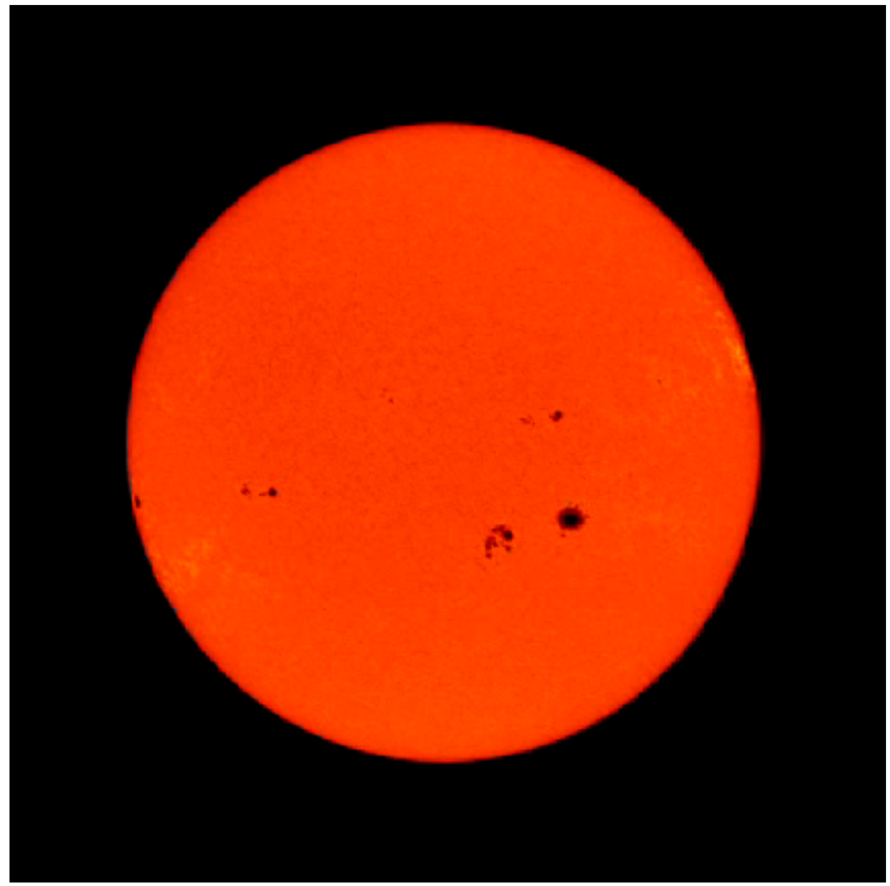
Lecture 16 - The solar surface and atmosphere

- Topics to be covered:
  - Photosphere
  - Chromosphere
  - Transition region
  - Corona

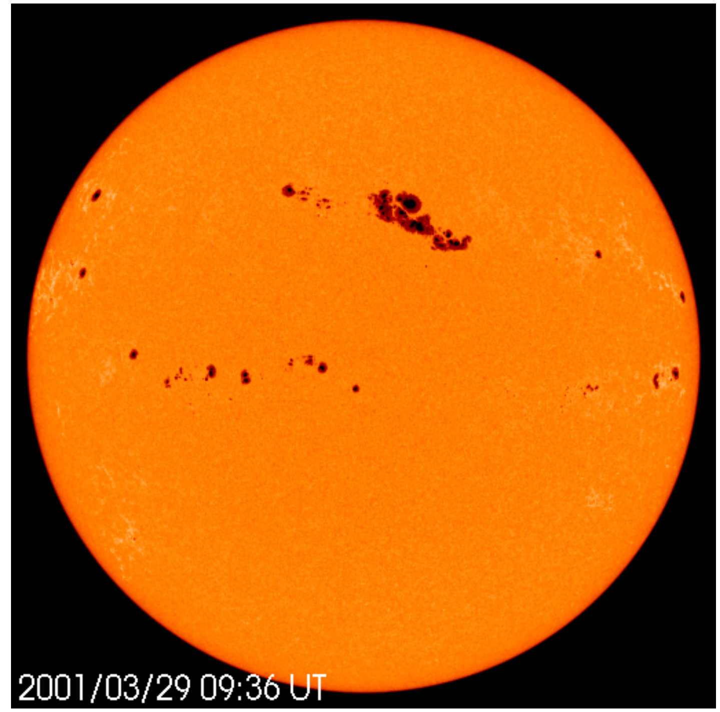


The solar atmosphere

- Photosphere
  - $T \sim 5{,}800\ K$
  - $d \sim 100$ km
- Chromosphere
  - $T \sim 10^5\ K$
  - d <2000 km.
- Transition Region
  - $T \sim 10^{5.5}\ K$
  - d ~2500 km
- Corona
  - $T > 10^6\ K$
  - $d > 10{,}000\ km$

The photosphere

- $T \sim 5{,}800\ K$
- $r \sim R_{Sun}$
- Photosphere is the visible surface of the Sun.
- At the photosphere, the density drops off abruptly, and gas becomes less opaque.
- Energy can again be transported via radiation. Photons can escape from Sun.
- Photosphere contains many features:
    - Sunspots
    - Granules

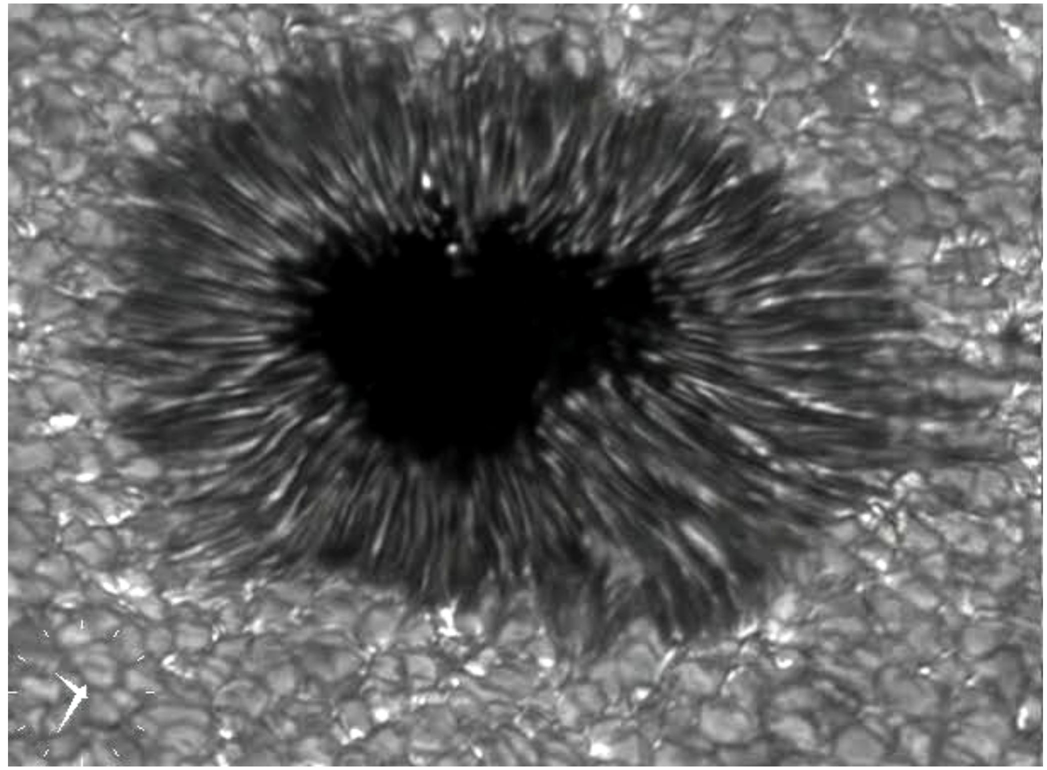


$$\beta = \frac{P_G}{P_B} = \frac{2nkT}{B^2/8\pi}$$

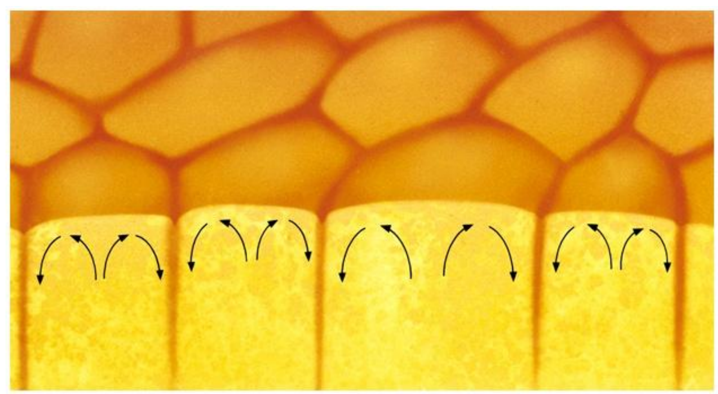
[?] $>>1$ in photosphere

The photosphere (cont.)

- Sunspots are dark areas in the photosphere.
  - Formed by the concentration of large magnetic fields (B>1000 G).
  - Sunspots appear dark because they are cooler (~4,300 K).

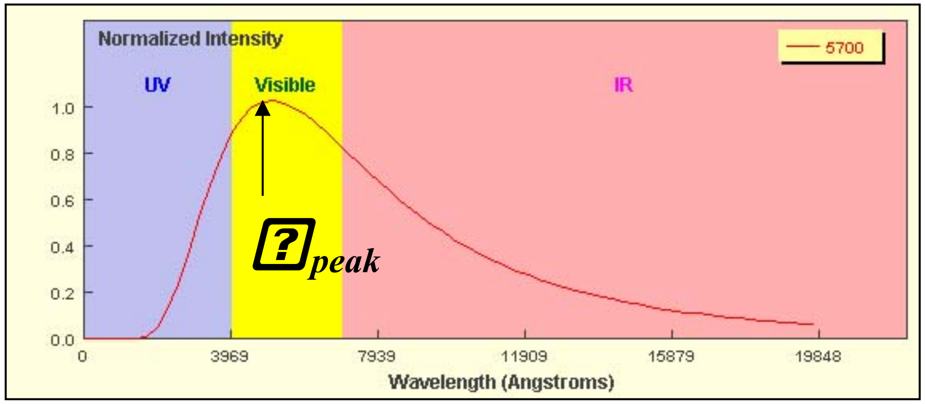


- Granulation is a small scale pattern of convective cells
  - Results from temperature gradients close to the solar surface.



Determining the photospheric temperature.

- The Sun emits a blackbody spectrum with $?_{peak} \sim 5100\ \AA$



- Using Wein's Law: $\boldsymbol{T = \dfrac{2.8978 \times 10^{-3}}{\lambda_{peak}}\ K}$

  and

$$\lambda_{peak} = 5100 \times 10^{-10}\, m$$

$$T_{sun} = \frac{2.8978 \times 10^{-3}}{5100 \times 10^{-10}}$$

$$\sim 5700\ K$$

The solar constant

- We know from Stephan-Boltzman Law that

$$L = A\boxed{?}T^4 \qquad\qquad W$$

- A is area of Sun's surface, T is temperature, and $\boxed{?}$ is Stephan-Boltzman constant (5.67 $\boxed{?}$ 10^{-8} $W\,m^{-2}\,K^{-4}$).

- The flux reaching the Earth is therefore:

$$F = L\,/\,4\pi d^2 = 4\pi R^2\boxed{?}T^4\,/\,4\pi d^2 \quad Wm^{-2} \quad [d = 1AU,\ R = \text{solar radius}]$$

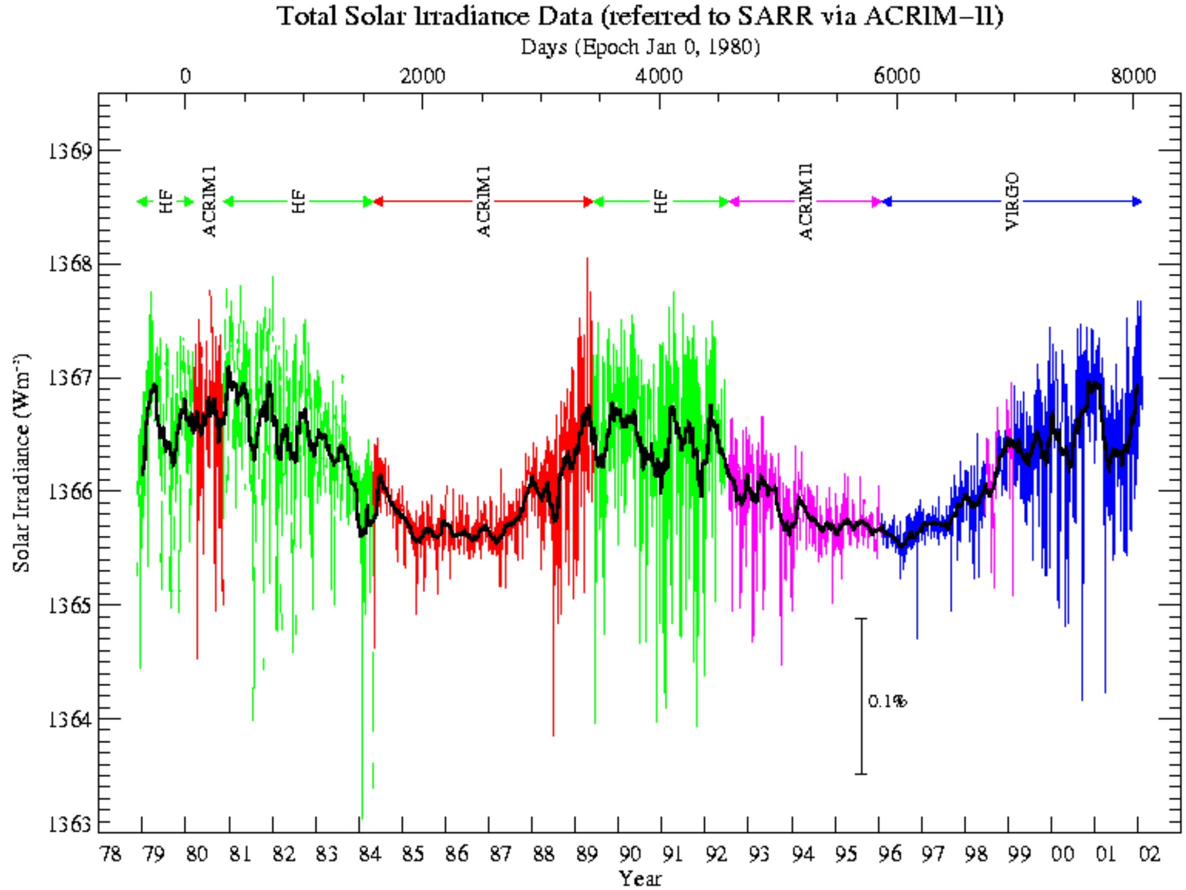
$$= \boxed{?}T^4\,(R/d)^2$$

$$= 1396\ W\,m^{-2}$$

- This is relatively close to the measured value of 1366 $W\,m^{-2}$.

The solar constant

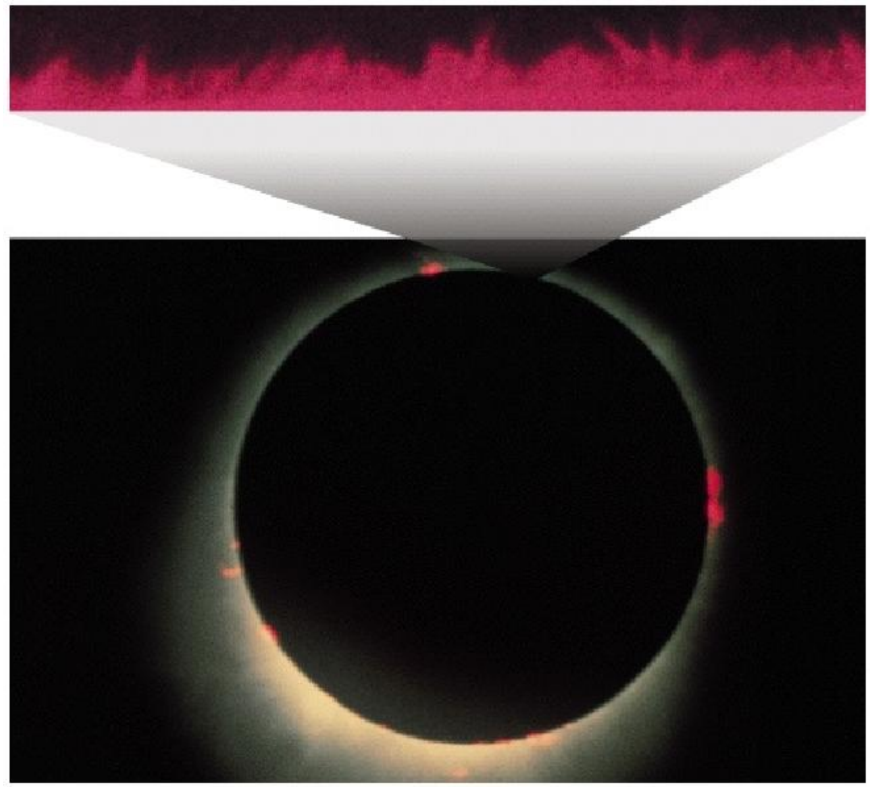
- The "solar constant" actually has a tiny variation (~0.1%) with the *solar cycle*.
- Represents the driver for Earth and planet climate modelling.



from: C. Fröhlich, *Space Science Reviews*, 94, pp. 15–24, 2000, with composite (vers d23_02), ACRIM-II/III (vers 10 100 1) and VIRGO v4_902 data (Feb 24, 2002)

The chromosphere

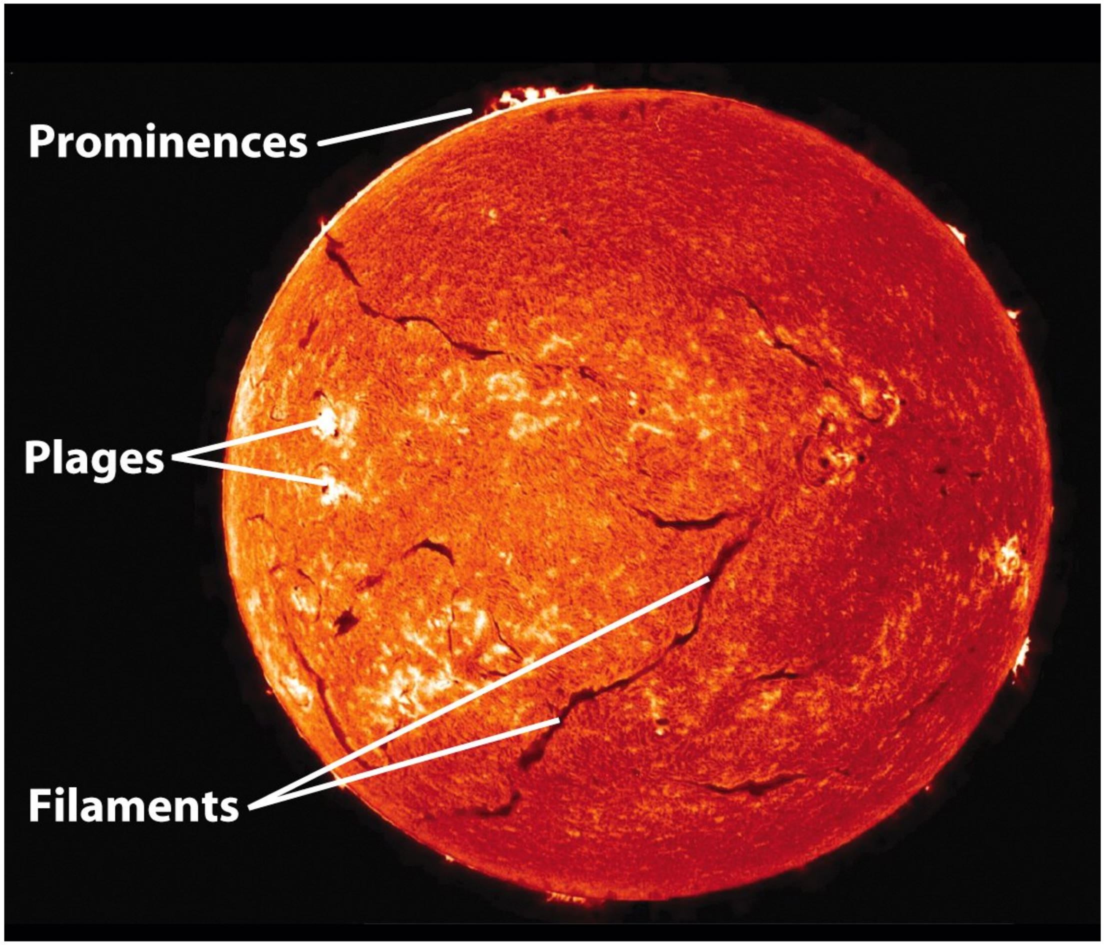
- Above the photosphere is a layer of less dense but higher temperature gases called the chromosphere.
- First observed at the edge of the Moon during solar eclipses.
- Characterised by "spicules", "plage", "filaments", etc.
- Spicules extend upward from the photosphere into the chromosphere.



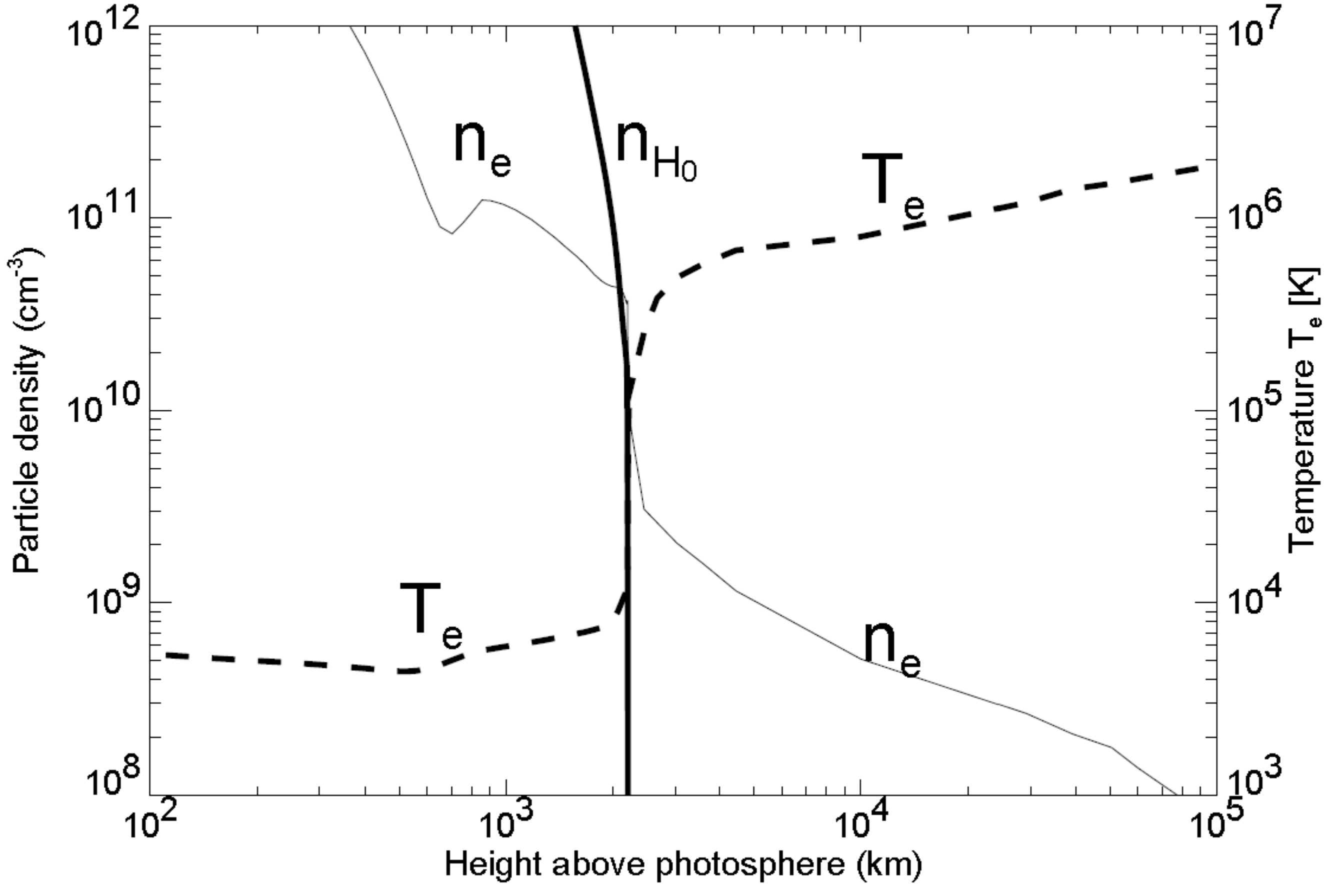
The chromosphere (cont.)

- *Prominence* and *filaments* are cool volumes of gas suspended above the chromosphere by magnetic fields.

- Plage is hot plasma (relative to the chromosphere), usually located near sunspots.



Model solar atmosphere

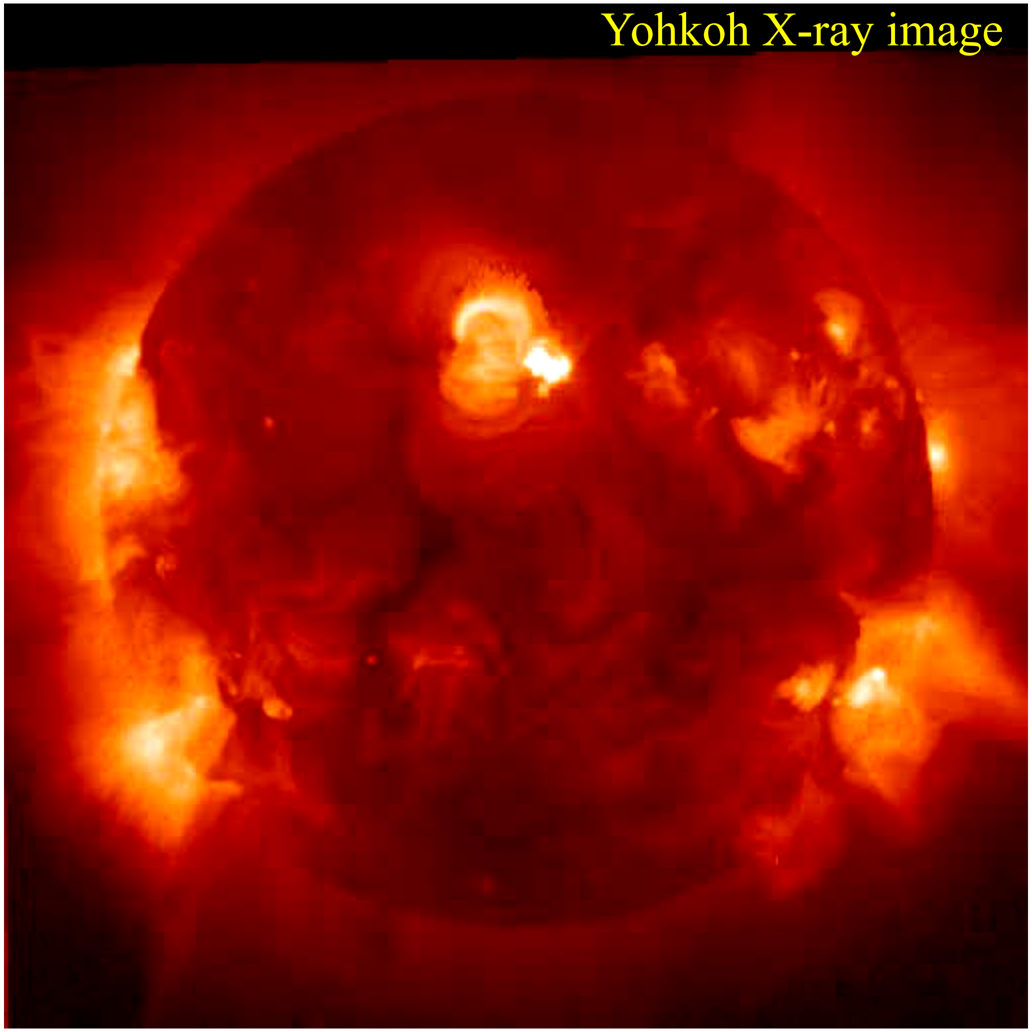


$$\beta = \frac{P_G}{P_B}$$

The corona

- Hot (*T >1MK)*, low density plasma (i.e. an ionized gas).
- There are currently two coronal heating theories:
  - Magnetic waves (AC).
  - Magnetic reconnection (DC).
- Coronal dynamics and properties are dominated by the solar magnetic field.

$$\beta = \frac{P_G}{P_B} = \frac{2nkT}{B^2/8\pi} << 1$$



Static model of the corona

- Assuming hydrostatic equilibrium: $\dfrac{dP}{dr} = -g\rho$ *Eqn. 3*

  where the plasma density is $\boxed{?}$ $= n\ (m_e + m_p) \approx nm_p$ (m_p= proton mass) and both electrons and protons contribute to pressure: $P = 2\ nkT = 2\boxed{?}kT/m_p$

- Substituting into *Eqn.3,* $\dfrac{2kT}{m_p}\dfrac{d\rho}{dr} = -g\rho$

  and integrating => $$\boxed{\rho = \rho_0 \exp\left(-\frac{mgr}{kT}\right)}$$

  where $\boxed{?}_0$ is the density at $r \sim R$. The scale height is $H = kT\,/\,mg$.

- OK in low coronae of Sun and solar-type stars (and planetary atmospheres).

Static model of the corona

- Chapman (1957) attempted to model a *static* corona with *thermal conduction*.

- Coronal heat flux is $q = \boxed{?}\,\boxed{?}T$

  where thermal conductivity is $\boxed{?} = \boxed{?}_0 T^{5/2}$,

- In absence of heat sources/sinks, $\boxed{?}\boxed{?}q = 0 \Rightarrow \boxed{?}\boxed{?}(\boxed{?}_0 T^{5/2}\boxed{?}T) = 0$

- In spherical polar coordinates,

$$\frac{1}{r^2}\frac{d}{dr}\left(r^2 \kappa_0 T^{5/2}\frac{dT}{dr}\right) = 0 \qquad \textit{Eqn. 1}$$

Static model of the corona

- *Eqn. 1 =>* $$r^2\kappa_0 T^{5/2}\frac{dT}{dr} = C$$
- Separating variables and integrating: $$\int T^{5/2}dT = \frac{C}{\kappa_0}\int\frac{dr}{r^2}$$ $$\Rightarrow \frac{2}{7}T^{7/2} = -\frac{C}{\kappa_0}\frac{1}{r}$$
- To ensure $T = T_0$ at r = r_0 and $T \sim 0$ as r $\boxed{?}$ ∞ set $$r_0 T_0^{7/2} = -\frac{C}{\kappa_0}\frac{7}{2}$$

$$\boxed{\therefore T = T_0\left(\frac{r_0}{r}\right)^{2/7}} \qquad \textit{Eqn. 2}$$

- For $T = 2 \times 10^6\,K$ at base of corona, $r_o = 1.05\,R \Rightarrow T \sim 4 \times 10^5\,K$ at Earth (1AU = 214R). Close to measured value.

Static model of the corona

- Subing for T from *Eqn. 2,* and inserting for P into *Eqn. 3* (i.e., including conduction),

$$\frac{d}{dr}\left(2\frac{\rho}{m_p}kT_0\left(\frac{r_0}{r}\right)^{2/7}\right) = -\frac{GM\rho}{r^2}$$

- Using multiplication rule, $$\frac{1}{r^{2/7}}\frac{d\rho}{dr} - 2/7\frac{\rho}{r^{9/7}} = -\frac{GMm_p}{2kT_0r_0^{2/7}}\frac{\rho}{r^2}$$

$$\int_{\rho_0}^{\rho}\frac{d\rho}{\rho} = 2/7\int_{r_0}^{r}\frac{dr}{r} - \frac{GMm_p}{2kT_0r_0^{2/7}}\int_{r_0}^{r}\frac{dr}{r^{12/7}}$$

$$\ln(\rho/\rho_0) = 2/7\ln(r/r_0) + \frac{7}{5}\frac{GMm_p}{2kT_0r_0}\frac{r_0^{5/7}}{r^{5/7}}$$

$$\rho(r) = \rho_0\left(\frac{r}{r_0}\right)^{2/7}\exp\left(\frac{7}{5}\frac{GMm_p}{2kT_0r_0}\left[\left(\frac{r_0}{r}\right)^{5/7} - 1\right]\right) \qquad \textit{Eqn. 4}$$

Static model of the corona

- Both electrons and protons contribute to pressure: $P = 2\ nkT = 2\ ?\ kT/m_p$
- Substituting into *Eqn. 4* =>

$$P(r) = P_0 \exp\left(\frac{7}{5}\frac{GMm_p}{2kT_0 r_0}\left[\left(\frac{r_0}{r}\right)^{5/7} - 1\right]\right) \qquad Eqn.\ 5$$

- As r ? ∞, *Eqn.4* => ? ? ∞ and *Eqn. 5* => P ? $const >> P_{ISM}$.
- $P_{ISM} \sim 10^{-15}\ P_0$. *Eqn. 5* => $P \sim 10^{-4}\ P_0$

=> There must be something wrong with the static model.