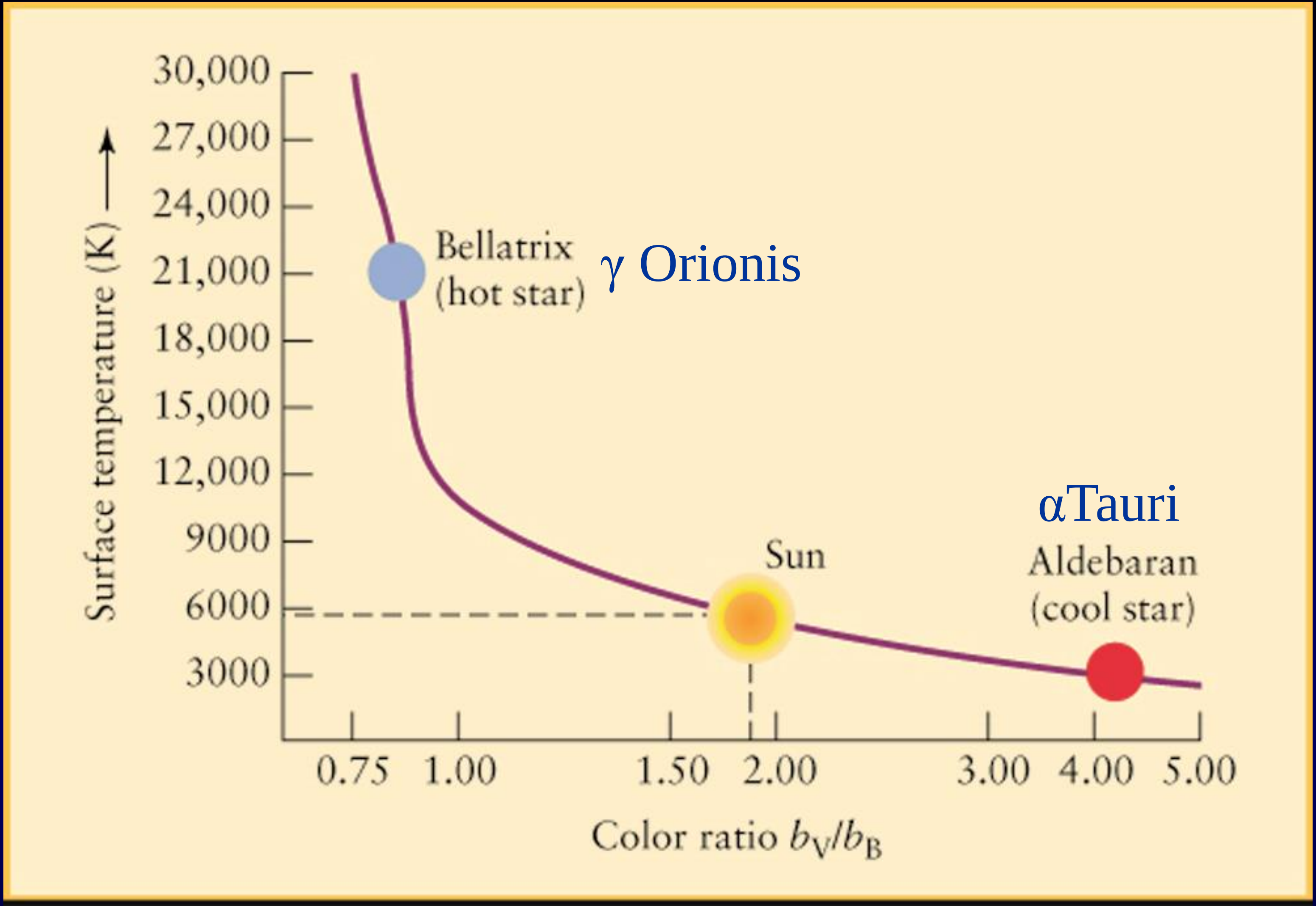

Messier 5 by HST
APOD 2014.04.25

特殊設計的濾光片(e.g., UBV）測量恆星亮度，

例如在藍光 (blue) 與綠光 (visual) 亮度的比值
→ 輻射強度在這兩個波段之間的斜率
→ 輻射體溫度



兩個波段的星等差，稱為**顏色指數 (color index)**

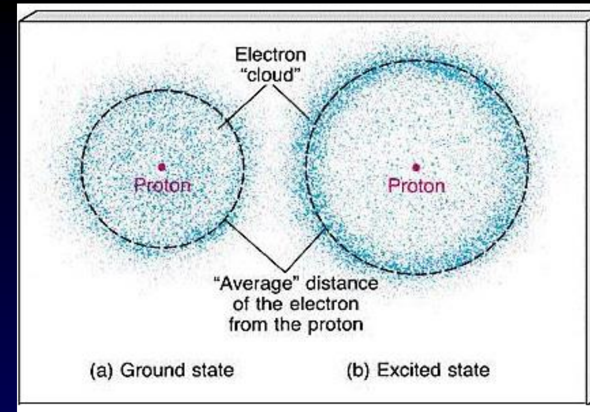


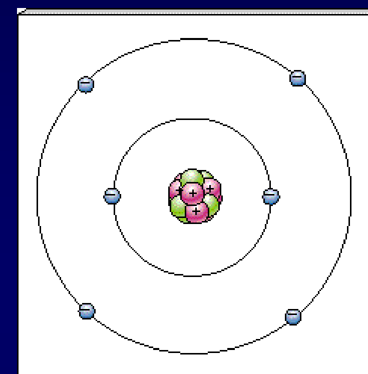
V與B兩個波段之間的亮度比（或是星等差）
(B – V) ➔ 恆星表面溫度

電子躍遷，吸收特定能量的入射光
→ 吸收線

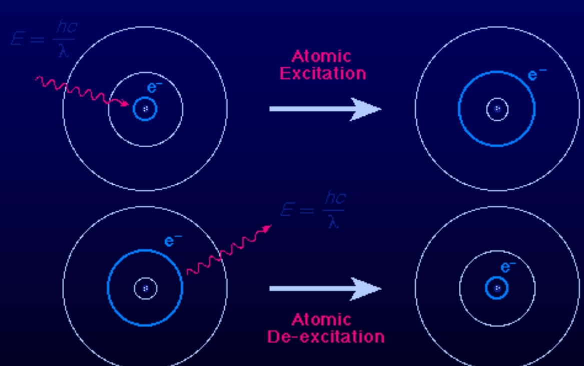
原子核的庫倫力，決定這些特定能量的強弱

不同元素產生各自特有吸收光譜，有如「指紋」般。因此我們利用天體光譜，可以推測天體的化學成分，以及所在的物理狀態

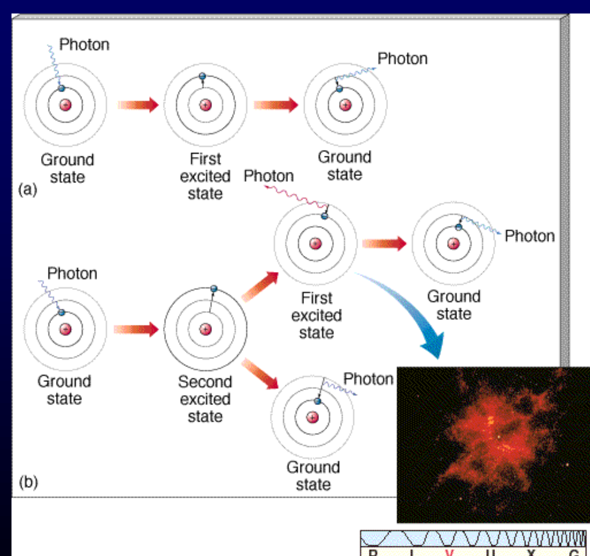


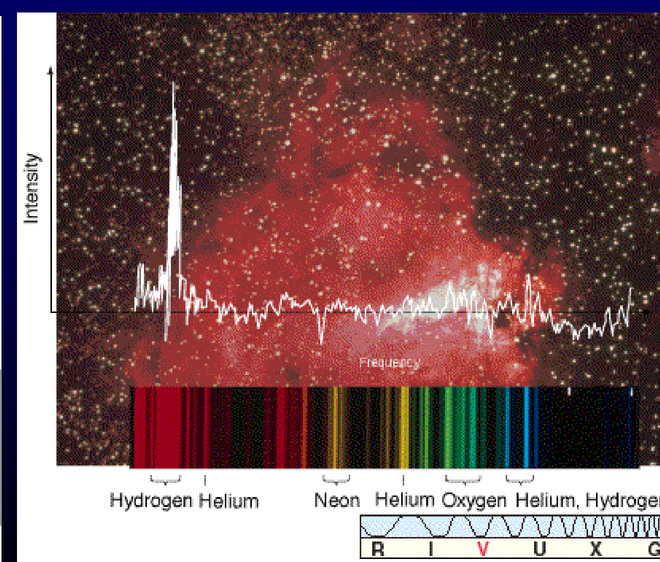


複雜原子（例如碳）



原子光譜





19世紀末 Harvard College Observatory 一批女性天文學家以光譜為恆星分類

Figure 11-6a
Discovering the Universe, Seventh Edition

Annie Jump Cannon 為恆星光譜分類之先驅，她逐一檢視共分類了超過30萬顆恆星

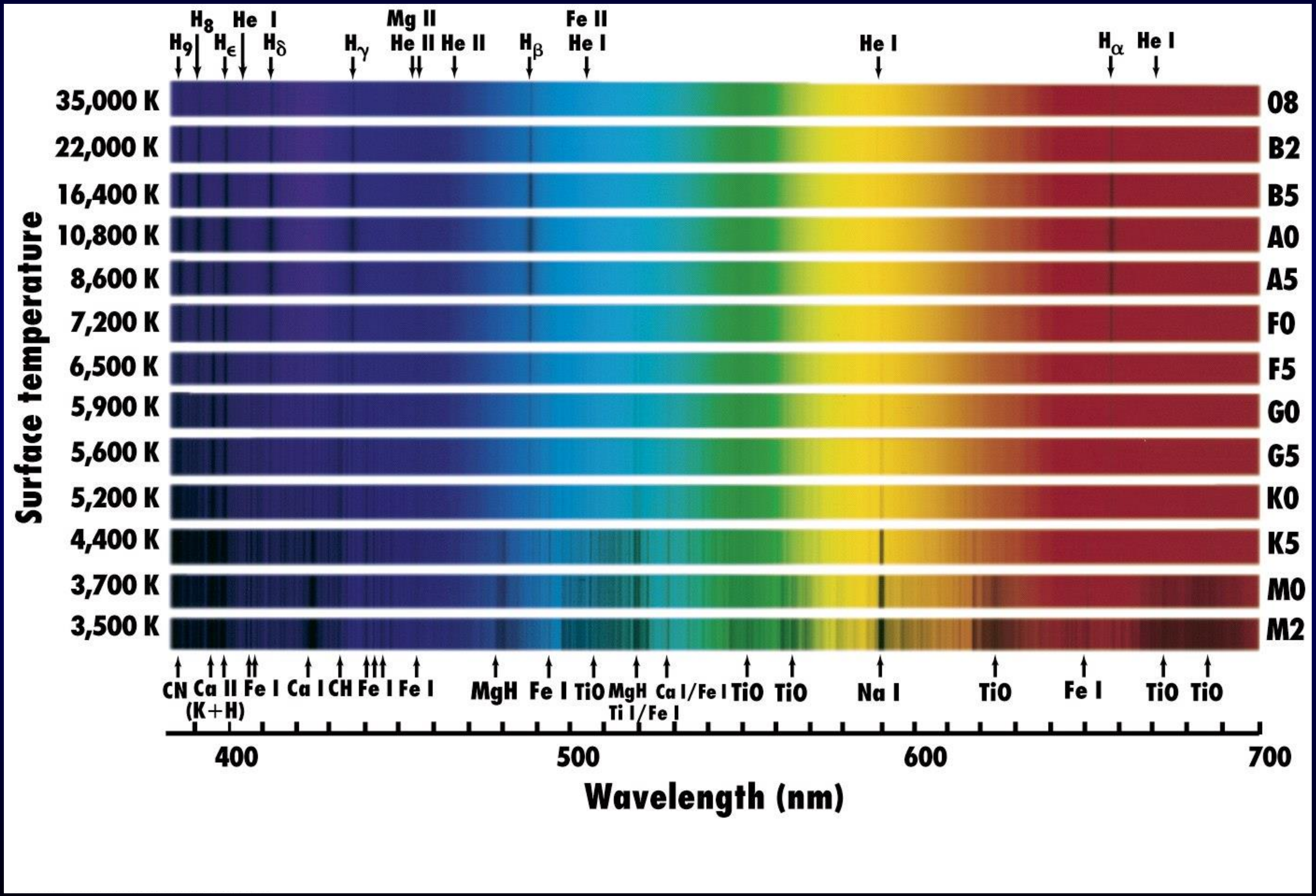
Figure 11-6b
Discovering the Universe, Seventh Edition

光譜型態與表面溫度

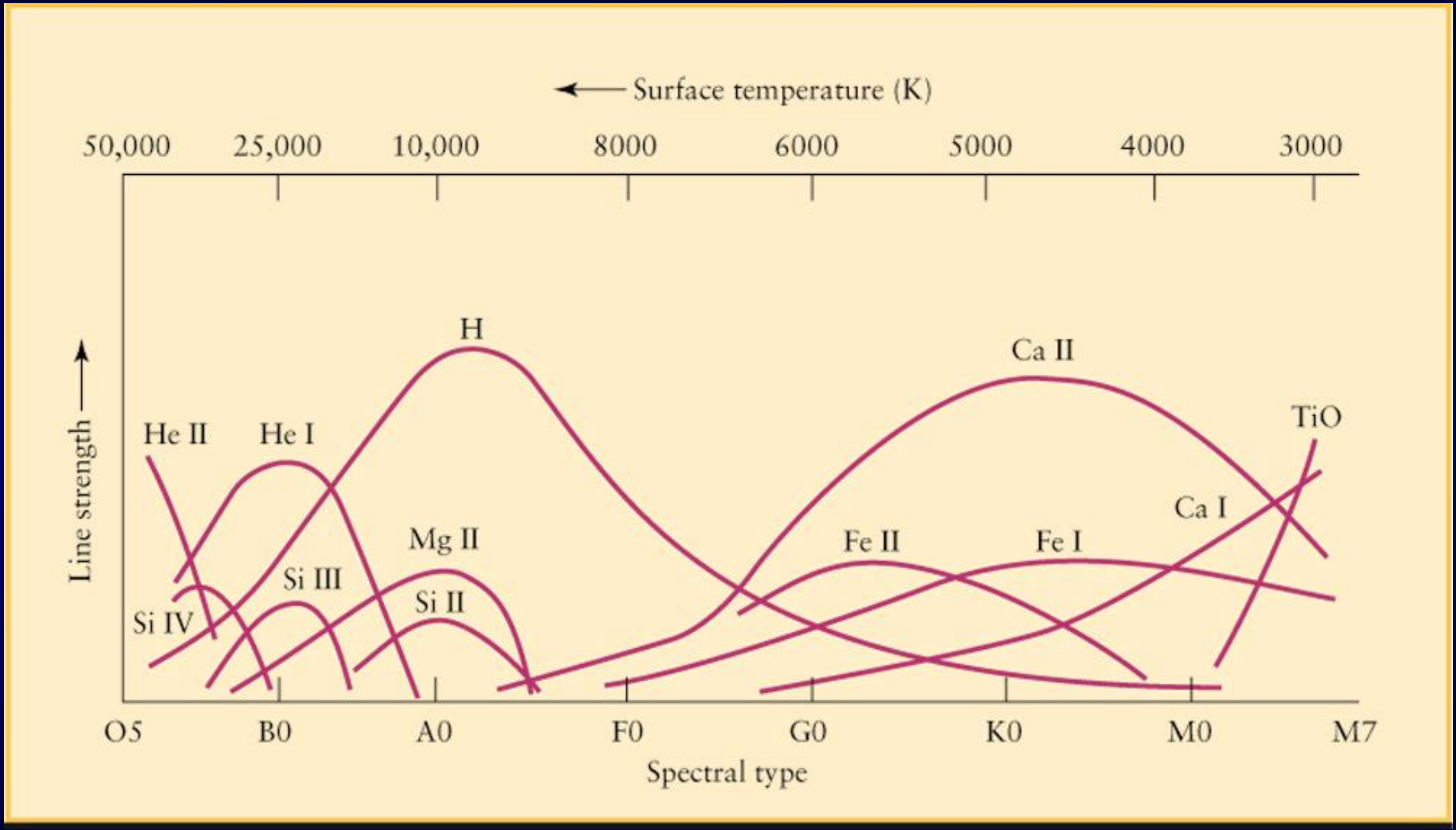
- 以光譜中氫元素的譜線明顯程度，將恆星分類，最強的為A，依序為B, C, …
- 後來發現在眾多影響氫譜線強度的因素中，溫度最重要
- 若以溫度由高到低排列，光譜型態的順序為 **O-B-A-F-G-K-M-L-T-Y**。O型恆星表面溫度最高，達30,000～50,000；M型恆星只有2500～4000度; L、T嚴格說不算恆星，而屬棕矮星 subclasses 0 to 9
- 太陽是顆G型恆星，屬於中等光度

Oh, Be A Fine Guy/Girl, Kiss Me!

不同溫度、成分 → 不同激發程度 → 不同譜線

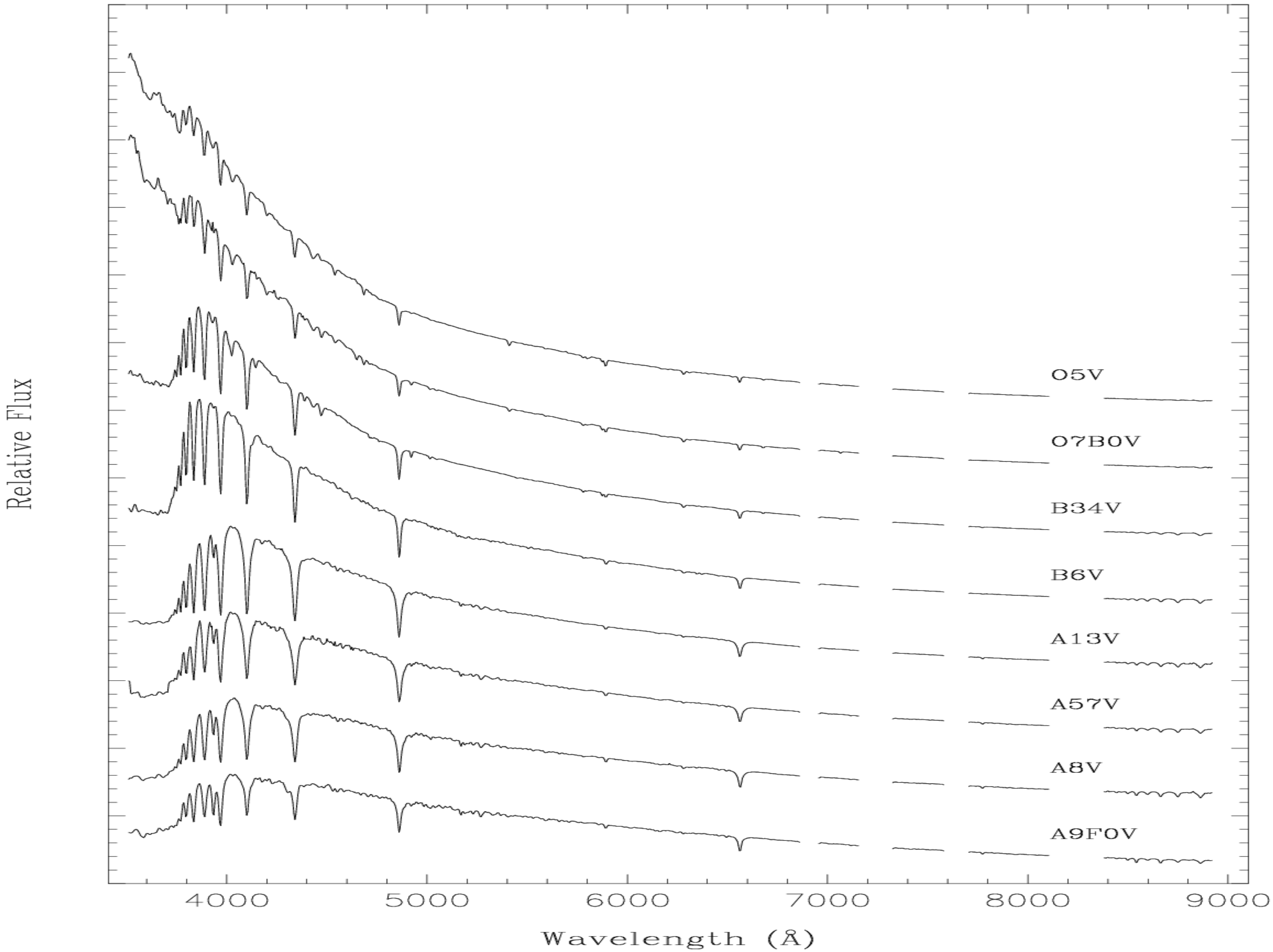


恆星表面環境（e.g., 溫度 → 吸收線強度

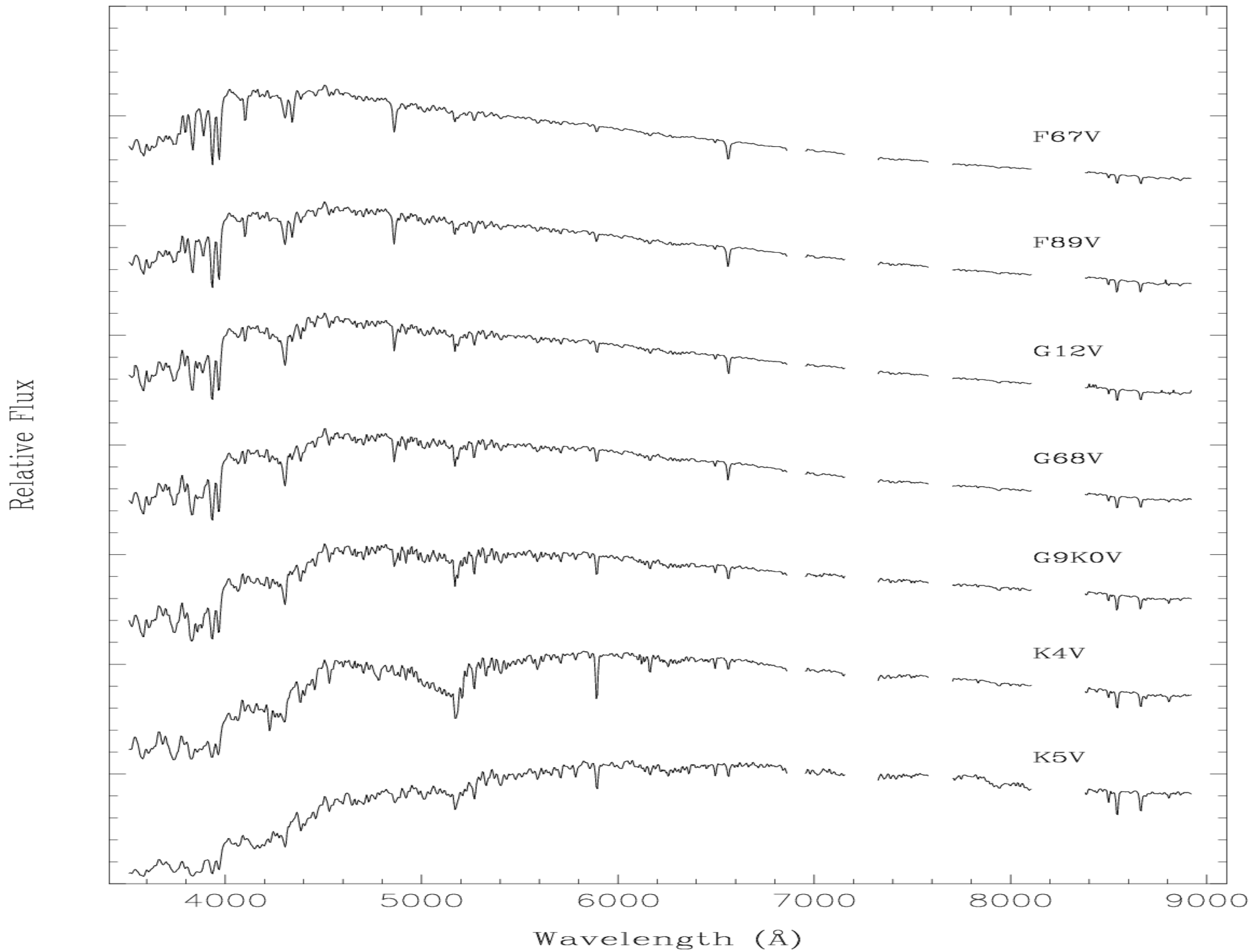


I：中性原子；II：一次游離； III：兩次 …

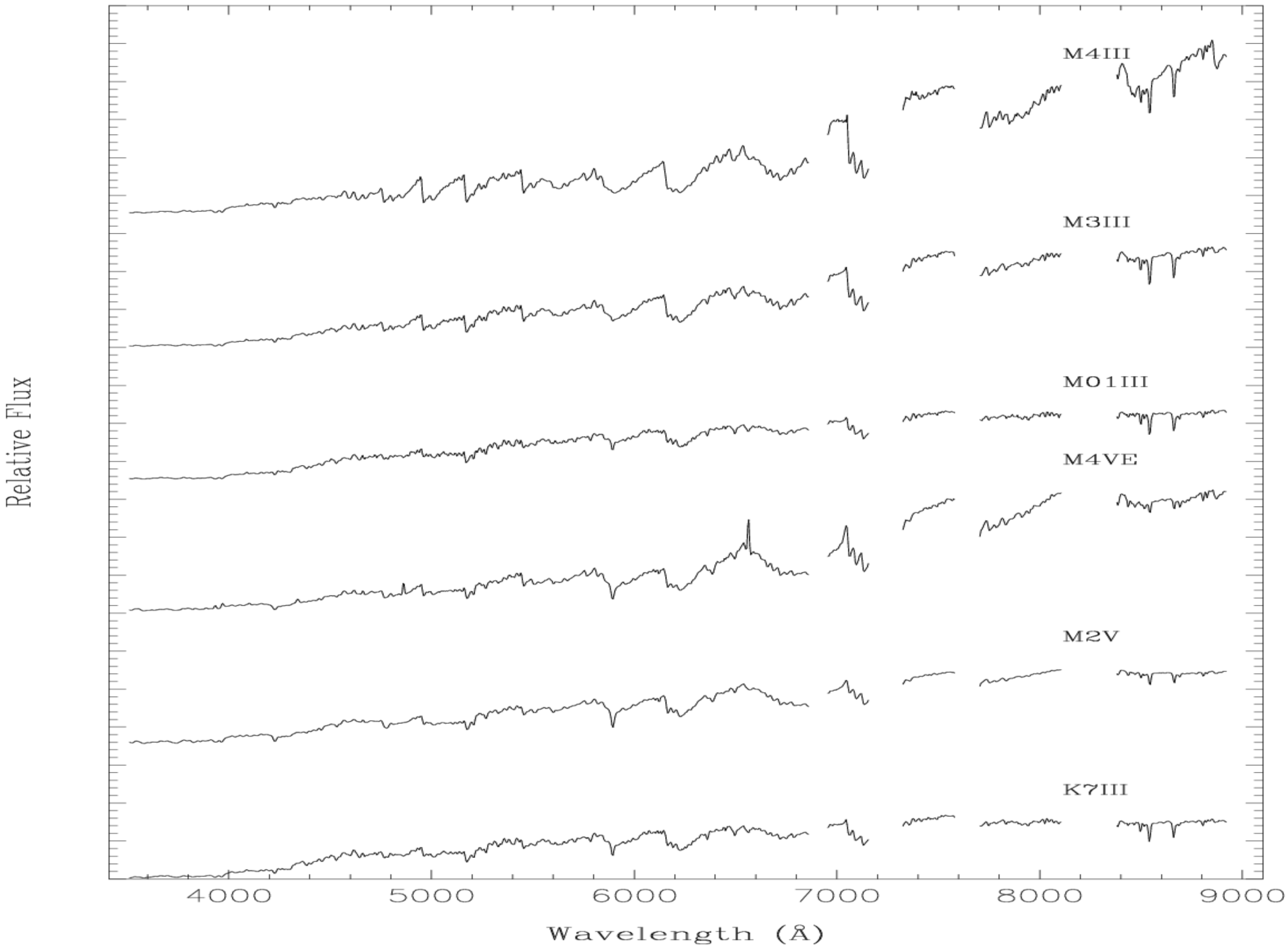
高熱的恆星──短波強、長波弱；氫線、氦線



溫熱的恆星──短波、長波相當；氫線明顯

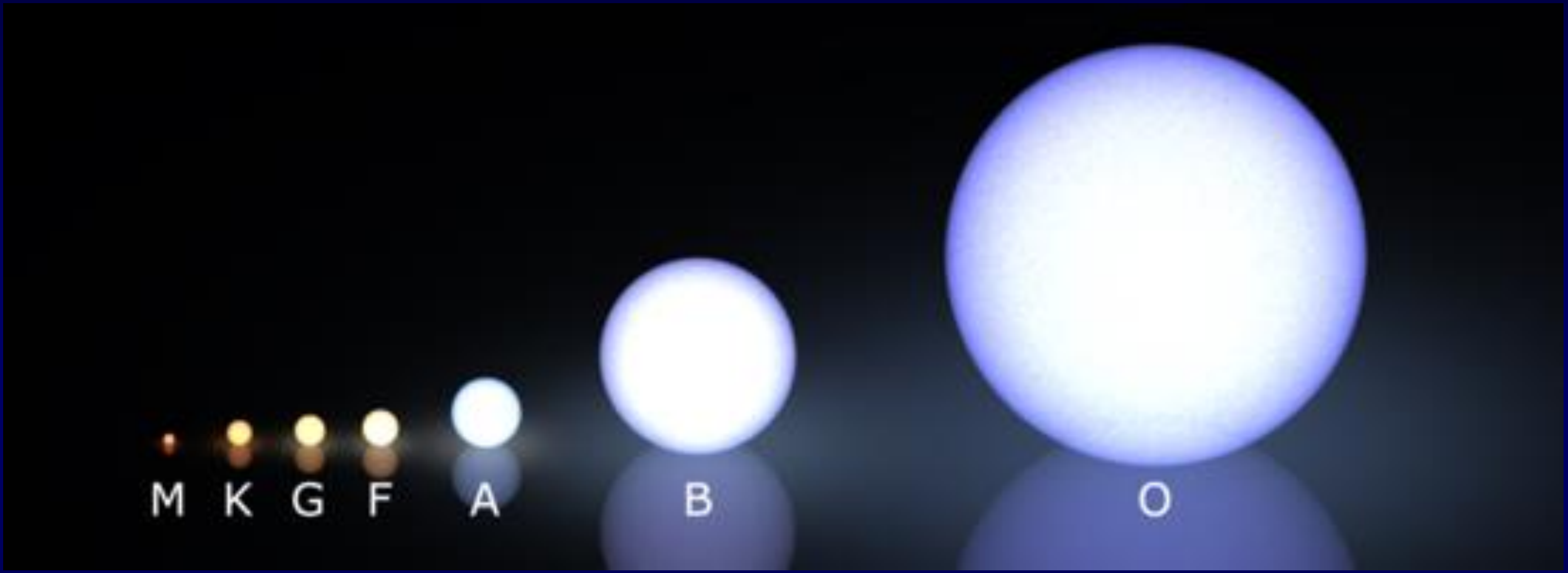


低溫的恆星──短波弱、長波強；分子線明顯

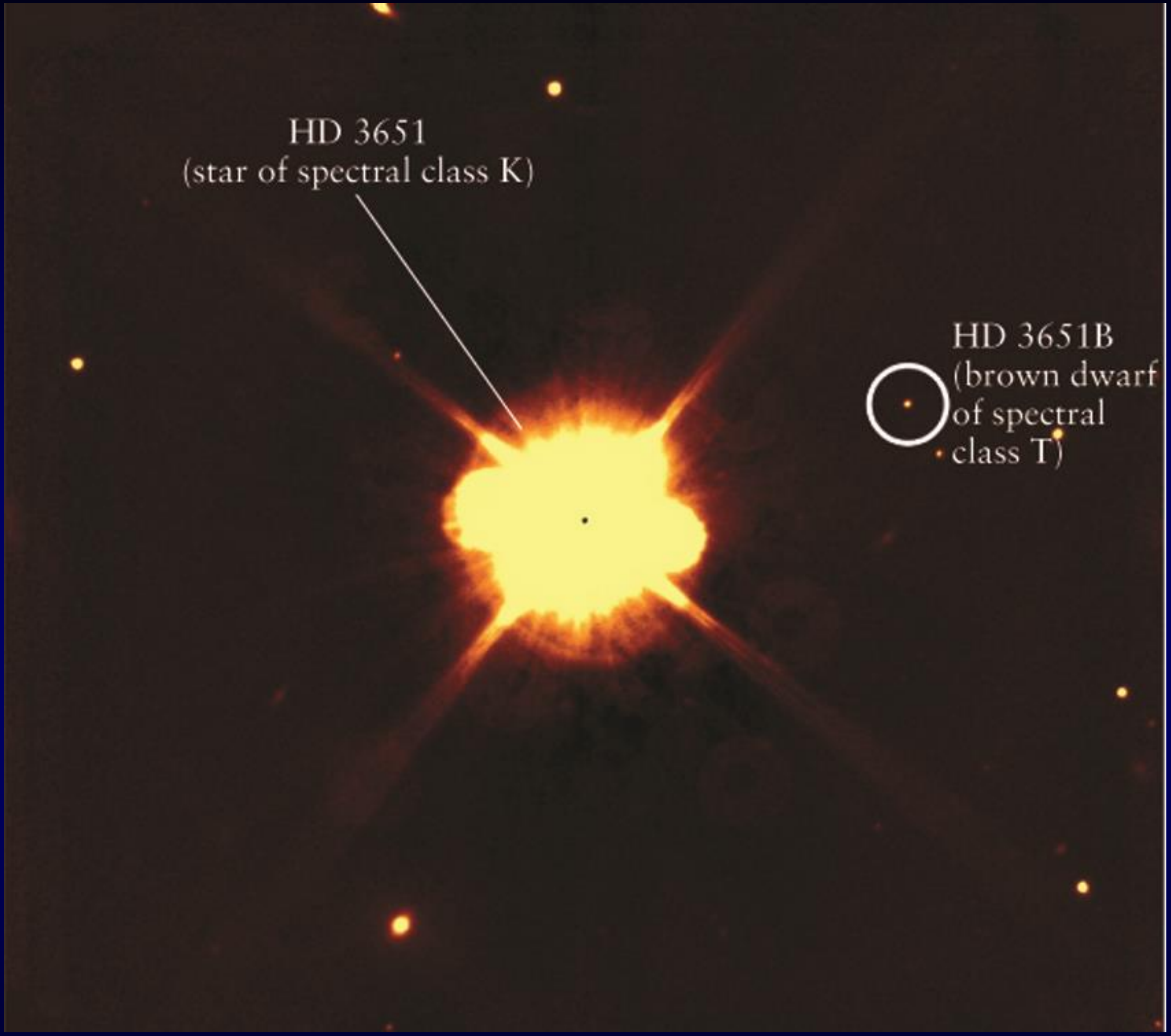


The Spectral Sequence

Spectral class	Color	Temperature (K)	Spectral lines	Examples
O	Blue-violet	30,000–50,000	Ionized atoms, especially helium	Naos (ζ Puppis), Mintaka (δ Orionis)
B	Blue-white	11,000–30,000	Neutral helium, some hydrogen	Spica (α Virginis), Rigel (β Orionis)
A	White	7500–11,000	Strong hydrogen, some ionized metals	Sirius (α Canis Majoris), Vega (α Lyrae)
F	Yellow-white	5900–7500	Hydrogen and ionized metals such as calcium and iron	Canopus (α Carinae), Procyon (α Canis Minoris)
G	Yellow	5200–5900	Both neutral and ionized metals, especially ionized calcium	Sun, Capella (α Aurigae)
K	Orange	3900-5200	Neutral metals	Arcturus (α Boötis), Aldebaran (α Tauri)
M	Red-orange	2500-3900	Strong titanium oxide and some neutral calcium	Antares (α Scorpii), Betelgeuse (α Orionis)
L	Red	1300-2500	Neutral potassium, rubidium, and cesium, and metal hydrides	Brown dwarf Teide 1
T	Red	< 1300	Strong neutral possisium, and some water	Brown dwarf Gliese 229B



http://en.wikipedia.org/wiki/Stellar_classification

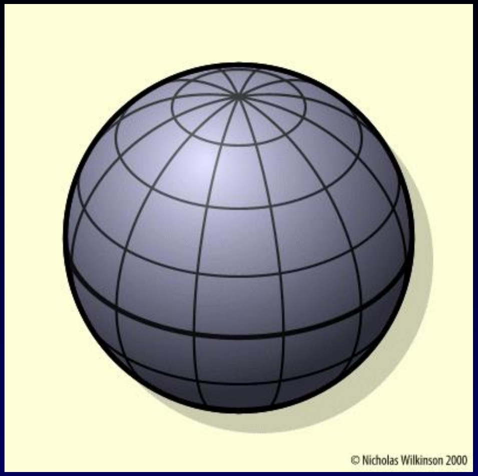


HD: Henry Draper Catalogue

恆星幾乎如黑體般輻射

$$L = (\sigma T^4)\,(4\pi R^2)$$

$$\text{Stefan} - \text{Boltzmannconstant}\ \sigma = 5.67 \times 10^{-8}\ \text{W m}^2\ \text{K}^{-4}$$



有時使用太陽單位很方便

$$\frac{L}{L_\odot} = \left(\frac{R}{R_\odot}\right)^2 \left(\frac{T}{T_\odot}\right)^4$$

Q: Betelgeuse (Alpha Orionis) is 60,000 times more luminous than the Sun and has a surface temperature of 3500 K. What is its radius?

A: $R/R_\odot$ = (5800 K/3500 K)^2 (6 x 10^4)$^{1/2}$ = 670

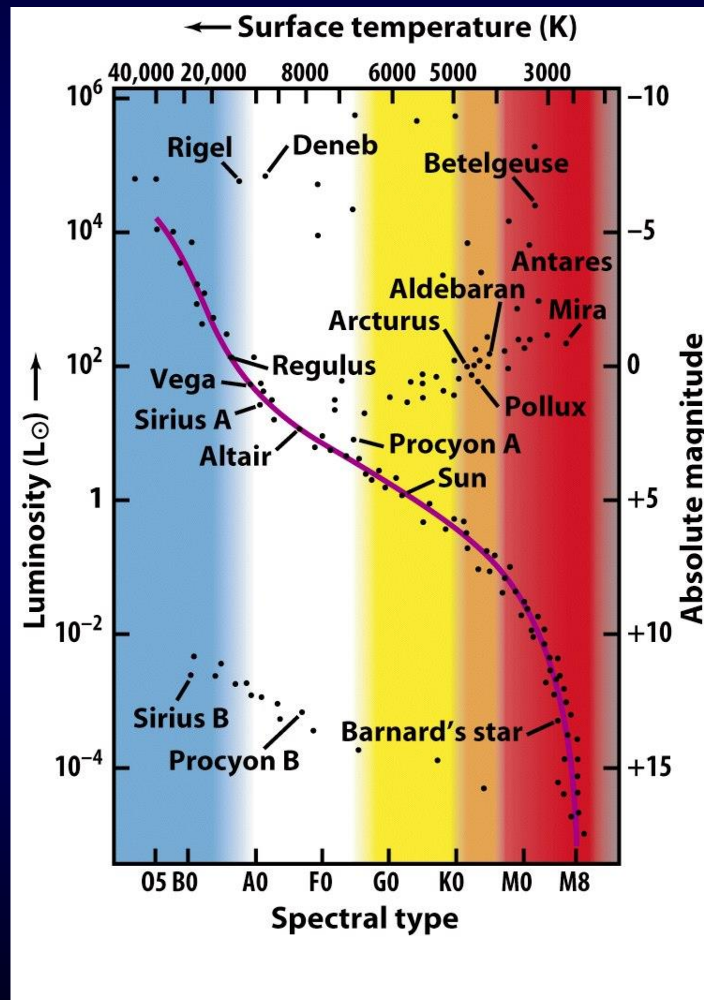
The Sun's radius is 6.96 x 10^8 km, so $R_{Betelgeuse}$ ~ 3 AU!

This is beyond the orbit of Mars in the solar system.

恆星光度與表面溫度的關係
Hertzsprung-Russell diagram

赫羅圖

表面溫度



光譜型態

光度

向上增加

向左增加！

1911 by Ejnar Hertzsprung (Danmark) & 1913 by Henry Norris Russell (USA)

The H-R diagram --- An astronomer's "*tool of the trade*"

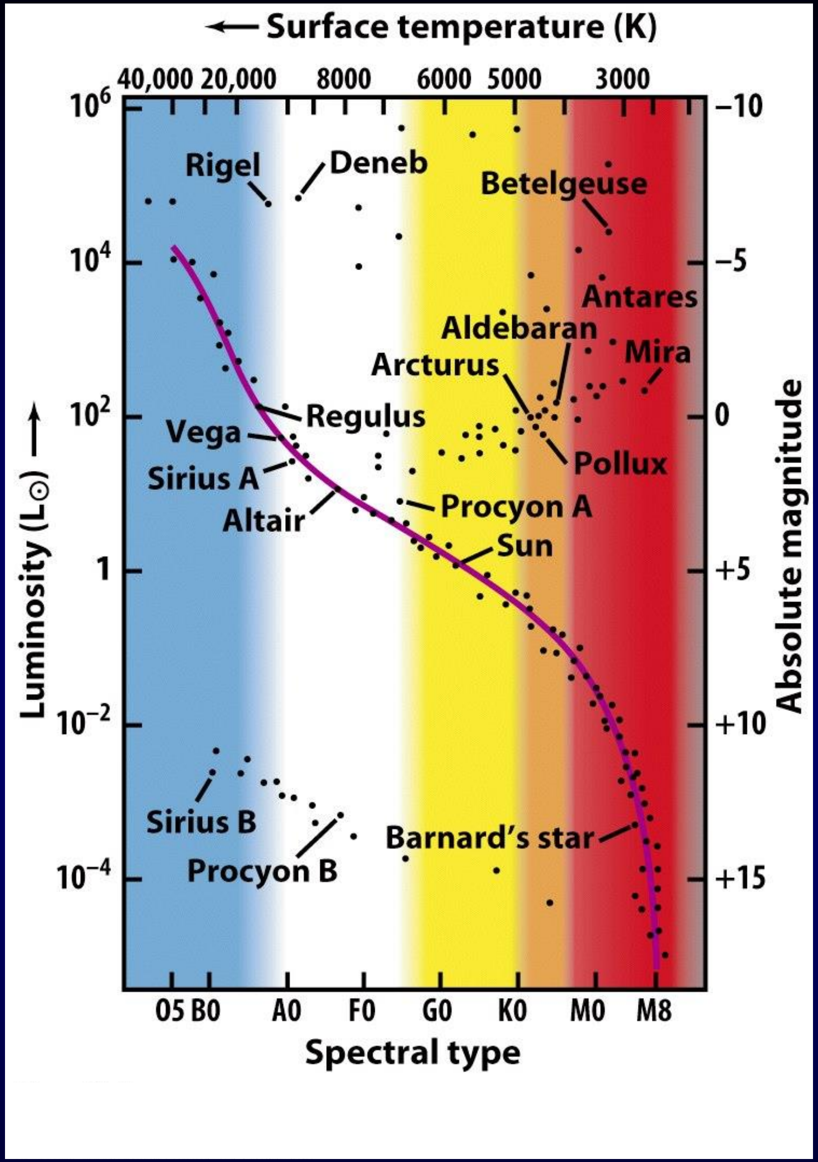
強

↑

光度

↓

弱



在 HR diagram上，90%的恆星集中在一條帶狀分佈，稱為「主序」(main sequence)

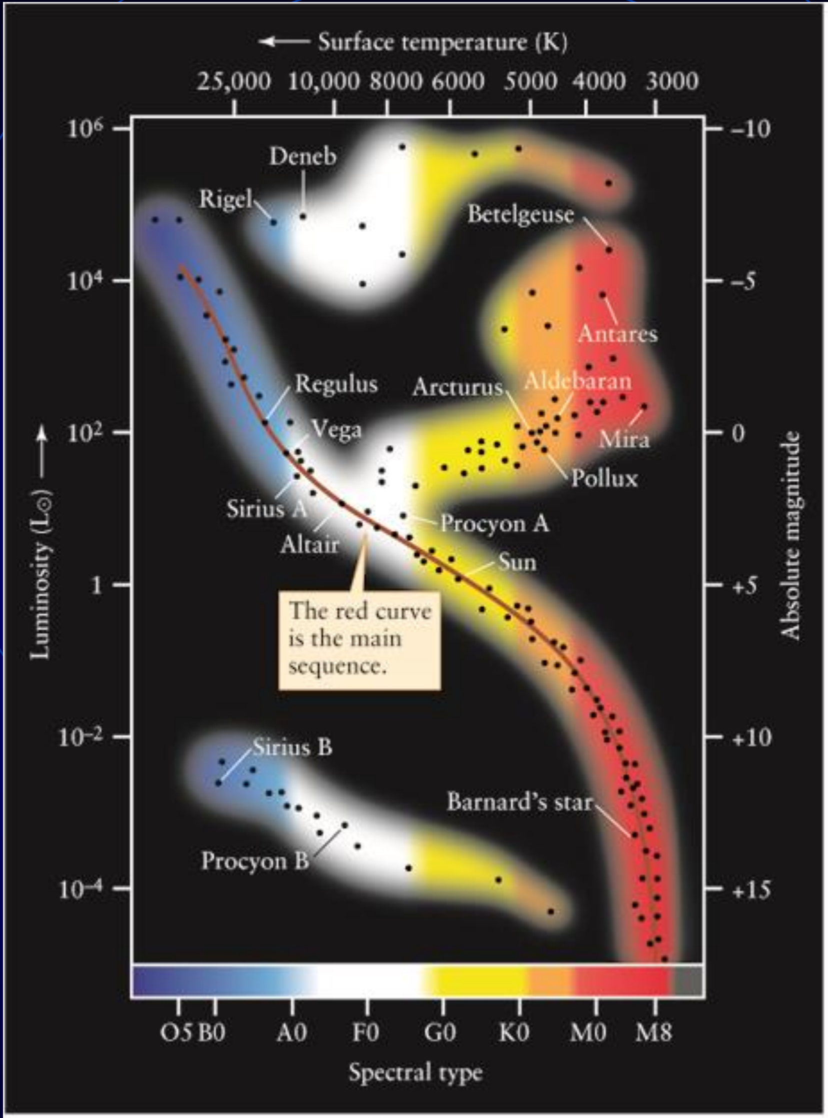
主序恆星遵循「**表面溫度越高，光度越強**」的關係

高← 表面溫度 →低

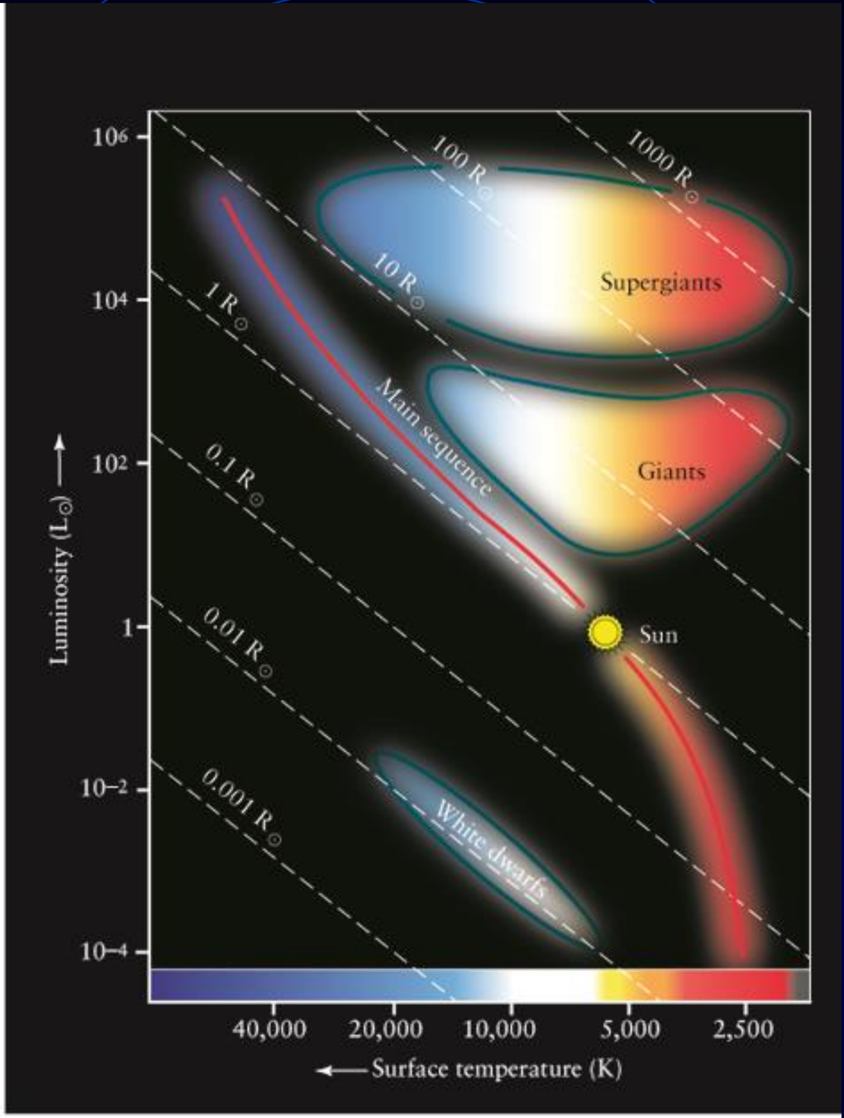
O B A F G K M Spectral type

解讀「赫羅圖」（H-R diagram）

- 赫羅圖為研究天體的基本重要工具
- 「正常」的星球，也就是平衡、穩定的恆星
  → **主序星 (main-sequence stars)**
- 赫羅圖右上角的星球，溫度低、光度明亮
  → **紅巨星 (red giants)**、
  紅超巨星 (red supergiants)
- HR圖左下角的星球，溫度高、光度微弱
  → **白矮星 (white dwarfs)**

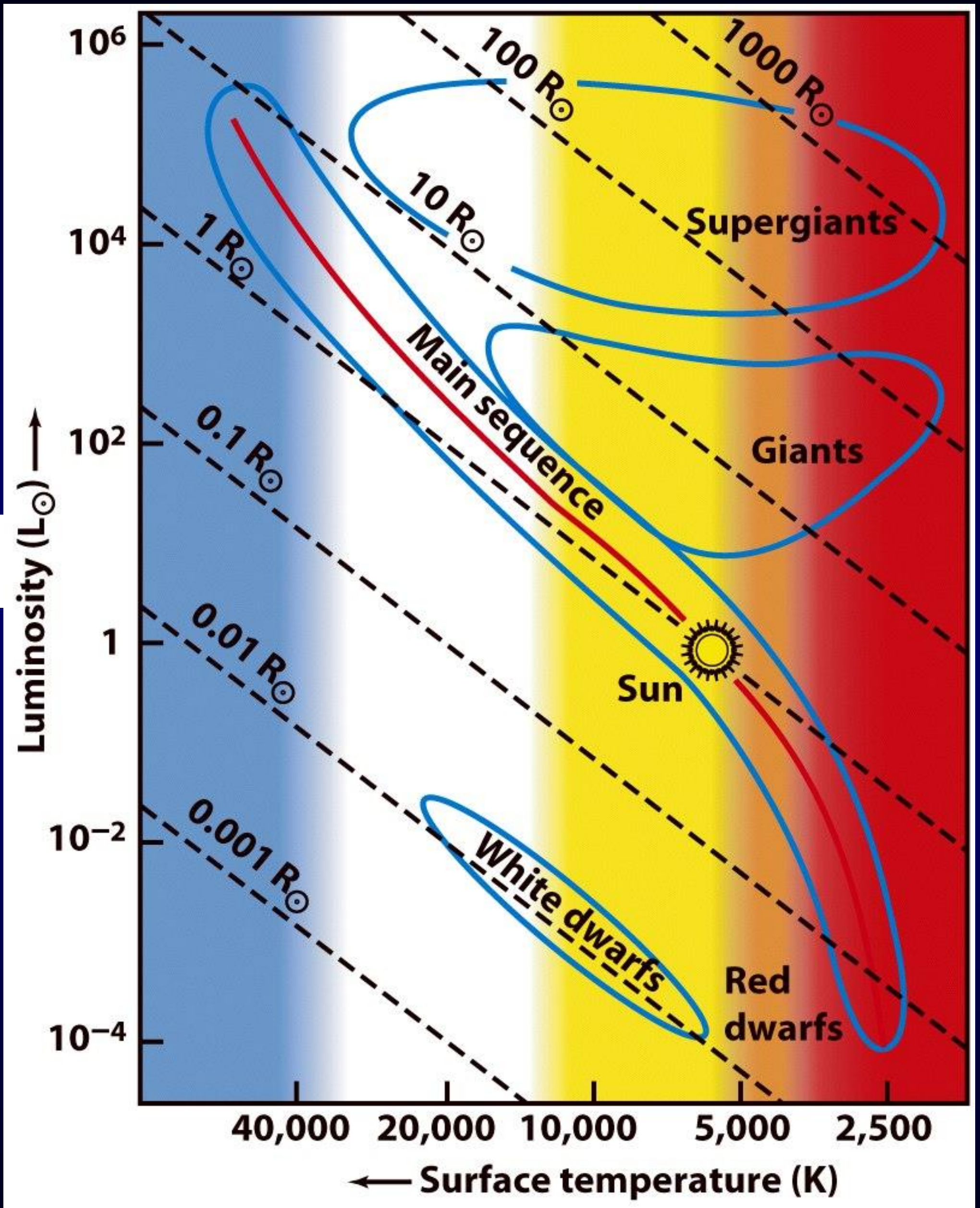


(a) A Hertzsprung-Russell (H-R) diagram



(b) The sizes of stars on an H-R diagram

體積大



log L

log T

體積小

L = luminosity

radiation per unit area

$$L = (\sigma T^4)\,(4\pi R^2)$$

total surface area

T = surface temperature

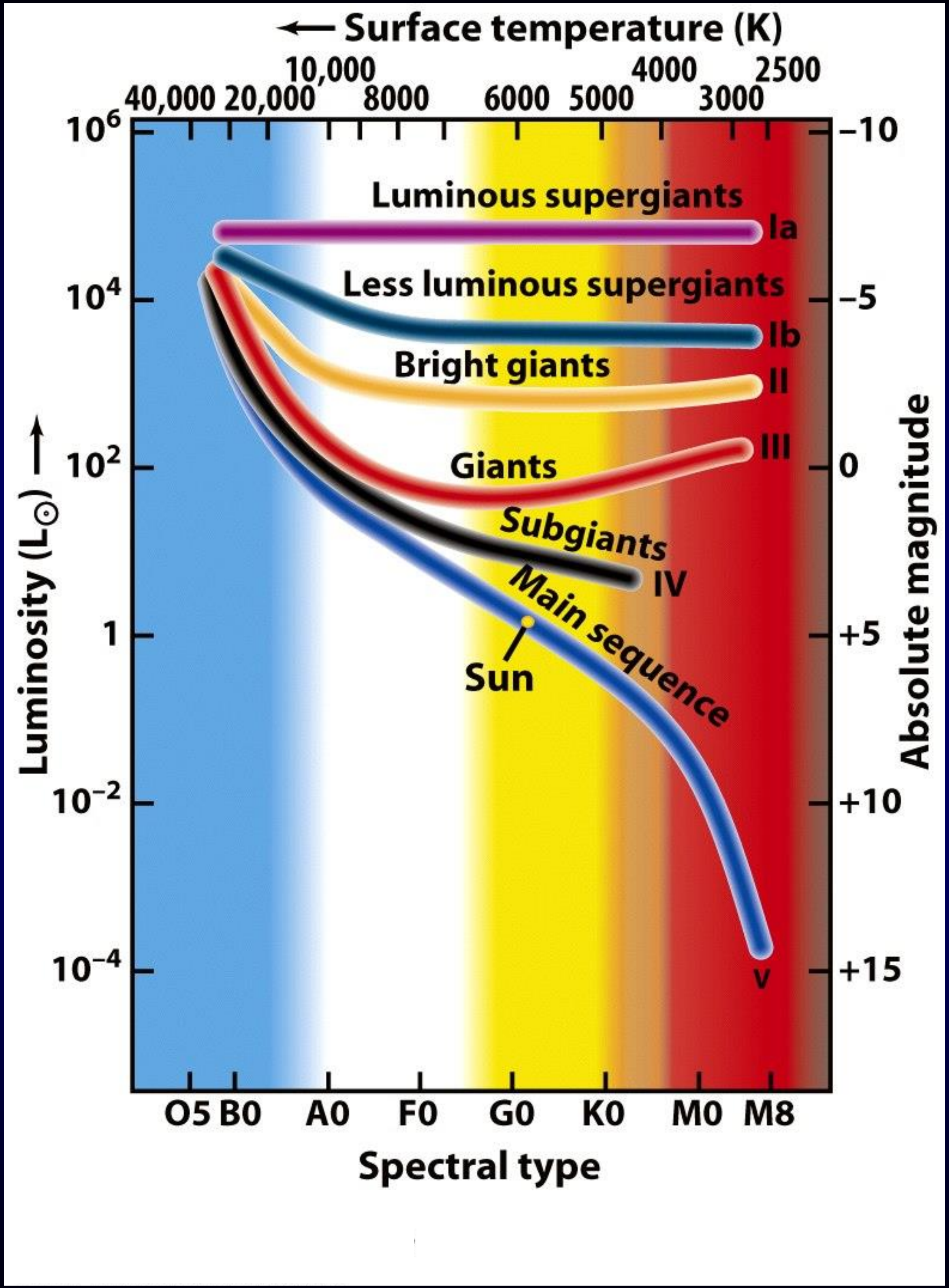
σ = Boltzmann const.

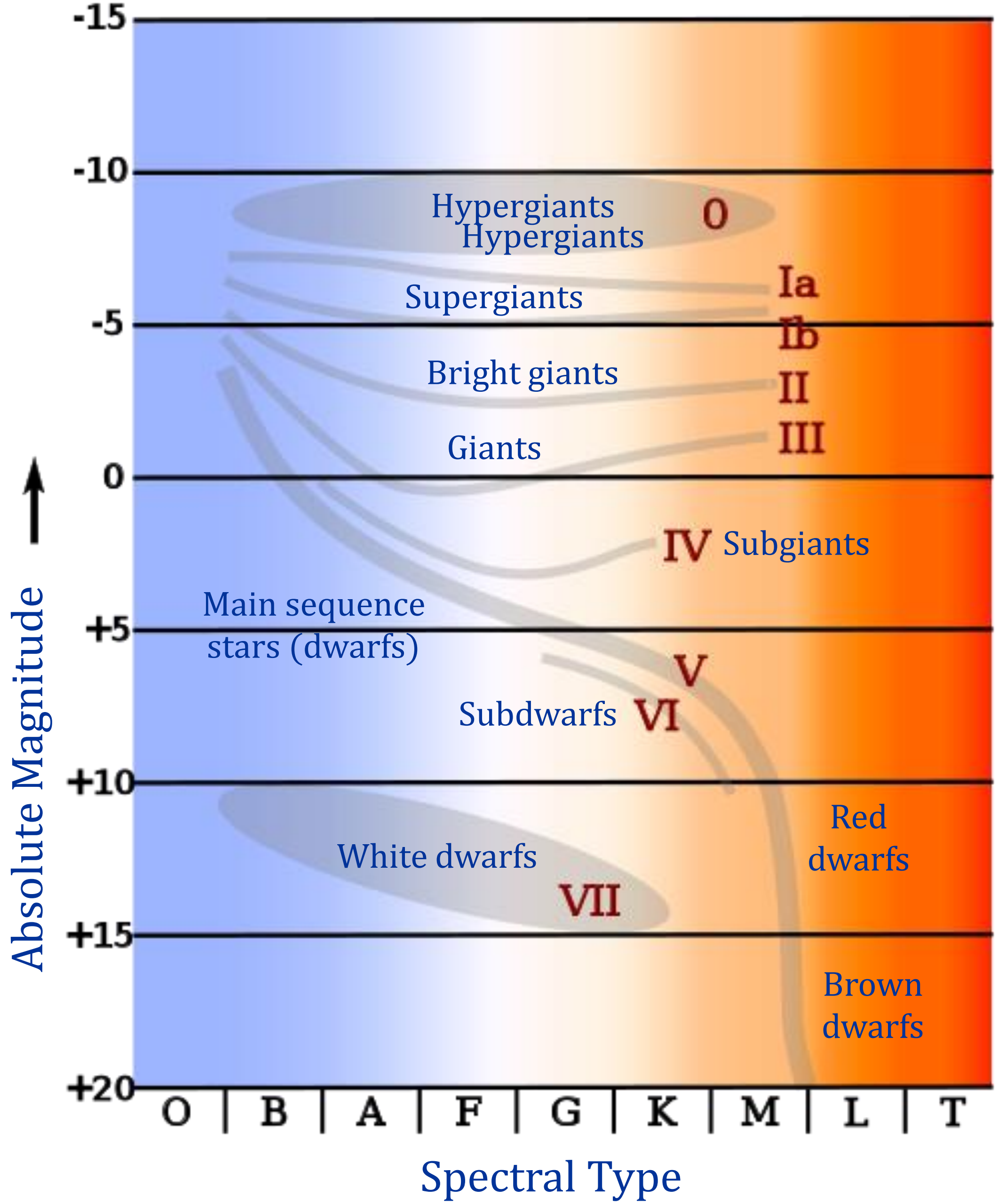
R = stellar radius

恆星表面溫度
→ 光譜型態

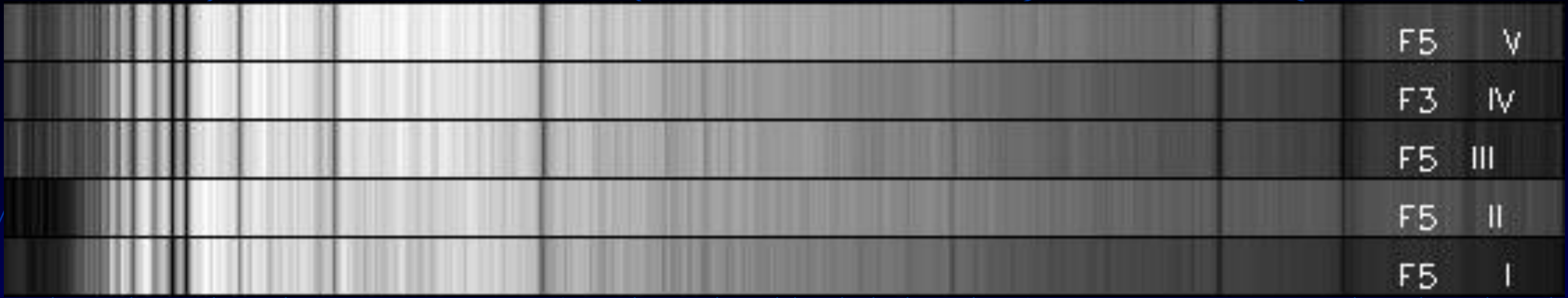
但是同樣溫度（例如 5800 K）的星球可以是白矮星、主序星，或是巨星、超巨星

研究光譜中的吸收線（被恆星大氣的密度與壓力影響）
→ luminosity class

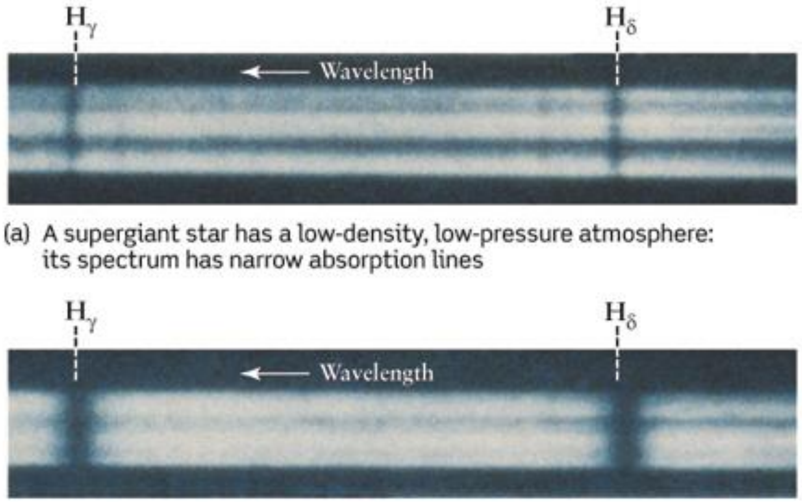




http://en.wikipedia.org/wiki/Stellar_classification



Spectra near spectral type F5, for different luminosity classes . Adapted from data in the electronic version of "A Library of Stellar Spectra," by Jacoby G.H., Hunter D.A., Christian C.A. Astrophys. J. Suppl. Ser., 56, 257 (1984). http://web.njit.edu/%7Egary/321/Lecture6.html



(a) A supergiant star has a low-density, low-pressure atmosphere: its spectrum has narrow absorption lines

(b) A main-sequence star has a denser, higher-pressure atmosphere: its spectrum has broad absorption lines

- 主序星就是核心在進行（氫）核反應的星球 → 穩定平衡，有如安全閥機制
- 一旦核心的氫用完，失去提供氣體壓力的能量來源，再也不能與萬有引力平衡

  → 恆星走向衰亡
- 我們的太陽已經穩定發光了約50億年，預計還可以存活50億年

這時恆星結構上分成兩部分：**核心**的氫（核燃料）已經用完，但是**外層**卻還有很多氫

估計恒星的距離

- **視差法**（直接，最遠距離目前限於 < 1 kpc）
- **類比法**（外觀類似，其他性質也相似）

光譜型態 (O, B, A, F, G, K, M)

＋

光度分類 (I, II, III, IV, V)

→ 絕對星等

↕ → 距離

視星等

光譜型態與光度分類皆來自光譜觀測，故此方法也稱為**光譜視差法 (spectroscopic parallax)** 但其實沒有量任何角度

估計恆星的質量

- 恆星最重要的性質，因為質量決定（自我）萬有引力大小
- 質量決定星際雲氣是否產生恆星，產生哪種恆星，日後也決定恆星如何衰亡
- 對於主序星（內部核反應達到靜力平衡的穩定星體）而言，質量決定核反應快慢（光度）以及表面溫度的高低（光譜型態）
- **雙星 (binary)** 可用來估計恆星質量

Animations --- http://www.astronomy.ohio-state.edu/~pogge/Ast162/Movies/

雙星的種類　恆星多半爲雙星，甚至多星系統 why?

- optical doubles (apparent binaries) 光學雙星

  兩顆星恰巧在天球上角度很近，其實彼此**無關**

真正的雙星

- visual binaries 視雙星　e=0.4

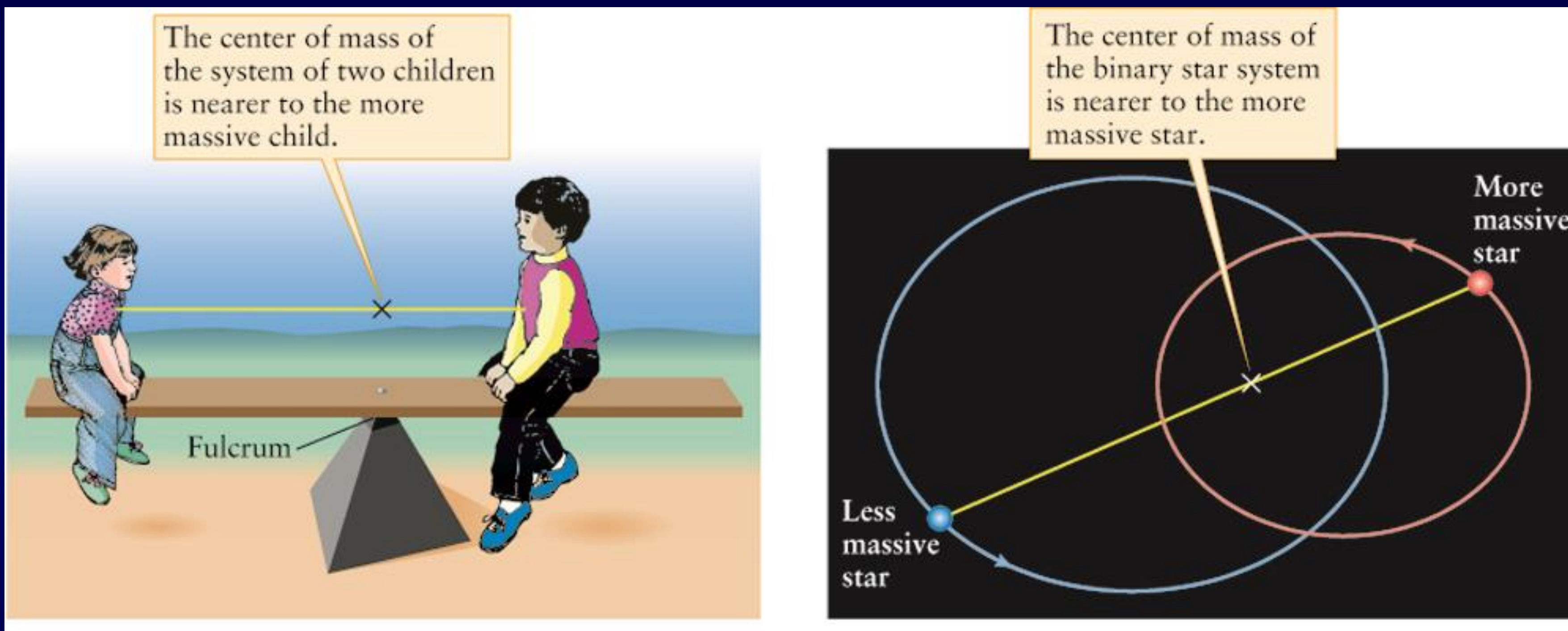
  兩顆星互繞質量中心，且兩顆星都看得到

$$M_1 + M_2 = a^3/P^2$$

M 以「太陽質量」為單位；*a* 軌道半長軸以「AU」為單位；*P* 軌道週期以「年」為單位

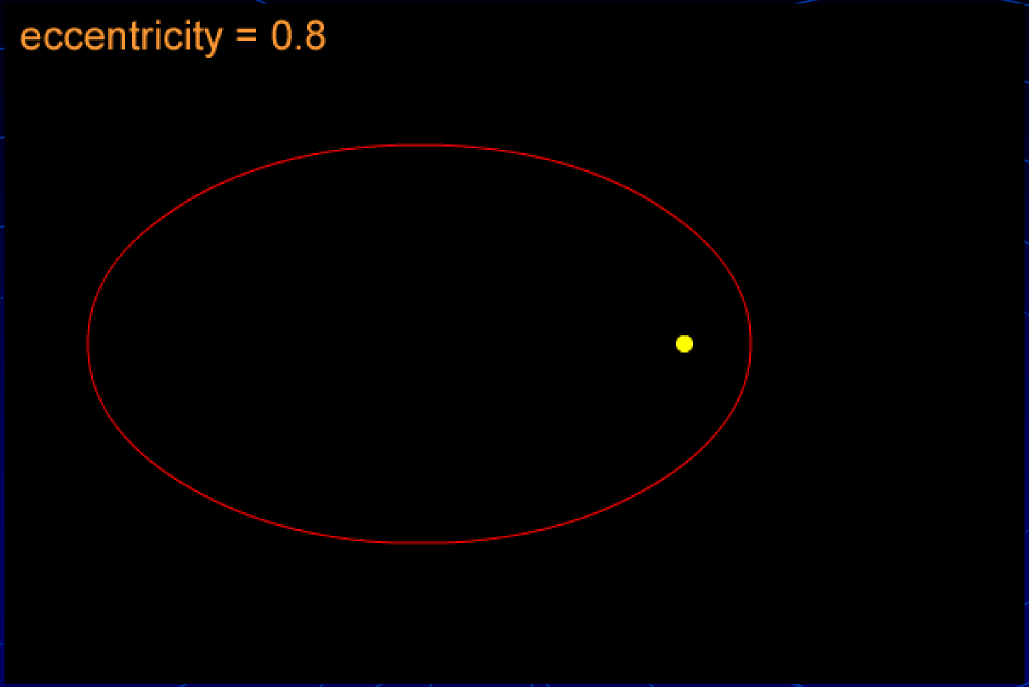
例：某雙星其中一顆星的橢圓軌道半長軸為 4 AU，週期為 2.5 年，則兩顆星的質量和為

$$M_1 + M_2 = 4^3/2.5^2 = 10.2\ \mathrm{M}_\odot$$

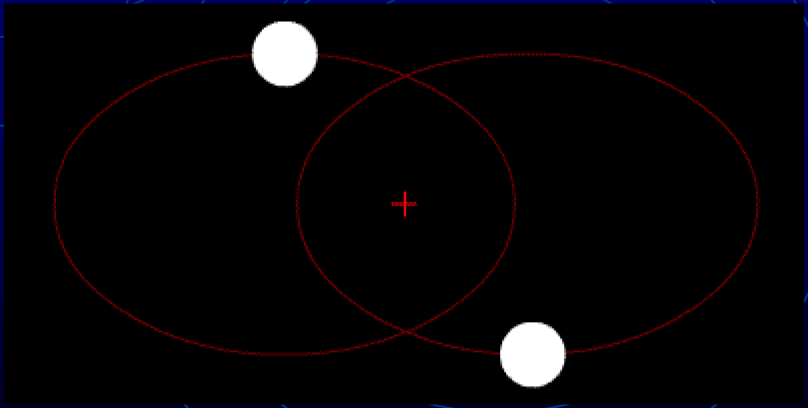


(a) A "binary system" of two children

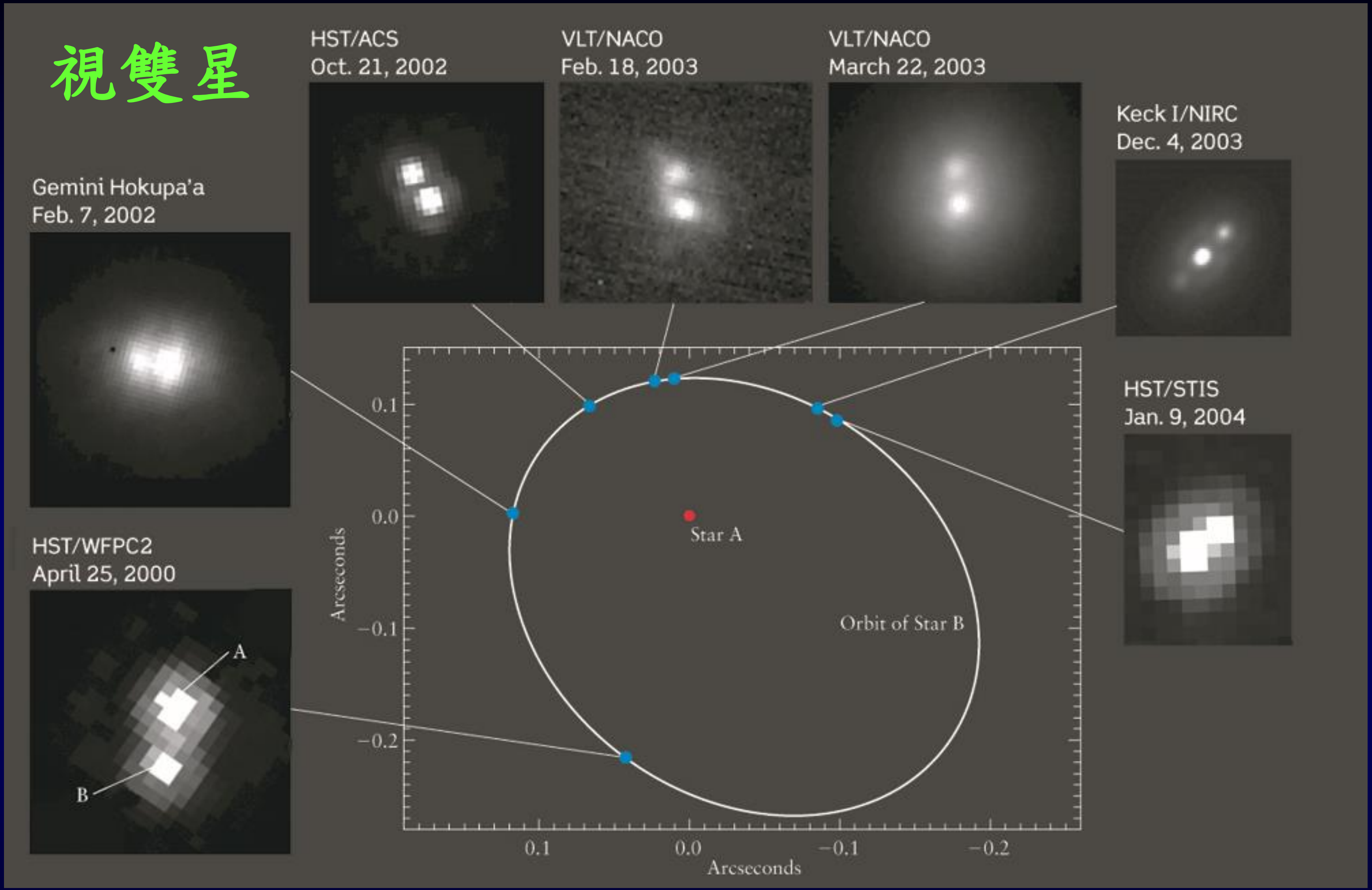
(b) A binary star system



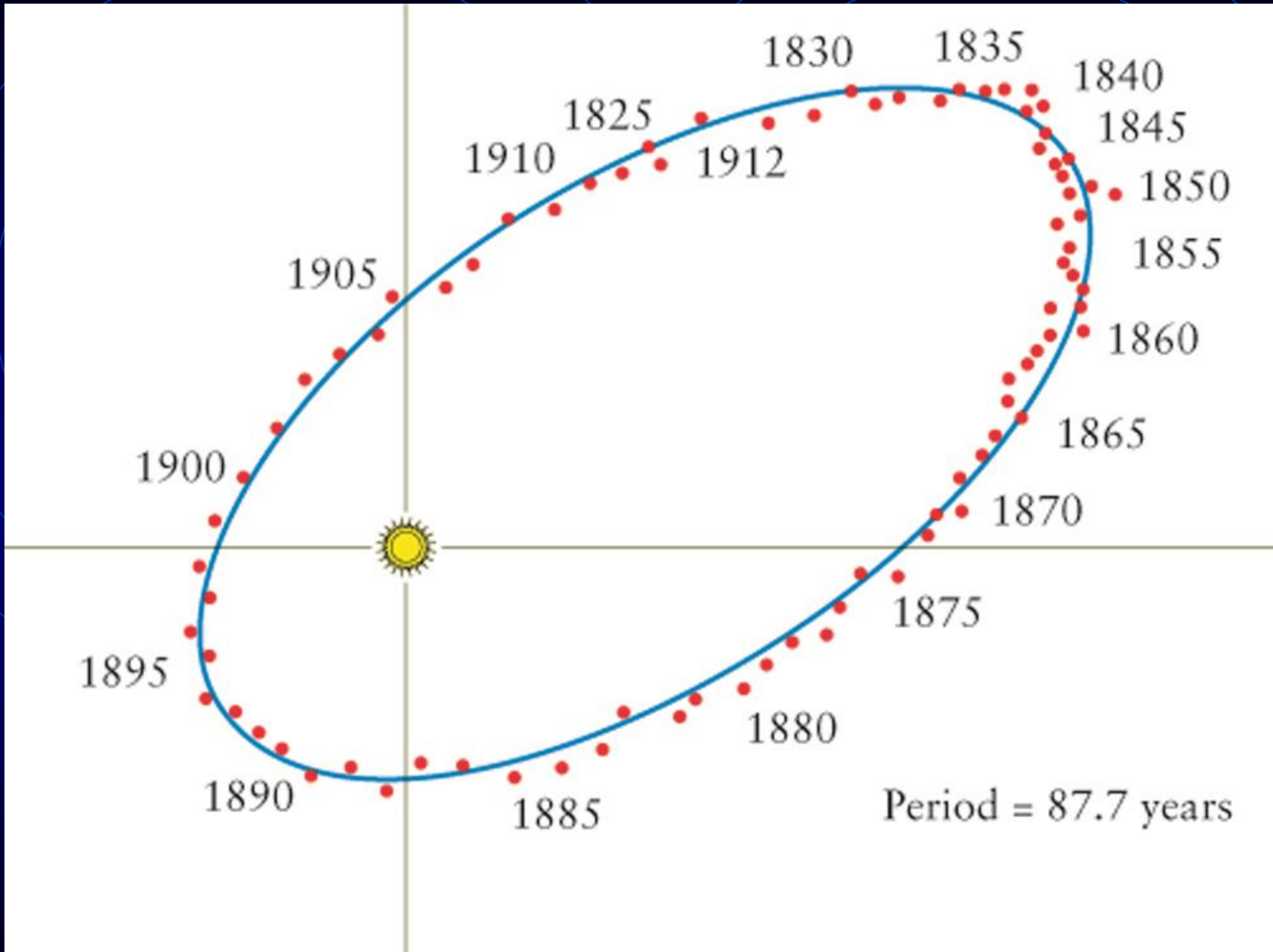
http://www.windows.ucar.edu/tour/link=/physical_science/physics/mechanics/orbit/ellipse.html



http://upload.wikimedia.org/wikipedia/commons/0/0e/Orbit5.gif



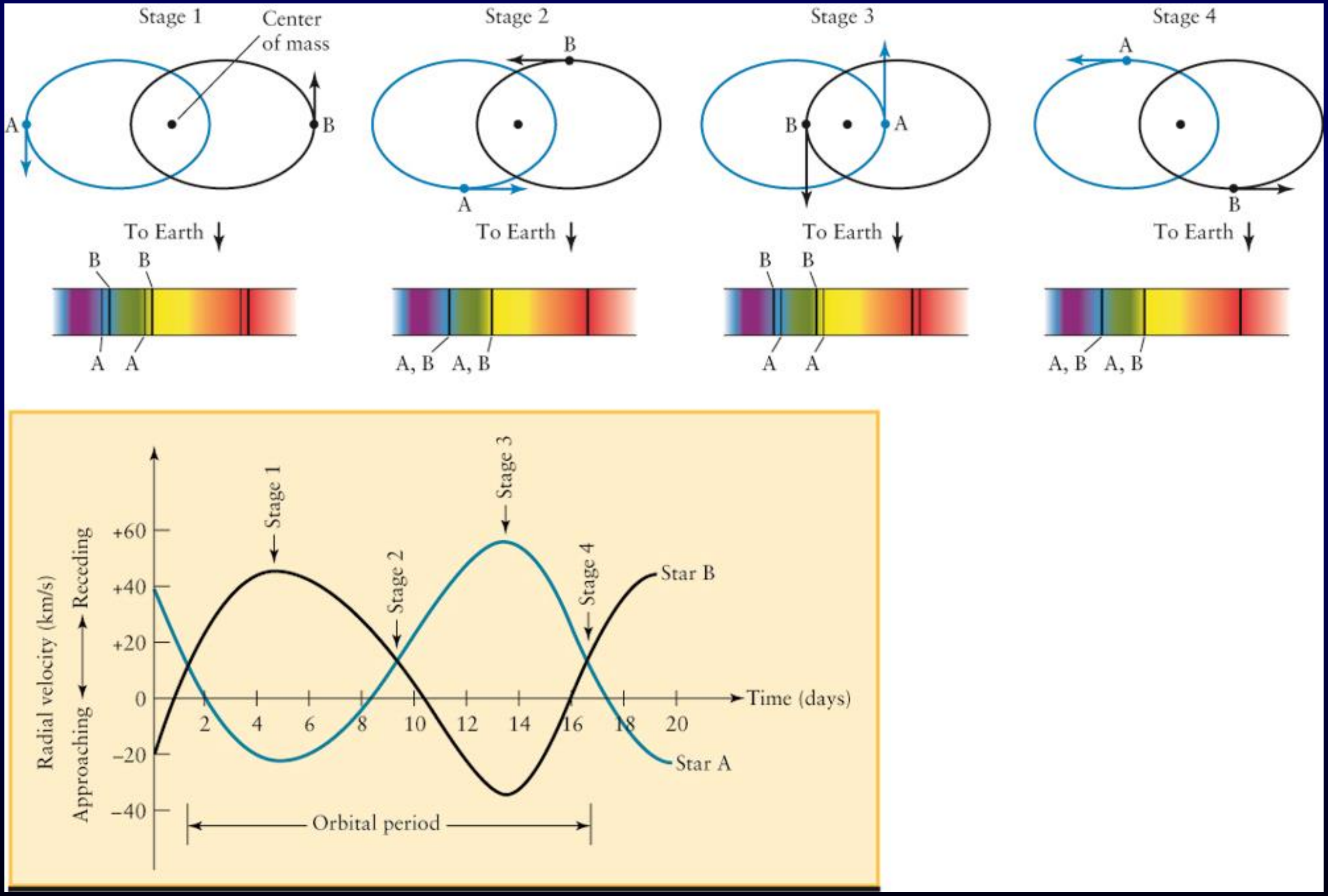
2MASSSW J074625+2000321 is a binary system separated by ~1/3”, observed respectively by the HST, VLT, Keck I, and Gemini North.


1830
1835
1840
1825
1845
1910
1912
1850
1855
1905
1860
1865
1900
1870
1875
1895
1880
1890
1885
Period = 87.7 years

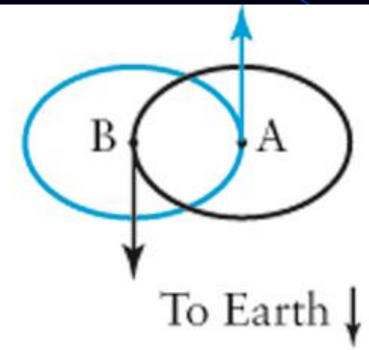
真正的雙星 (cont.)

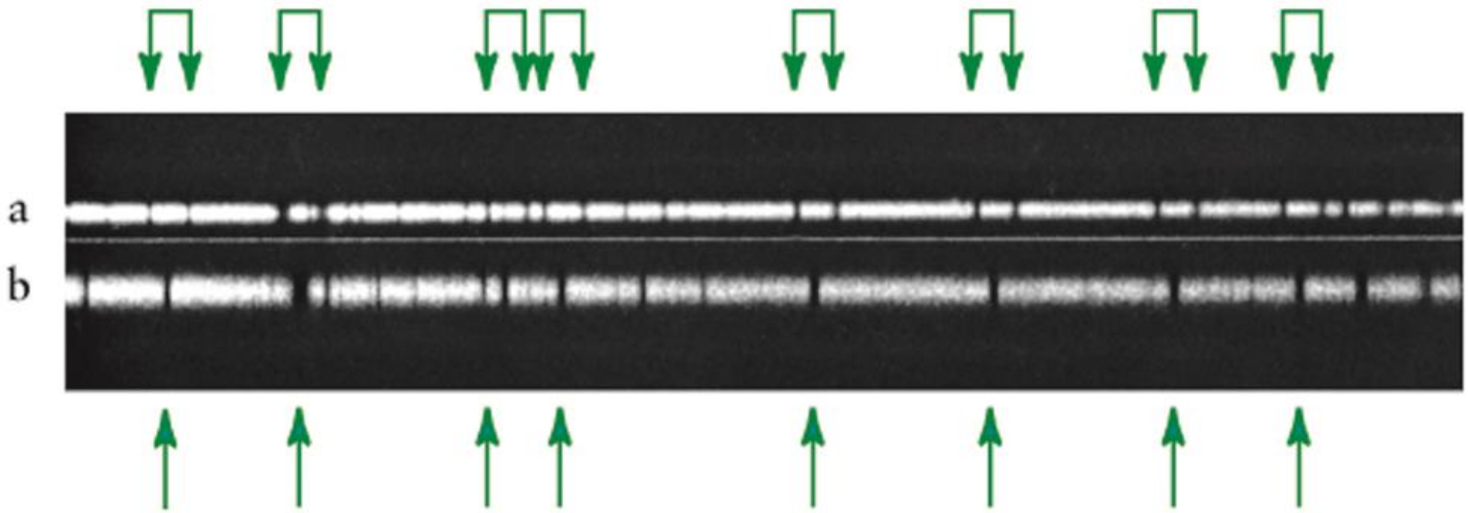
- spectroscopic binaries 光譜雙星

  兩顆星互繞質量中心，無法直接看出兩顆星，但是光譜顯示存在兩顆星

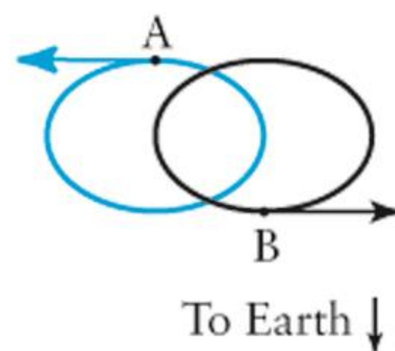


When one of the stars in a spectroscopic binary is moving toward us and the other is receding from us, we see *two* sets of spectral lines due to the Doppler shift.





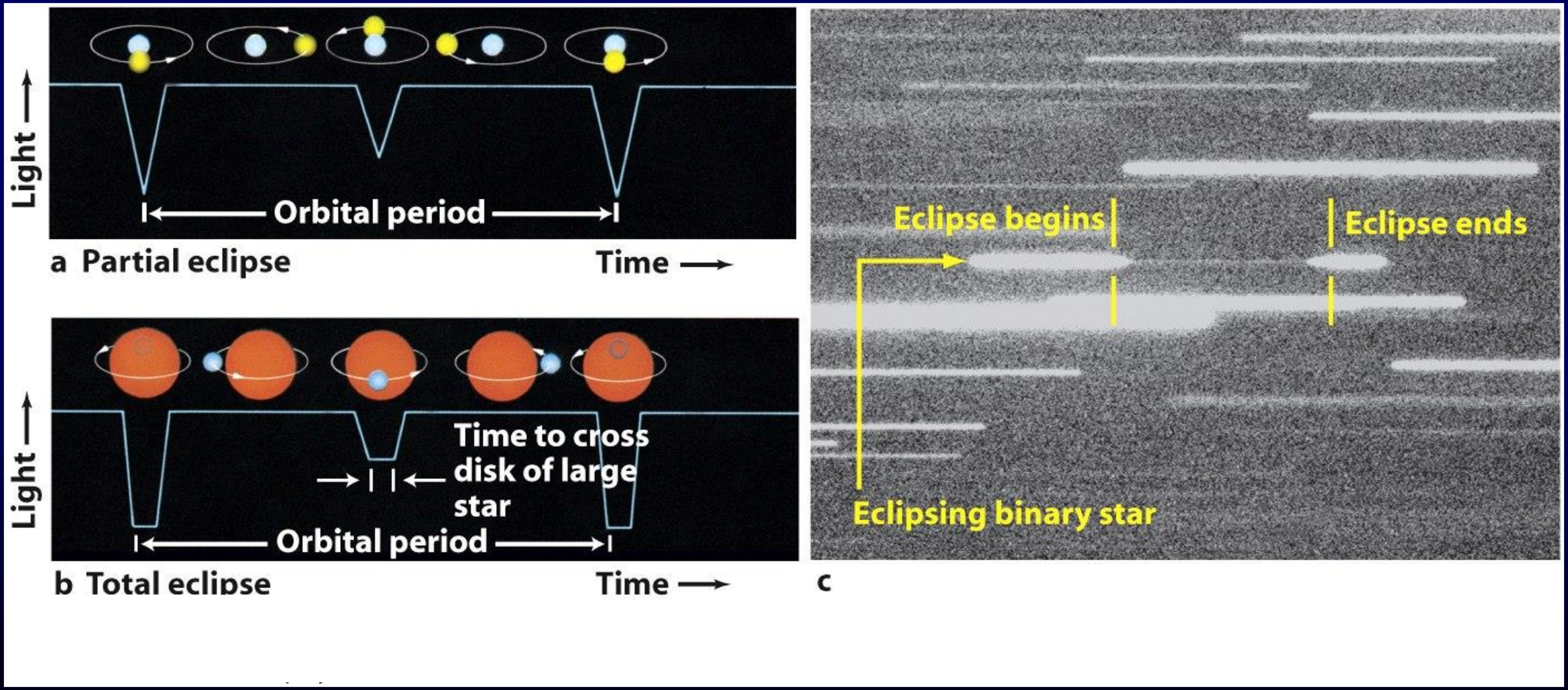
When both stars are moving perpendicular to our line of sight, there is no Doppler splitting and we see a *single* set of spectral lines.



真正的雙星 (cont.)

- eclipsing binaries 食雙星

  兩顆星互繞質量中心，無法直接看出兩顆星，但是恆星互食（遮住），光變曲線顯示雙星



- 主序星的**質量**與**光度**關係 (mass-luminosity relation; **質 光 關 係**)

Roughly L ~ $M^{3.5}$