太陽 (The Sun)

你覺得呢？

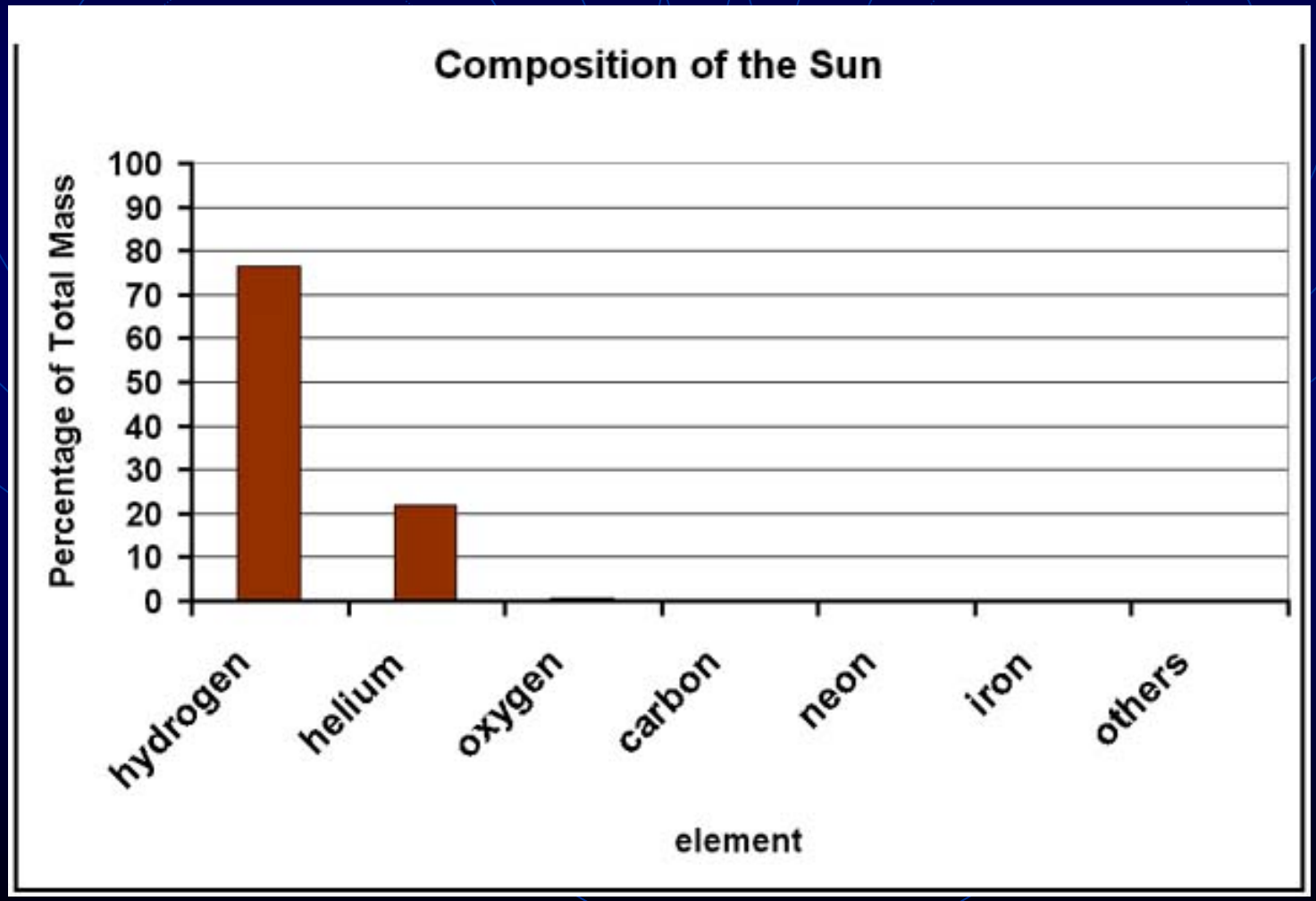
- 太陽佔了太陽系多少質量？
- 太陽像地球一樣，內部爲固體與液體嗎？
- 太陽表面是什麼情形？裡面呢？怎麼知道？
- 太陽會轉動嗎？
- 太陽爲何會發光？

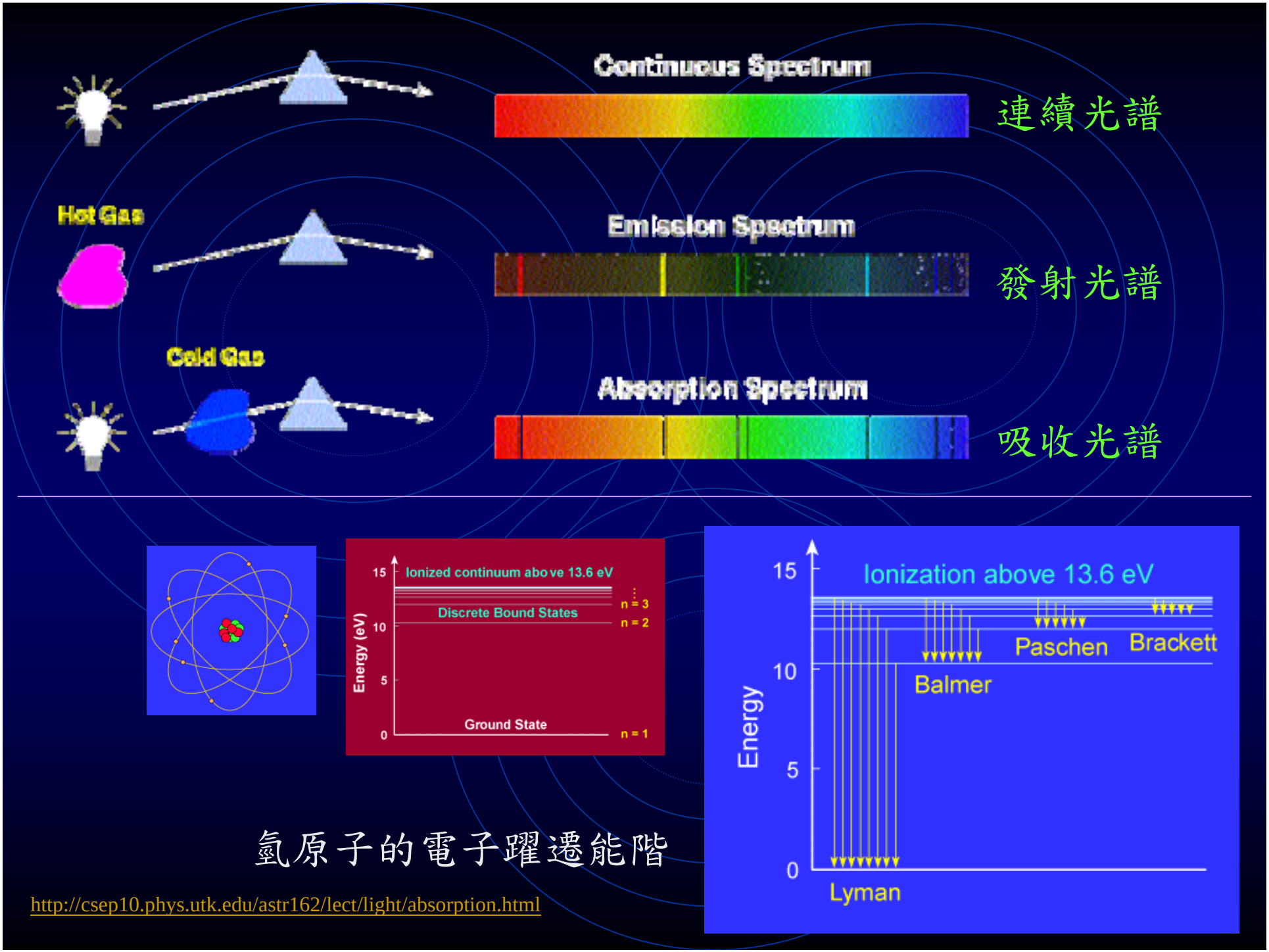
太陽的基本資料

- 表面溫度：5800 K（觀測得知）
- 核心溫度：1.5×10^7 K（理論推測）
- 目視大小：32'
- 實際大小：7×10^5 km（70萬公里）
  = 約地球的100倍 = 約木星的10 倍
- 視星等：-26.74（c.f. 天狼星爲 -1.45）
- 與地球距離： 1 AU（一億五千萬公里）
- 質量：2×10^{30} kg = 地球 33萬倍
  = 所有行星加起來的 700 倍 ＝太陽系總質量99.85％
- 密度：1.4 公克/立方公分（水是 1；地球是 6.4）
- 光度 (luminosity)： $1\ L_\odot = 4 \times 10^{26}$ W
- 赤道自轉一圈需時：約25天

太陽質量約74%是氫，25%是氦，其他元素 (共1%) 都少得多

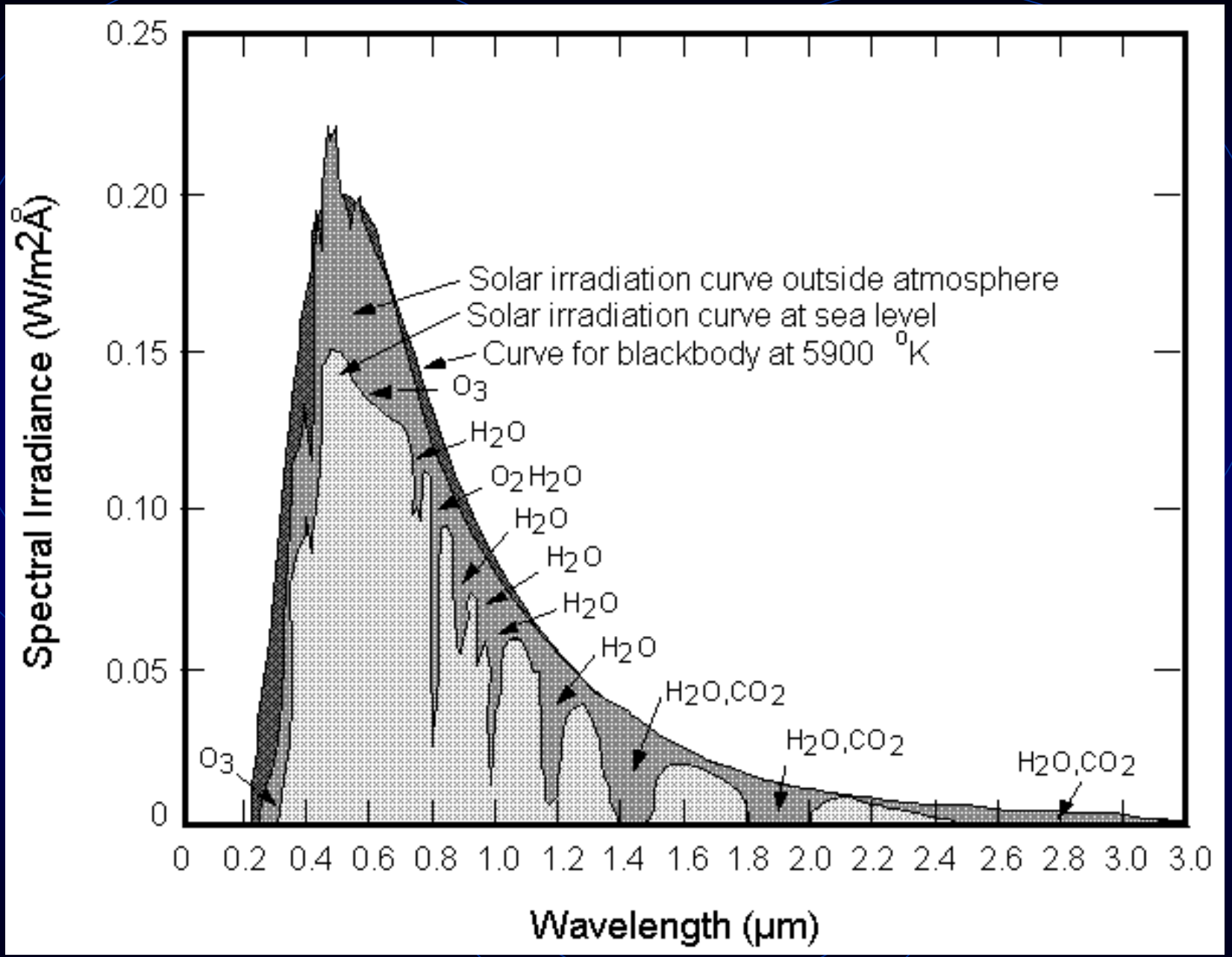
地球呢？

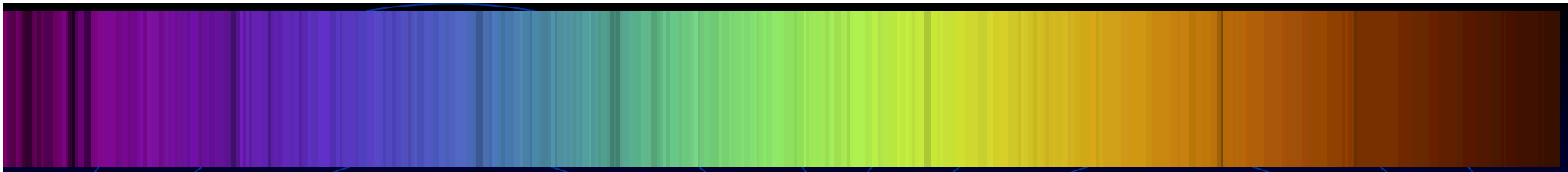




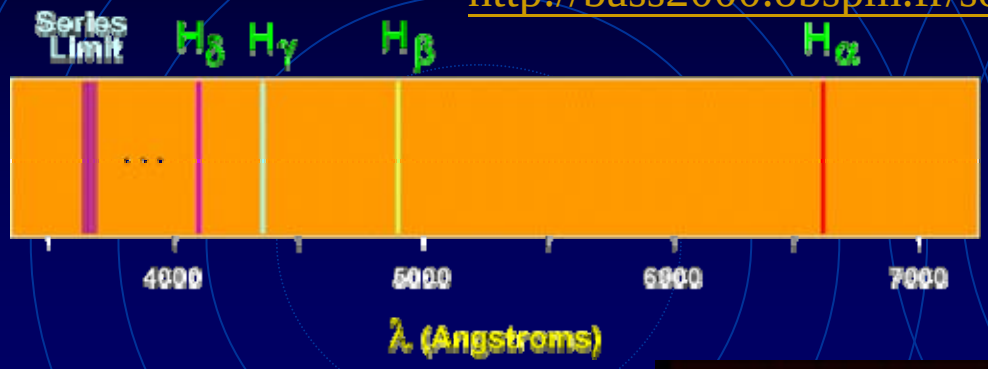
氫原子的電子躍遷能階

http://csep10.phys.utk.edu/astr162/lect/light/absorption.html

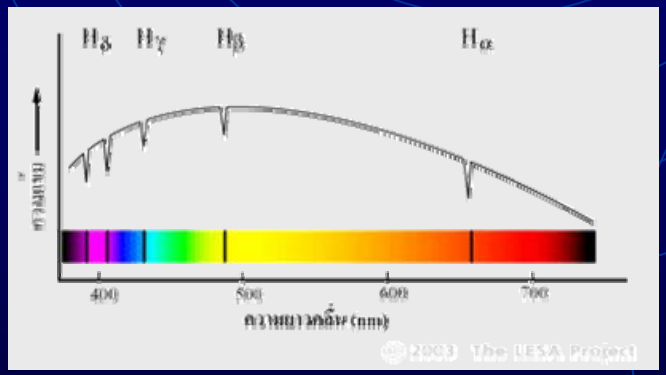

0.25
0.20
0.15
0.10
0.05
0
Spectral Irradiance (W/m2Å)
Solar irradiation curve outside atmosphere
Solar irradiation curve at sea level
Curve for blackbody at 5900 °K
O3
H2O
O2 H2O
H2O
H2O
H2O
H2O
H2O,CO2
H2O,CO2
H2O,CO2
O3
0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0 2.2 2.4 2.6 2.8 3.0 3.0
Wavelength (µm)

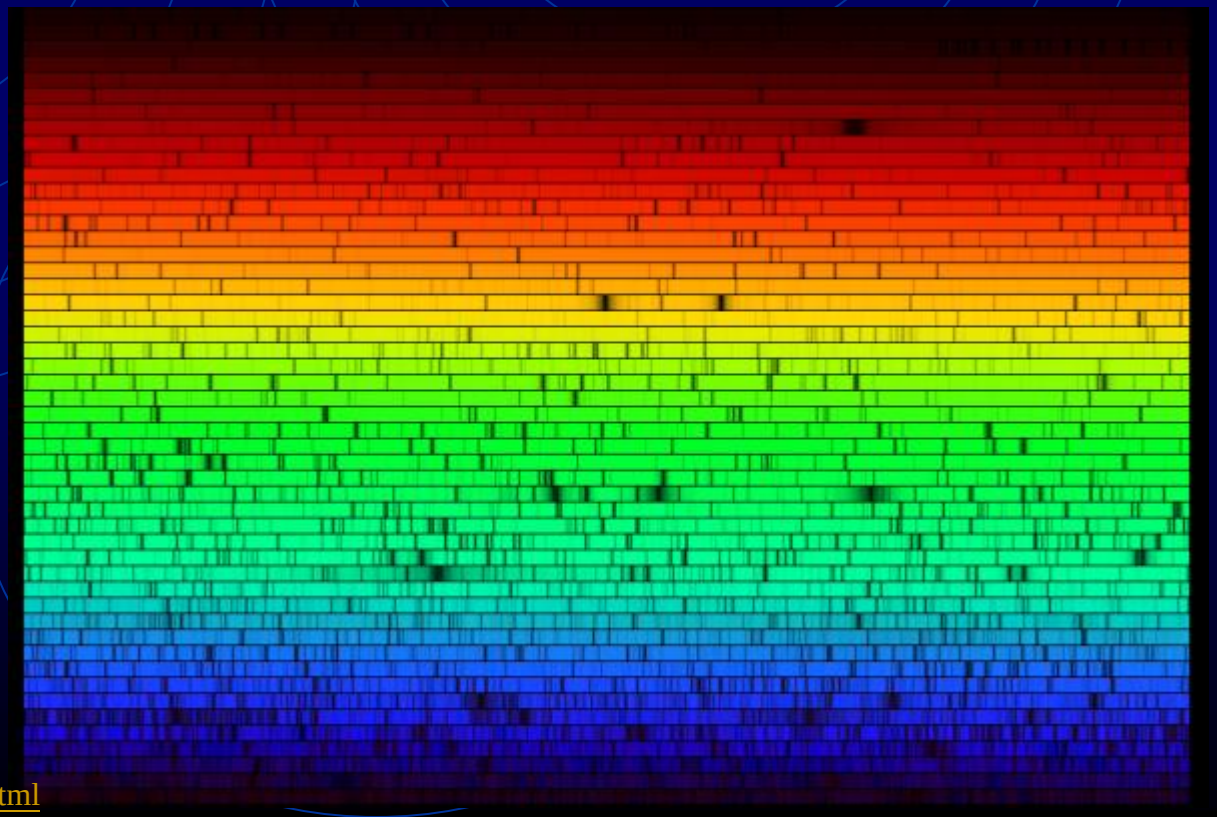


http://bass2000.obspm.fr/solar_spect.php 670-54000 Å



http://csep10.phys.utk.edu/astr162/lect/light/absorption.html





4000-7000 Å
http://www.noao.edu/image_gallery/html/im0600.html

太陽由氣體組成，核心密度爲水的150倍！

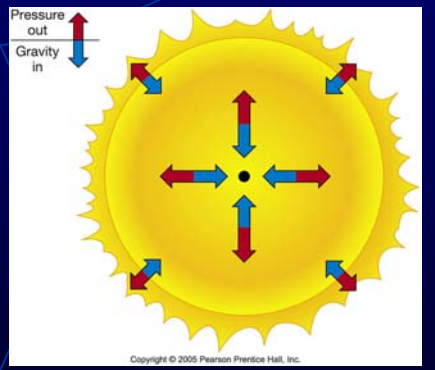
核心部分溫度高（百萬度），進行核子反應，
產生能量向外以**輻射**方式傳送

氣體溫度高，分子運動快
→ 互相推擠 → 氣體壓力

向內萬有引力 = 向外氣體壓力 → 平衡

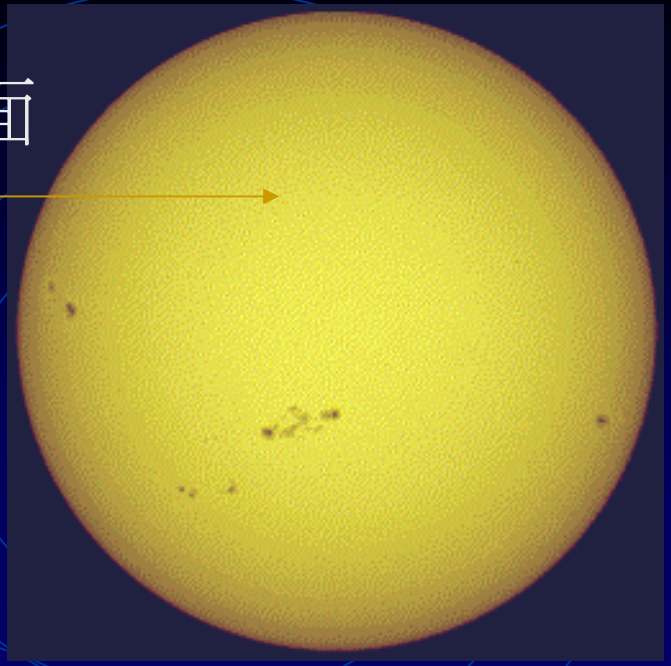
越向外溫度越來越低
外層改以**對流**方式傳送能量

太陽表面爲翻騰的氣體
（有如煮沸的水）溫度超過攝氏5000度

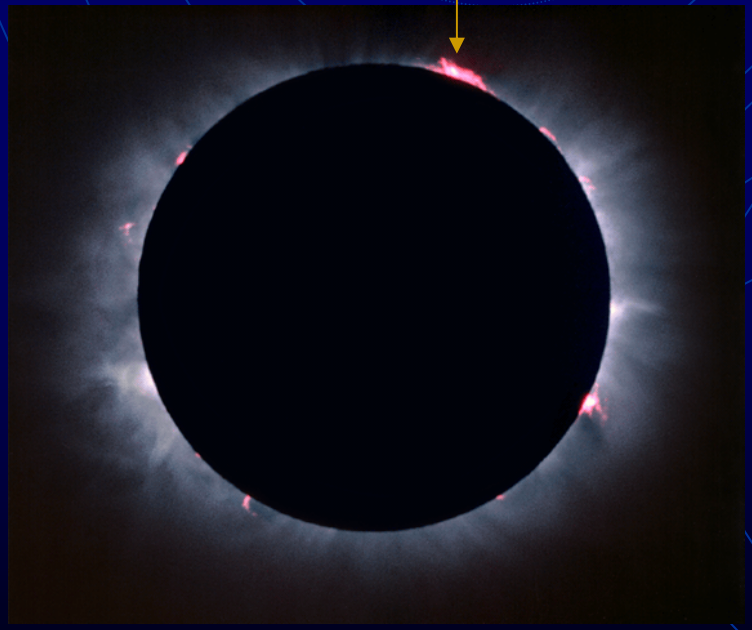


太陽表面

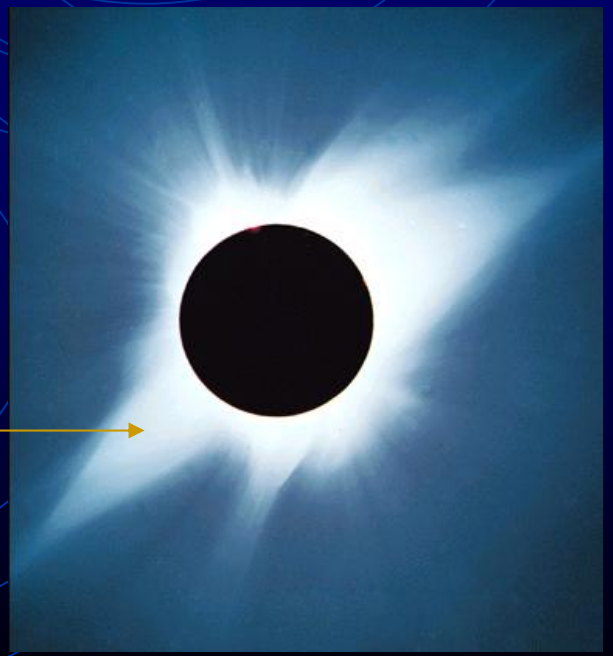
我們所見的日面
— 光球



色球



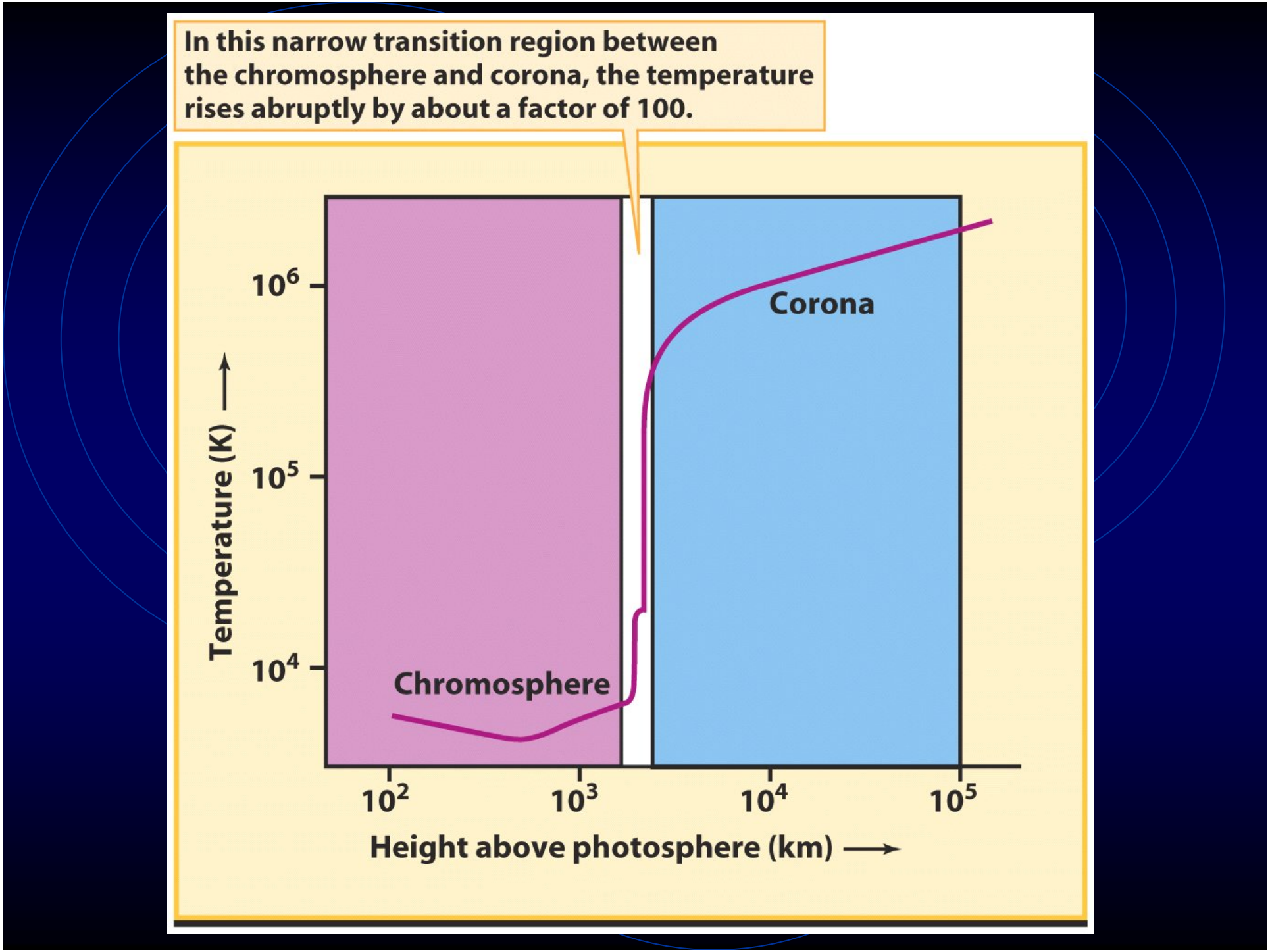
日冕



http://ircamera.as.arizona.edu/NatSci102/lectures/sun.htm

太陽大氣層

- **光球 (photosphere)**
  太陽大氣最低的一層；厚度約 400 km；是我們肉眼看到的太陽「盤面」
- **色球 (chromosphere)**
  比光球暗；密度也較低，只有在光球被擋住（如日全食）時，才見看得到色球。呈粉紅色；厚度約 500 km
- **日冕 (corona)**
  太陽大氣最外層；延伸數百萬公里；整個日冕在可見光的亮度，只相當於滿月，i.e., 只有 photosphere 的百萬分之一。只在日全食或利用日冕儀 (coronagraph) 擋住光球，才能看到 corona

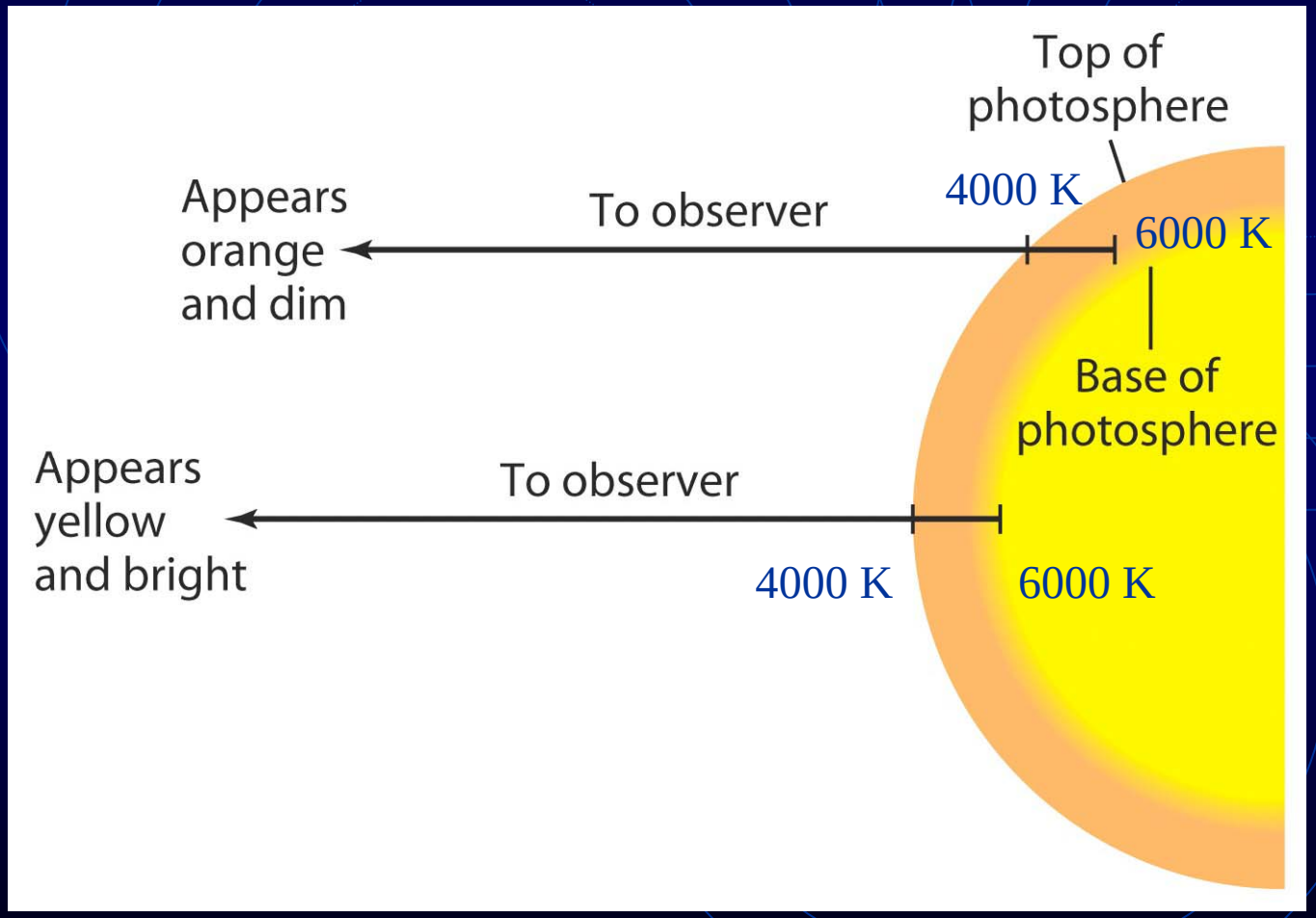

In this narrow transition region between the chromosphere and corona, the temperature rises abruptly by about a factor of 100.
Corona
Chromosphere
Temperature (K)
10^6
10^5
10^4
10^2
10^3
10^4
10^5
Height above photosphere (km)

太陽外表特徴

- 縁暗現象 (limb darkening)
- 太陽黒子 (sunspots)
- 米粒組織 (granulation)
- 針状結構 (spicules)

緣暗現象

視線透過等量的氣體

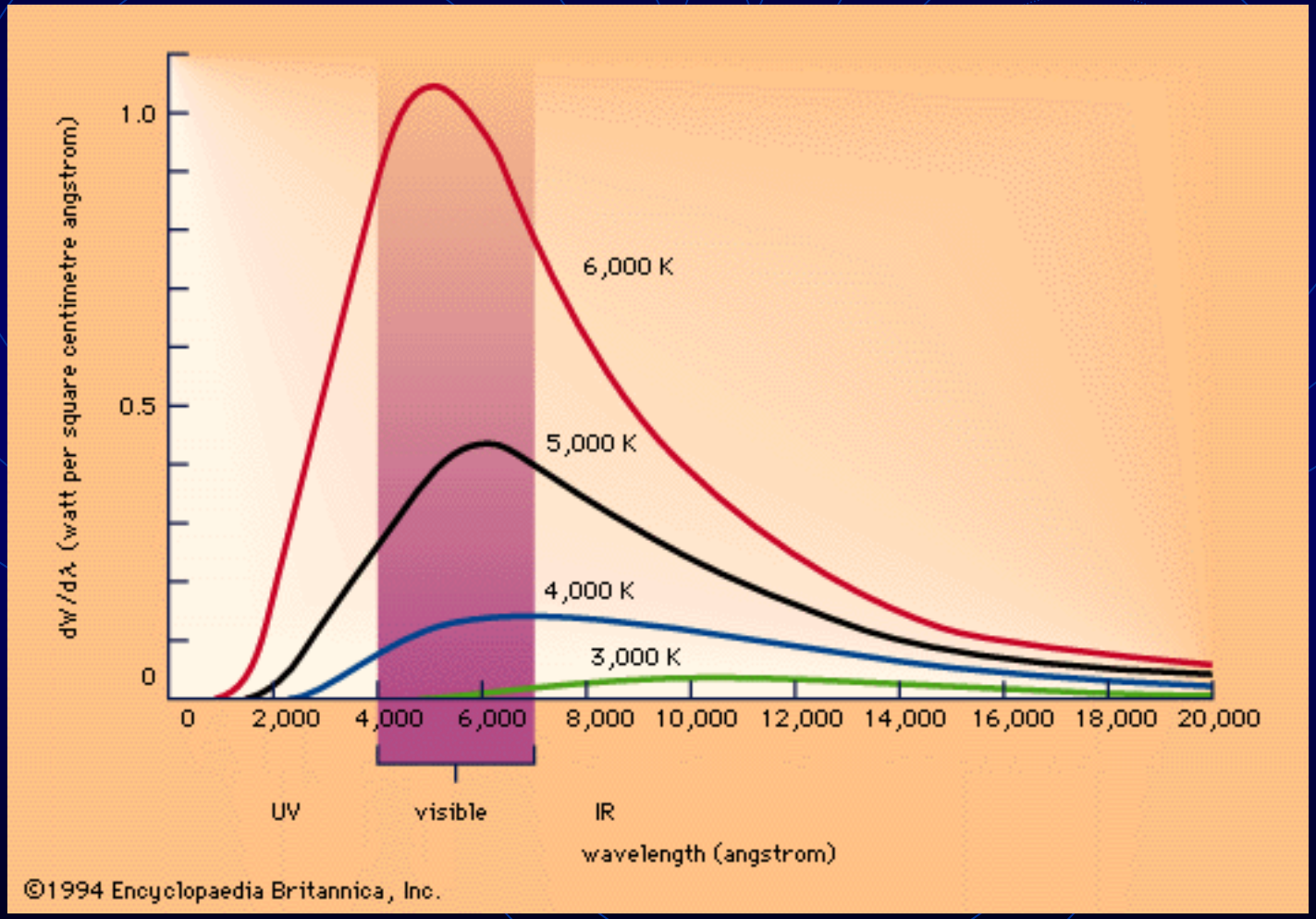


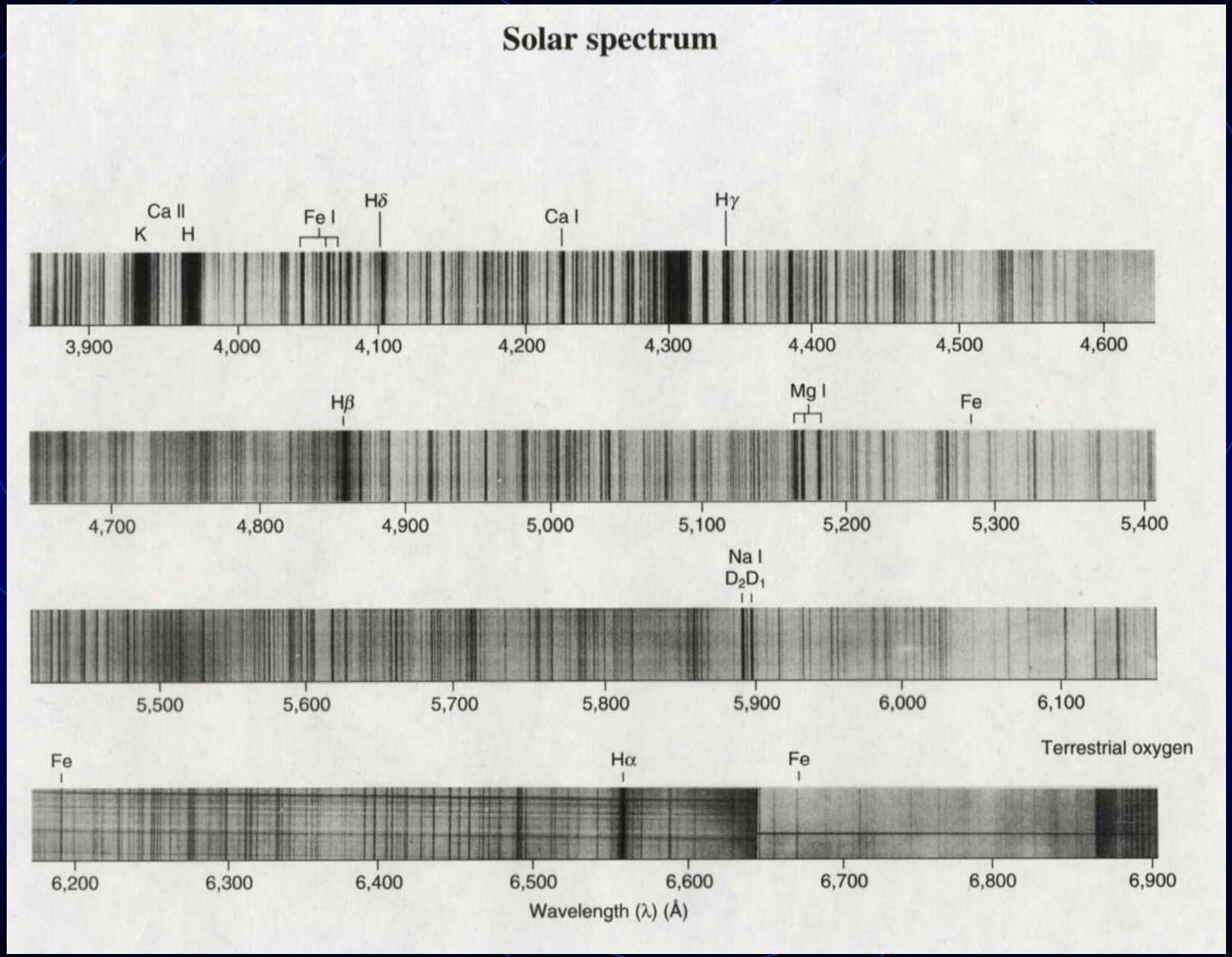
盤面邊緣透過較冷的高層大氣

盤面中央透過較內部、較熱的氣體

➔ 比較明亮

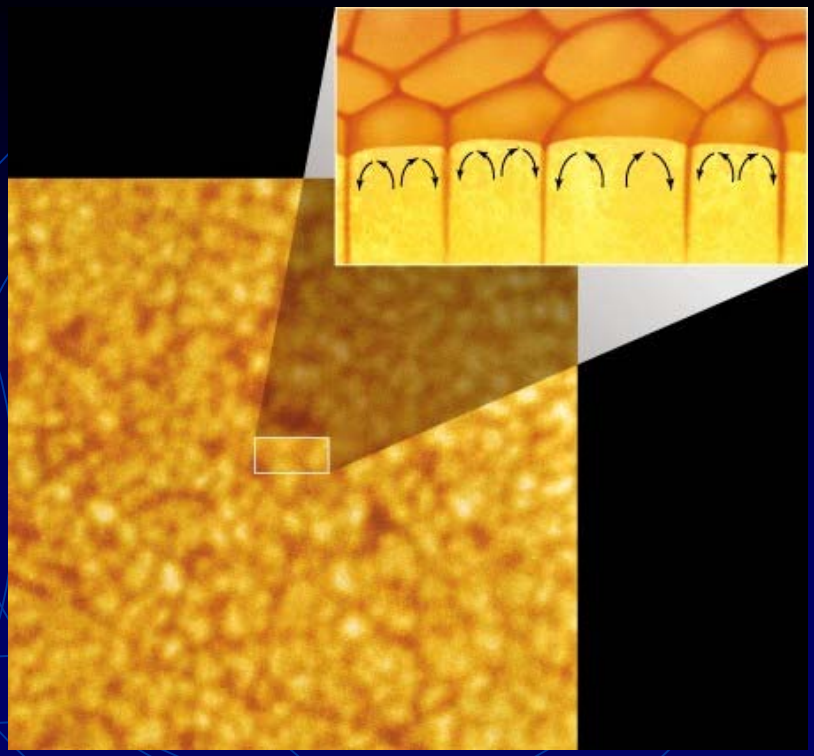
溫度低 → 輻射強度弱

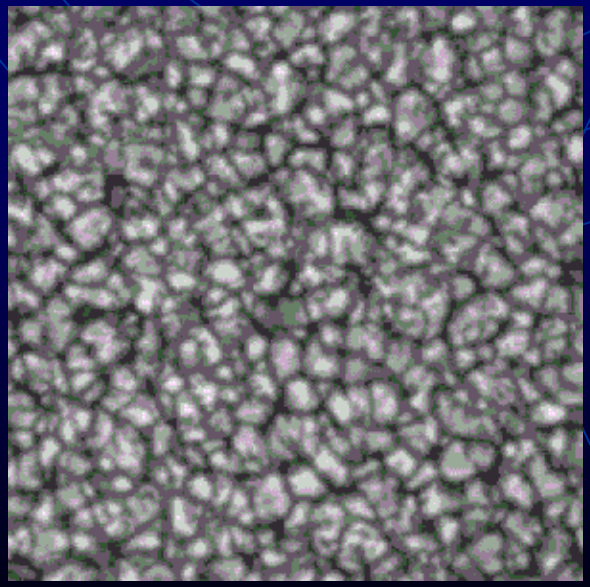

dW/dλ (watt per square centimetre angstrom)
1.0
0.5
0
6,000 K
5,000 K
4,000 K
3,000 K
0
2,000
4,000
6,000
8,000
10,000
12,000
14,000
16,000
18,000
20,000
UV
visible
IR
wavelength (angstrom)
©1994 Encyclopaedia Britannica, Inc.

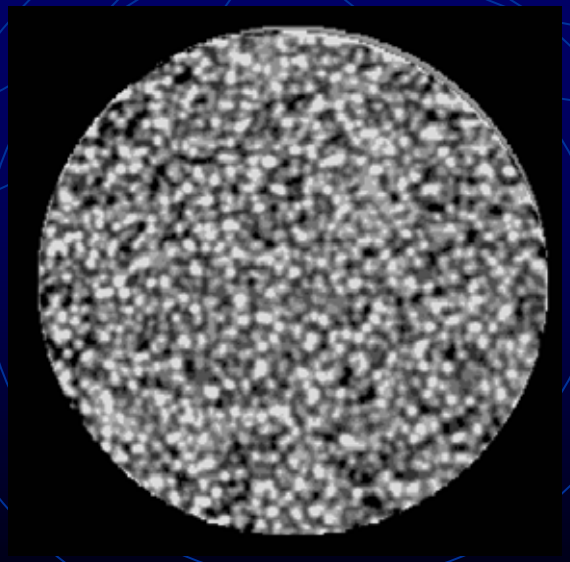

Solar spectrum
Ca II
K
H
Fe I
Hδ
Ca I
Hγ
3,900
4,000
4,100
4,200
4,300
4,400
4,500
4,600
Hβ
Mg I
Fe
4,700
4,800
4,900
5,000
5,100
5,200
5,300
5,400
Na I
D2D1
5,500
5,600
5,700
5,800
5,900
6,000
6,100
Terrestrial oxygen
Fe
Hα
Fe
6,200
6,300
6,400
6,500
6,600
6,700
6,800
6,900
Wavelength (λ) (Å)

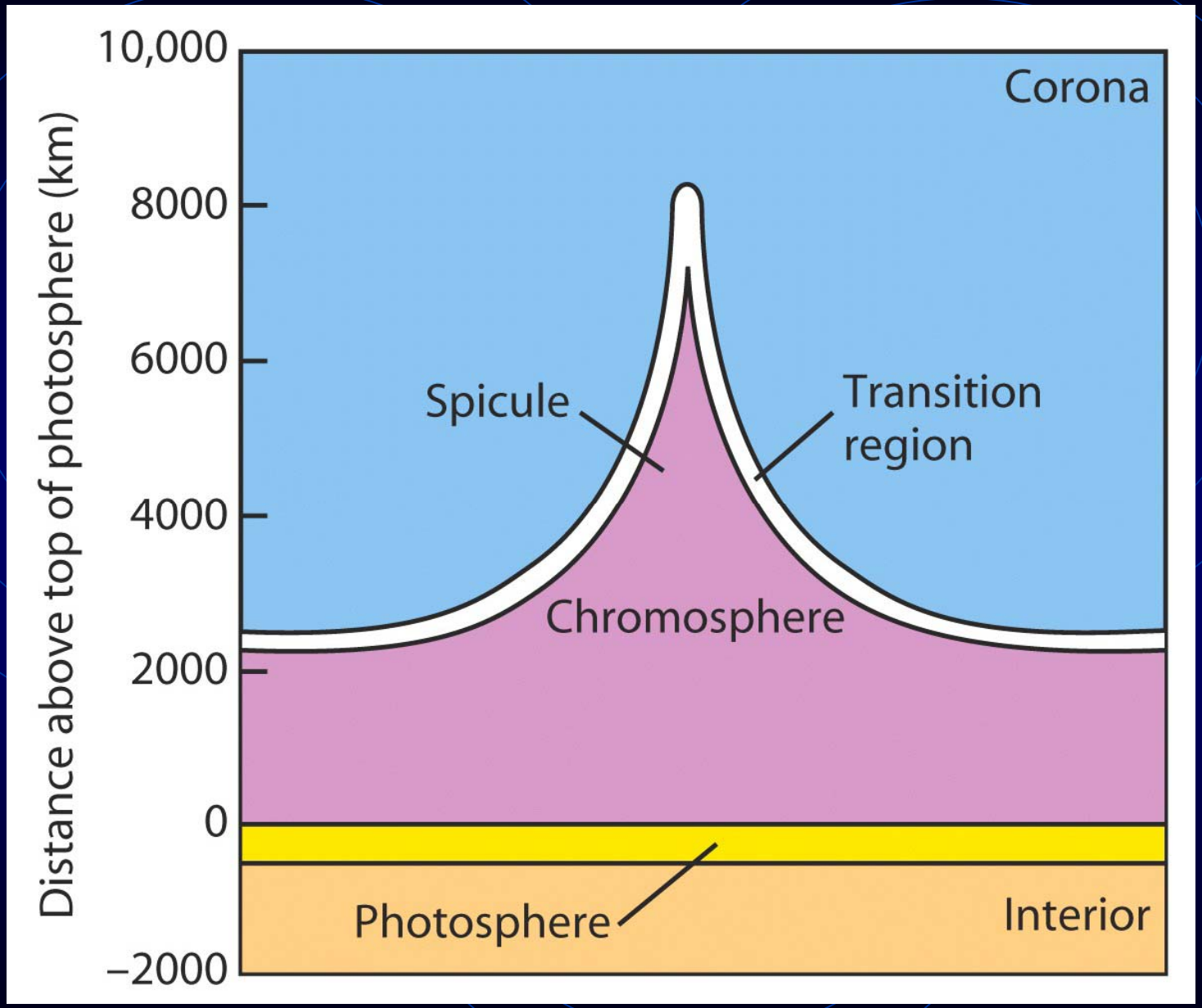
米粒組織 (granulation)

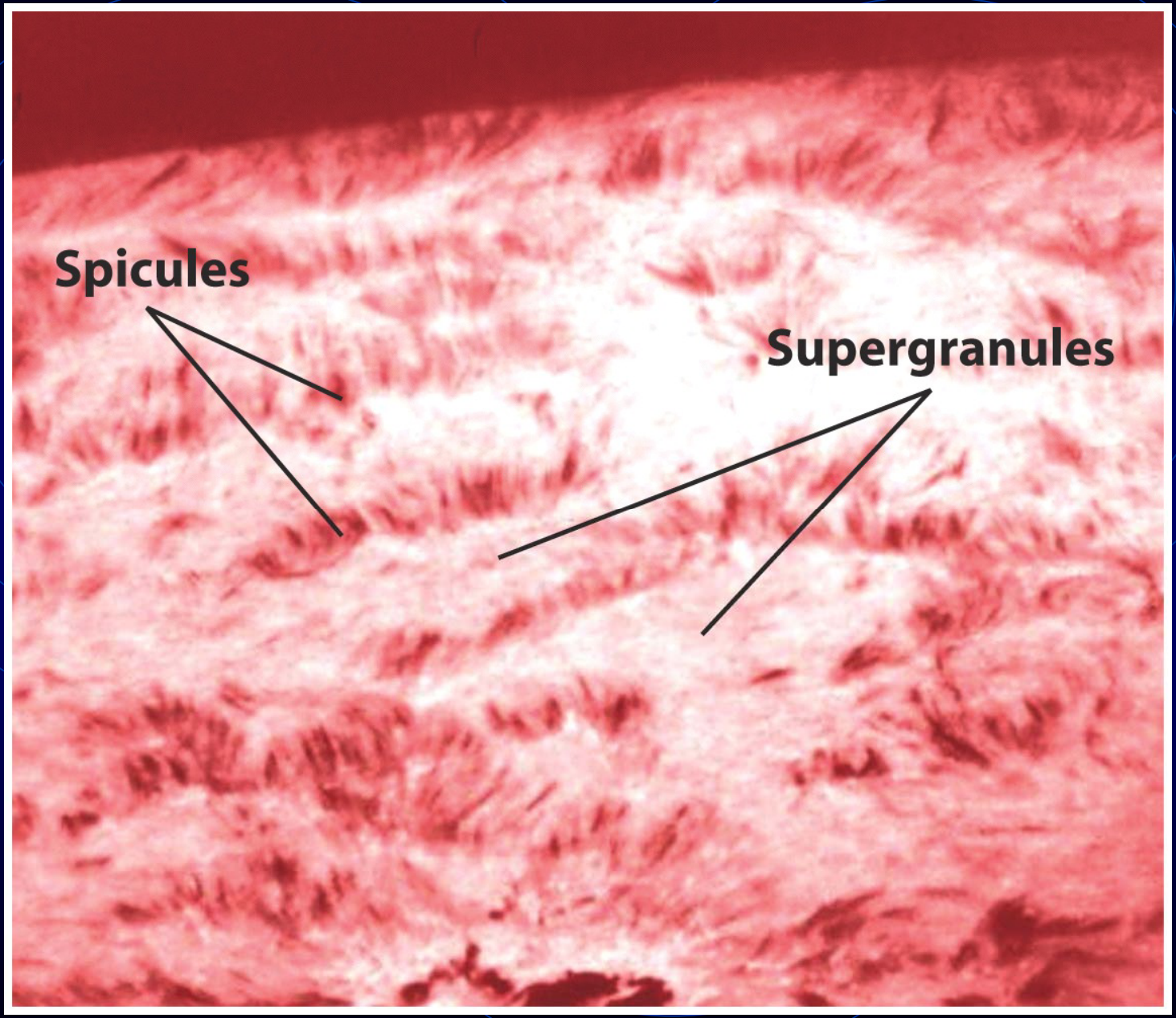
太陽氣體從內部到表面對流翻騰的證據

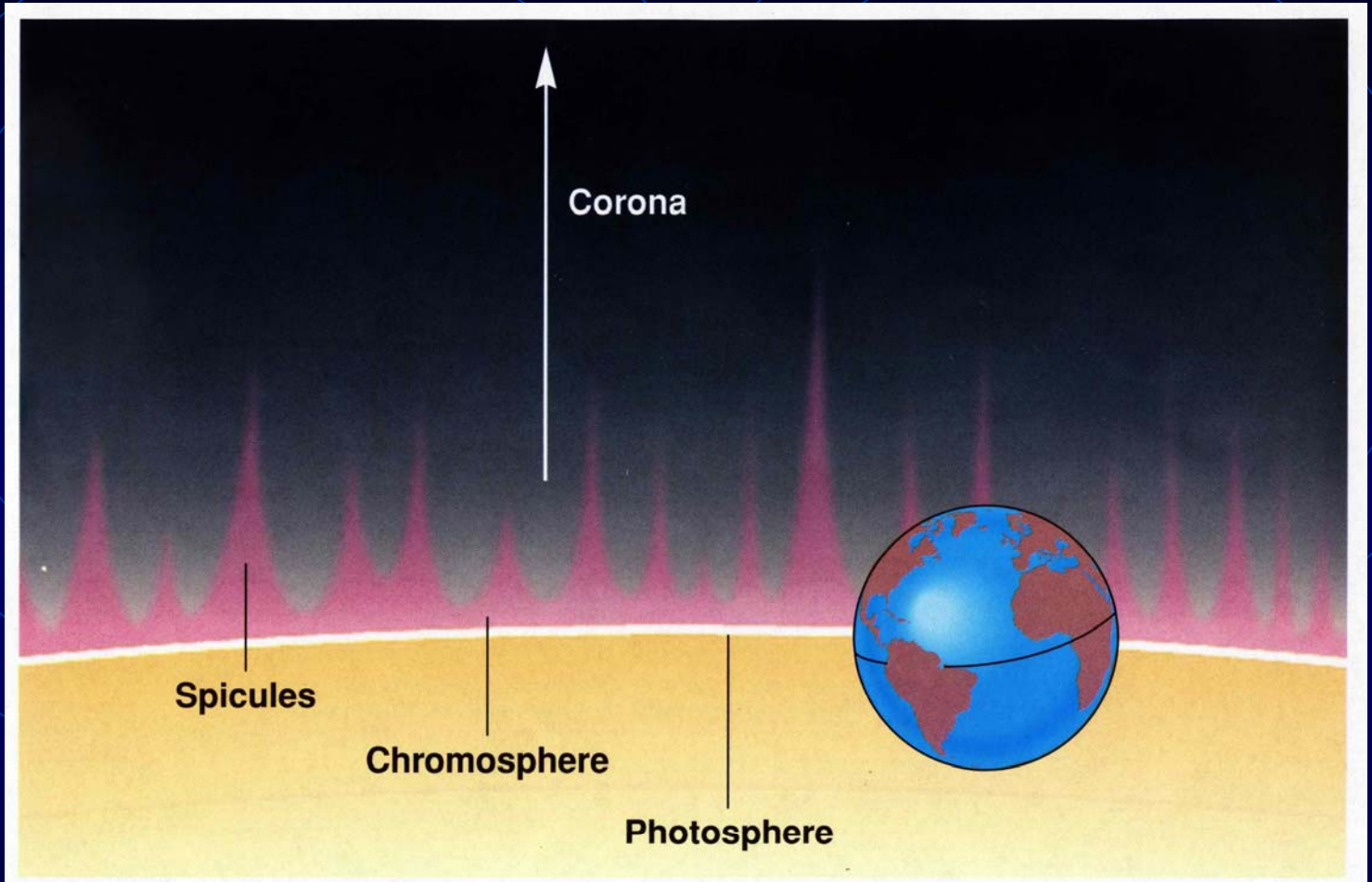







Distance above top of photosphere (km)
10,000
8000
6000
4000
2000
0
–2000
Corona
Spicule
Transition region
Chromosphere
Photosphere
Interior


Spicules
Supergranules



Cross section of photosphere.

http://crab0.astr.nthu.edu.tw/~hchang/ga1/f1801-atmosphere1.JPG

Pop Quiz 061213

針對下列名詞翻譯並簡單解釋

（1）greatest elongation

（2）Occam's razor

（3）exoplanet

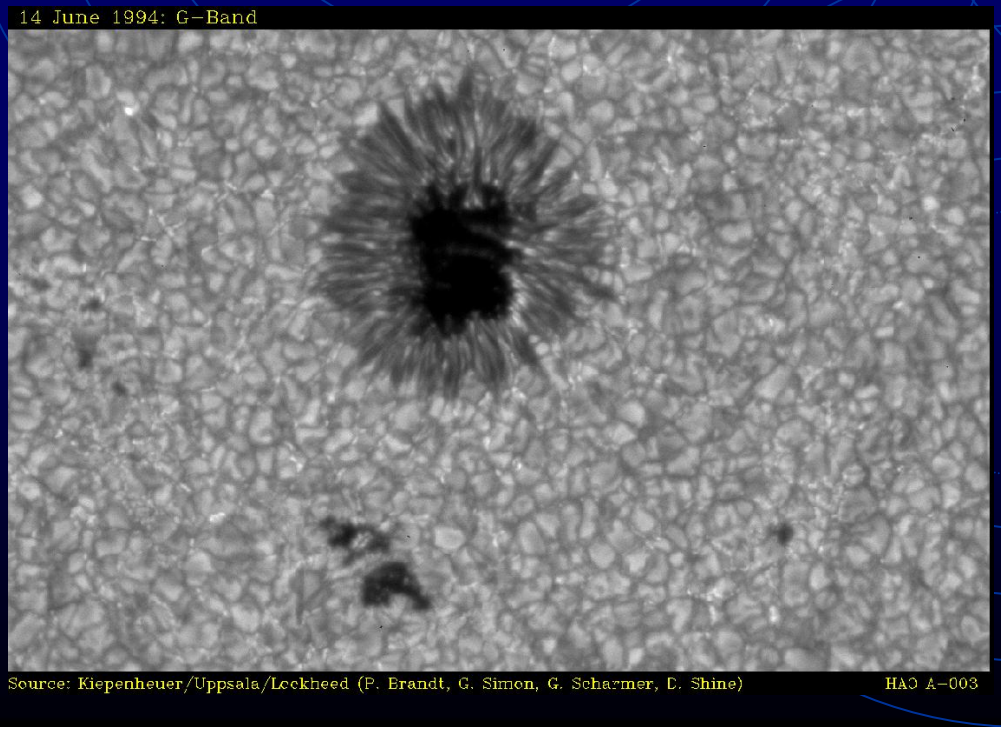
（4）Great Red Spot

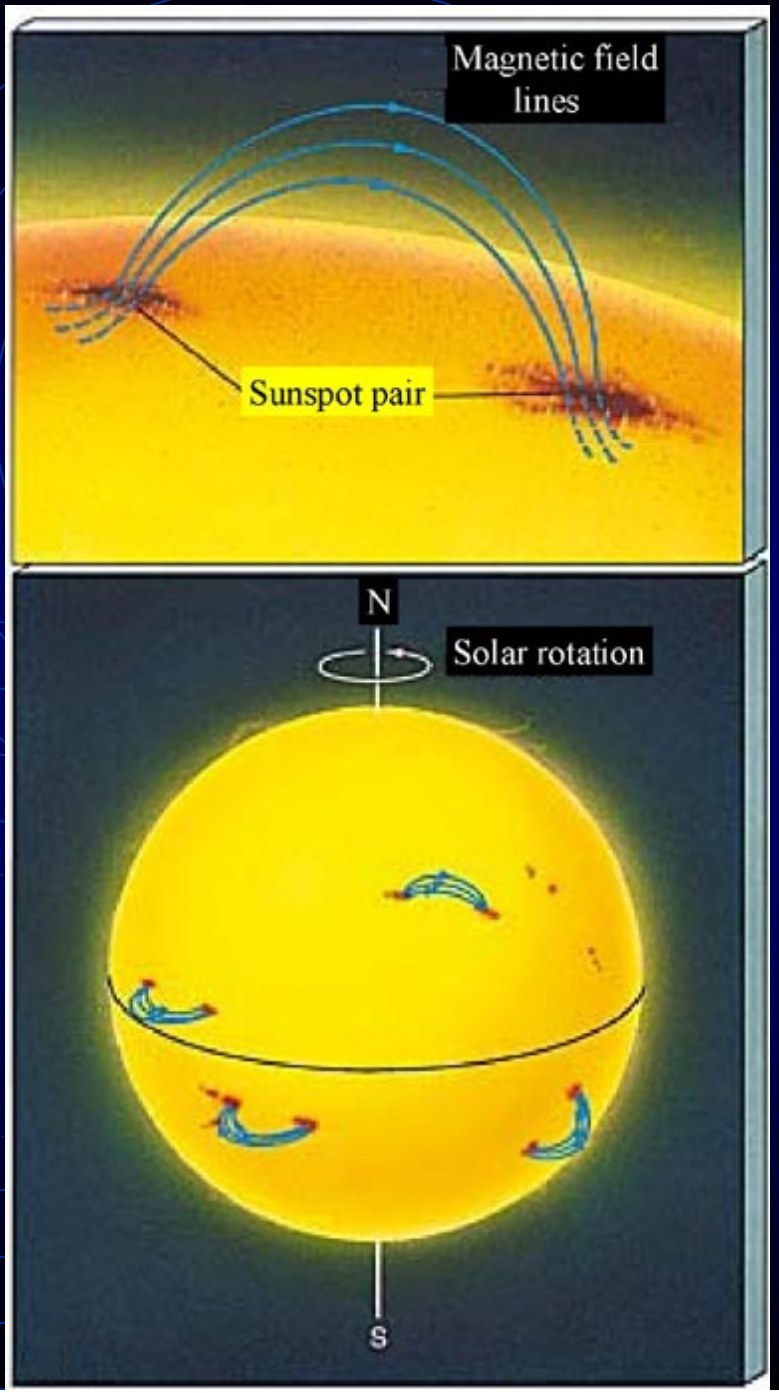
（5）green house effect

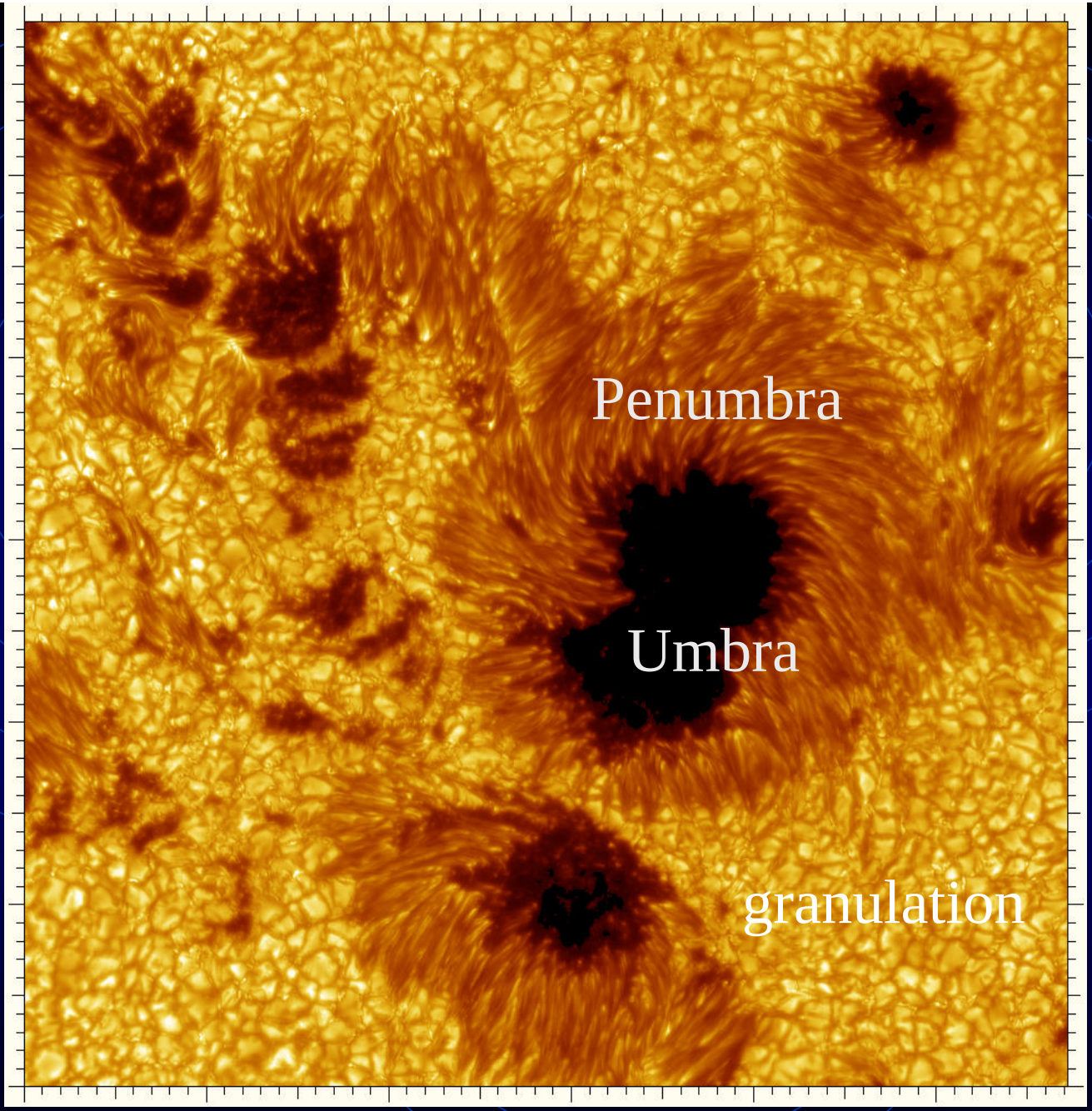
太陽黑子 (sunspots)

爲表面低溫地區，
「看起來」比較暗

該處磁場強，抑制了內部傳遞出來的能量

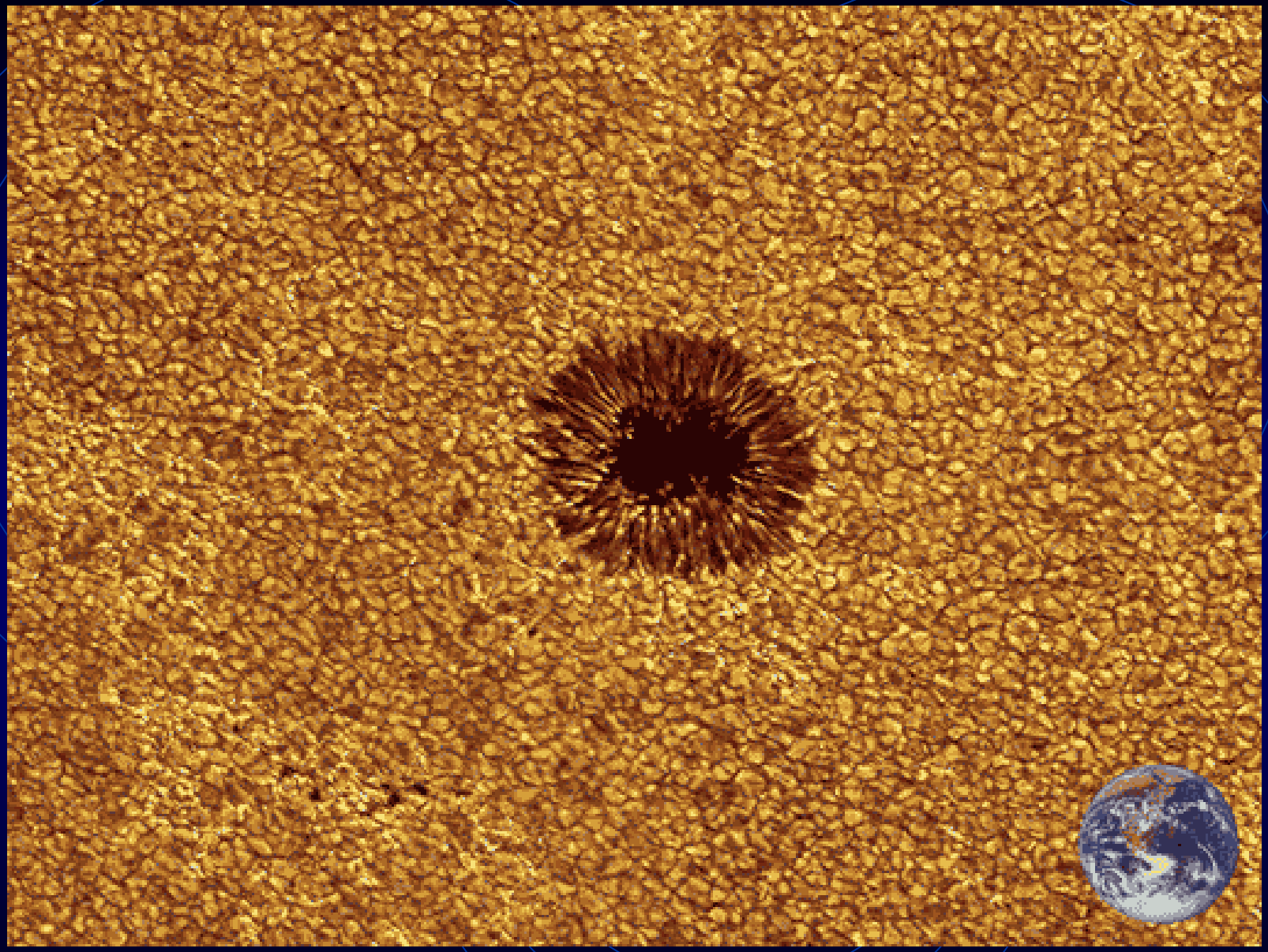






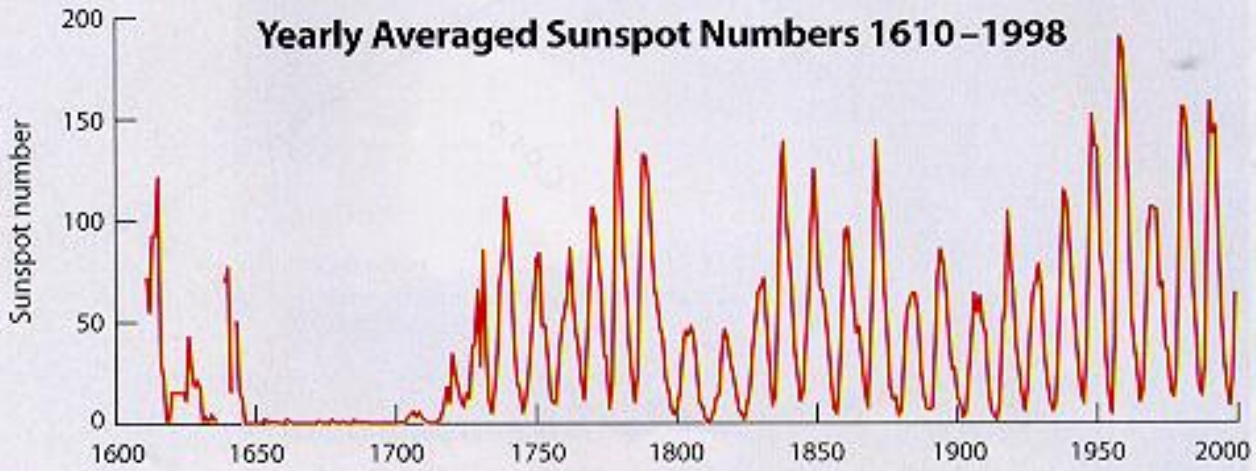
movie

http://www.solarphysics.kva.se/NatureNov2002/



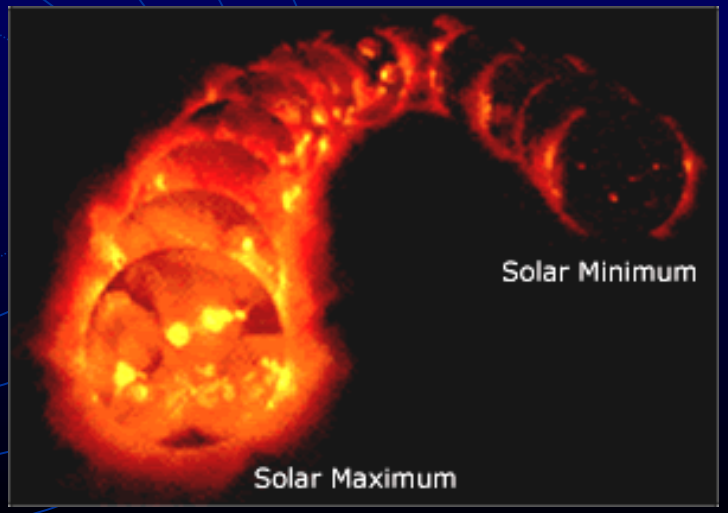
Sunspot Metamorphosis: From Bottom to Top APOD 2005/02/16

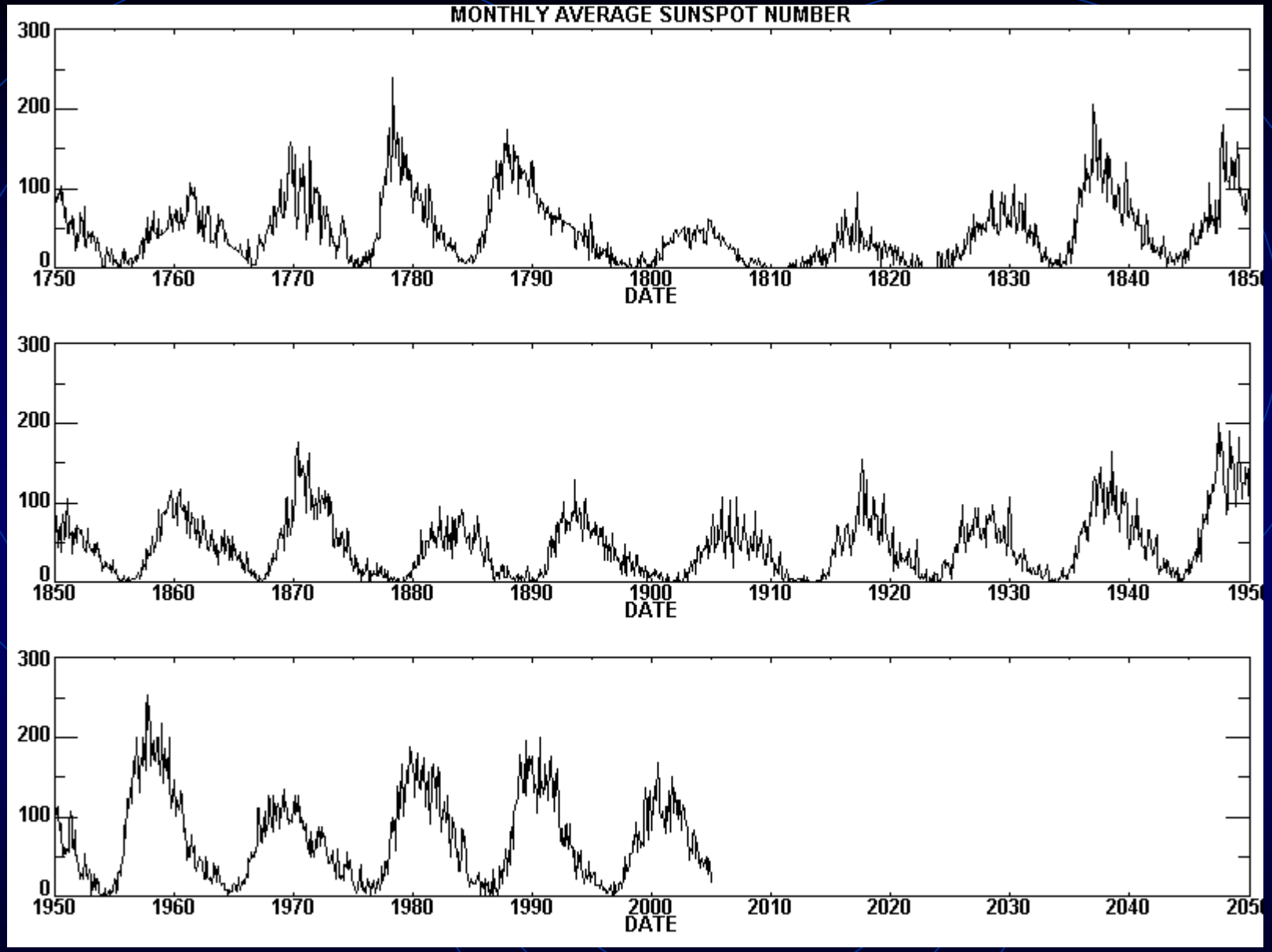
Since the invention of the telescope, sunspots have been studied, and historical records, while sketchy, make it clear that our star was essentially spot-free for the latter half of the 17th century — a period of unusually harsh winters and noticeable year-round global cooling. Observations of other Sun-like stars suggest that such temporary breakdowns in dynamo activity are not uncommon. Courtesy David Hathaway.



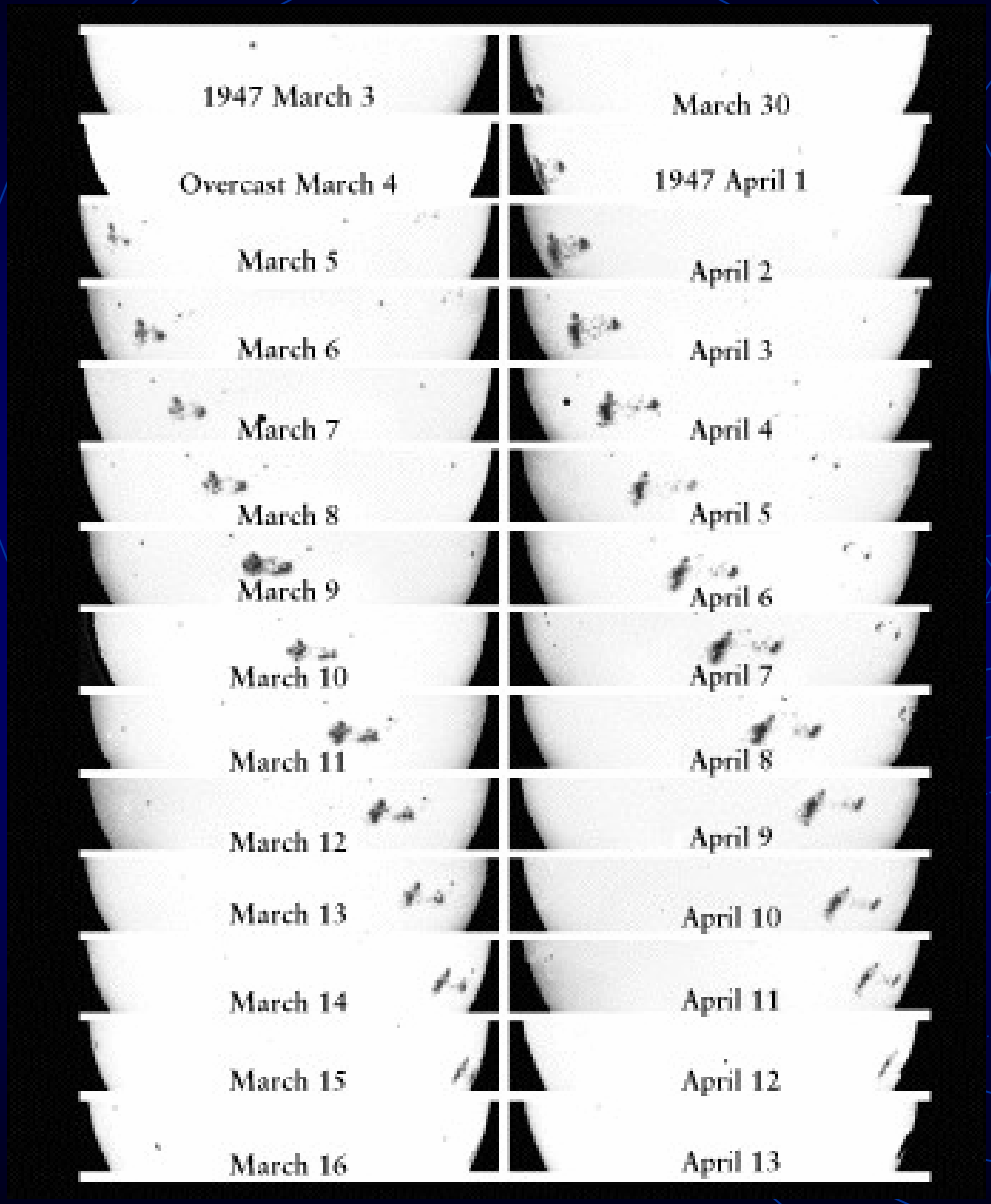
太陽黑子數目呈現11年週期變化

整個太陽的活動亦然，包括日冕大小





http://abyss.uoregon.edu/~js/ast121/lectures/lec23.html



黑子會有消長

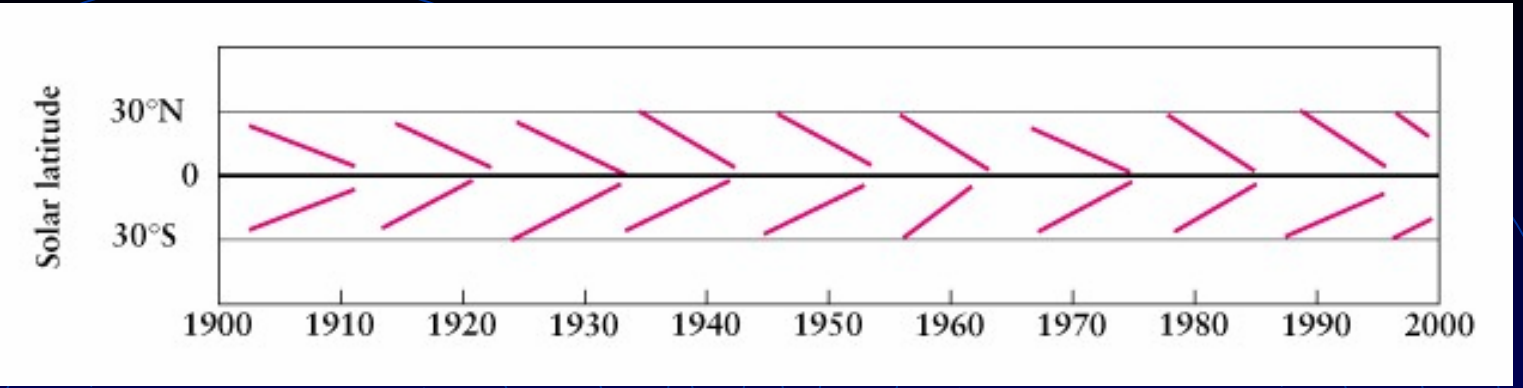
藉由同一個黑子群在太陽盤面的運動可以研究太陽轉動

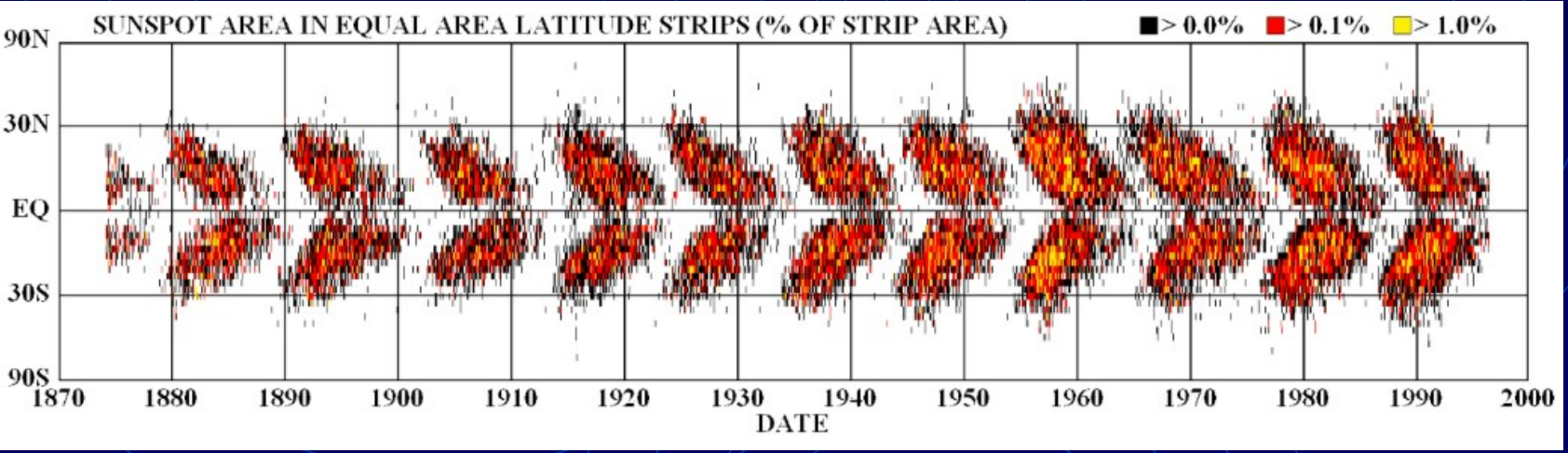
赤道附近轉一圈約25天

緯度30度附近轉一圈約需時 27 天

兩極附近約35天

➔ 差動自轉

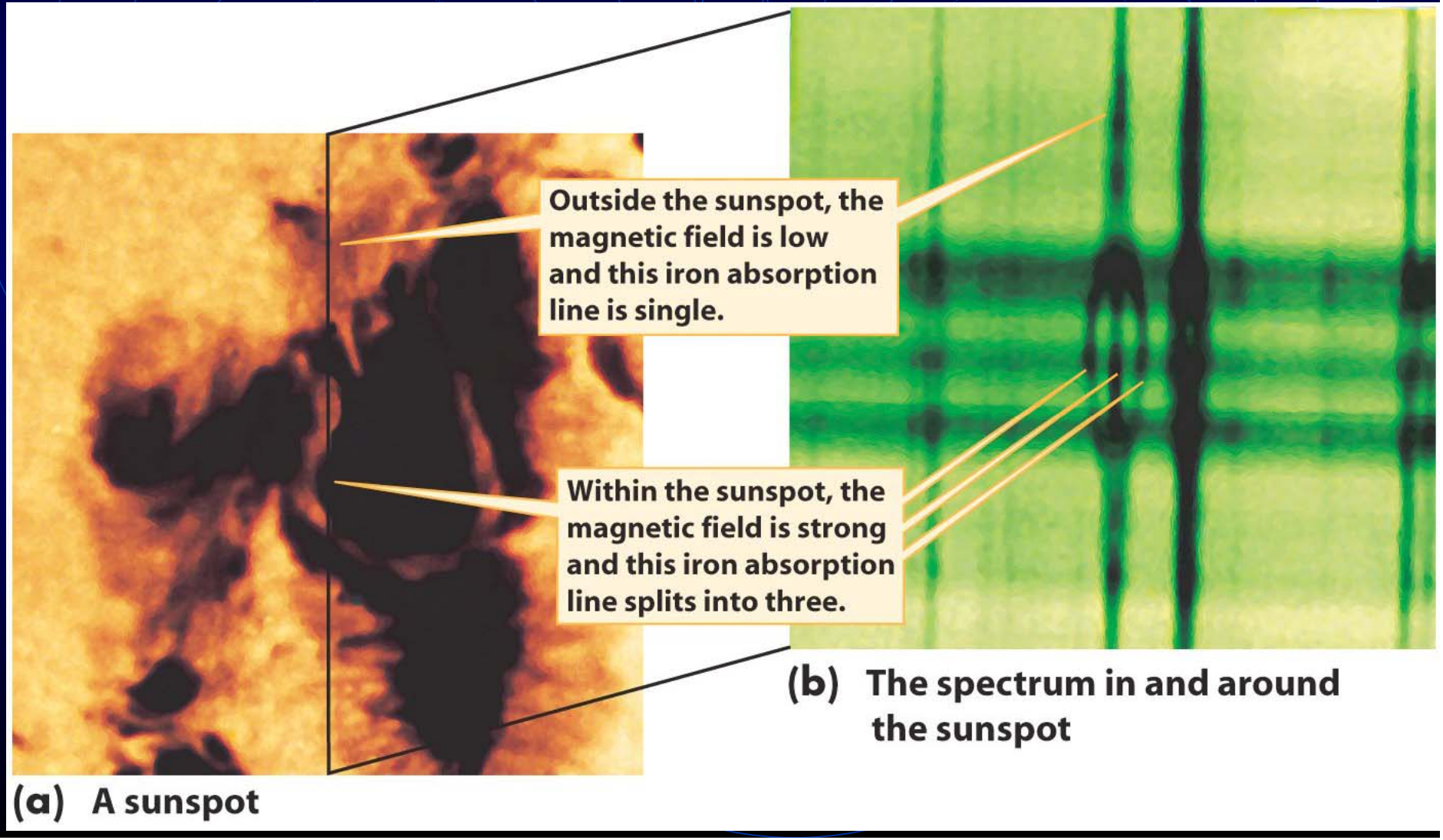


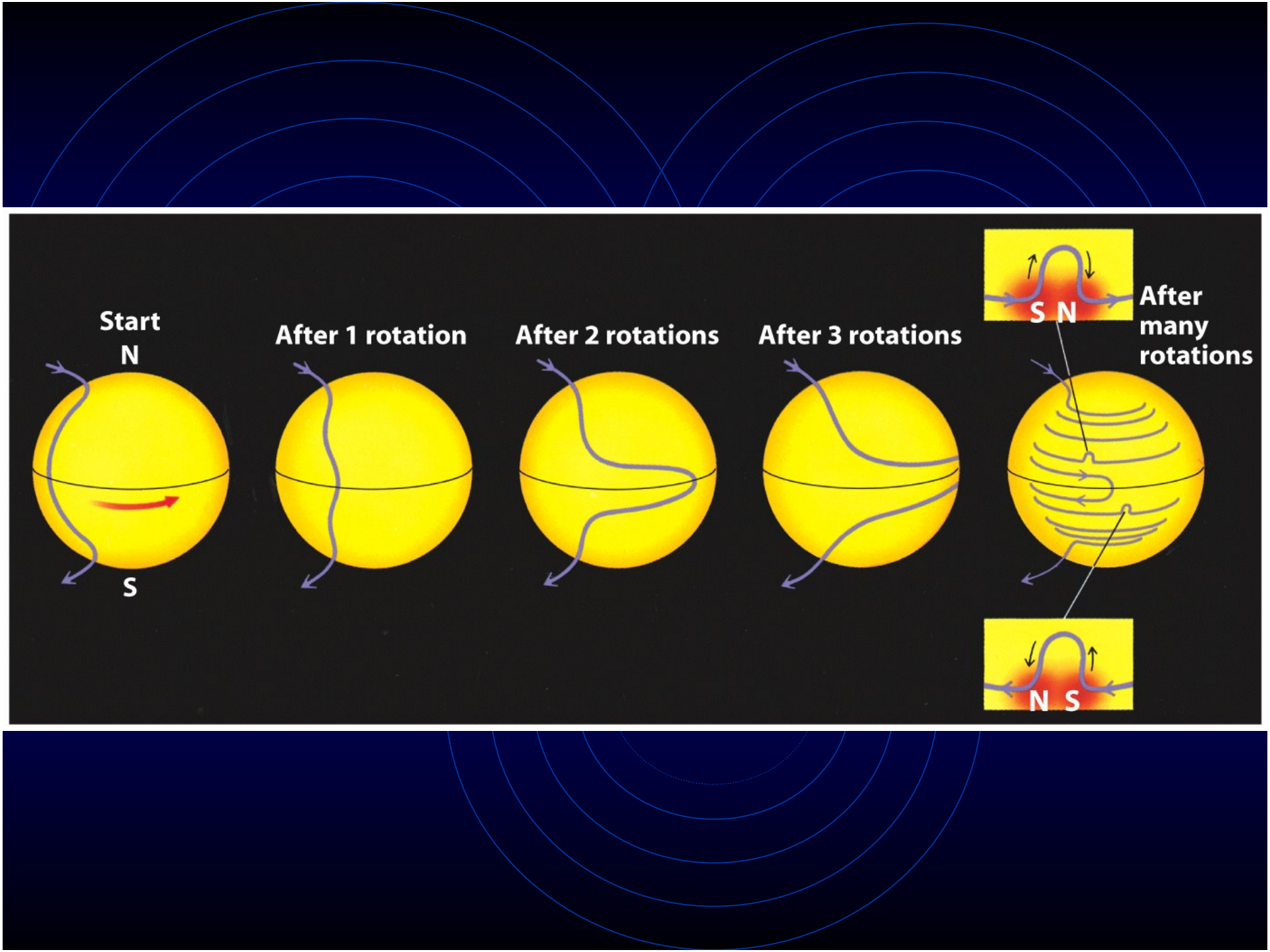


每個太陽週期之初，黑子多半在約緯度30度附近出現，隨後黑子出現的緯度越來越接近赤道（**蒙氏蝴蝶圖 Maunder butterfly diagram**）

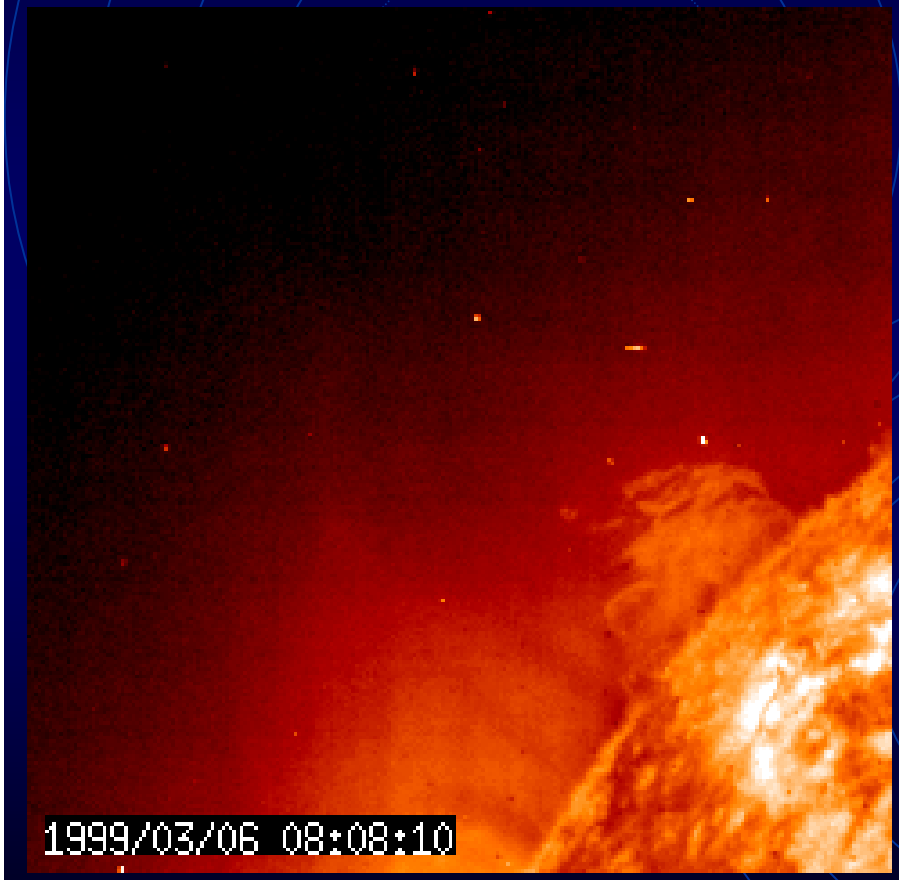
太陽極大時期發出的能量比極小時期多0.1%

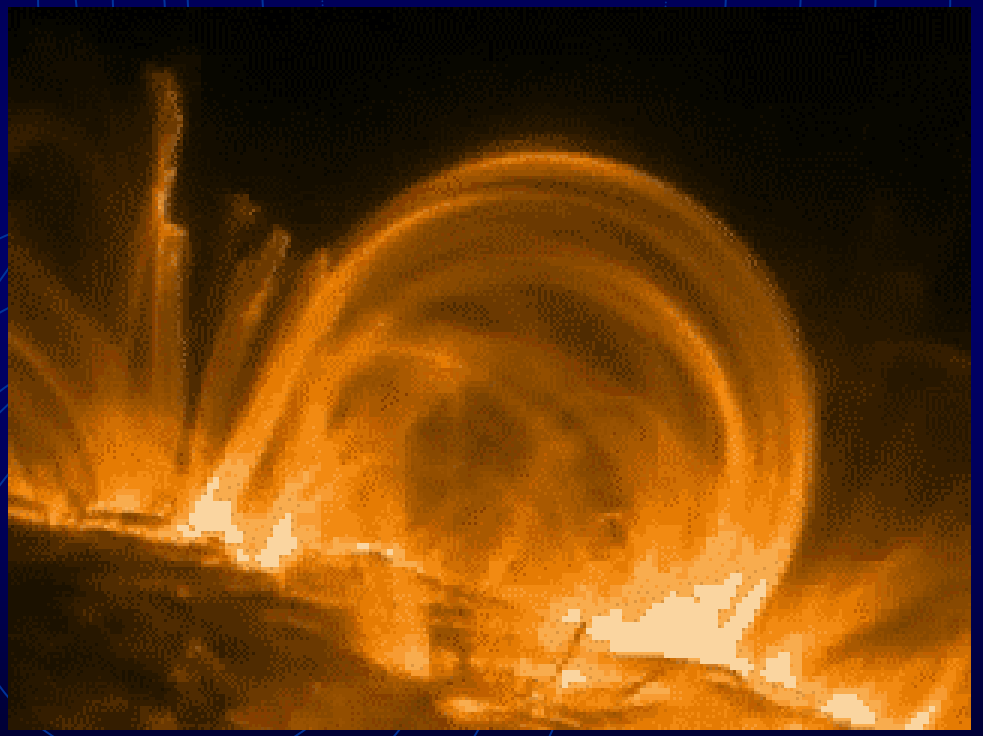
Zeeman Effect --- splitting of a spectral line by magnetic field

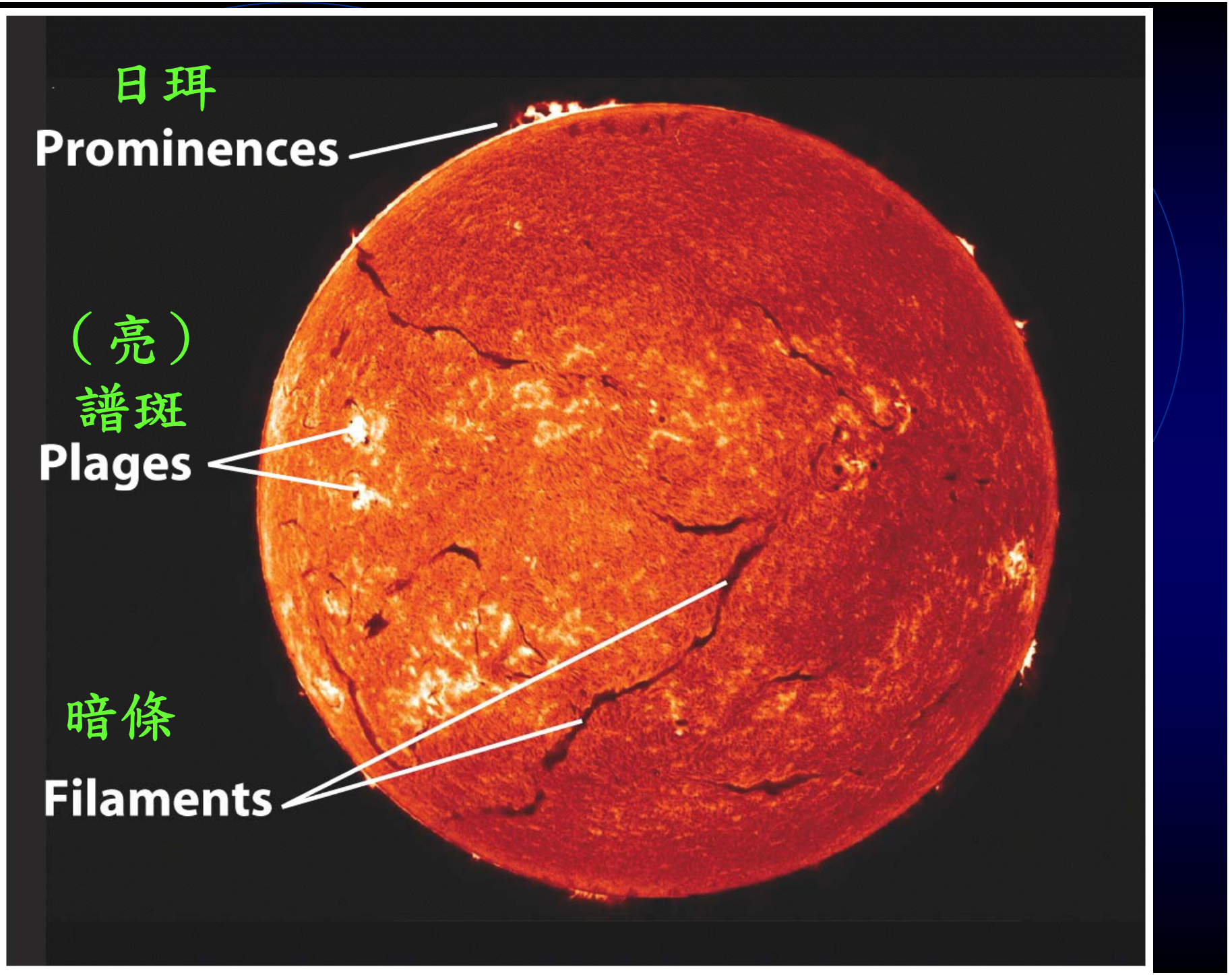


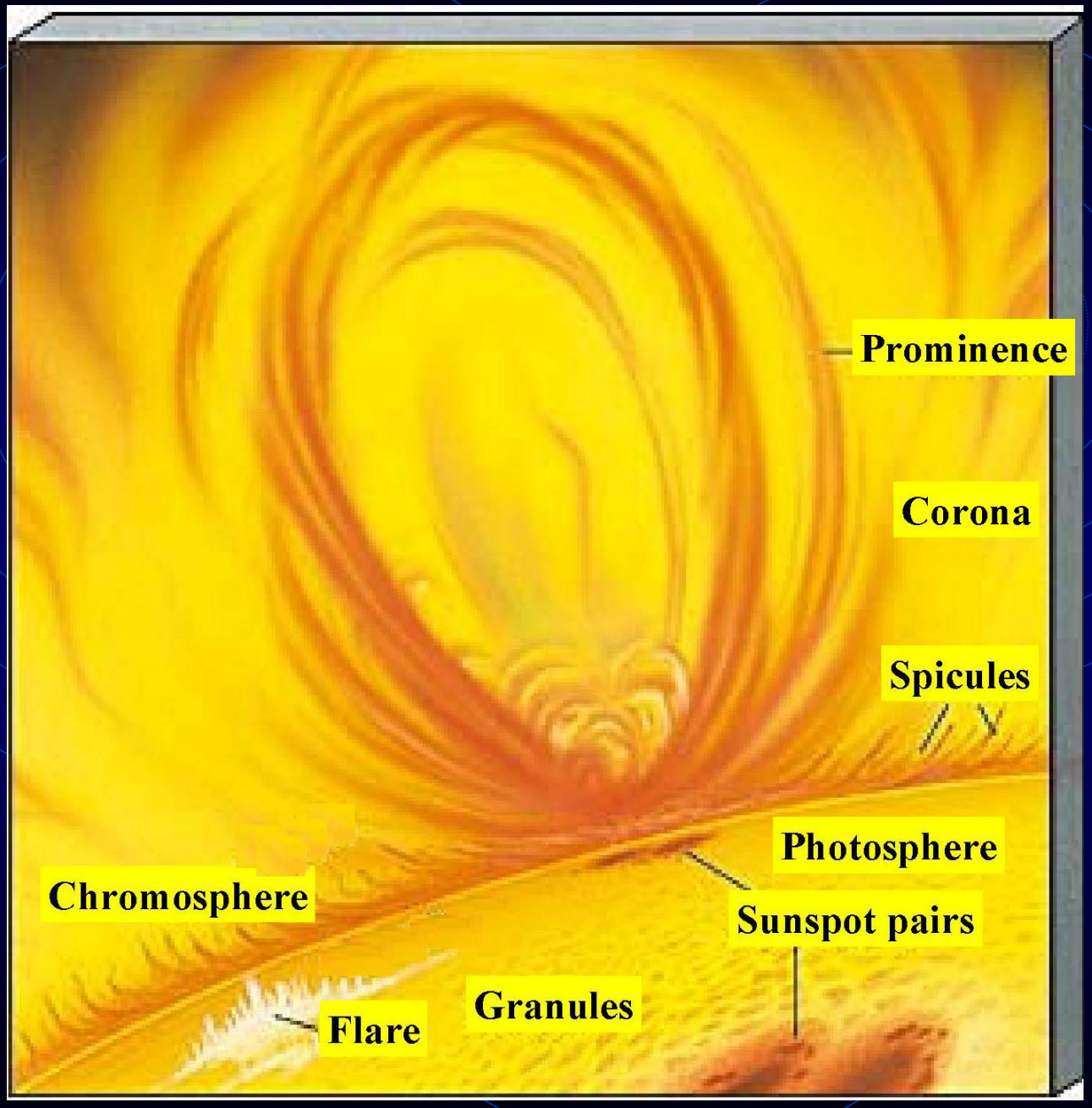

Start
N
S
After 1 rotation
After 2 rotations
After 3 rotations
S N
After many rotations
N S

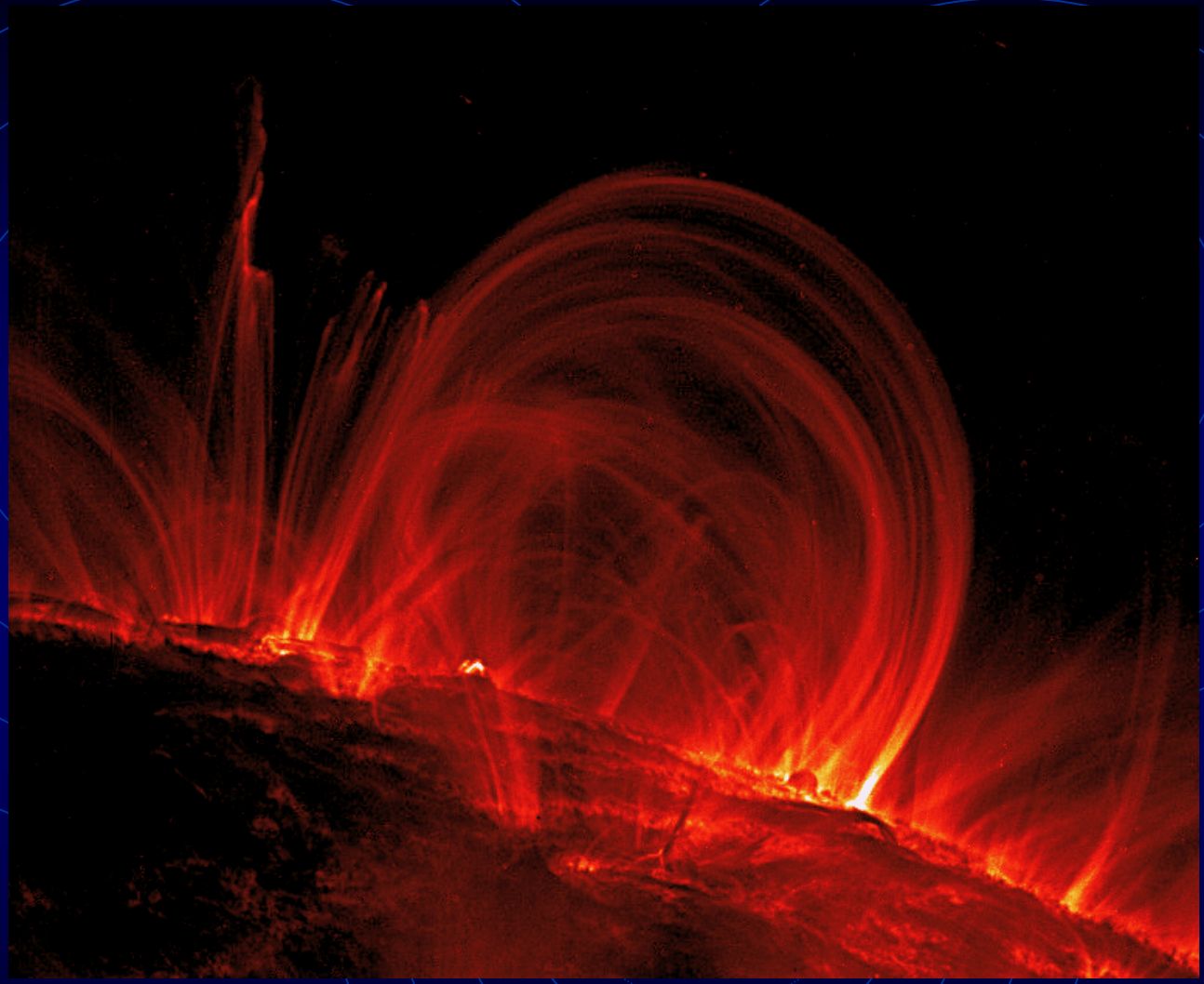
太陽表面常有劇烈活動，物質高速噴發，常看得出磁場結構



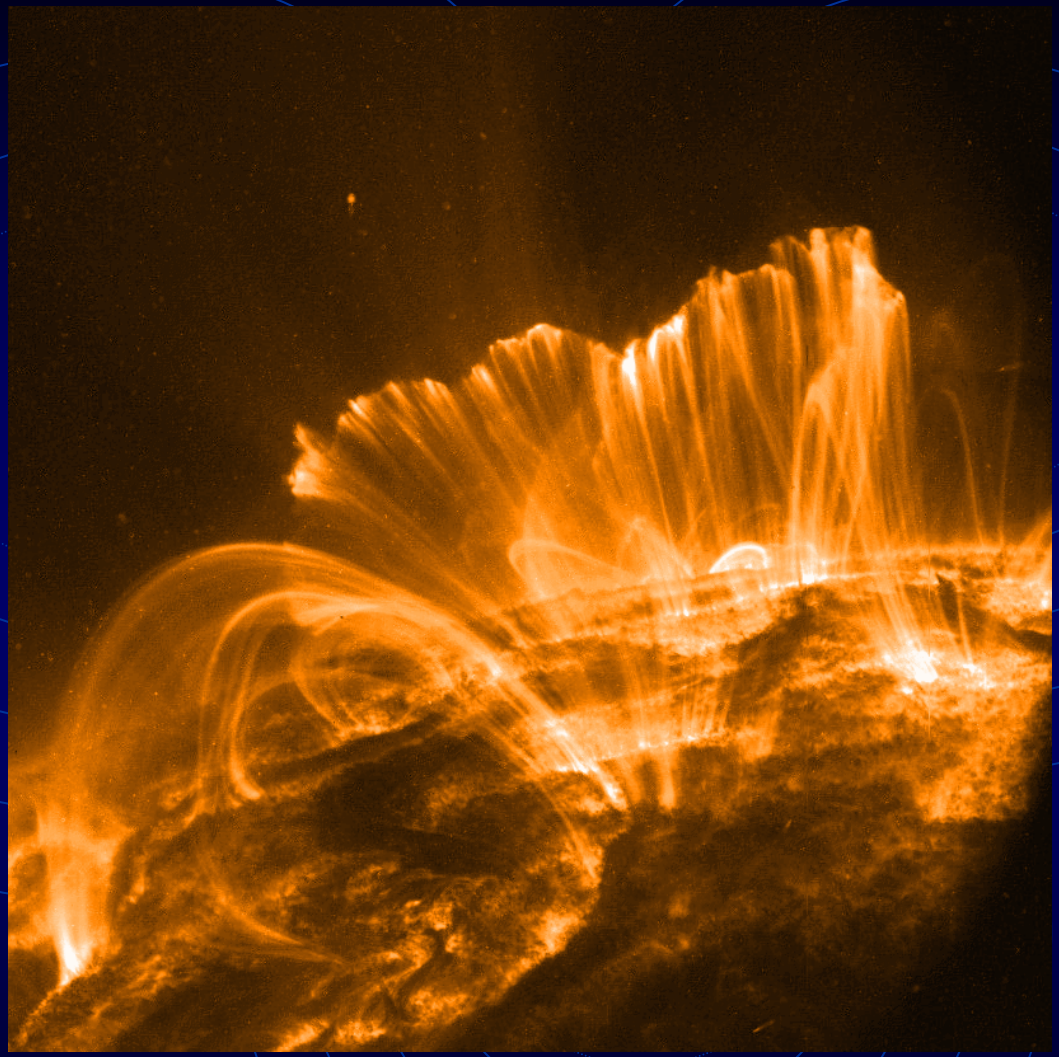



日珥
Prominences
（亮）
譜斑
Plages
暗條
Filaments

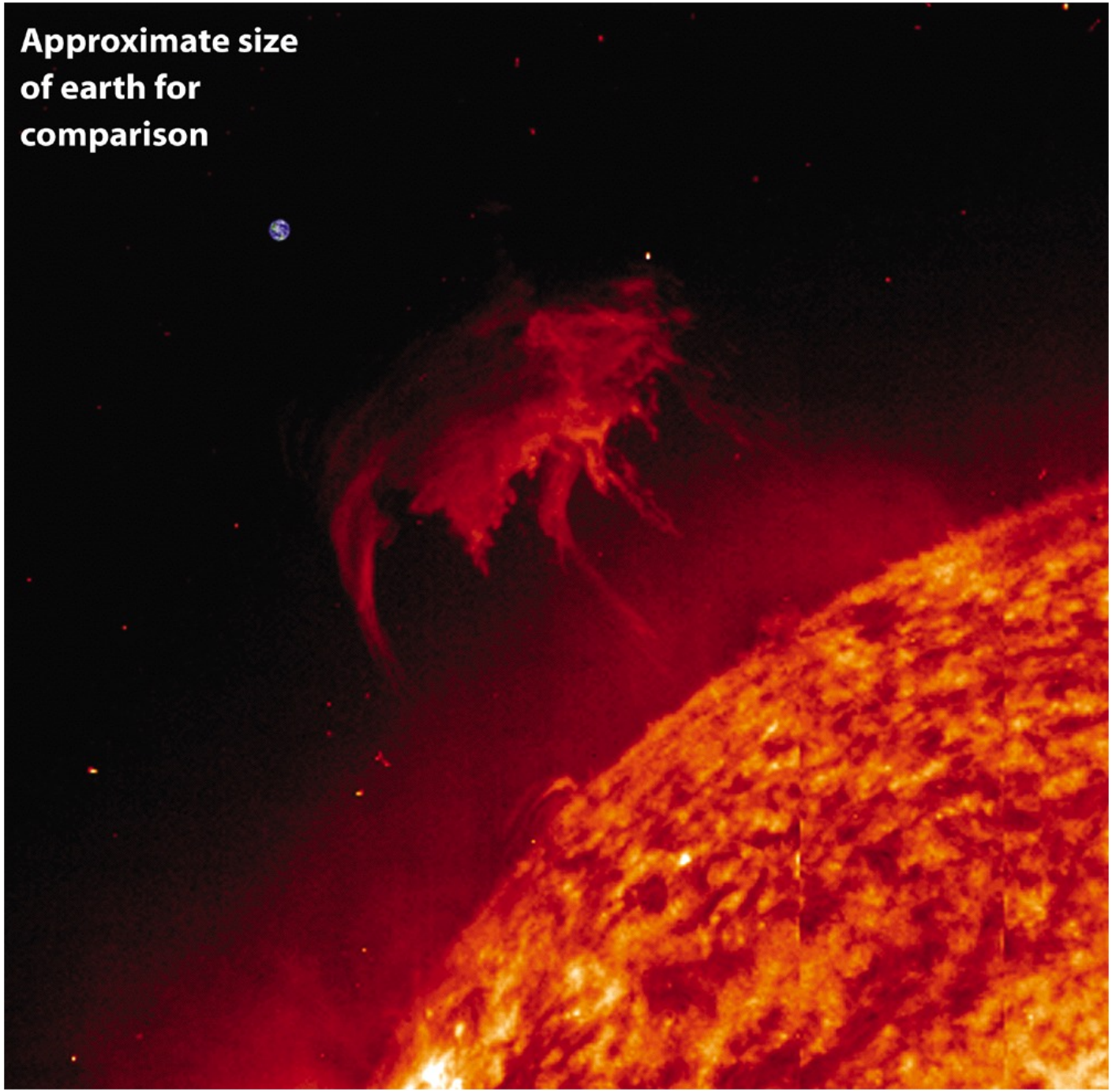

Prominence
Corona
Spicules
Photosphere
Chromosphere
Sunspot pairs
Granules
Flare



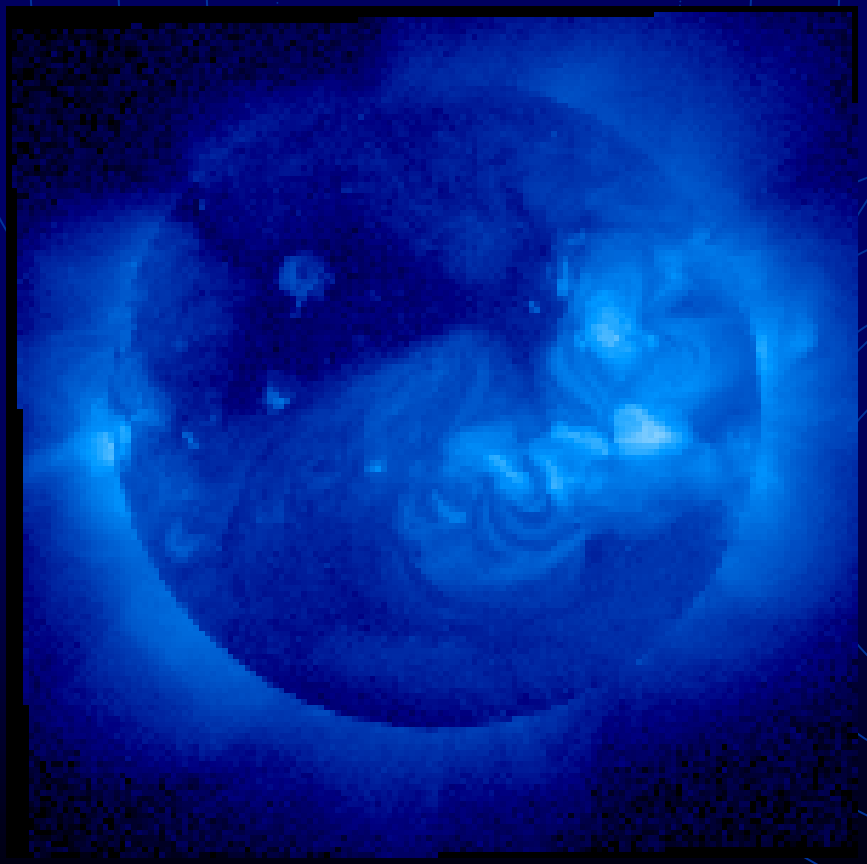
http://soi.stanford.edu/results/SolPhys200/Schrijver/images/TRACE171_991106_023044.gif

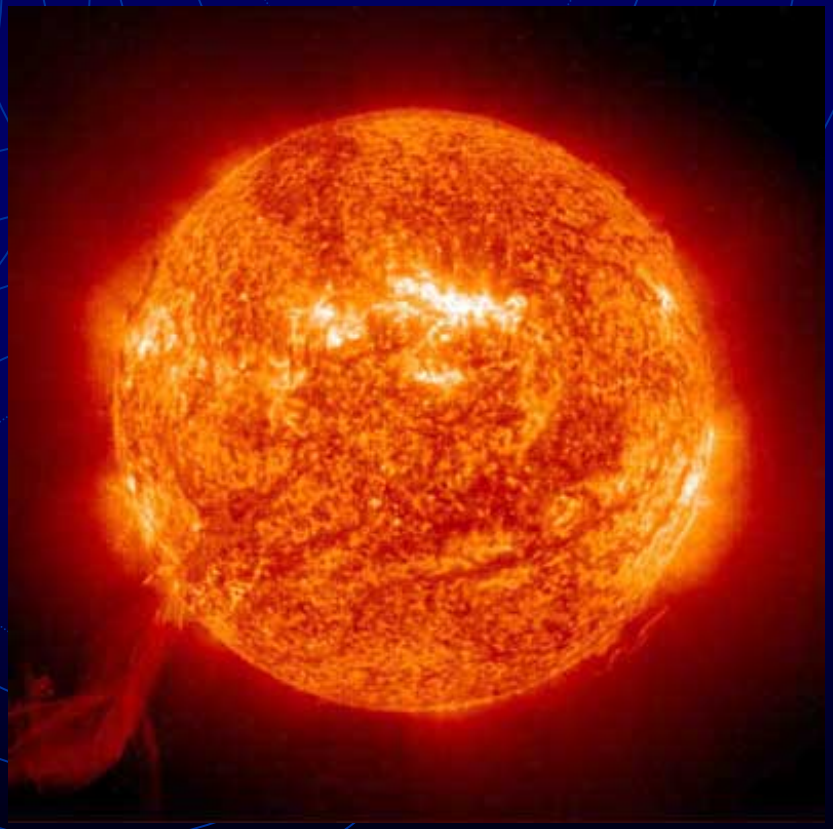


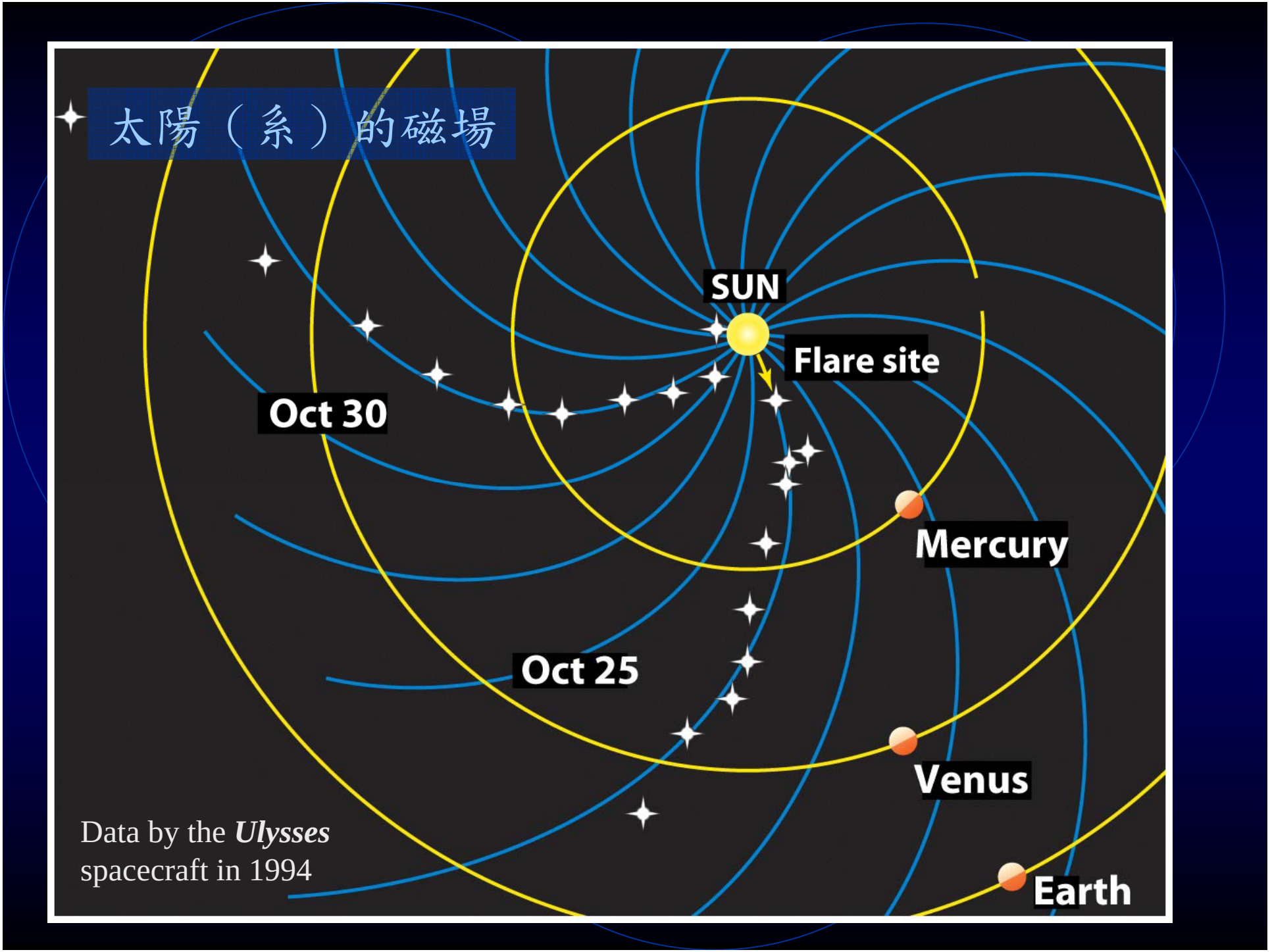
http://soi.stanford.edu/results/SolPhys200/Schrijver/images/arcade_9_nov_2000.gif


Approximate size
of earth for
comparison

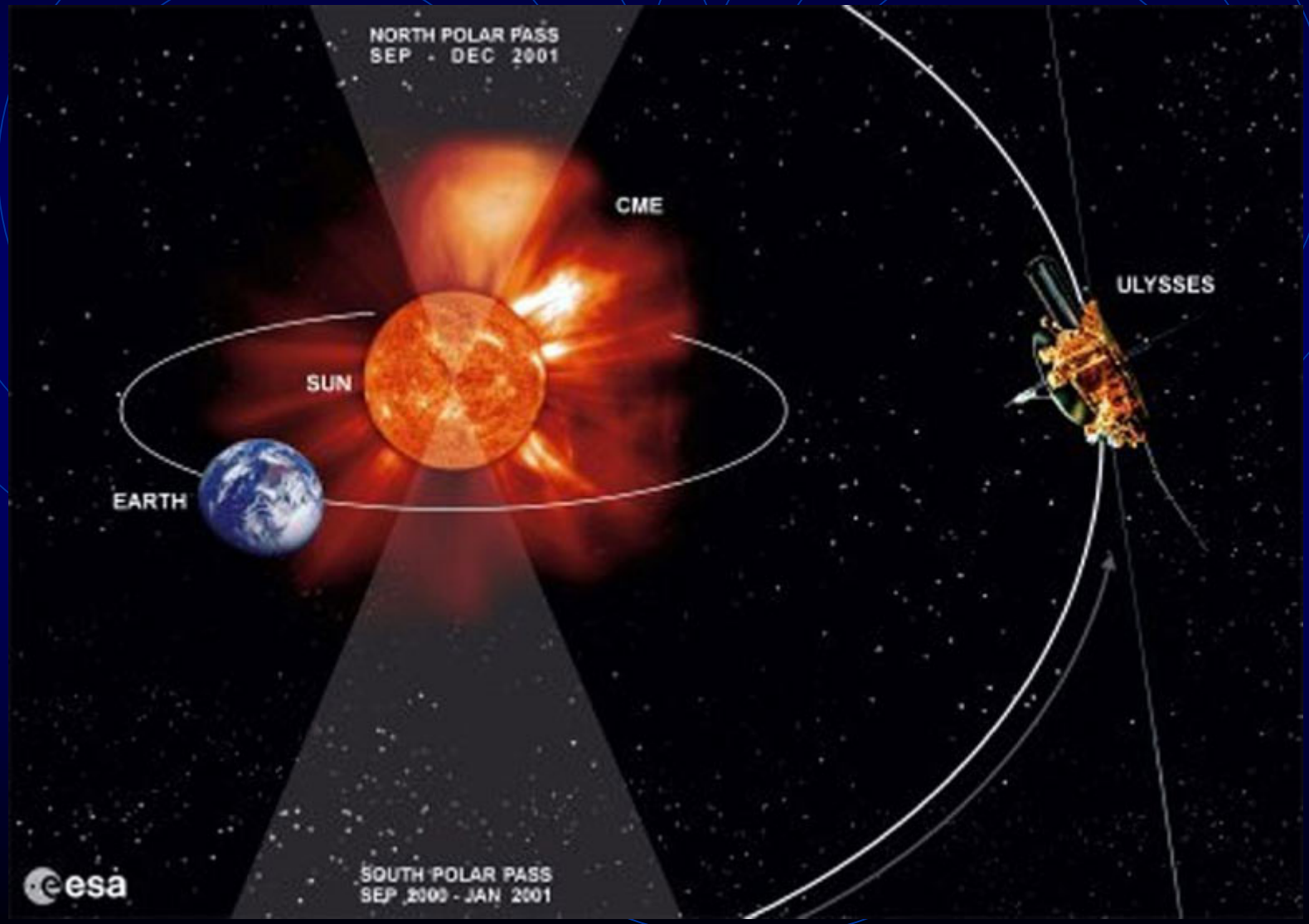
日冕中的氣體溫度非常高溫度非常高，約百萬度。corona 中的氣體以高速運動（時速百萬公里）→ 逃逸到太空 ➔ **solar wind（太陽風）**；每秒拋出百萬噸的物質（質子、電子）

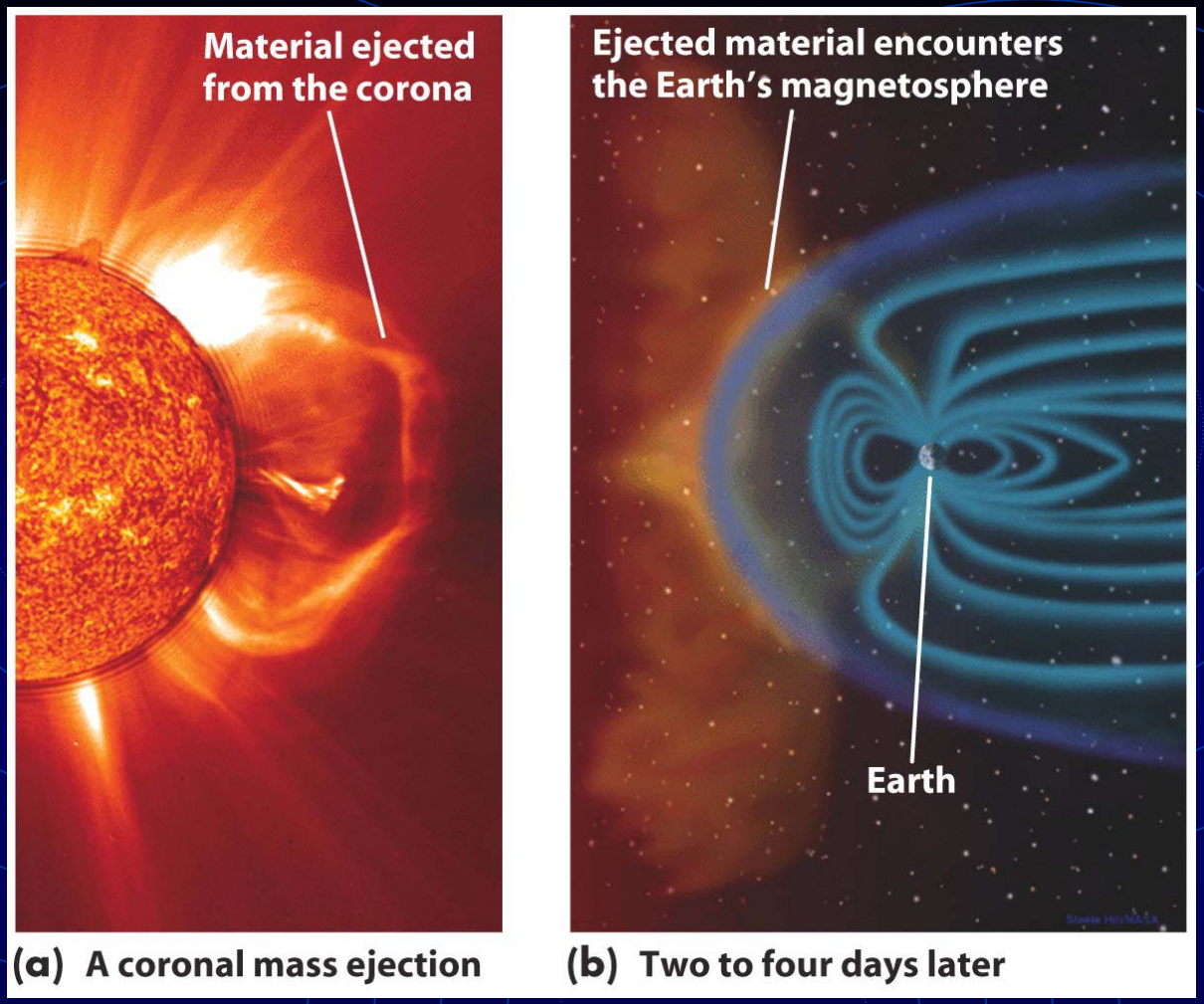





太陽（系）的磁場
SUN
Flare site
Oct 30
Mercury
Oct 25
Venus
Earth
Data by the *Ulysses*
spacecraft in 1994

尤力西斯 (Ulysses) 是第一架從黃道面上方研究星際空間的太空船





CME animation

2-4天以後

SOHO 太空船所拍攝太陽 coronal mass ejection 的X射線影像

最高能量的氣體粒子到達地球，多半被地球磁場偏折離去，但仍有少數衝向地球，造成極光、中斷通訊與電力供應、損害衛星

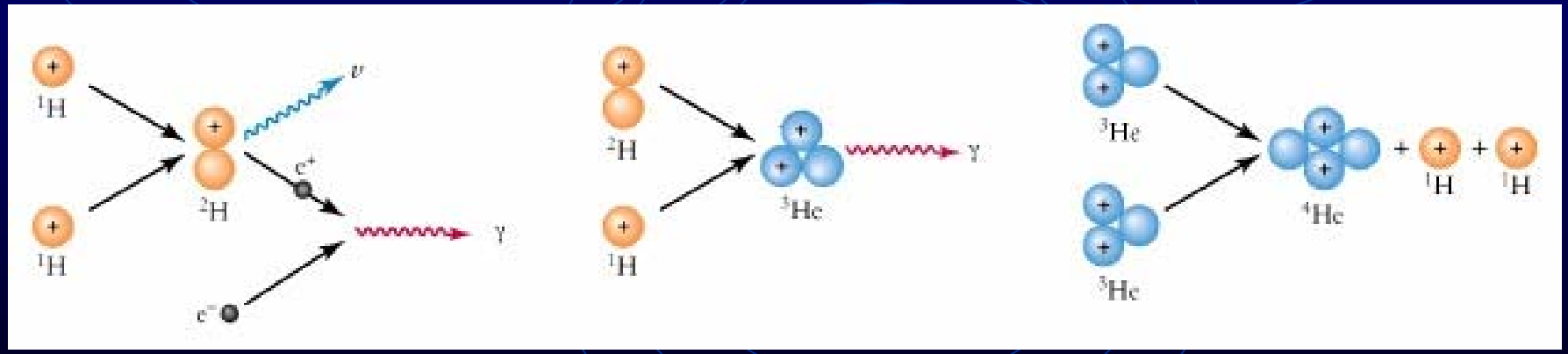
太陽（恒星）内部的核反應

簡單的原子核　結合 → 較複雜的原子核

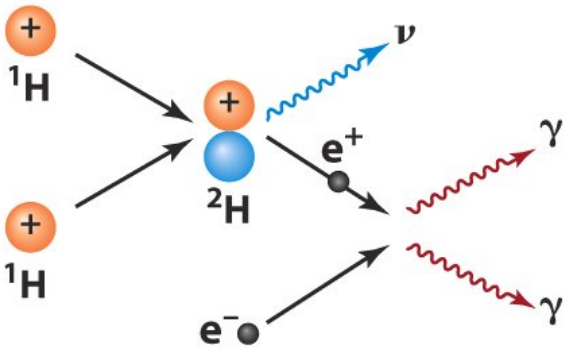
原子核強作用力把自己「抓得」比較緊

→ 放出能量（γ射線、X射線、光）

例如：（4個）氫原子核 → （1個）氦原子核

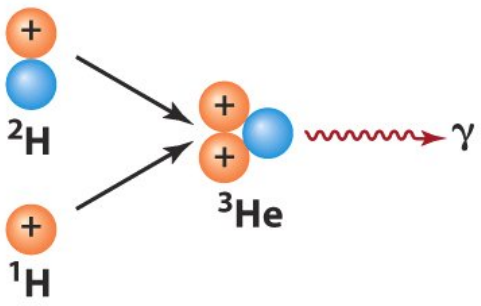


animation: cold gas　　animation: hot gas



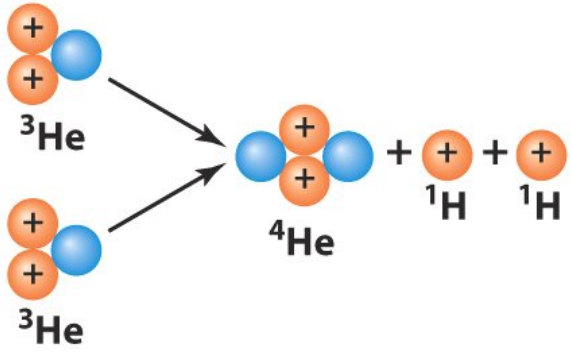
(a) Step 1:

- Two protons (hydrogen nuclei, ^{1}H) collide.
- One of the protons changes into a neutron (shown in blue), a neutral, nearly massless neutrino (ν), and a positively charged electron, or positron (e^+).
- The proton and neutron form a hydrogen isotope (^{2}H).
- The positron encounters an ordinary electron (e^-), annihilating both particles and converting them into gamma-ray photons (γ).



(b) Step 2:

- The ^{2}H nucleus from the first step collides with a third proton.
- A helium isotope (^{3}He) is formed and another gamma-ray photon is released.



(c) Step 3:

- Two ^{3}He nuclei collide.
- A different helium isotope with two protons and two neutrons (^{4}He) is formed and two protons are released.

proton-proton (PP) chain 反應

步驟一：

兩個質子 (proton) 碰撞

其中一個變成中子（藍色），放出一個微中子(neutrino)，及一個正子 (positron)

質子與中子形成氘 (^{2}H)

正子與一般電子相互湮滅 (annihilate)，並放出迦瑪射線

步驟二：

步驟一的 ^{2}H 與另一個（第三個）質子碰撞，形成氦三 (^{3}He)

放出另一個迦瑪射線光子

步驟三：

兩個氦三 (^{3}He) 碰撞，形成氦四 (^{4}He)

放出兩個質子

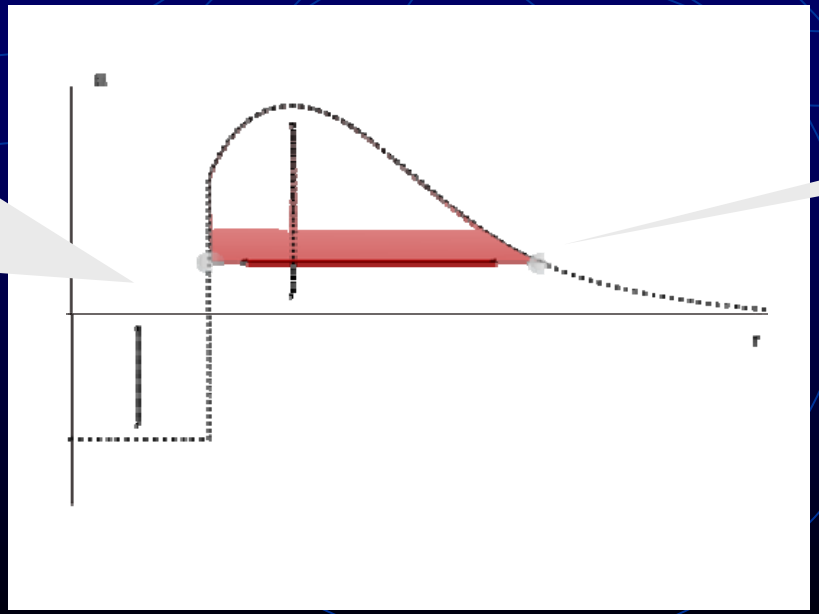
animation: pp chain

淨反應：4個質子產生1個氦四

Q: 原子核（質子）帶正電，彼此有庫侖排斥力，那麼它們如何融合呢？

A: quantum tunneling effect
（量子穿隧效應）

在古典力學裡，像這樣速度（能量）不夠的球滾不過去



波動函數（也就是發現粒子的機率）能穿透到這個區域

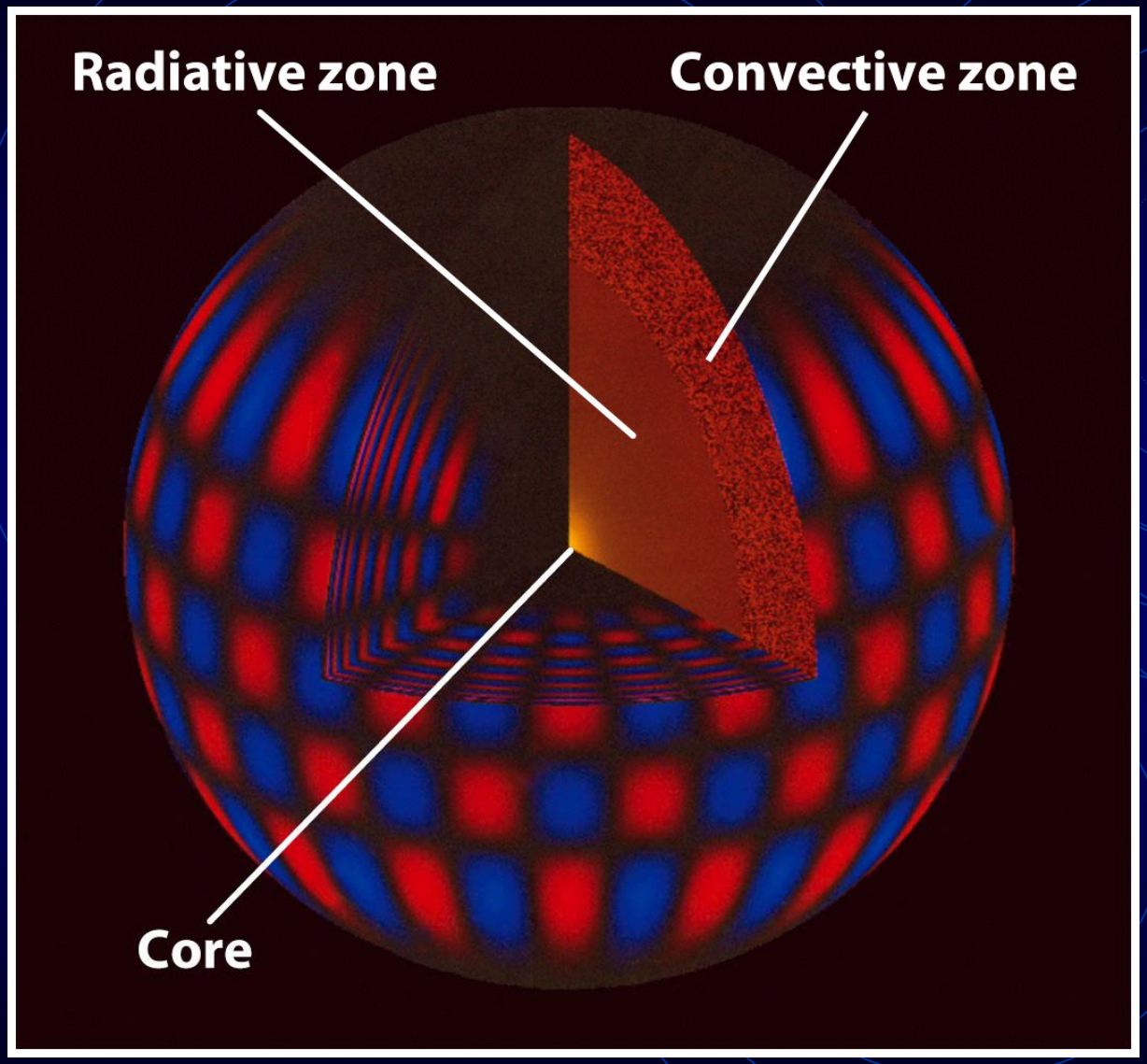
粒子有波動性

Energy Gained in a PP Chain

- 4H → 1 He + neutrinos + energy
- Mass of 4 H = 6.693×10^{-27} kg
  — Mass of 1 He = 6.645×10^{-27} kg

  Mass deficit → 0.048×10^{-27} kg

- $E = mc^2 = (0.048 \times 10^{-27}\ kg) \times (3 \times 10^8\ m/s)^2$
  $= 4.3 \times 10^{-12}$ J
- For 1 $L_\odot = 3.9 \times 10^{26}$ W, the sun needs to convert some 600 million tons（六億公噸）of H into He in its core per second.

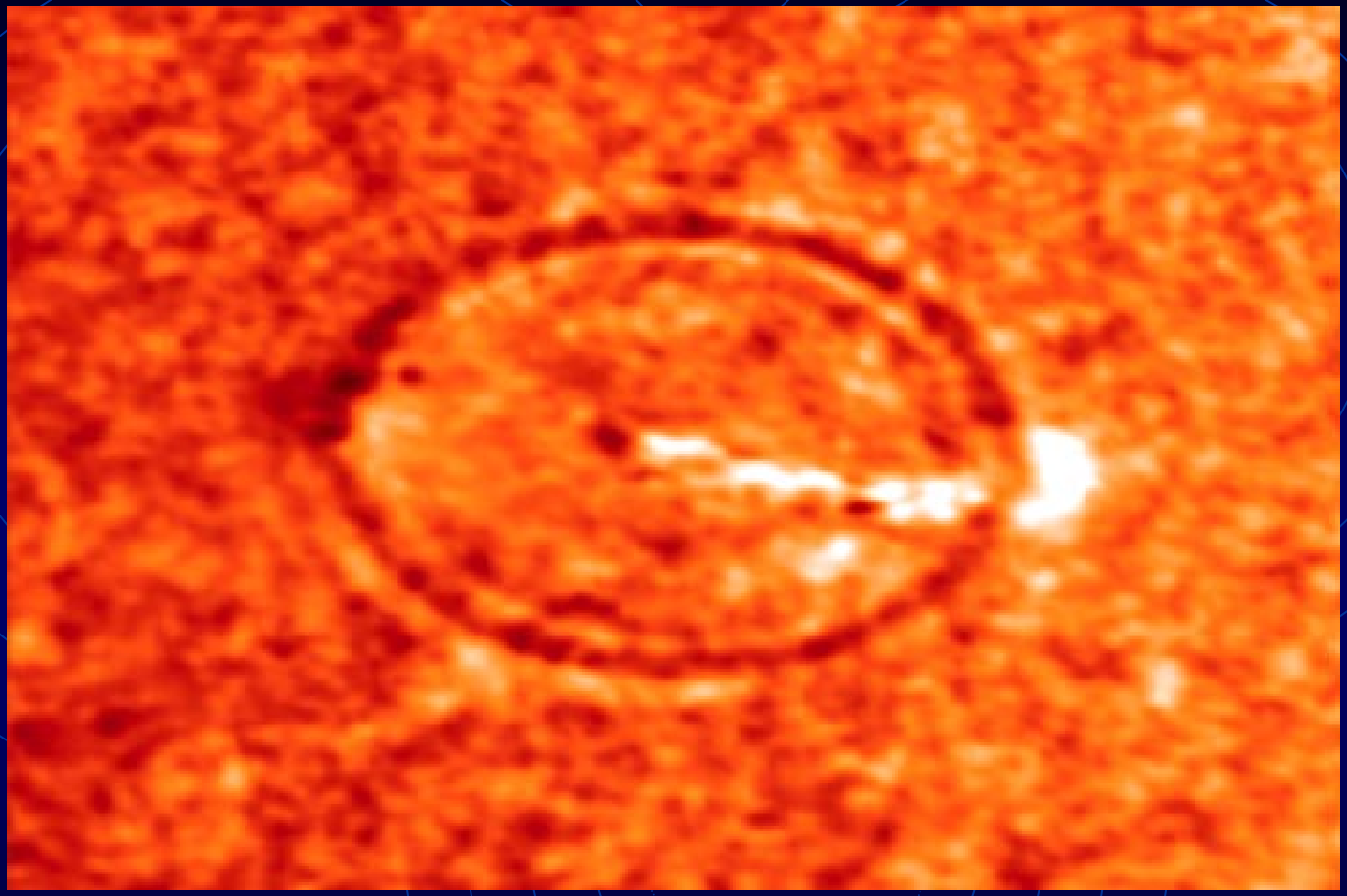


買西瓜時，
敲一敲，
聽一聽！

到底敲什麼，
聽什麼？

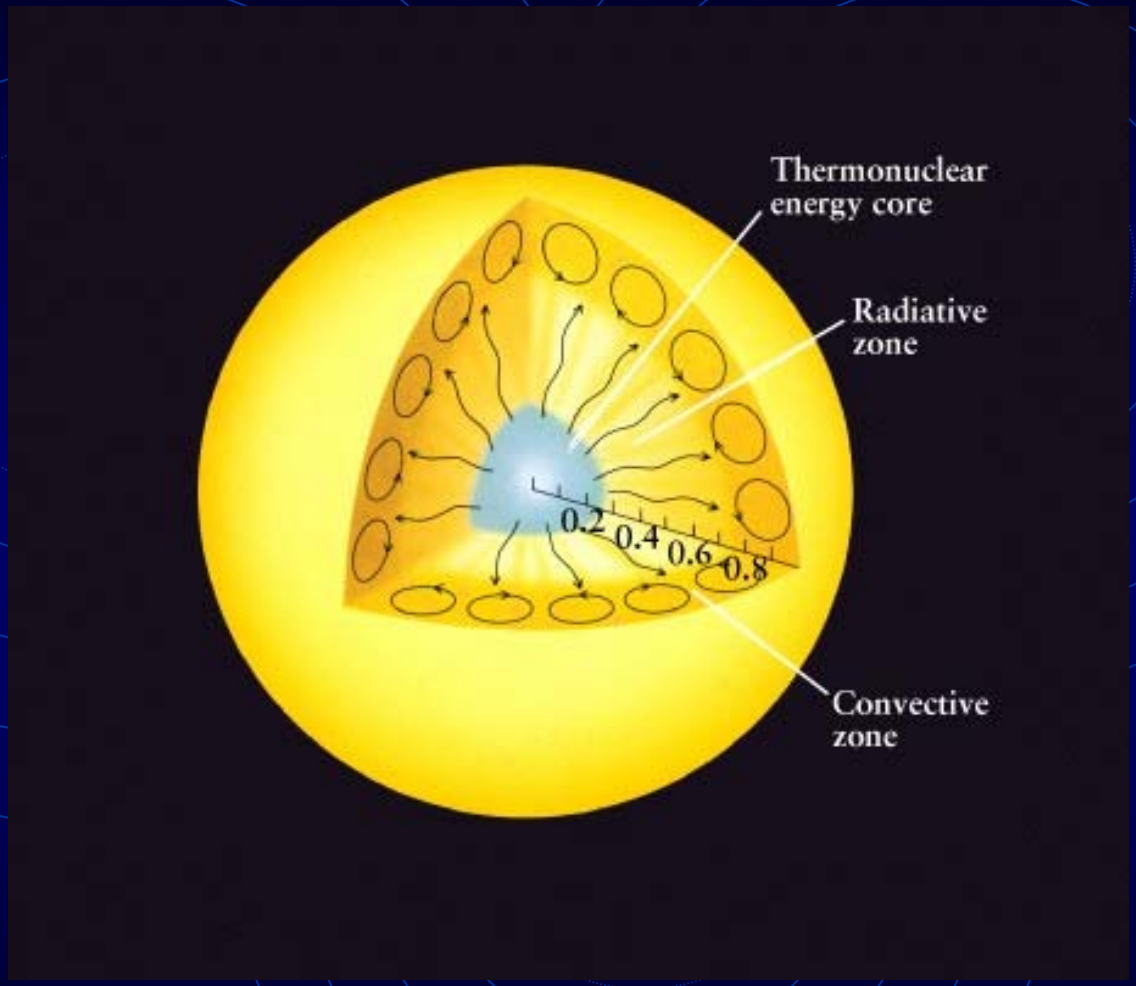
觀測震動情形
藉以研究星球
內部結構

和理論建構的
模型比較



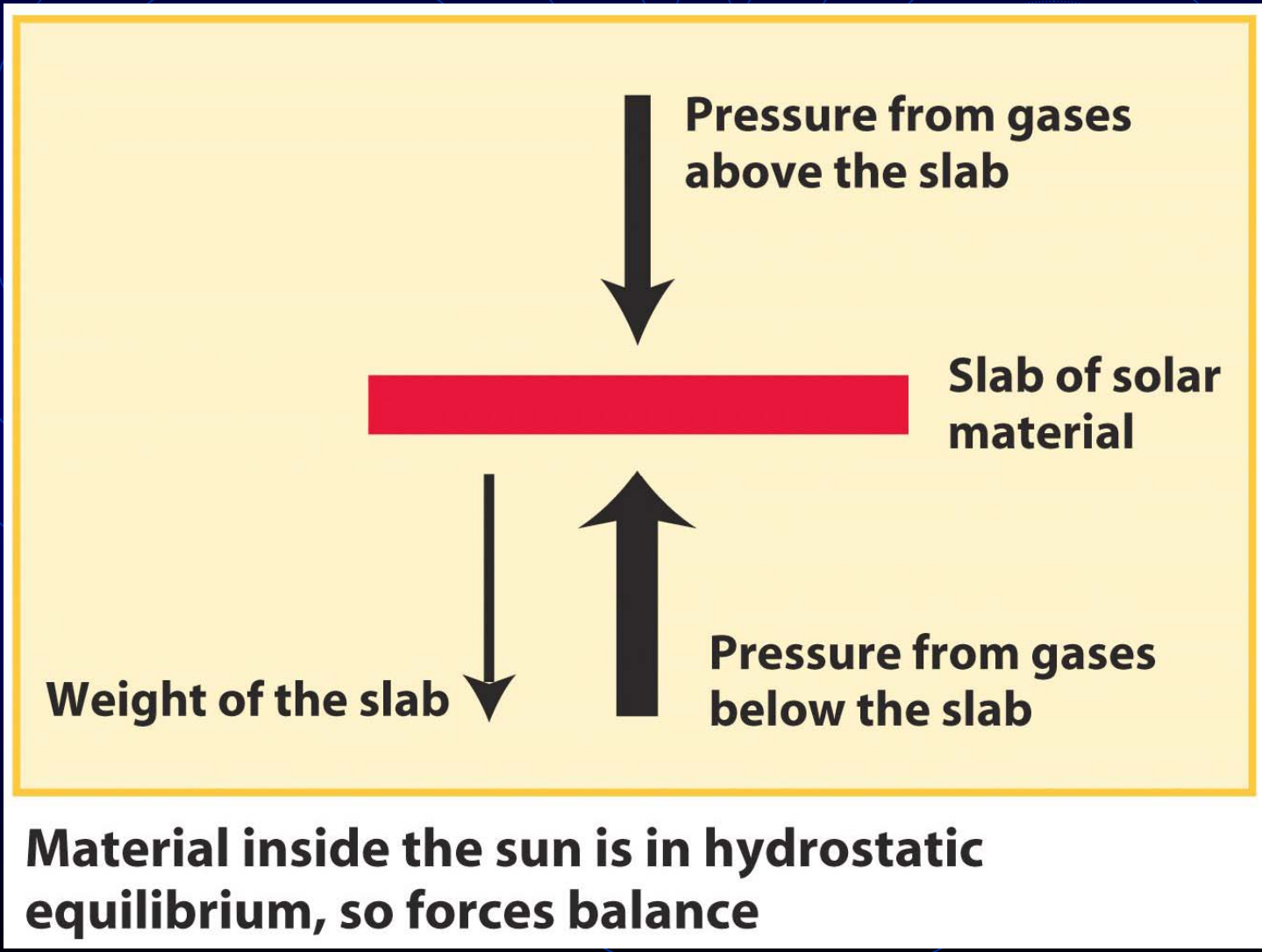
Solar Flares Cause Sun Quakes APOD 1998.06.01

太陽內部結構

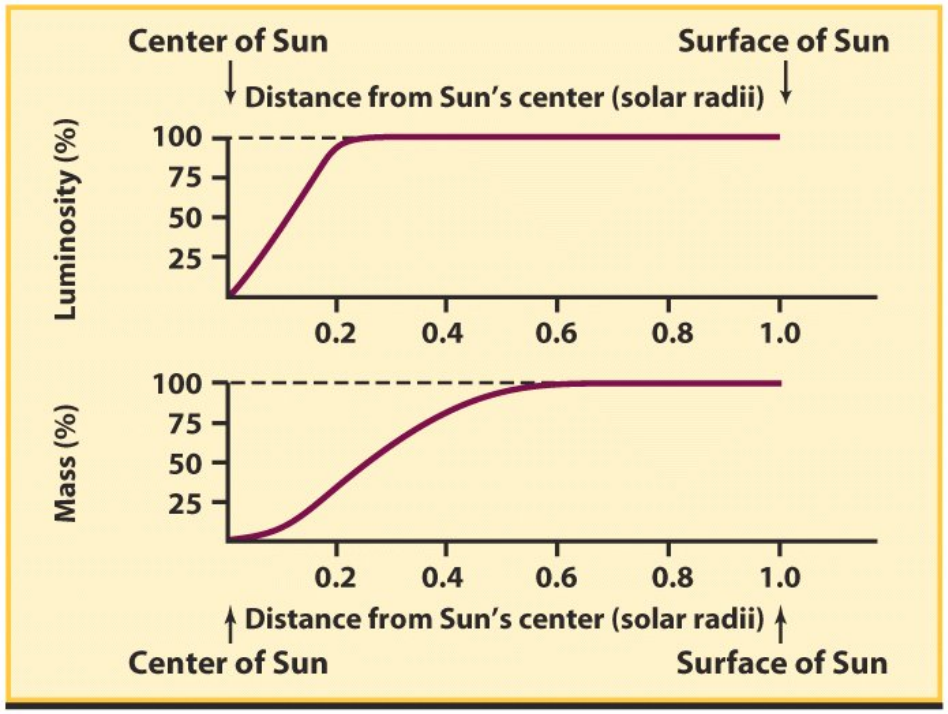


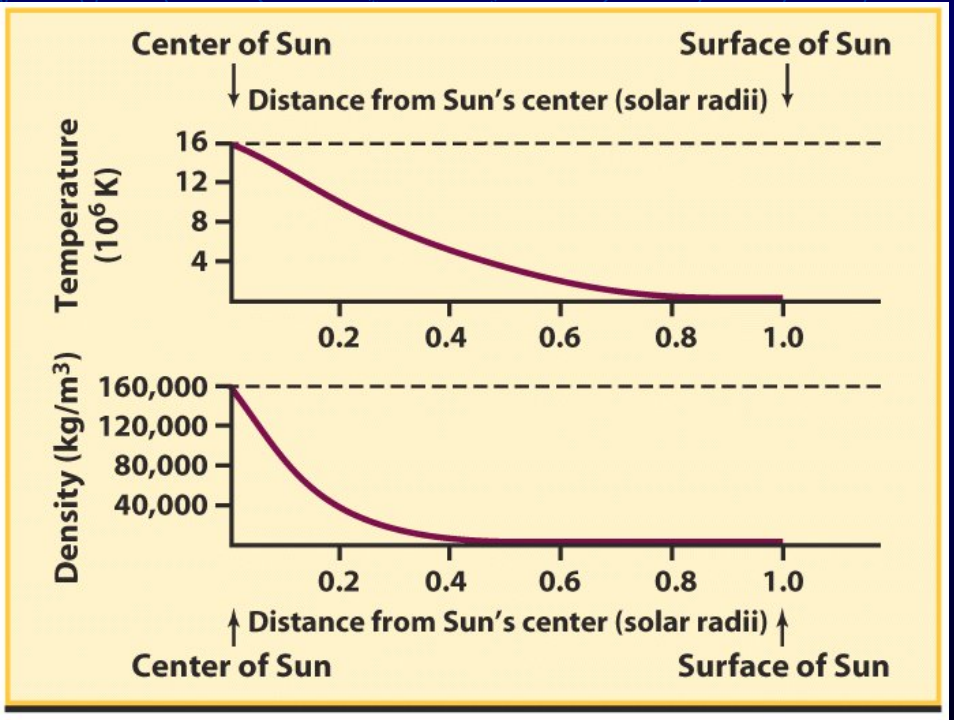
半徑1/4之內的核心進行核反應，釋放的能量藉輻射與對流方式傳到表面，然後輻射到太空

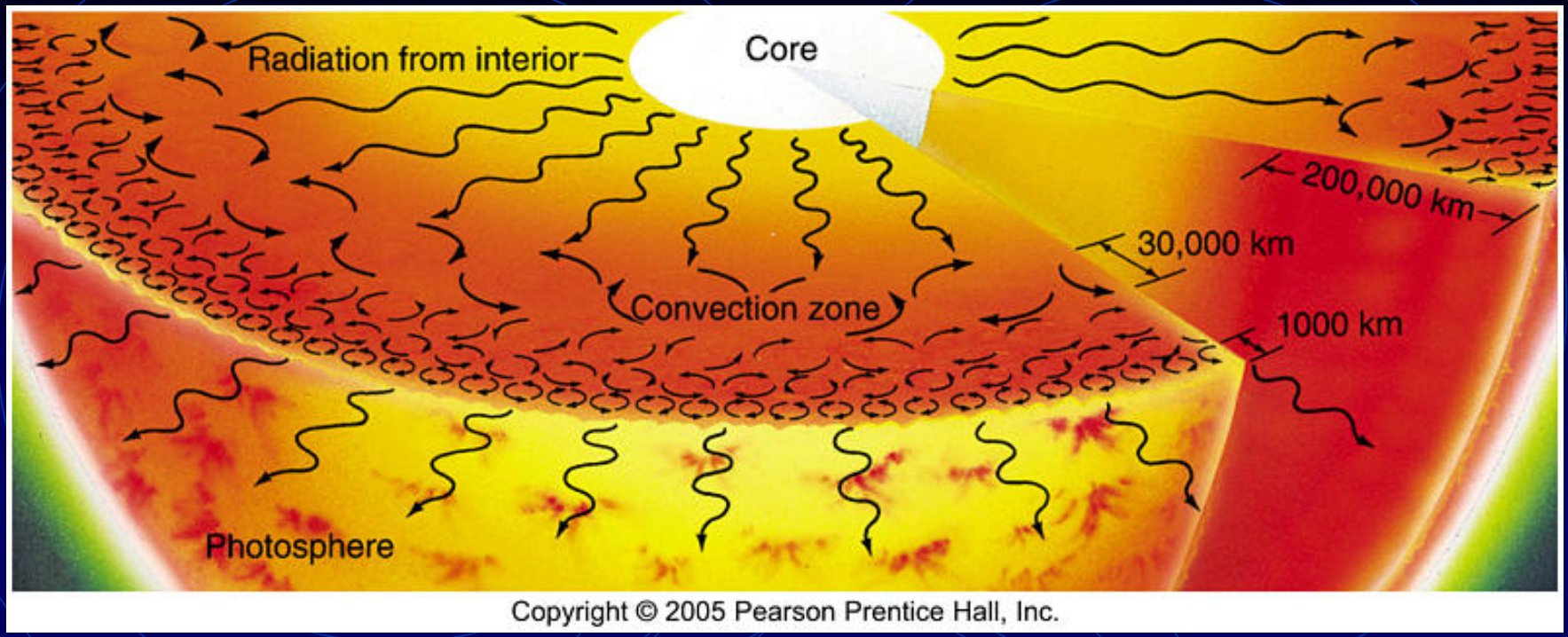
太陽各部分處於靜力平衡 (hydrostatic equilibrium)



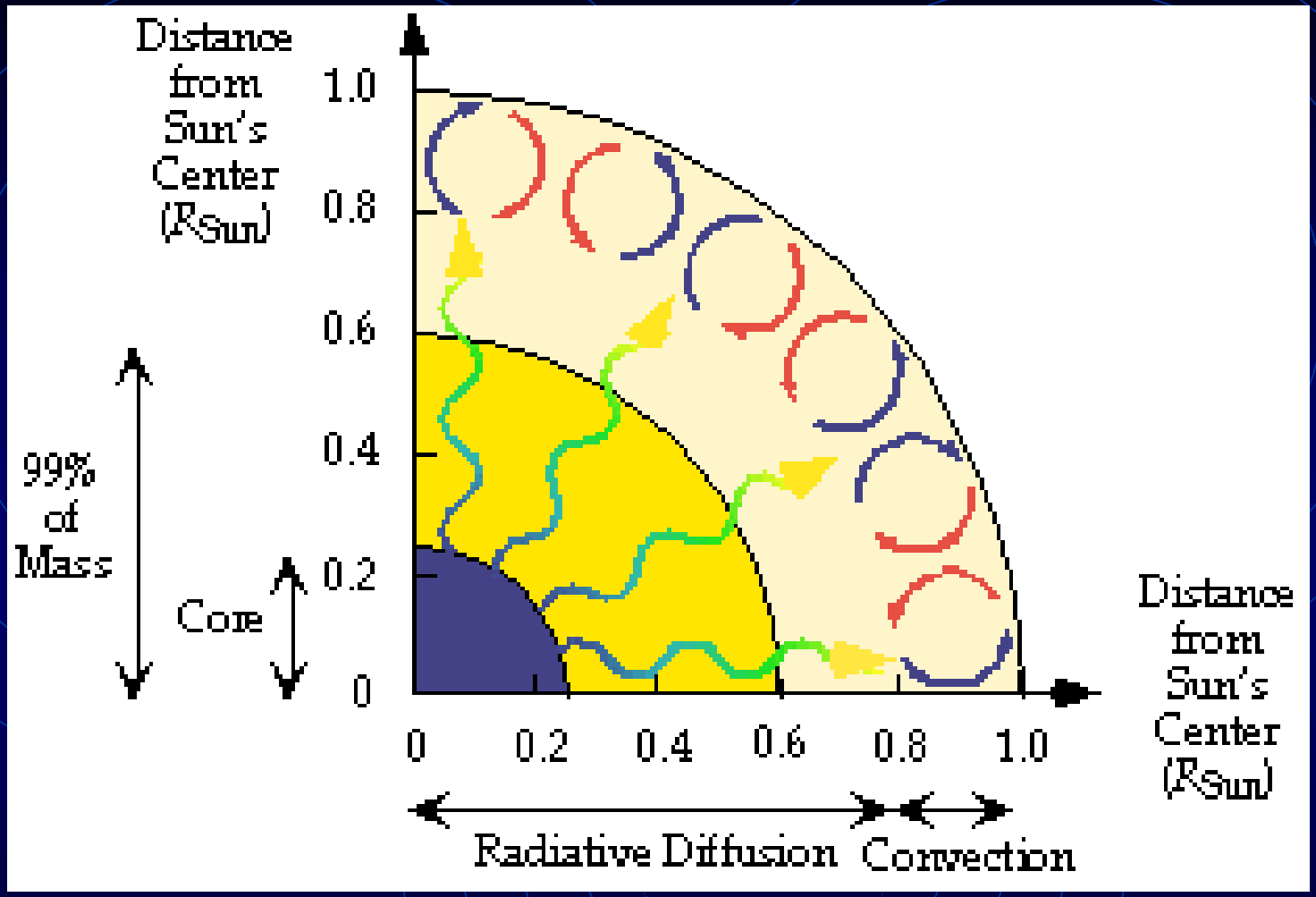
太陽的結構模型


Center of Sun
Surface of Sun
Distance from Sun's center (solar radii)
Luminosity (%)
100
75
50
25
0.2
0.4
0.6
0.8
1.0
Mass (%)
100
75
50
25
0.2
0.4
0.6
0.8
1.0
Distance from Sun's center (solar radii)
Center of Sun
Surface of Sun

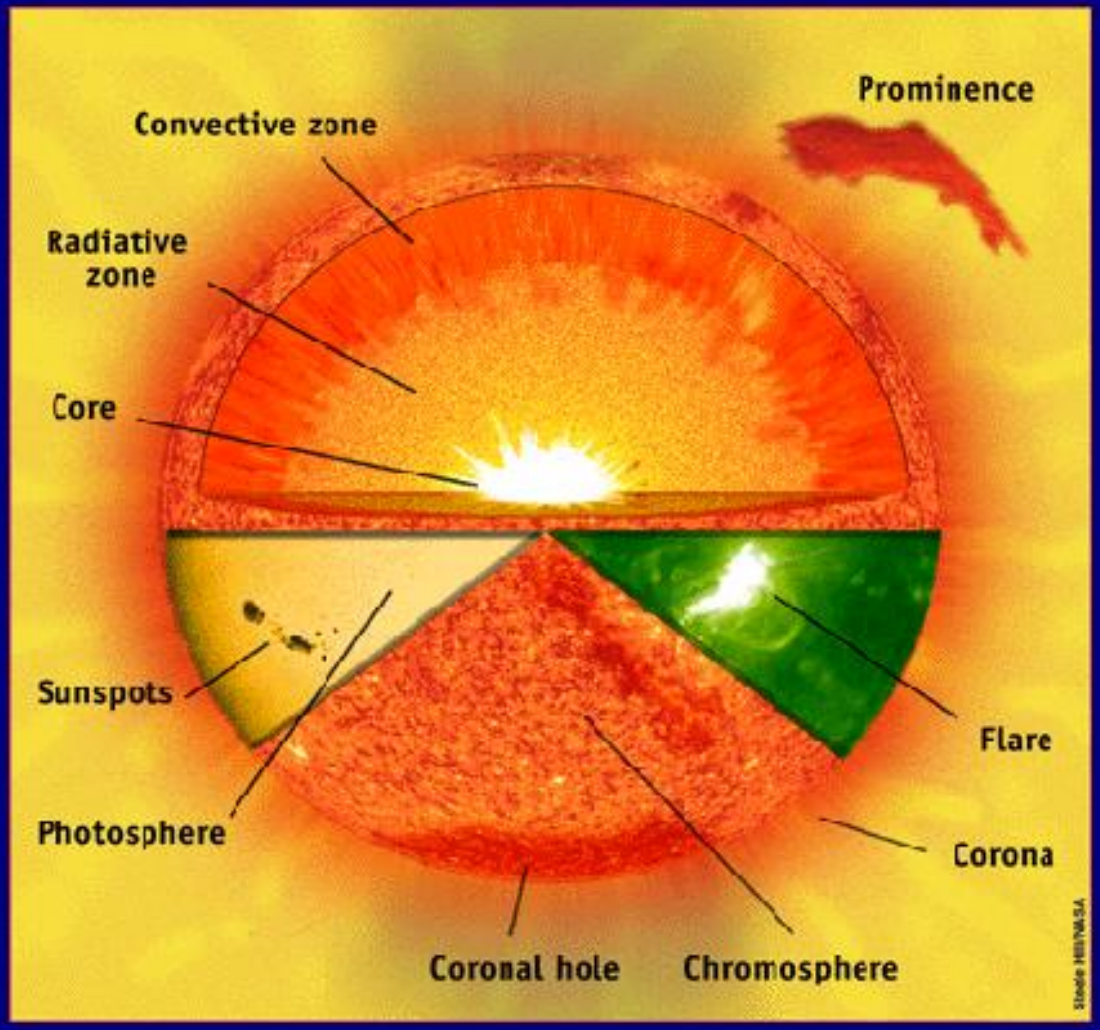

Center of Sun
Surface of Sun
Distance from Sun's center (solar radii)
Temperature (10^6 K)
16
12
8
4
0.2
0.4
0.6
0.8
1.0
Density (kg/m^3)
160,000
120,000
80,000
40,000
0.2
0.4
0.6
0.8
1.0
Distance from Sun's center (solar radii)
Center of Sun
Surface of Sun

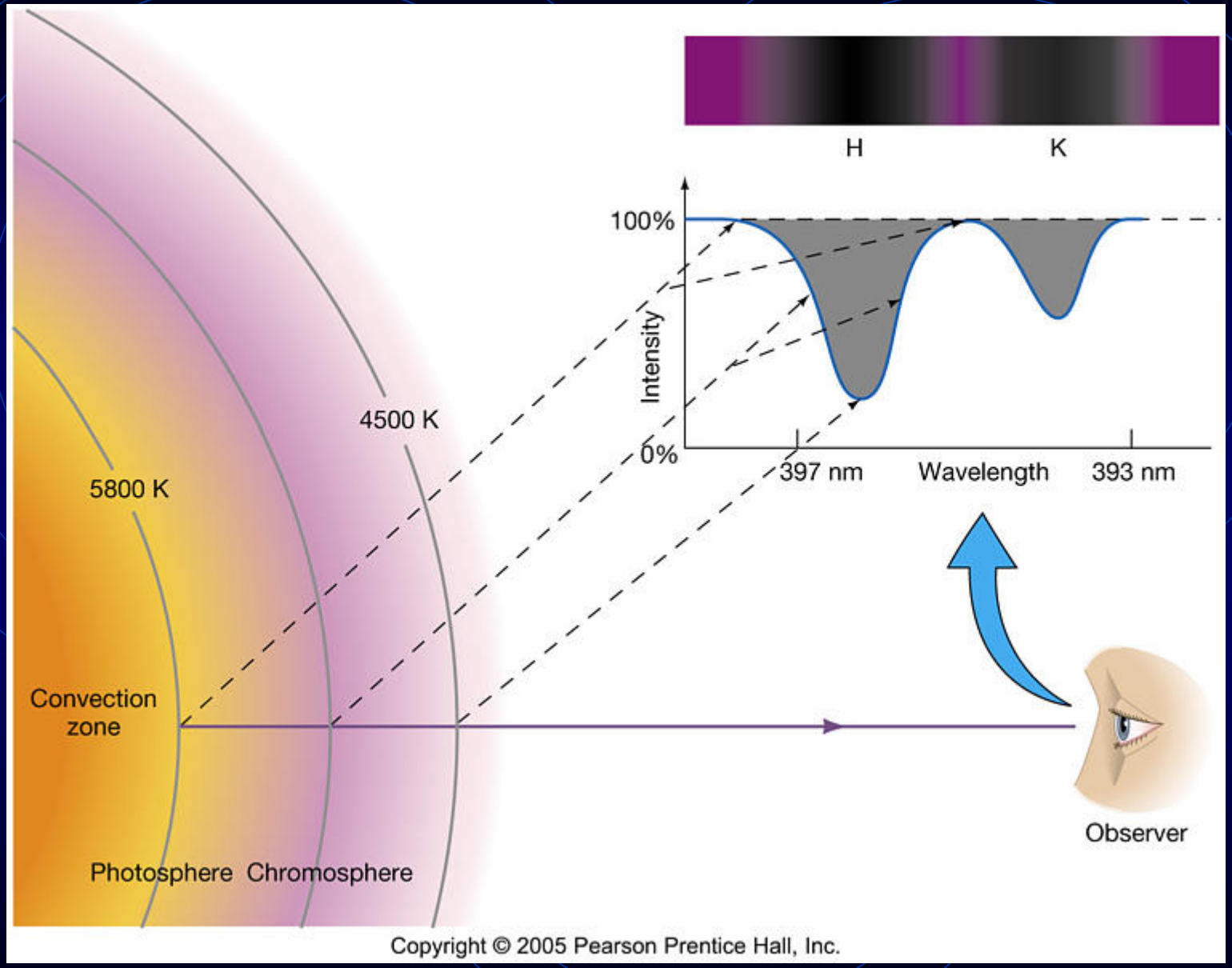


http://physics.uoregon.edu/~jimbrau/BrauImNew/Chap16/FG16_09.jpg


Distance from Sun's Center (RSun)
1.0
0.8
0.6
0.4
0.2
0
99% of Mass
Core
0
0.2
0.4
0.6
0.8
1.0
Distance from Sun's Center (RSun)
Radiative Diffusion
Convection

The Atmosphere and Interior of the Sun





http://physics.uoregon.edu/~jimbrau/BrauImNew/Chap16/FG16_12.jpg