太陽 (The Sun)

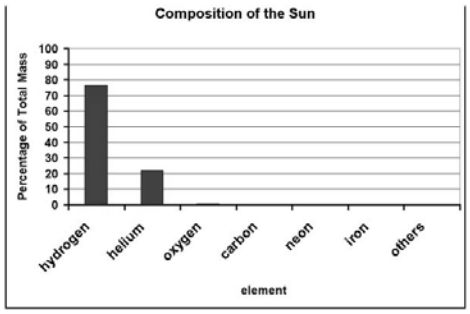
學習目標

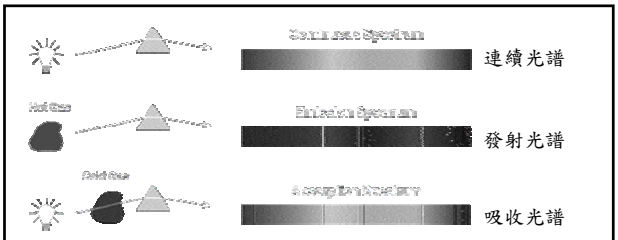
- ❖ 太陽的能量來源
- ❖ 太陽表面是什麼情形？內部結構呢？怎麼知道的？
- ❖ 太陽黑子是什麼東西？
- ❖ 太陽爲何會發光？
- ❖ 太陽的壽命有多長？

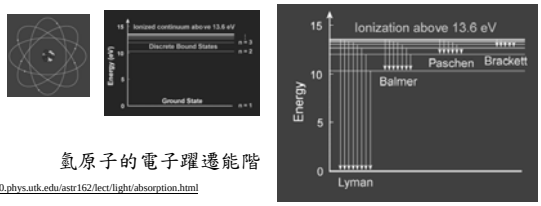
太陽的基本資料

- **表面溫度**：5800 K（觀測）
- **核心**：1.5×10^7 K （理論）
- **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**：1 $M_\odot$ ＝ 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 $L_\odot$ ＝ 4×10^{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？

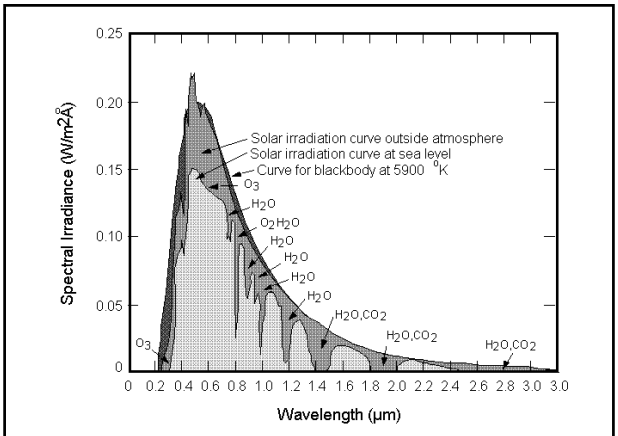


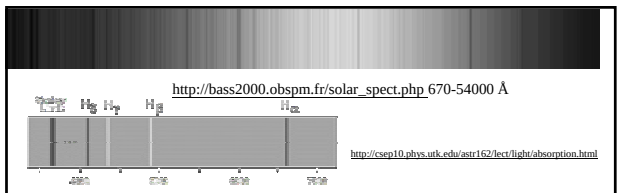




氫原子的電子躍遷能階

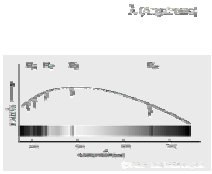
http://csep10.phys.utk.edu/astr162/lect/light/absorption.html

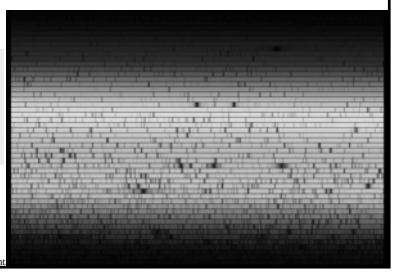




http://bass2000.obspm.fr/solar_spect.php 670-54000 Å

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





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

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

太陽的能量來源 I

- **Chemical burning?**
  Typically 10^{-19} J per atom.
  How long can the Sun shine by chemical burning?

$1\ L_\odot = 4\times10^{26}$ W → 4×10^{45} atoms per second

The Sun contains about 2×10^{30} kg/2 x 10-27 kg ~ 10^{57} atoms

➔ 3×10^{11} s ~ 10,000 years

太陽的能量來源 II

- 1800s 英國 Lord Kelvin and German Hermann von Helmholtz: contraction compresses interior gases → heat
  Kelvin-Helmholtz contraction

Gravitational energy ~ $GM^2/R \sim 4 \times 10^{41}$ J
$1\ L_\odot = 4\times10^{26}$ W

➔ 3×10^7 yr

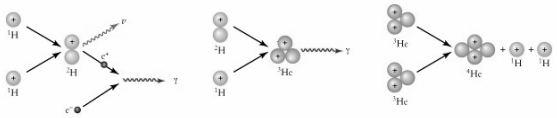
太陽的能量來源 III

簡單的原子核 結合 → 較複雜的原子核

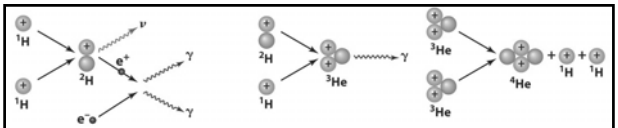
原子核強作用力把自己「抓得」比較緊

➔ **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 **Thermonuclear fusion**



(a) Step 1:
- Two protons (hydrogen nuclei, ^1H) 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 (^2H).
- The positron encounters an ordinary electron (e^-), annihilating both particles and converting them into gamma-ray photons (γ).

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

(c) Step 3:
- Two ^3He nuclei collide.
- A different helium isotope with two protons and two neutrons (^4He) 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 (^2H)
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 ^2H 與另一個（第三個）質子碰撞，形成氦三 (^3He)
放出另一個迦瑪射線光子

步驟三：
兩個氦三 (^3He) 碰撞，形成氦四 (^4He)
放出兩個質子

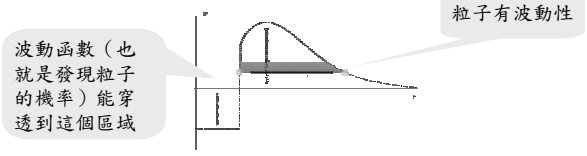
animation: pp chain

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



Energy Gained in a PP Chain

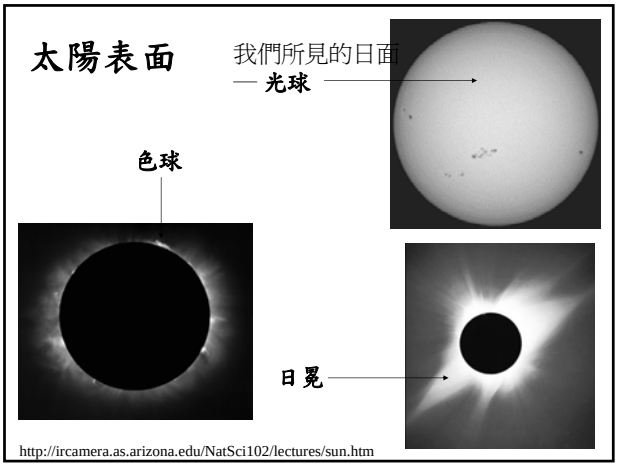
- 4H → 1 He + neutrinos + energy
- Mass of 4 H = 6.693×10^{-27} kg
  − Mass of 1 He = 6.645×10^{-27} kg
  Mass deficit → 0.048×10^{-27} kg
- $E = mc^2 = (0.048 \times 10^{-27}\ kg) \times (3 \times 10^8\ m/s)^2$
  $= 4.3 \times 10^{-12}$ J
- For 1 $L_\odot = 3.9 \times 10^{26}$ W, the sun needs to convert some **600 million tons**（六億公噸）of H into He in its core per second.

太陽表面

我們所見的日面
— **光球**

色球

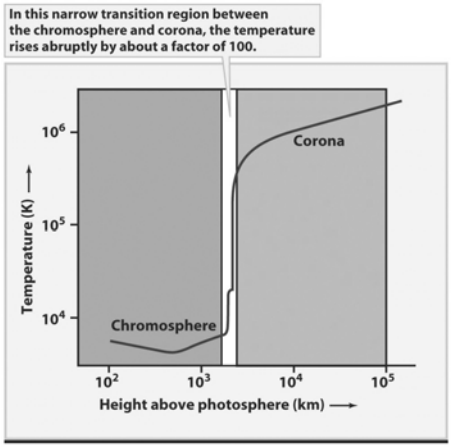
日冕



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

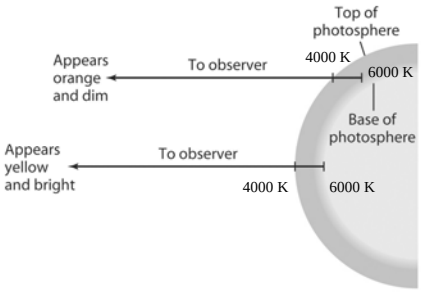


太陽外表特徵

- 緣暗現象 (limb darkening)
- 太陽黑子 (sunspots)
- 米粒組織 (granulation)
- 針狀結構 (spicules)

緣暗現象

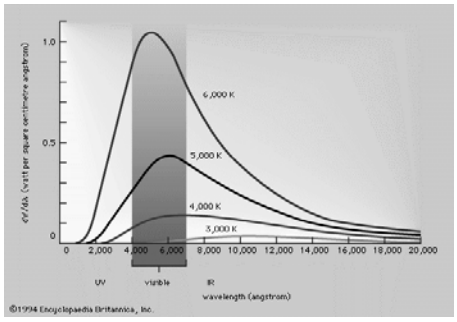
視線透過等量的氣體

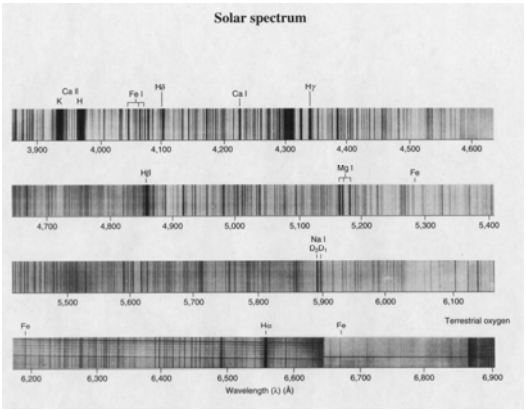


盤面邊緣透過較冷的高層大氣

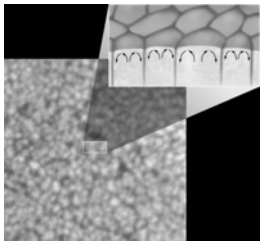
盤面中央透過較內部、較熱的氣體
→ 比較明亮

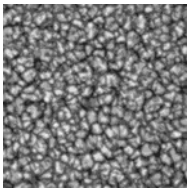
溫度低 → 輻射強度弱

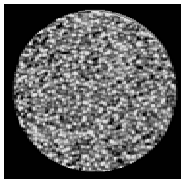


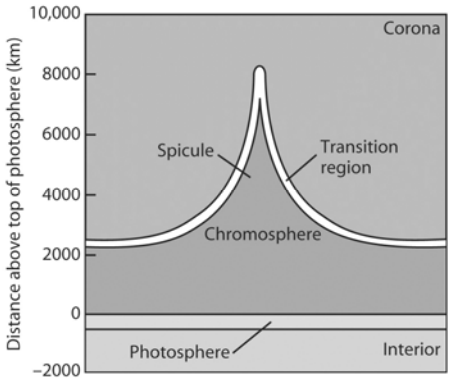


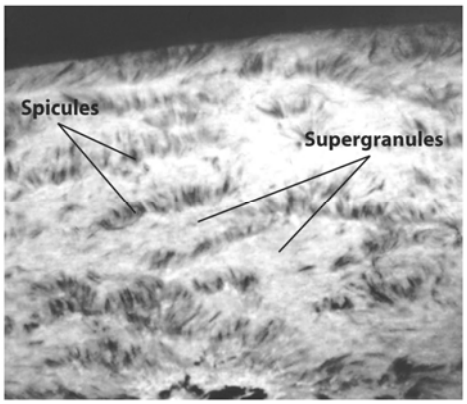
米粒組織 (granulation)
太陽氣體從內部到表面對流翻騰的證據

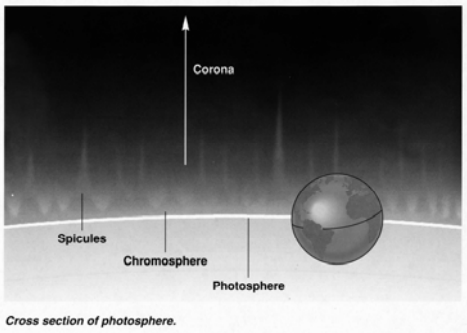












http://crab0.astr.nthu.edu.tw/~hchang/ga1/f1801-atmosphere1.JPG

Introduction to Astronomy

HW071224

due in one week

1. The *New Horizons* mission, launched in 2006, is expected to make a first-ever flyby of Pluto [illegible]. The spacecraft [illegible] most of spe[illegible] Pluto move quickly [illegible] calculate how long the journey of the *New Horizons* from Earth to Pluto would have taken by assuming an elliptical orbit around the Sun, with the perihelion at 1 AU (at the Earth) and the aphelion at 30 AU (at Pluto).

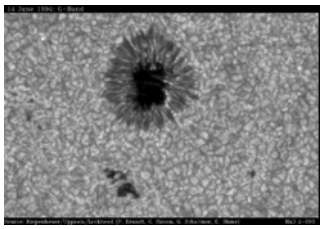
Merry Christmas

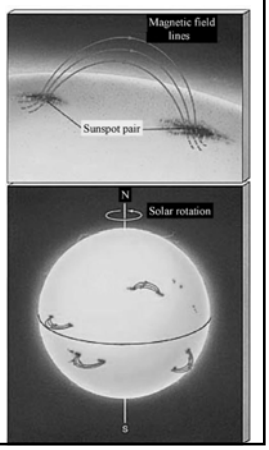
這次沒有過節精神了☹

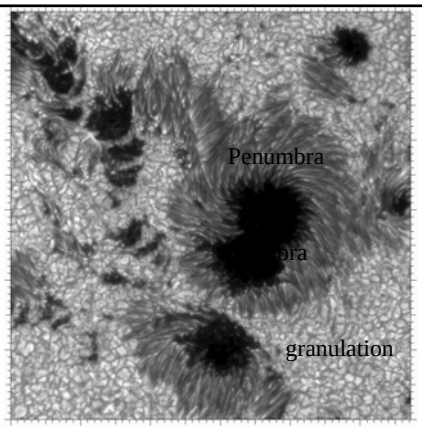
太陽黑子 (sunspots)

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

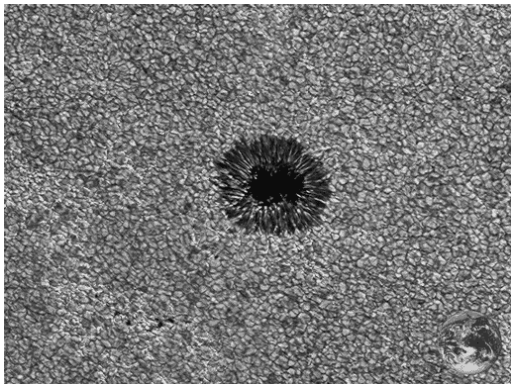




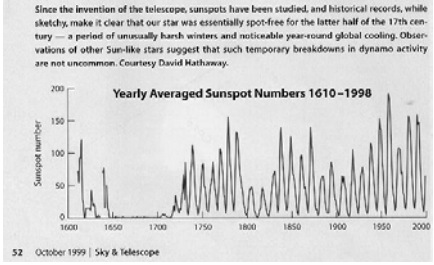


movie

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

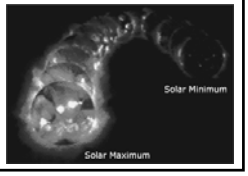


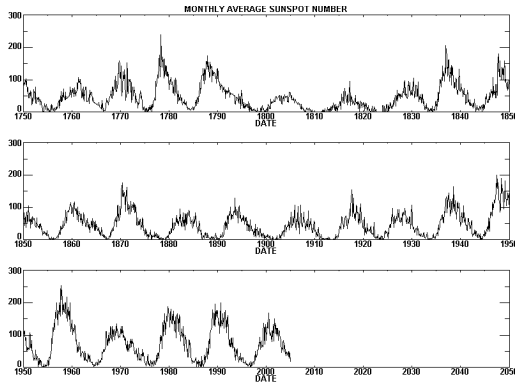
Sunspot Metamorphosis: From Bottom to Top APOD 2005/02/16



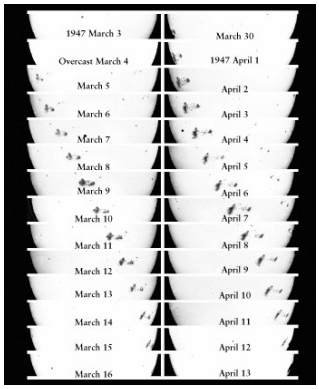
太陽黑子數目呈現11年週期變化

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

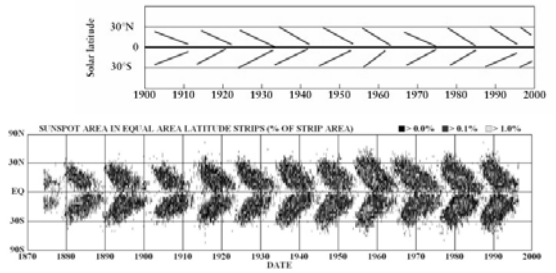
藉由同一個黑子群在太陽盤面的運動可以研究太陽轉動

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

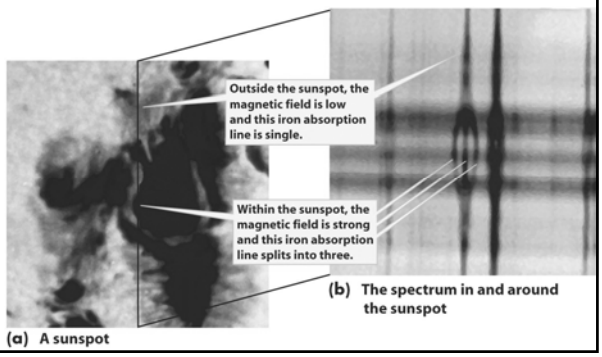
➔ 差動自轉

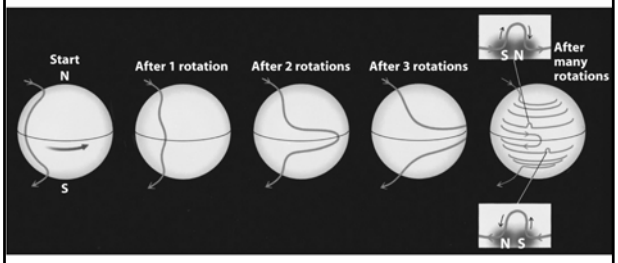


每個太陽週期之初，黑子多半在約緯度30度附近出現，隨後黑子出現的緯度越來越接近赤道（**蒙氏蝴蝶圖 Maunder butterfly diagram**）

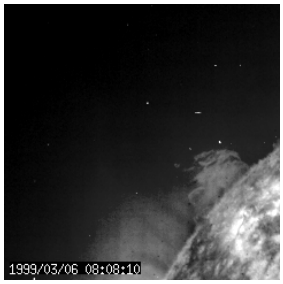
太陽極大時期發出的能量比極小時期多0.1%

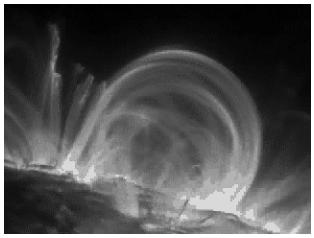
Zeeman Effect --- splitting of a spectral line by magnetic field

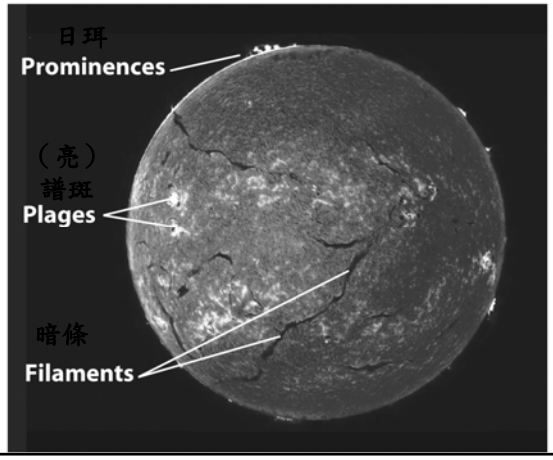


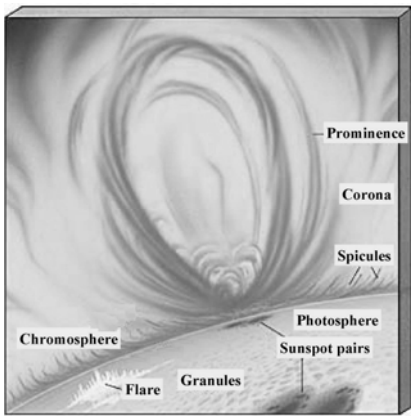


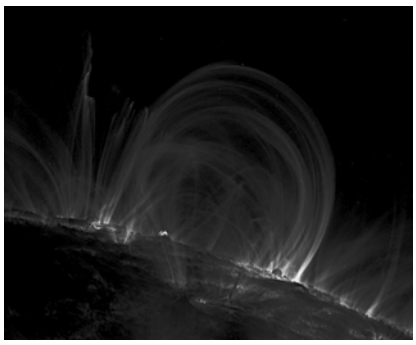
太陽表面常有劇烈活動，物質高速噴發，常看得出磁場結構



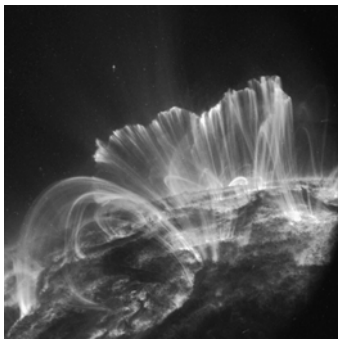




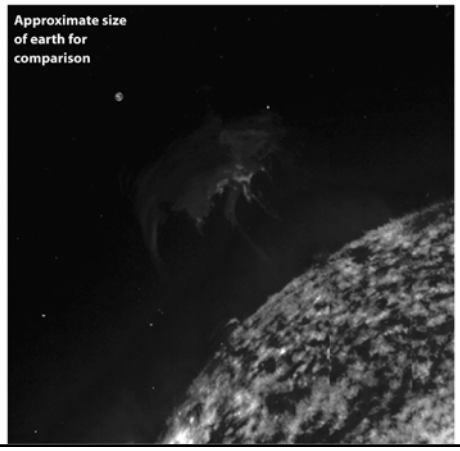




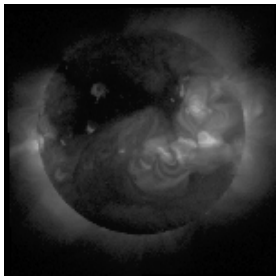
http://soi.stanford.edu/results/SolPhys200/Schrijver/images/TRACE171_991106_023044.gif

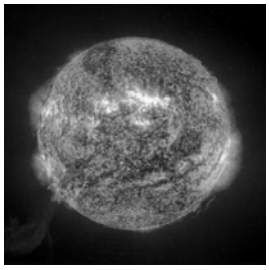


http://soi.stanford.edu/results/SolPhys200/Schrijver/images/arcade_9_nov_2000.gif

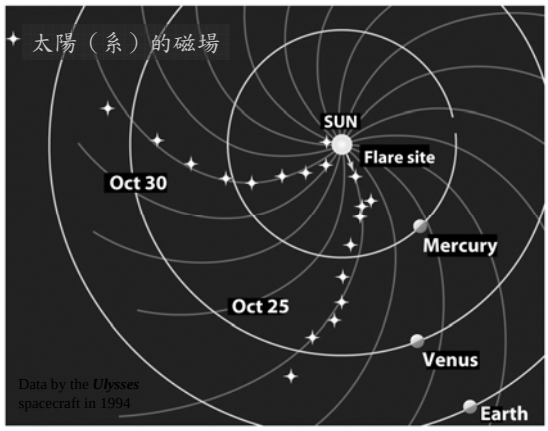


日冕中的氣體溫度非常高溫度非常高，約百萬度。corona 中的氣體以高速運動（時速百萬公里）→ 逃逸到太空 ➔ **solar wind（太陽風）**；每秒拋出百萬噸的物質（質子、電子）

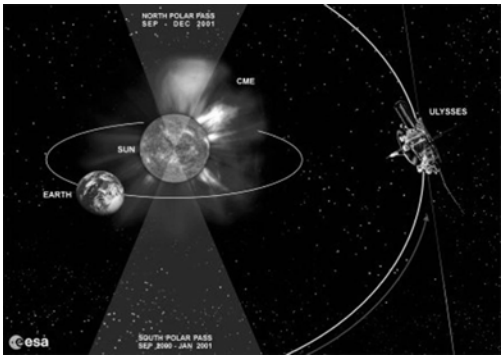


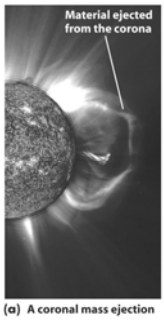


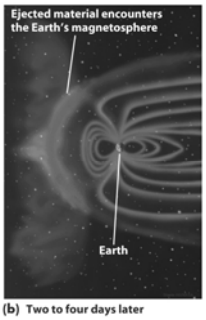
12/20



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





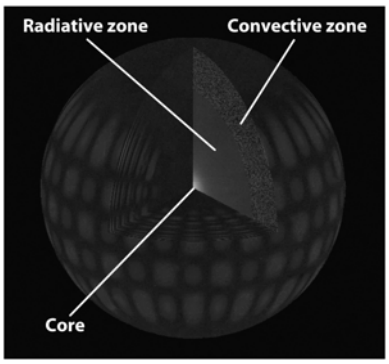


CME animation

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

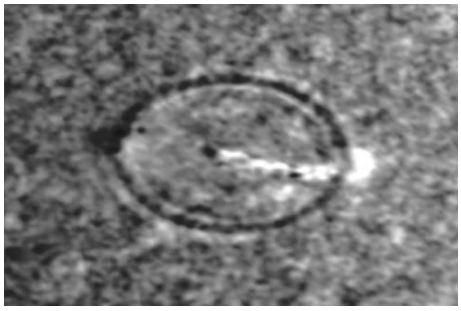


買西瓜時，敲一敲，聽一聽！

到底敲什麼，聽什麼？

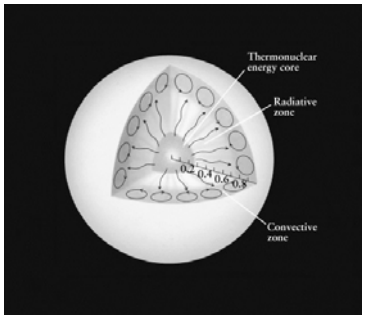
觀測震動情形藉以研究星球內部結構

和理論建構的模型比較



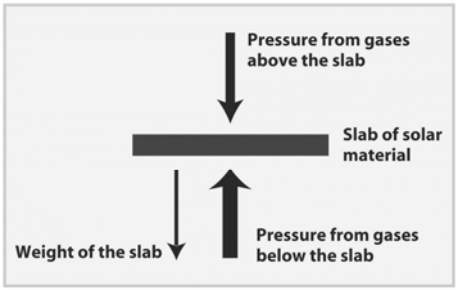
Solar Flares Cause Sun Quakes APOD 1998.06.01

太陽內部結構



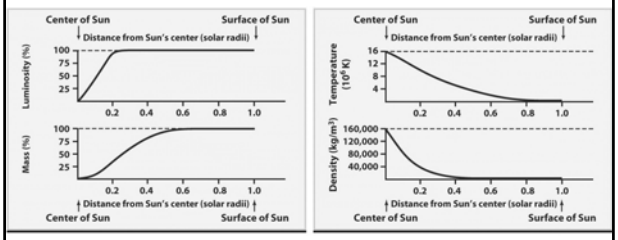
半徑1/4之內的核心進行核反應，釋放的能量藉輻射與對流方式傳到表面，然後輻射到太空

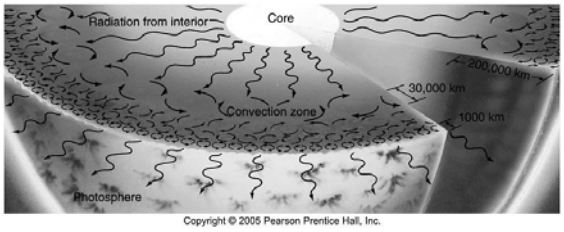
太陽各部分處於**靜力平衡 (hydrostatic equilibrium)**



Material inside the sun is in hydrostatic equilibrium, so forces balance

太陽的結構模型





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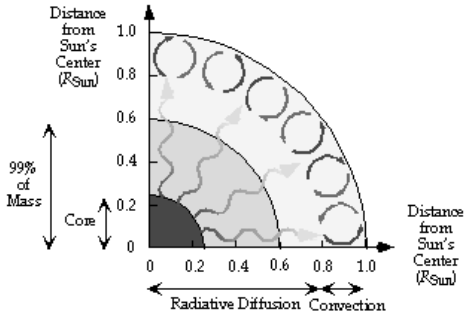

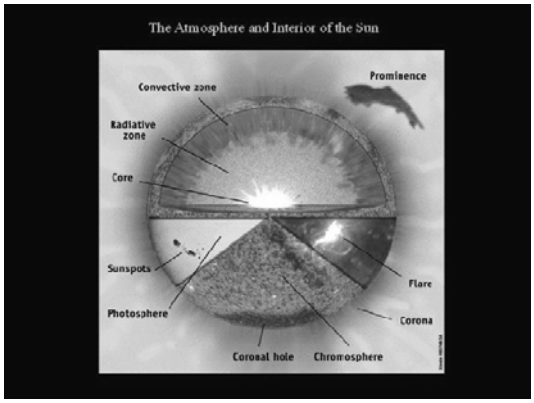

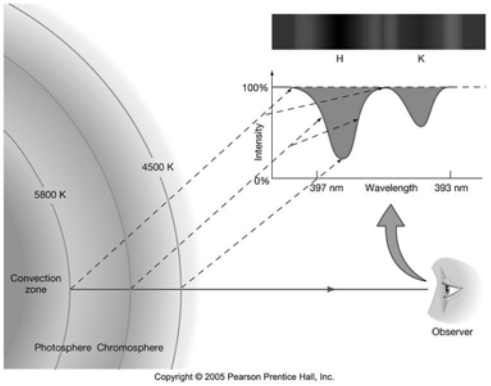

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