The Sun’s Temperature Structure

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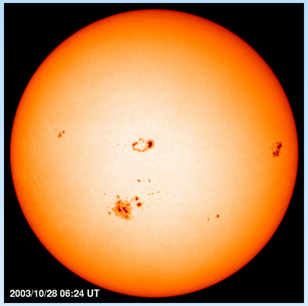
The Solar Atmosphere

The Outer layers (Atmospheres) of the Sun:

- Photosphere



- Chromosphere

- Corona

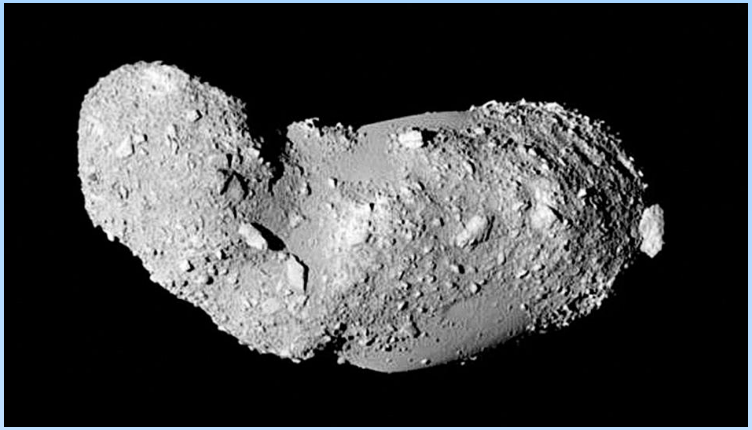
Formation of the Sun

Initially, have a blob of gas...

...and gravity:

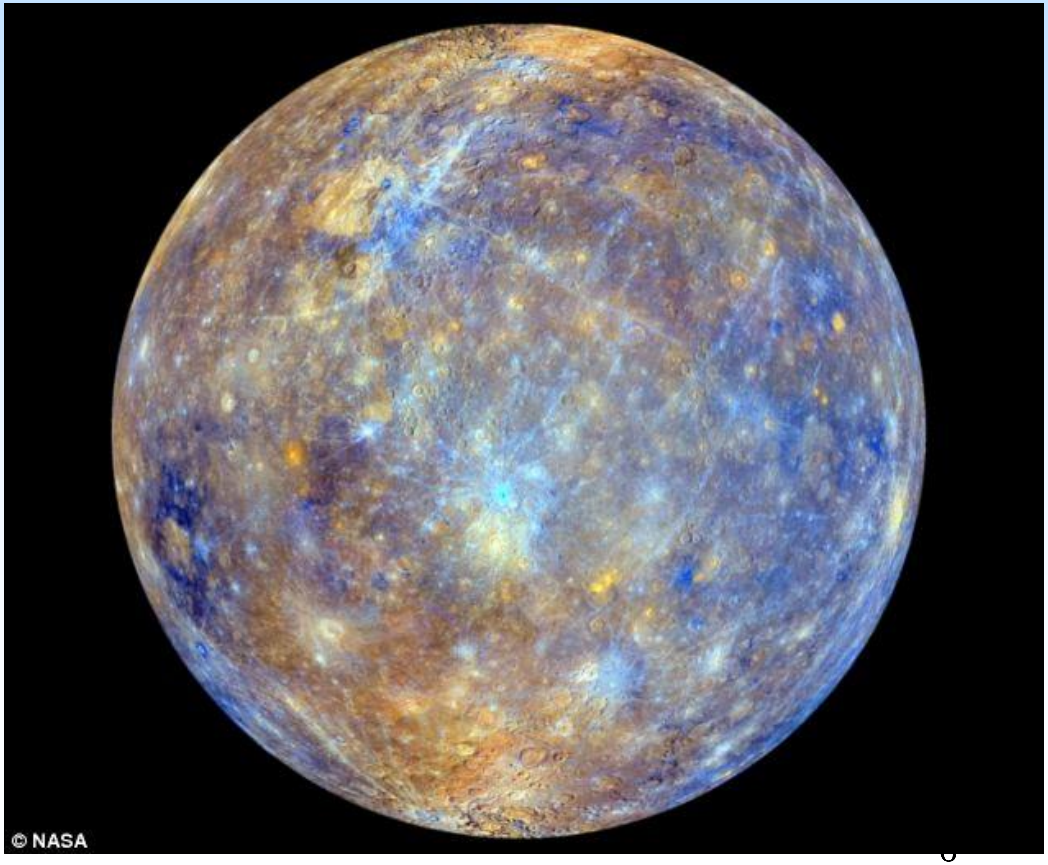
$$F = \frac{GMm}{r^2}$$

$$\mathbf{F} = \frac{GMm}{r^2}\hat{\mathbf{r}}$$



Length ~ 0.5 km

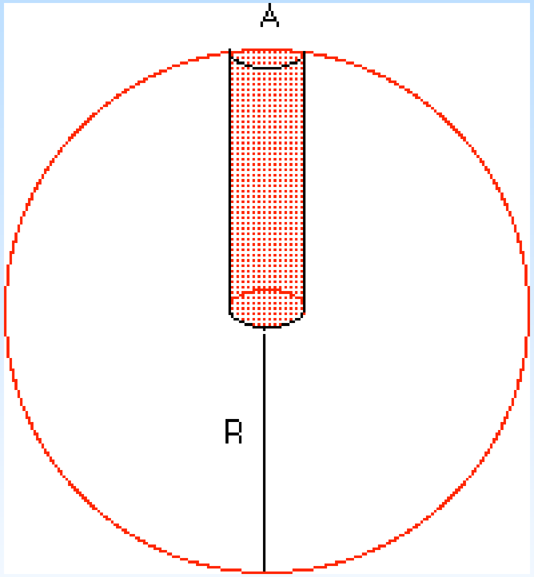
(Itokawa, from Hayabusa)



Diameter ~5000 km (Mercury, from Messenger)

Interior Temperature Structure

Sun's Central Core Temperature (Estimate)



cf. http://www.jgiesen.de/astro/temperature.htm

Sun’s Central Core Temperature (Estimate)

- $m = \rho A R$
- $F = G(m/2)M/R^2$
- $p = F/A = G\rho M/2R$
- $p/\rho = GM/2R$

- $pV = NkT$
- $p/\rho = kT/m_H$

- $GM/2R = kT/m_H$
- $T = Gm_H M/(2kR)$

- $T = 1 \cdot 10^7$ K

m,A,ρ=column mass, area, ave density

R,M=solar radius, mass

F=column force

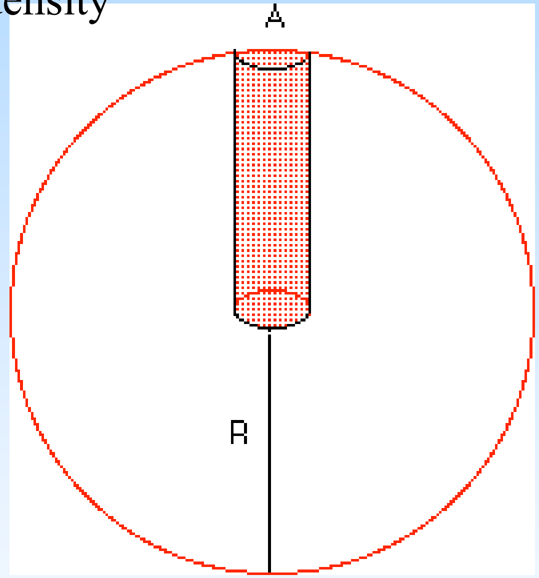
G=gravitational constant

P,T=solar center pressure, temperature

N=number of column particles

k=Boltzmann’s constant

m_H=hydrogen mass



cf. http://www.jgiesen.de/astro/temperature.htm

Might this *gravitational contraction* mechanism power the Sun (stars)??

=> Solar lifetime of ~3×10^7 years

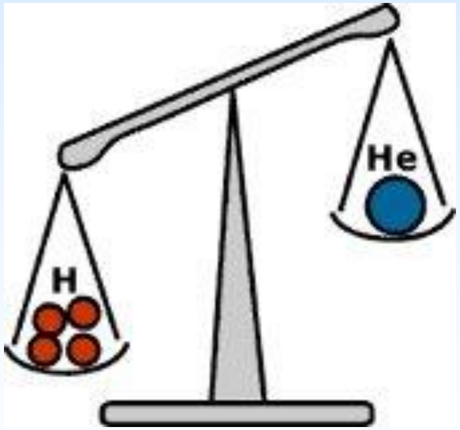
Problem!!

Need at least 3×10^8 years
(mid-1800s)

So this is ***not*** the main story for core and interior conditions

- Core conditions (temperature, density,...) sufficient to generate ***fusion***.
- Processes are complicated, but one of the consequences is:

$$4 \times {}^{1}\text{H} \rightarrow {}^{4}\text{He}$$



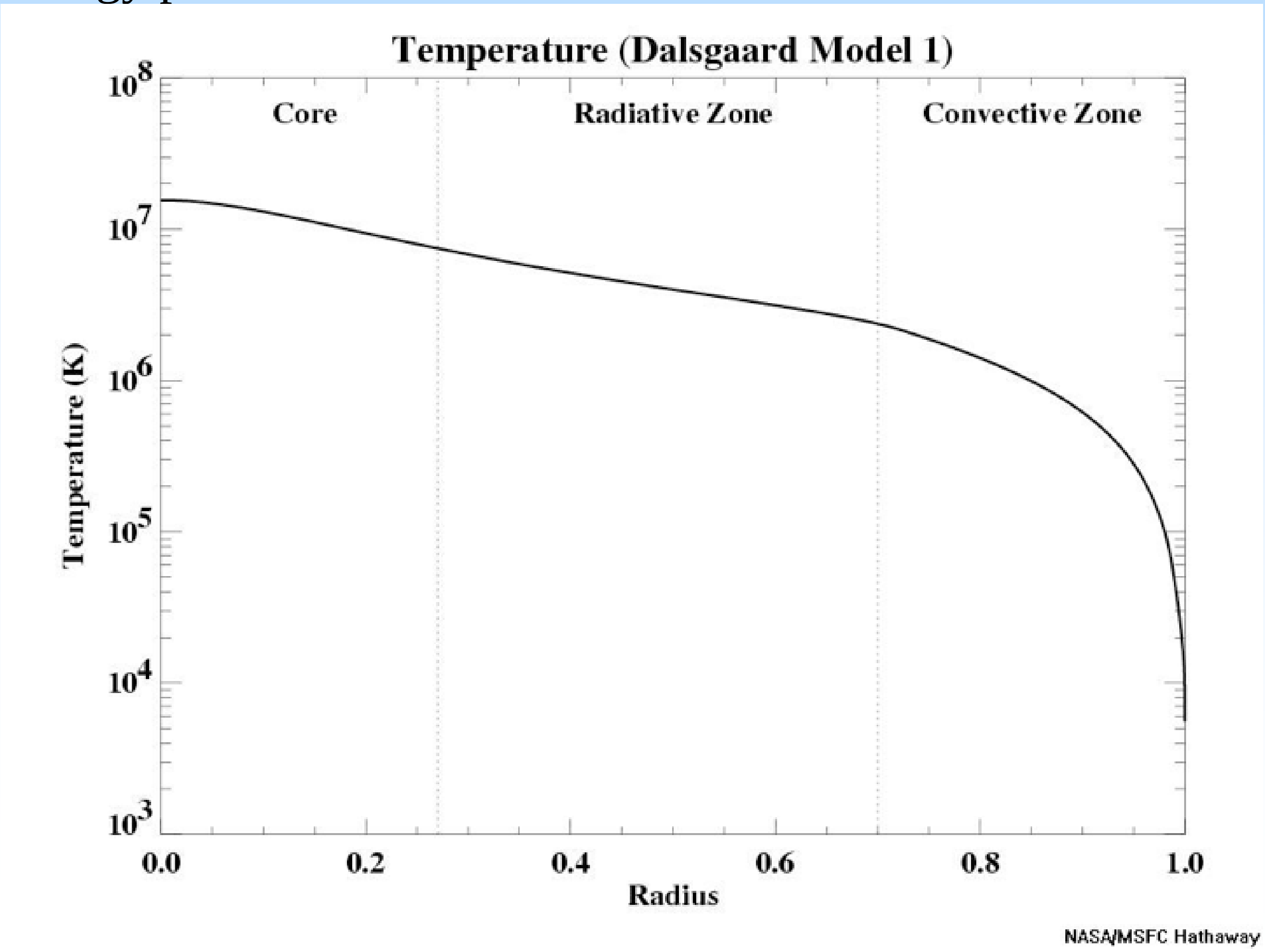
Mass "mismatch" of 0.0285 amu ~ 5 x10^{-26} g...

...which appears as ***energy*** via $E=mc^2$.

http://www.astro.caltech.edu/~george/ay20/Ay20-Lec7x.pdf

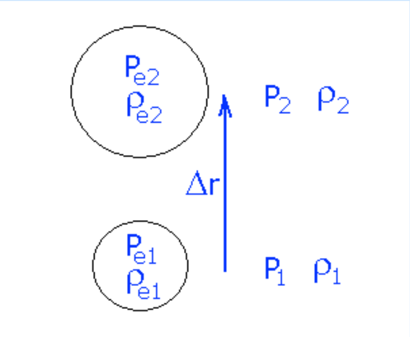
Get the full structure by solving equations for:

- Mass conservation
- Hydrostatic equilibrium
- Energy transport via radiation
- Energy production



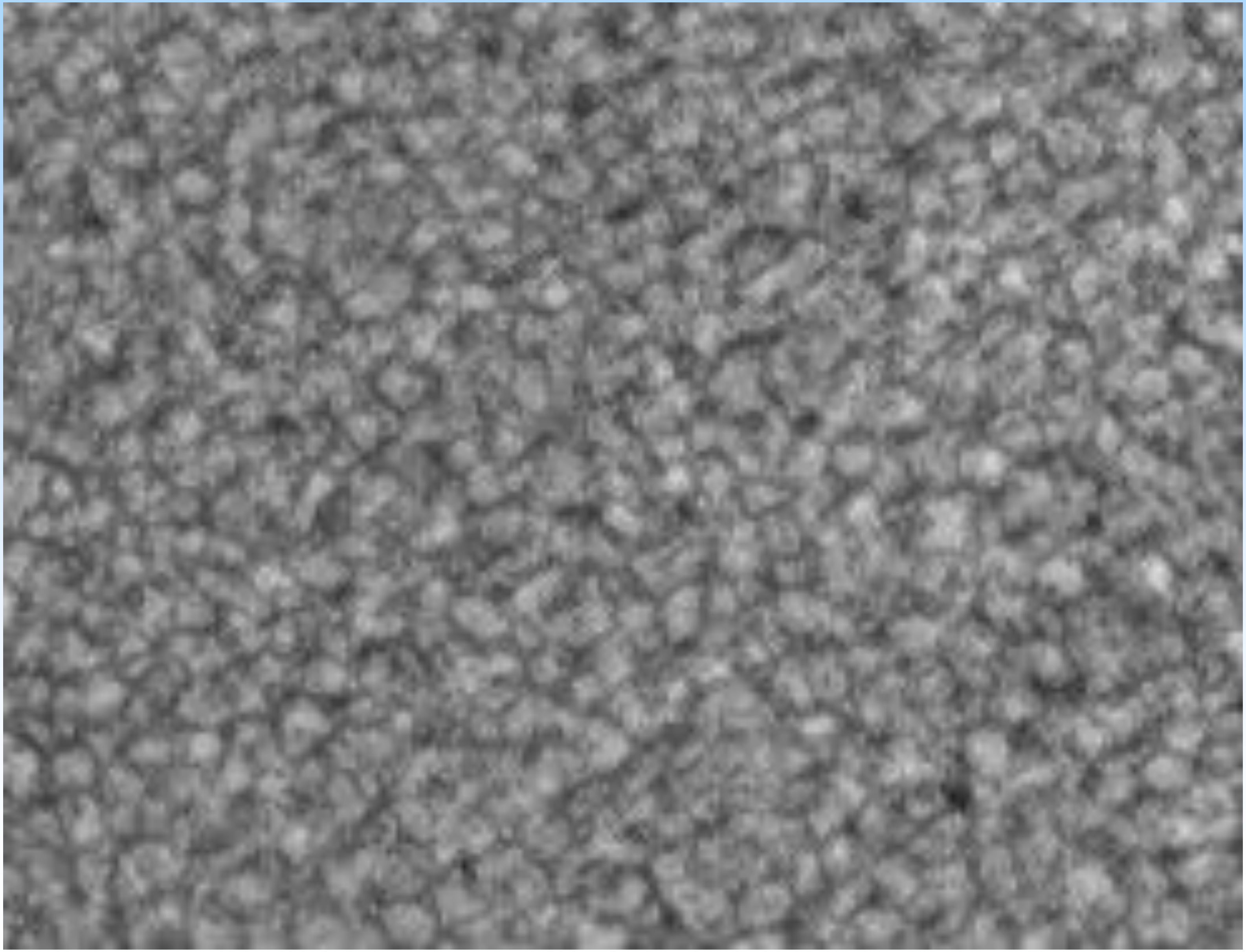
- Convective instability sets in when:

$$\left|\frac{dT}{dr}\right|_{outside} > \left|\frac{dT}{dr}\right|_{adiabatic}$$

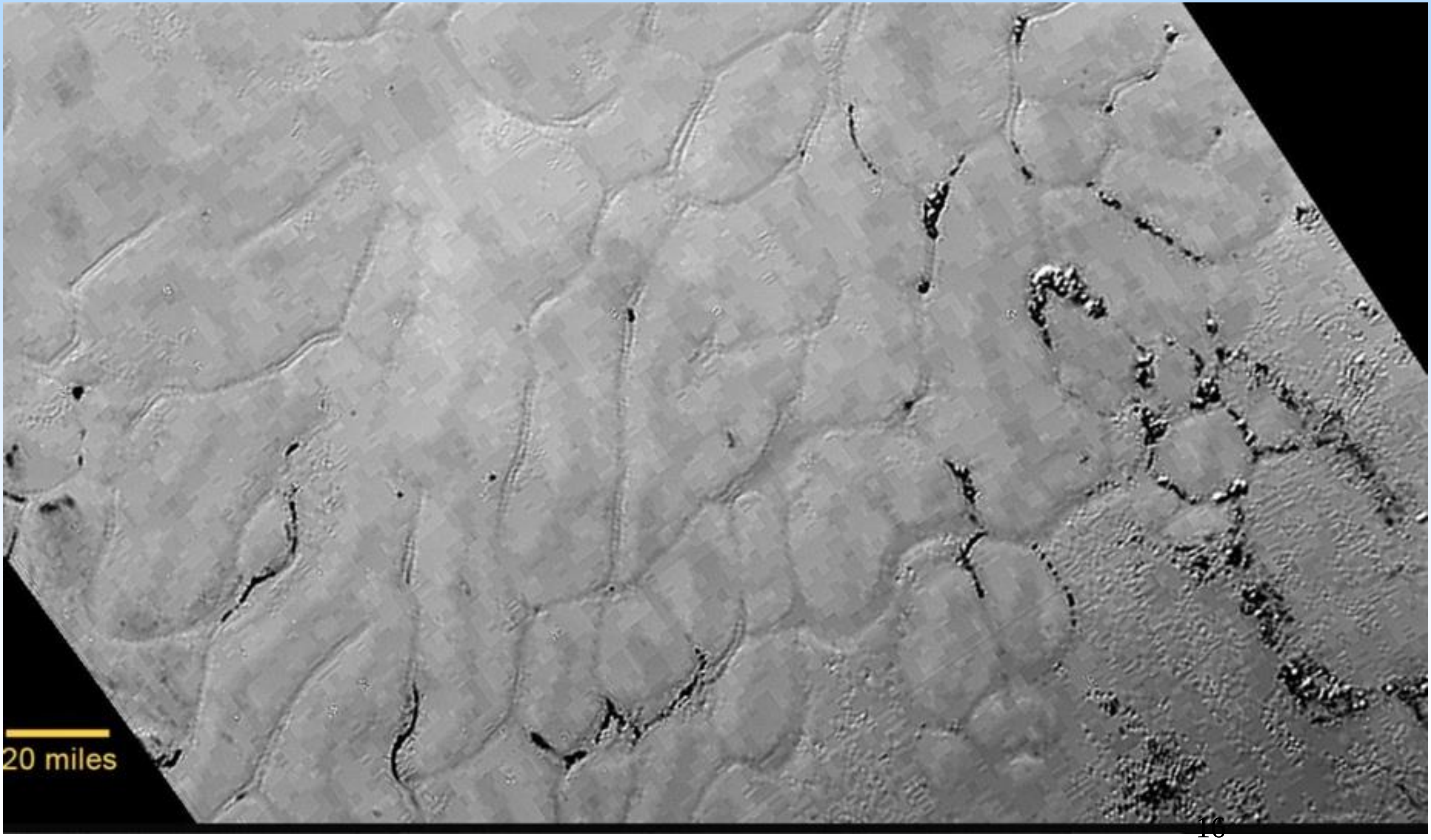


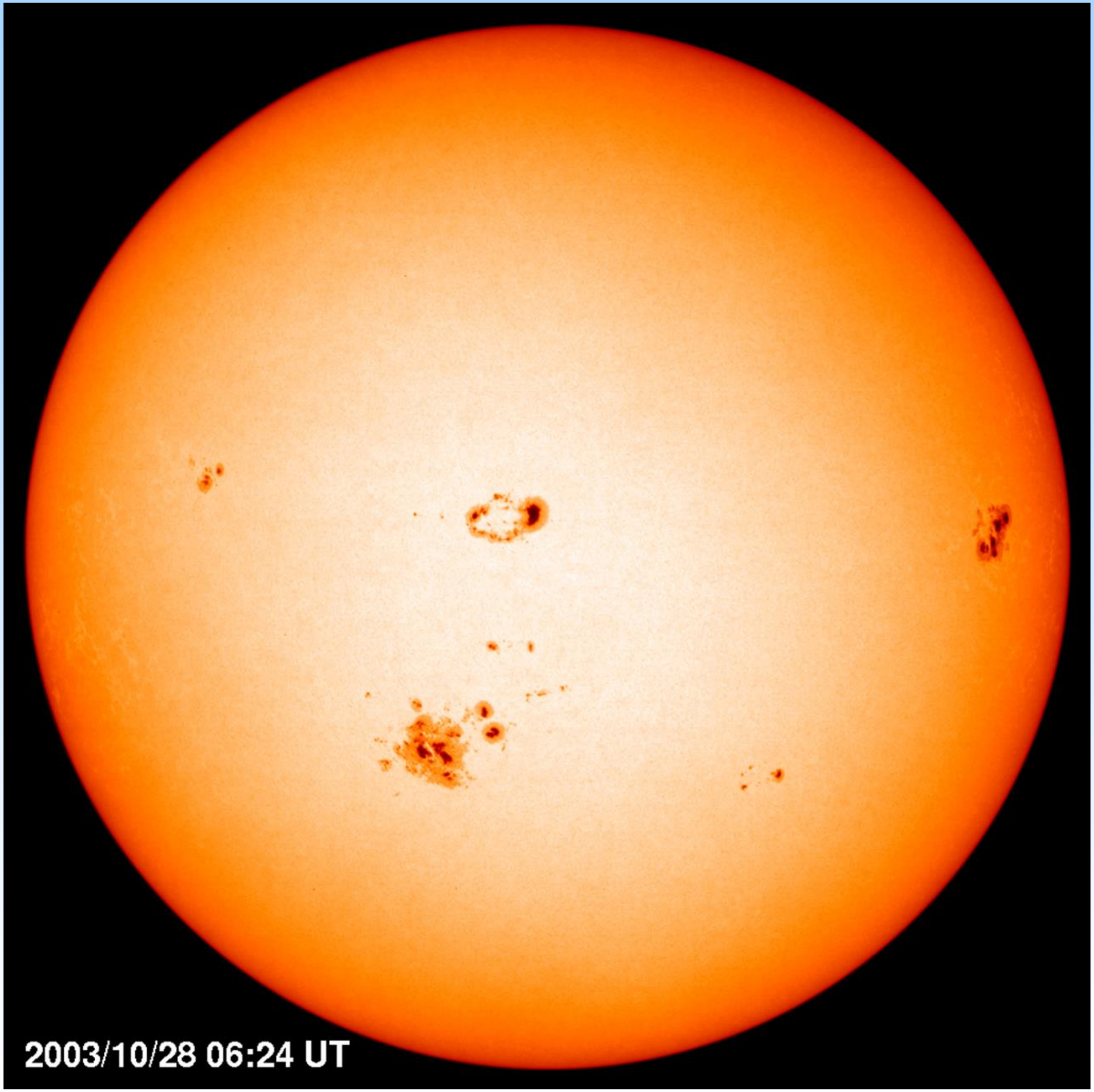
Hinode SOT Granulation Movie

BBSO Granulation (near IR; 60 min)



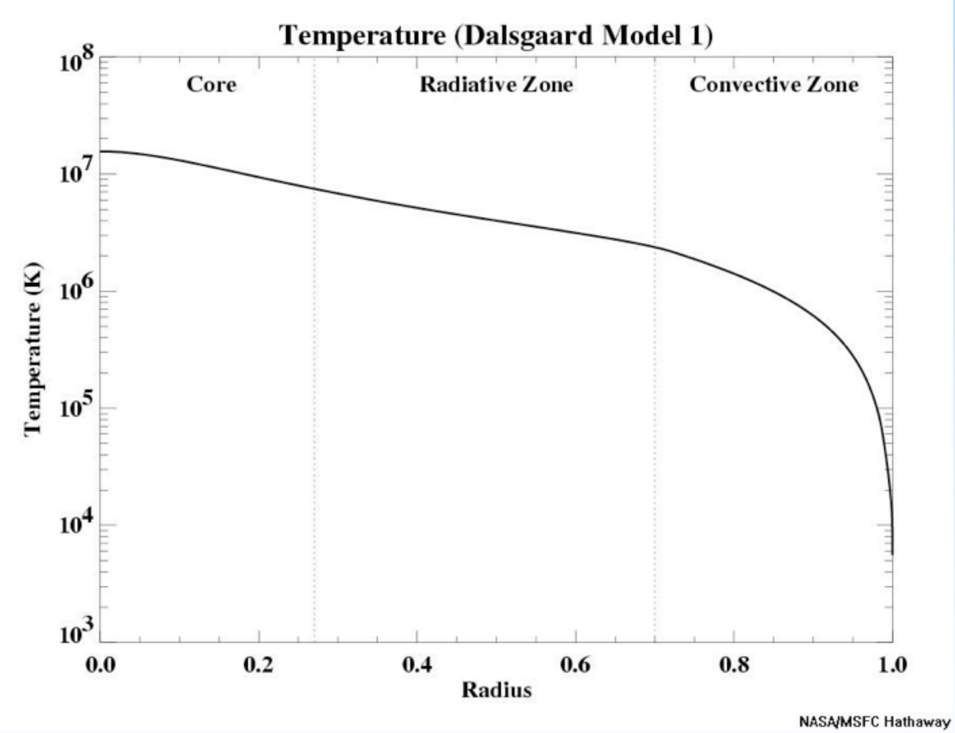
Convection on ***Pluto*** too??

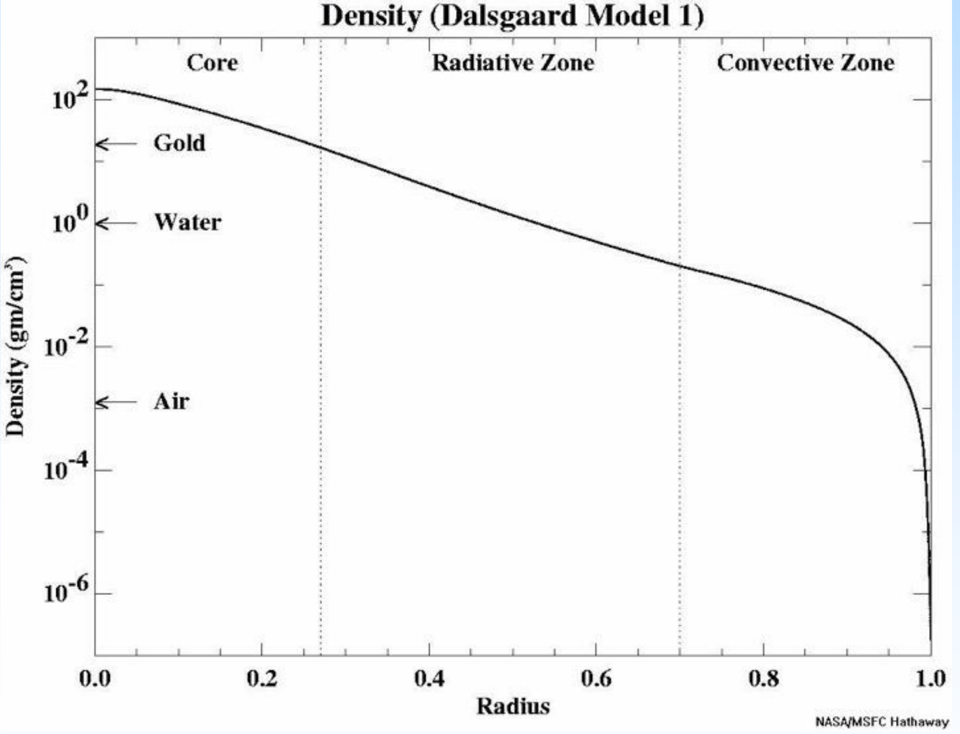




The Photosphere

The Solar Interior’s Temperature Distribution

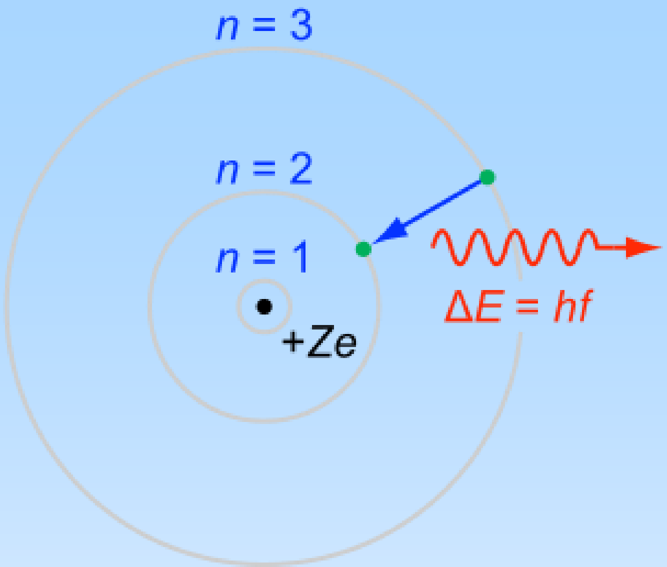




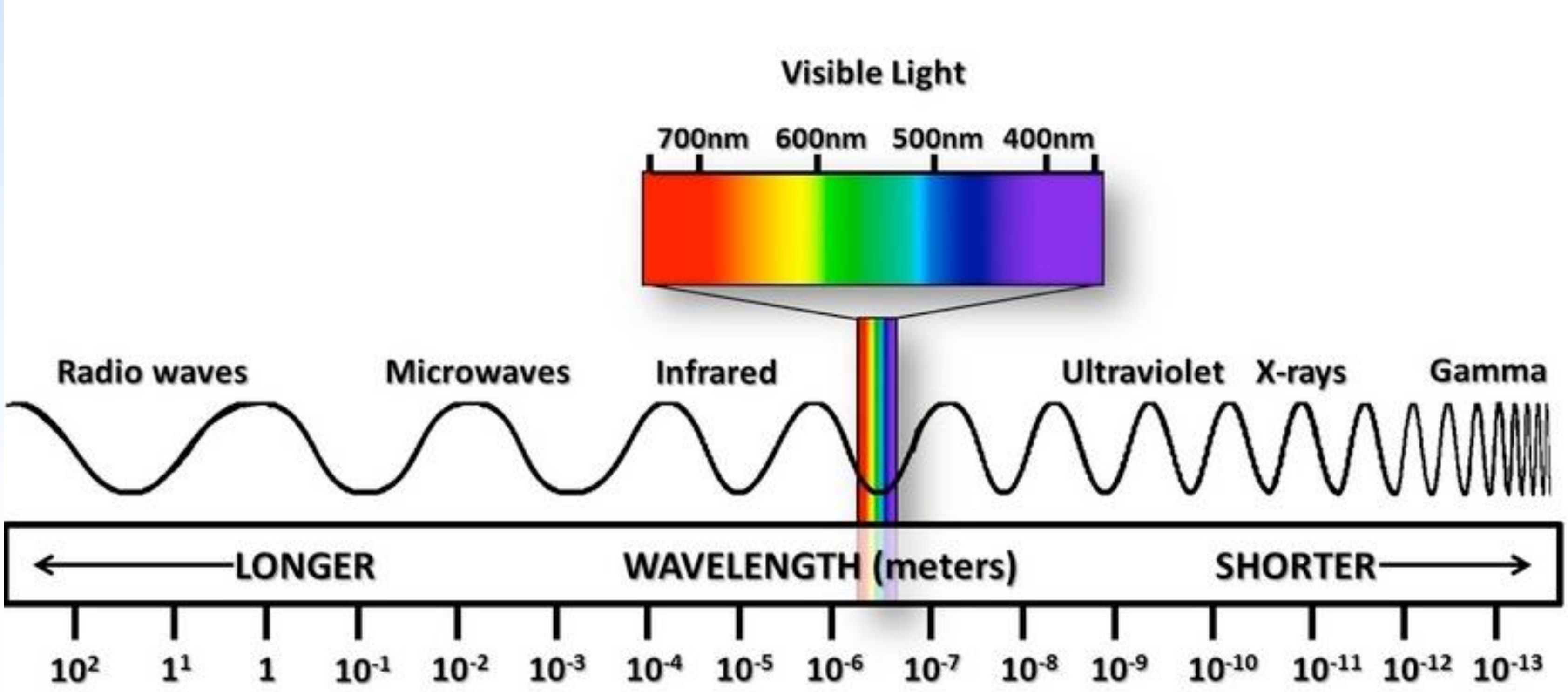
The Outer Solar Atmosphere

(First, an overview)

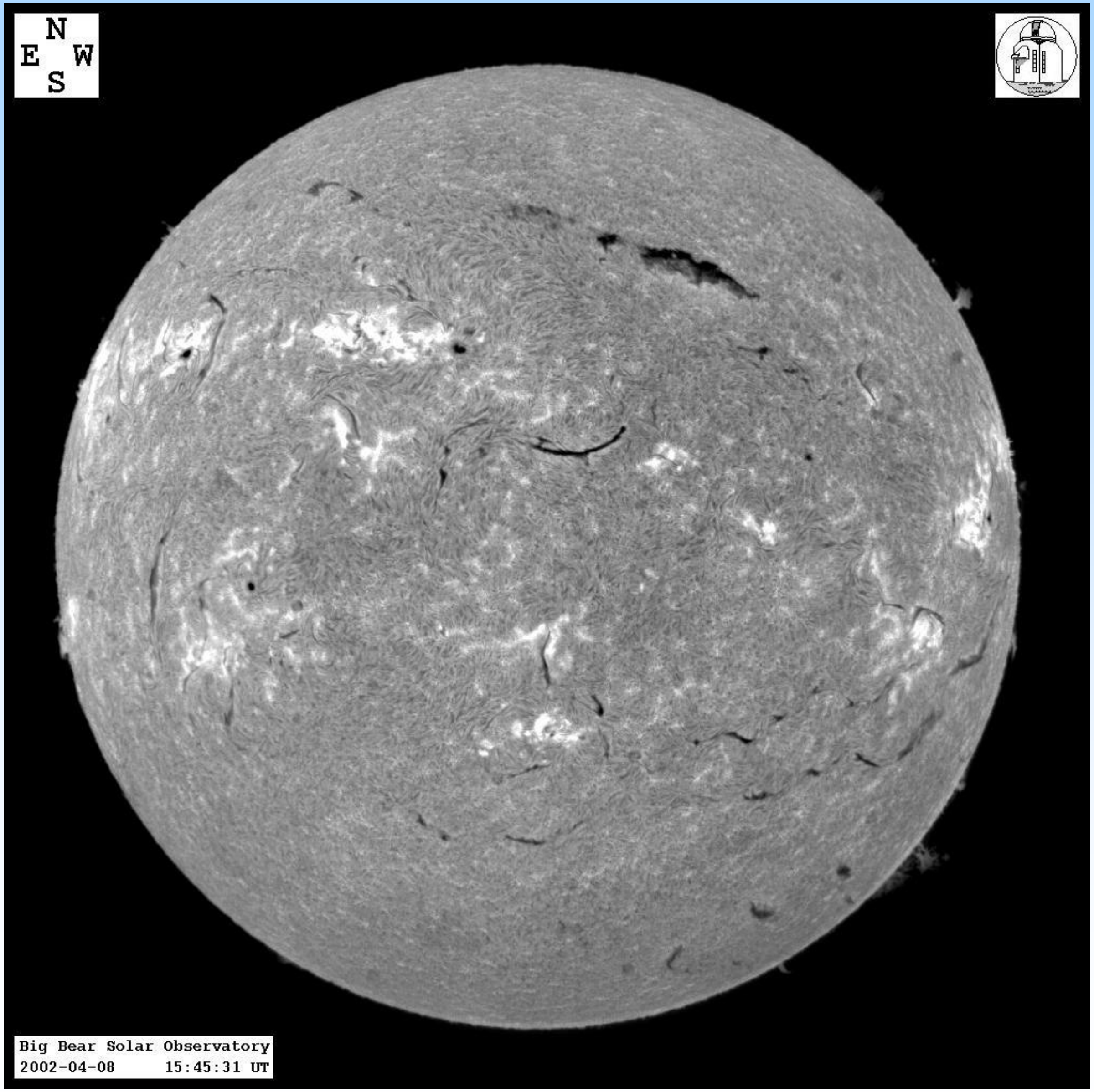
Chromosphere



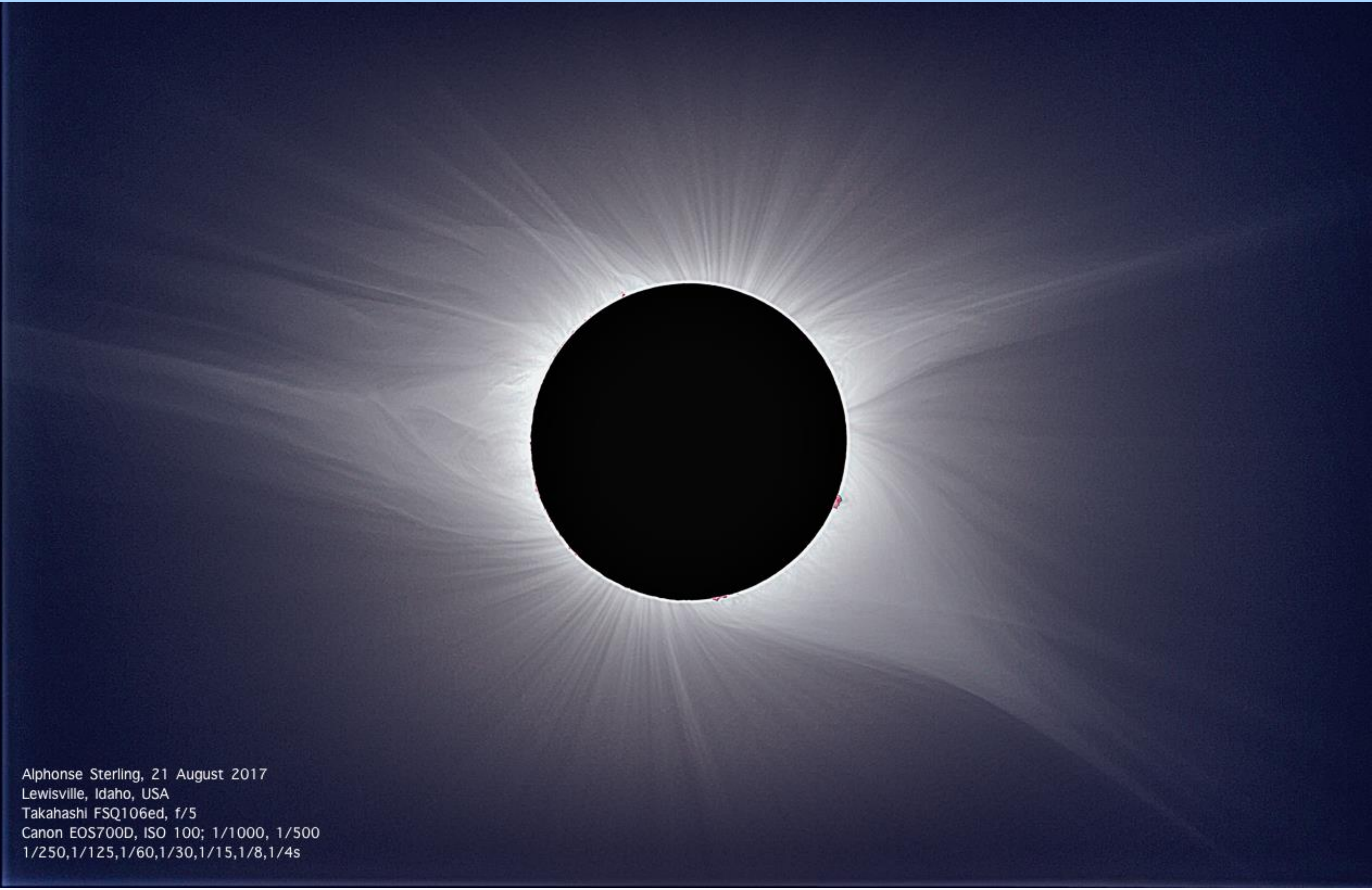
H-alpha (Hα) transition in hydrogen atom; 656.3 nm.



Chromosphere in Hα



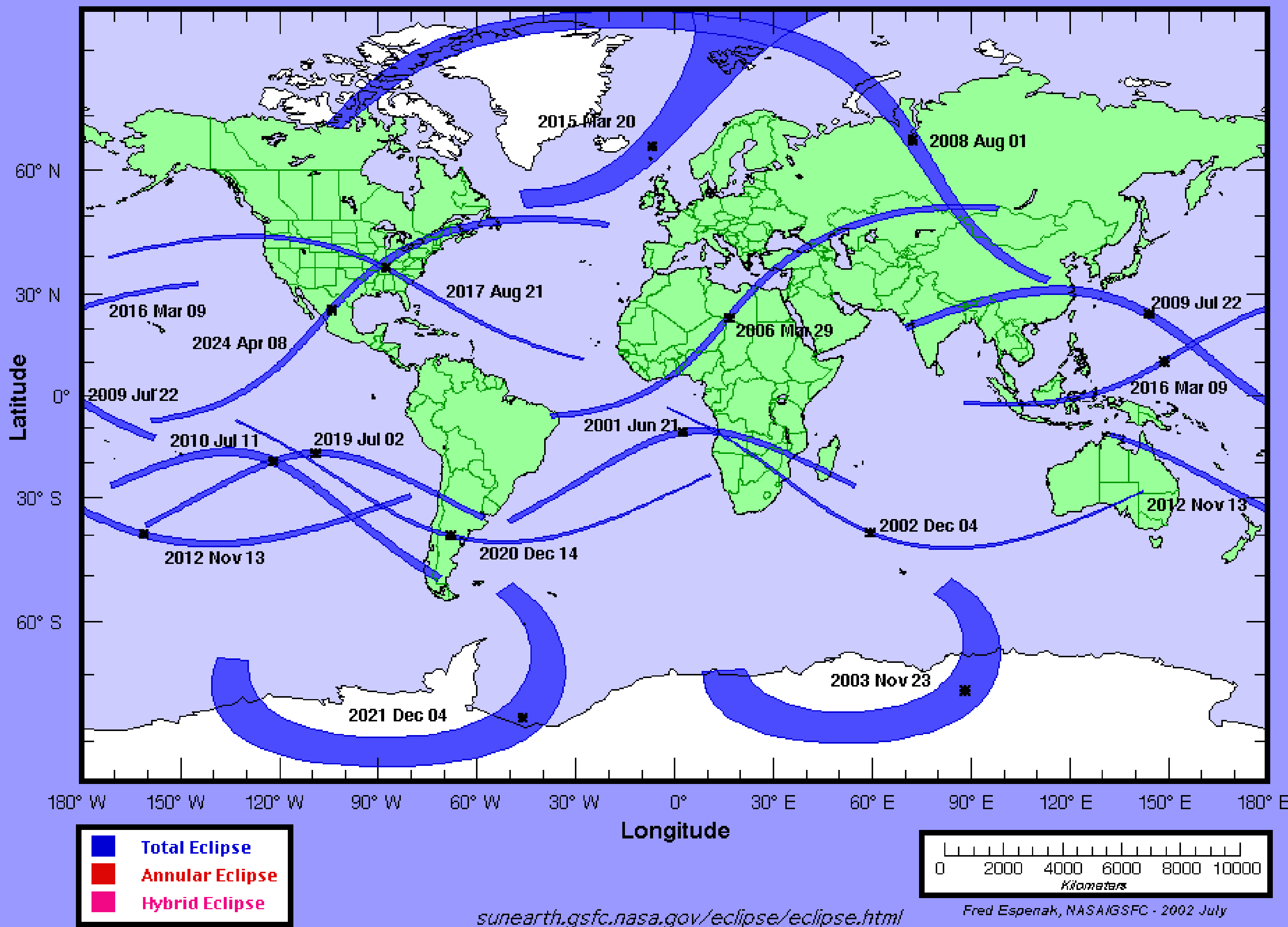

Solar Flare
1971 October 10
Big Bear Solar Observatory



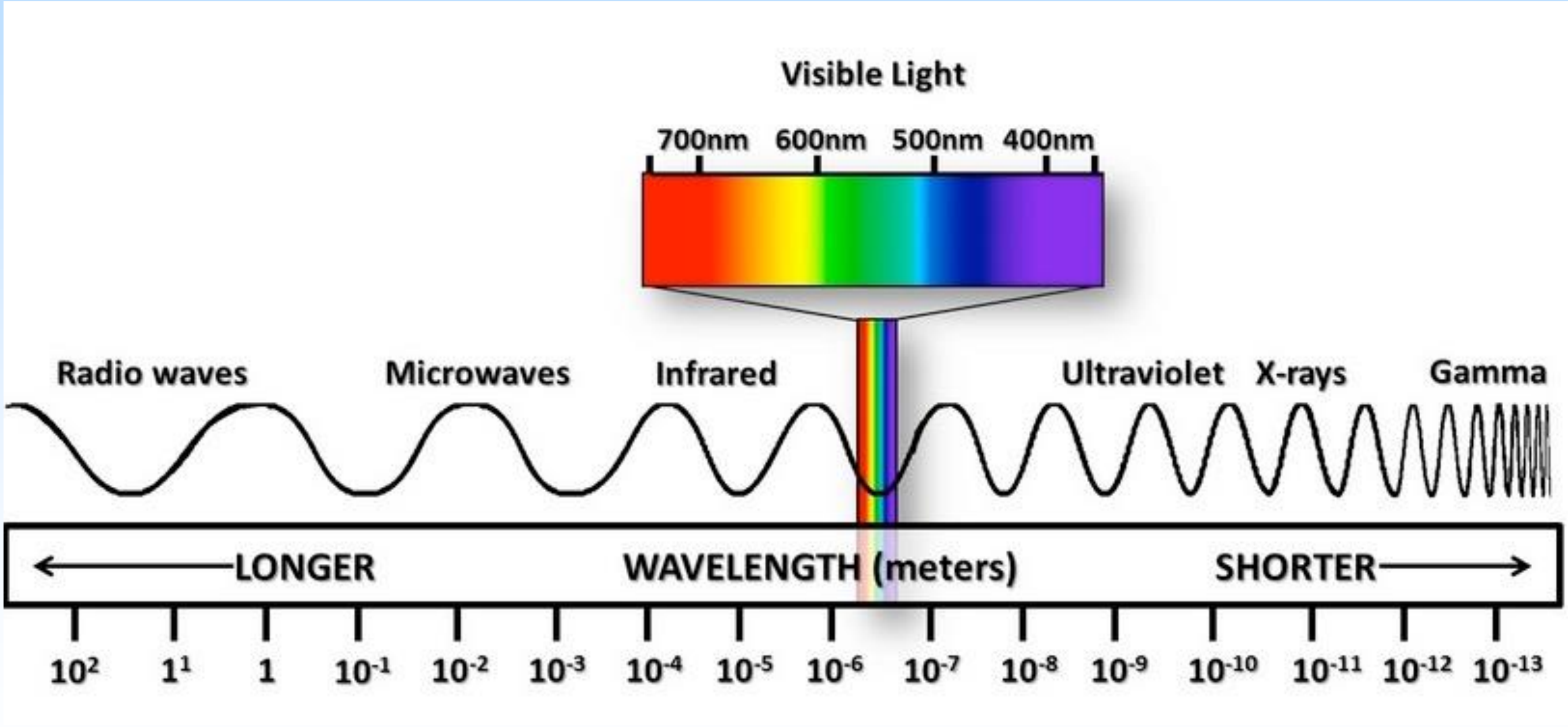
Corona – The Sun’s outermost atmosphere

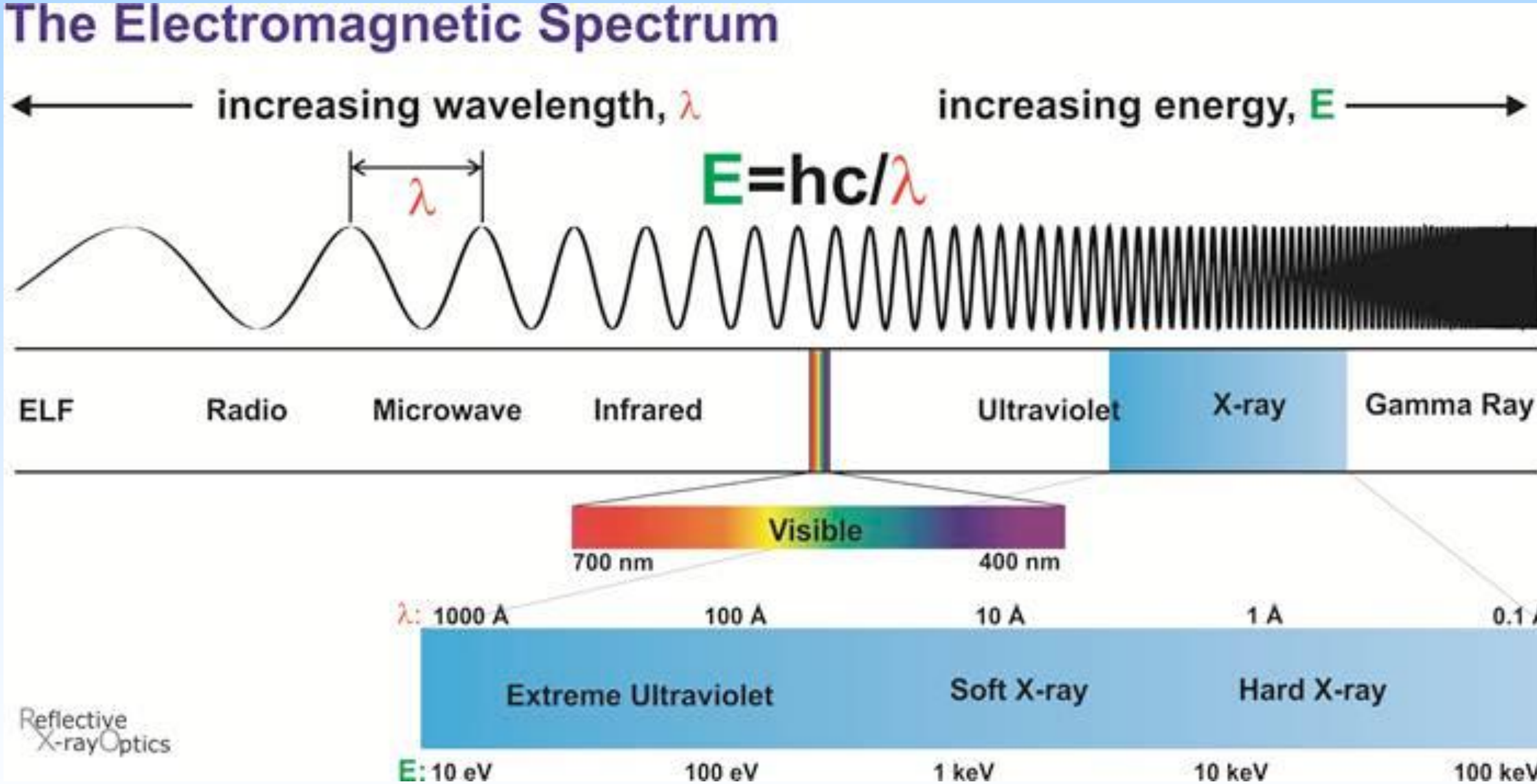
August 21, 2017 Total Solar Eclipse Path

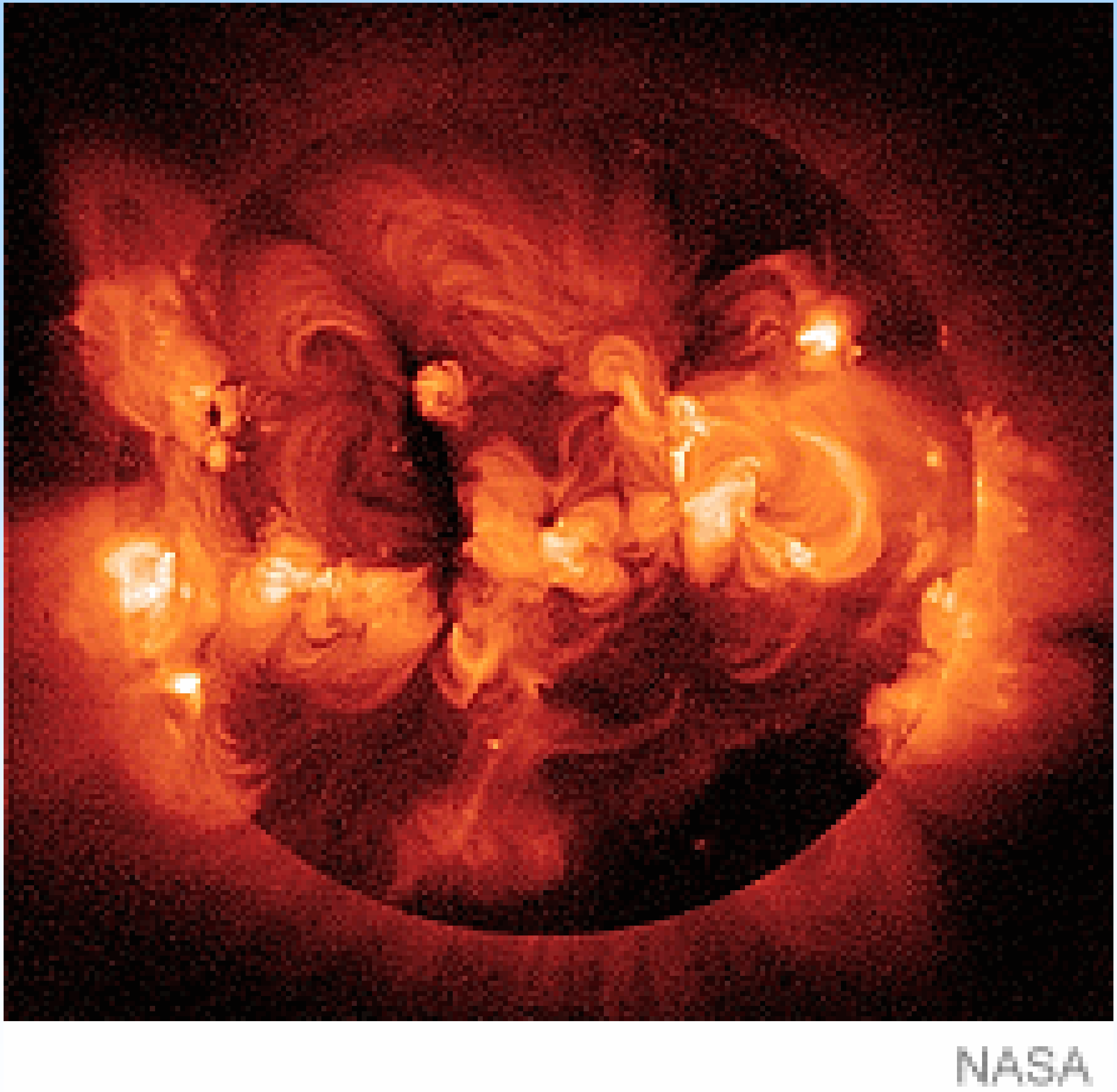
Total Solar Eclipse Paths: 2001–2025



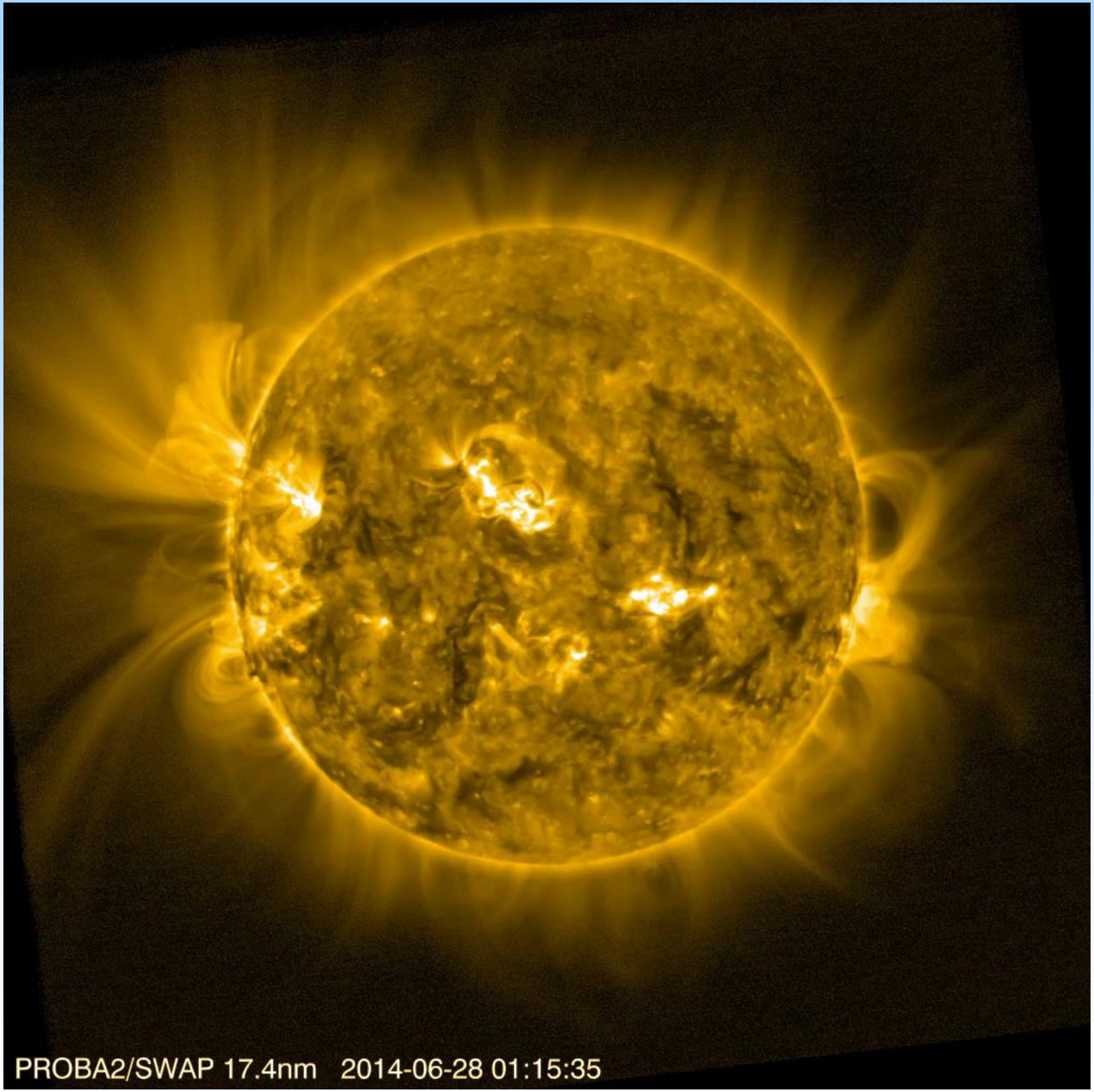
We have to go to ***space*** to see the Sun's outer atmosphere with regularity.




The Electromagnetic Spectrum
increasing wavelength, λ
increasing energy, E
E=hc/λ
λ
ELF
Radio
Microwave
Infrared
Ultraviolet
X-ray
Gamma Ray
Visible
700 nm
400 nm
λ: 1000 Å
100 Å
10 Å
1 Å
0.1 Å
Extreme Ultraviolet
Soft X-ray
Hard X-ray
Reflective X-ray Optics
E: 10 eV
100 eV
1 keV
10 keV
100 keV



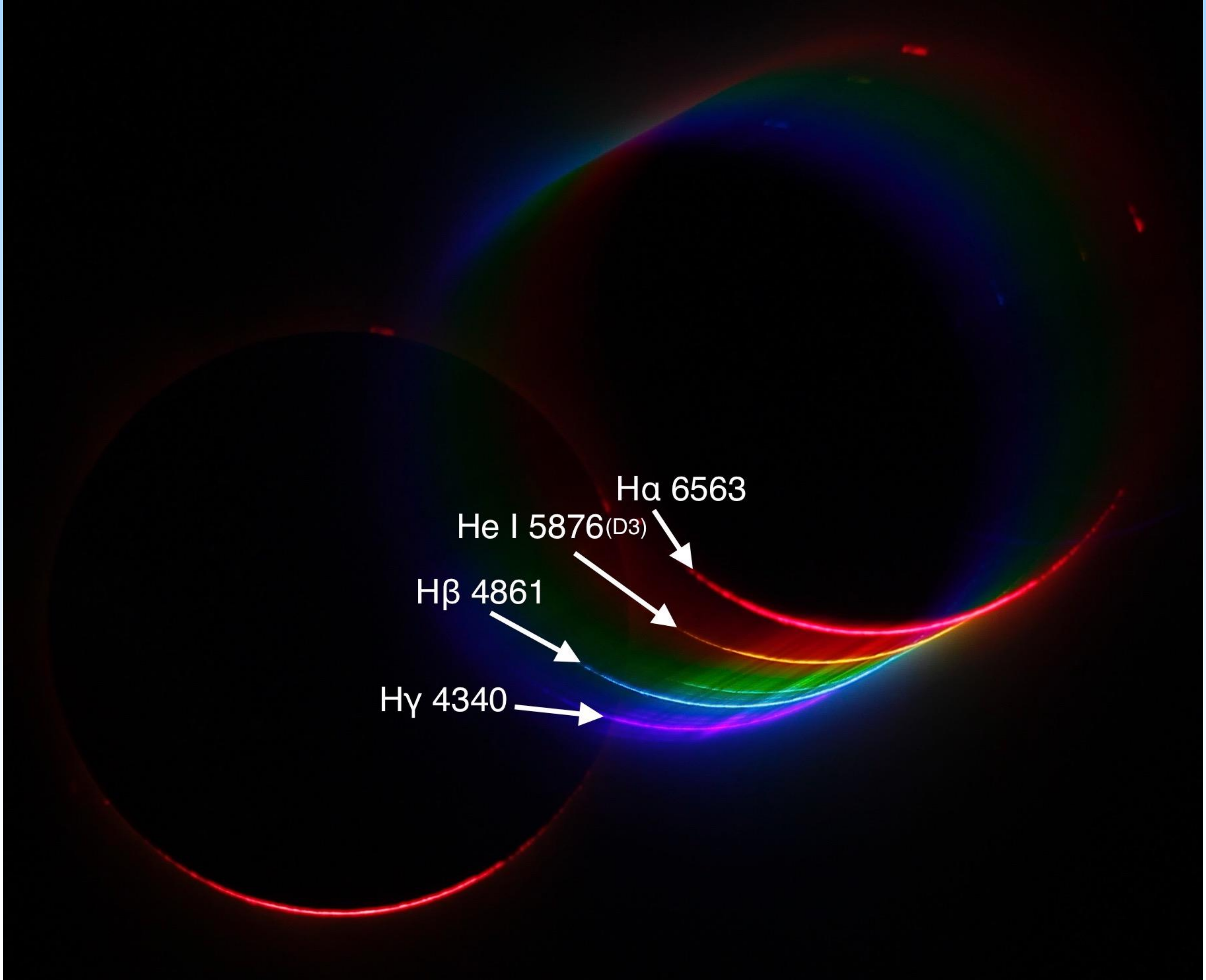
The Corona from Yohkoh/SXT


PROBA2/SWAP 17.4nm 2014-06-28 01:15:35

Atmosphere's Temperature Structure

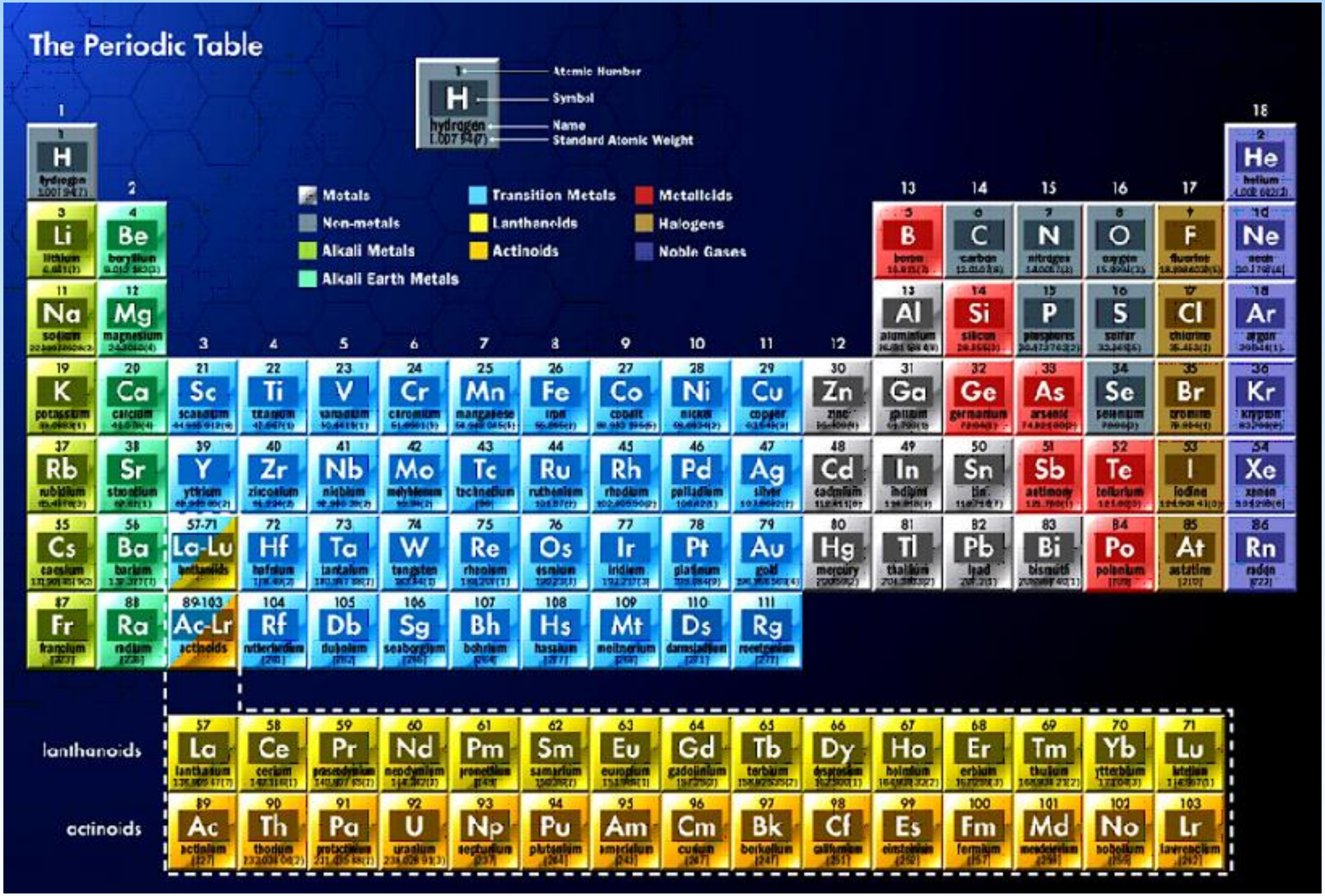
The Corona

- Expected to be cool, but found strange spectral lines, first during 1869 eclipse.


Hα 6563
He I 5876(D3)
Hβ 4861
Hγ 4340

The Corona

- Expected to be cool, but found strange spectral lines, first during 1869 eclipse.
- Many explanations considered, including a “new” element: *coronium*.
- **But this didn’t work....**


The Periodic Table
Atomic Number
Symbol
Name
Standard Atomic Weight
Metals
Non-metals
Alkali Metals
Alkali Earth Metals
Transition Metals
Lanthanoids
Actinoids
Metalloids
Halogens
Noble Gases
lanthanoids
actinoids

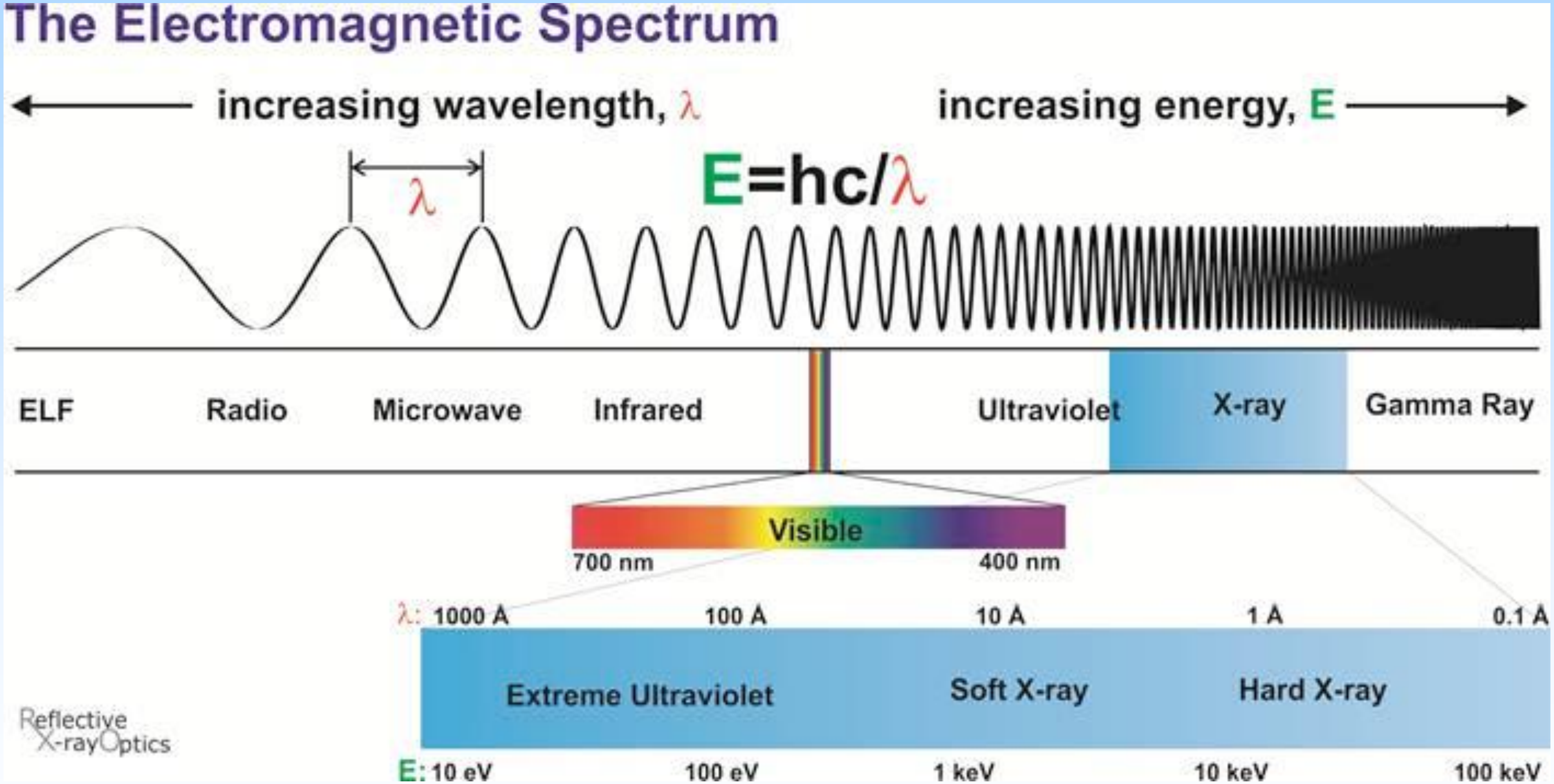
NASA/CXC/SAO

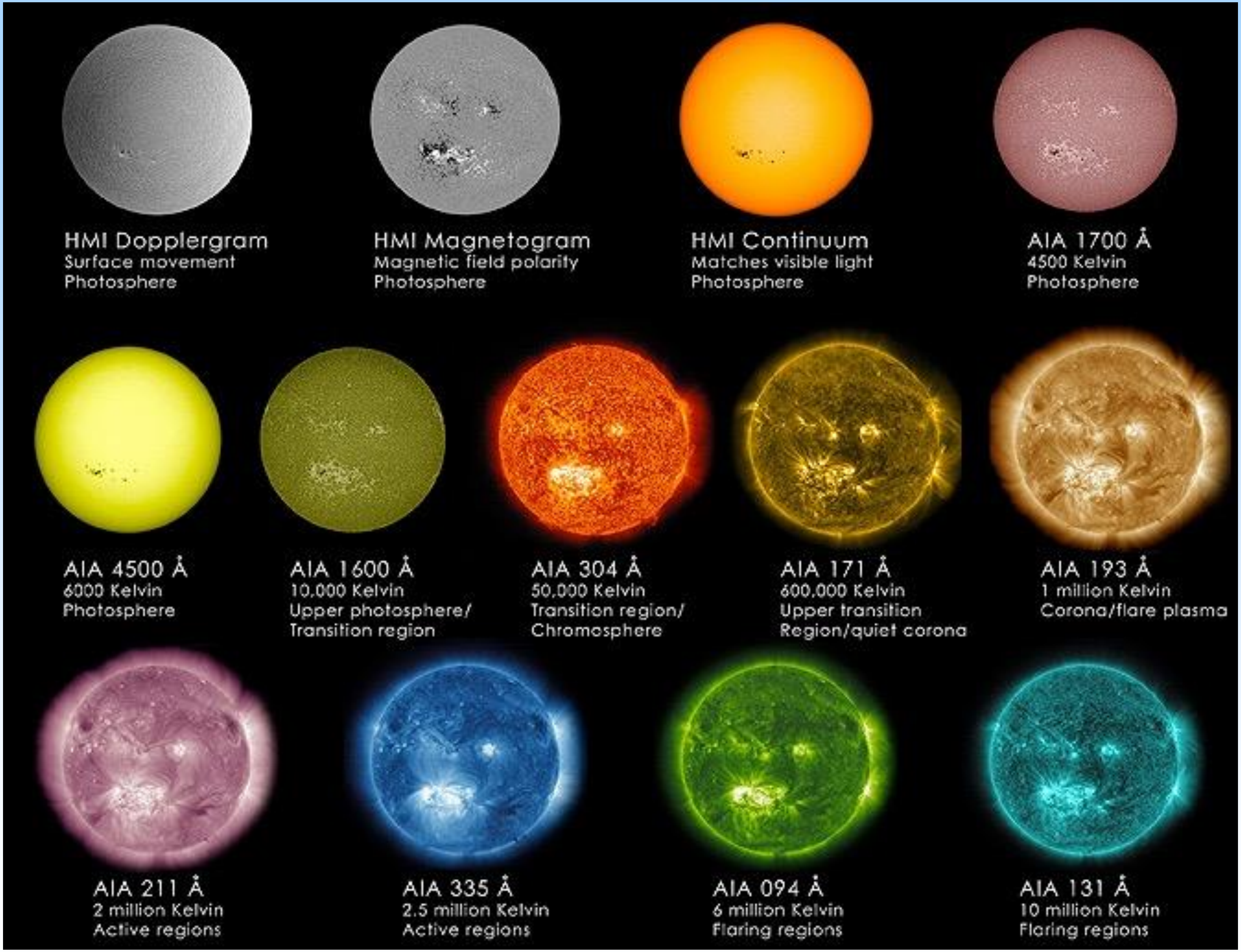
The Corona: Continued...

- The mystery spectral lines found to be due to highly-ionized familiar elements ~1940.

So this was a slooooow process: 1869 eclipse observations, and 1939~1943 explanation!!

- Structured with loops; late 1960s and 1970s observations from balloons, Skylab, etc.
- This structure due to the magnetic field.


The Electromagnetic Spectrum
increasing wavelength, λ
increasing energy, E
E=hc/λ
λ
ELF
Radio
Microwave
Infrared
Ultraviolet
X-ray
Gamma Ray
Visible
700 nm
400 nm
λ: 1000 Å
100 Å
10 Å
1 Å
0.1 Å
Extreme Ultraviolet
Soft X-ray
Hard X-ray
Reflective X-ray Optics
E: 10 eV
100 eV
1 keV
10 keV
100 keV


HMI Dopplergram
Surface movement
Photosphere
HMI Magnetogram
Magnetic field polarity
Photosphere
HMI Continuum
Matches visible light
Photosphere
AIA 1700 Å
4500 Kelvin
Photosphere
AIA 4500 Å
6000 Kelvin
Photosphere
AIA 1600 Å
10,000 Kelvin
Upper photosphere/
Transition region
AIA 304 Å
50,000 Kelvin
Transition region/
Chromosphere
AIA 171 Å
600,000 Kelvin
Upper transition
Region/quiet corona
AIA 193 Å
1 million Kelvin
Corona/flare plasma
AIA 211 Å
2 million Kelvin
Active regions
AIA 335 Å
2.5 million Kelvin
Active regions
AIA 094 Å
6 million Kelvin
Flaring regions
AIA 131 Å
10 million Kelvin
Flaring regions

The Corona: Continued Again...

Now, let’s consider the temperature structure between the photosphere and the corona.

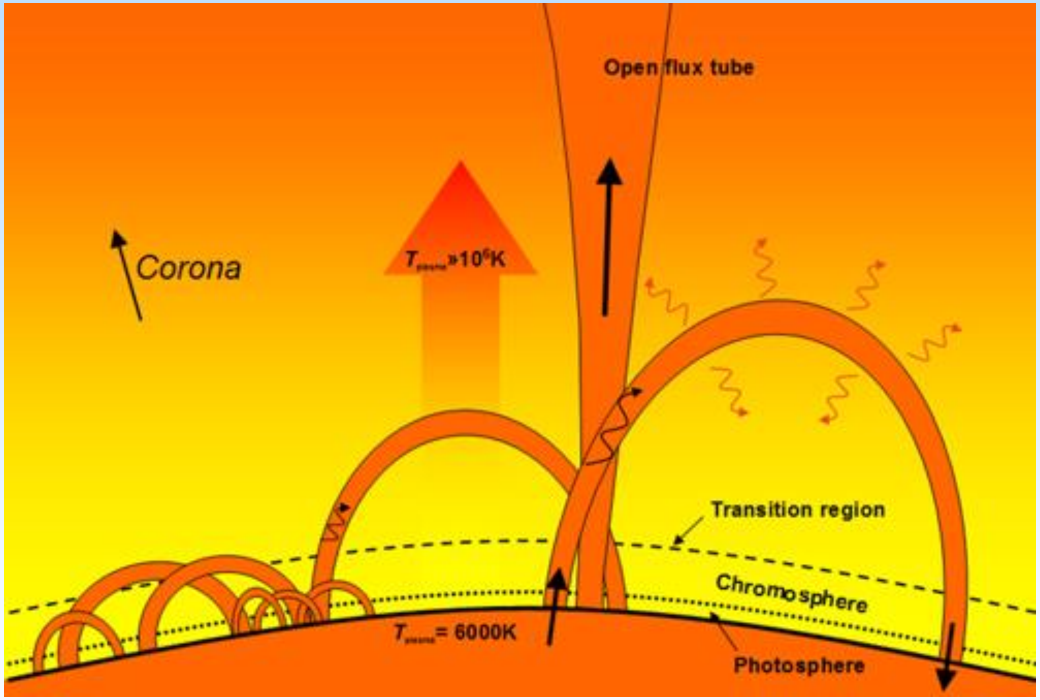
First question: What makes the corona hot??

And the answer for today is...

Magic!!

Actually, a hot corona is not as mysterious as it seems....

Just assume a hot corona. Now, what does the temperature structure look like?



Energy balance equation:

$$H - R = C$$

R=Radiation losses; “known.”

C= Thermal Conduction; form known.

H= the “magic” Heating.

Recipe: Adjust H until predictions of energy-balance equation match observations. (Rosner, Tucker, Vaiana 1978.)

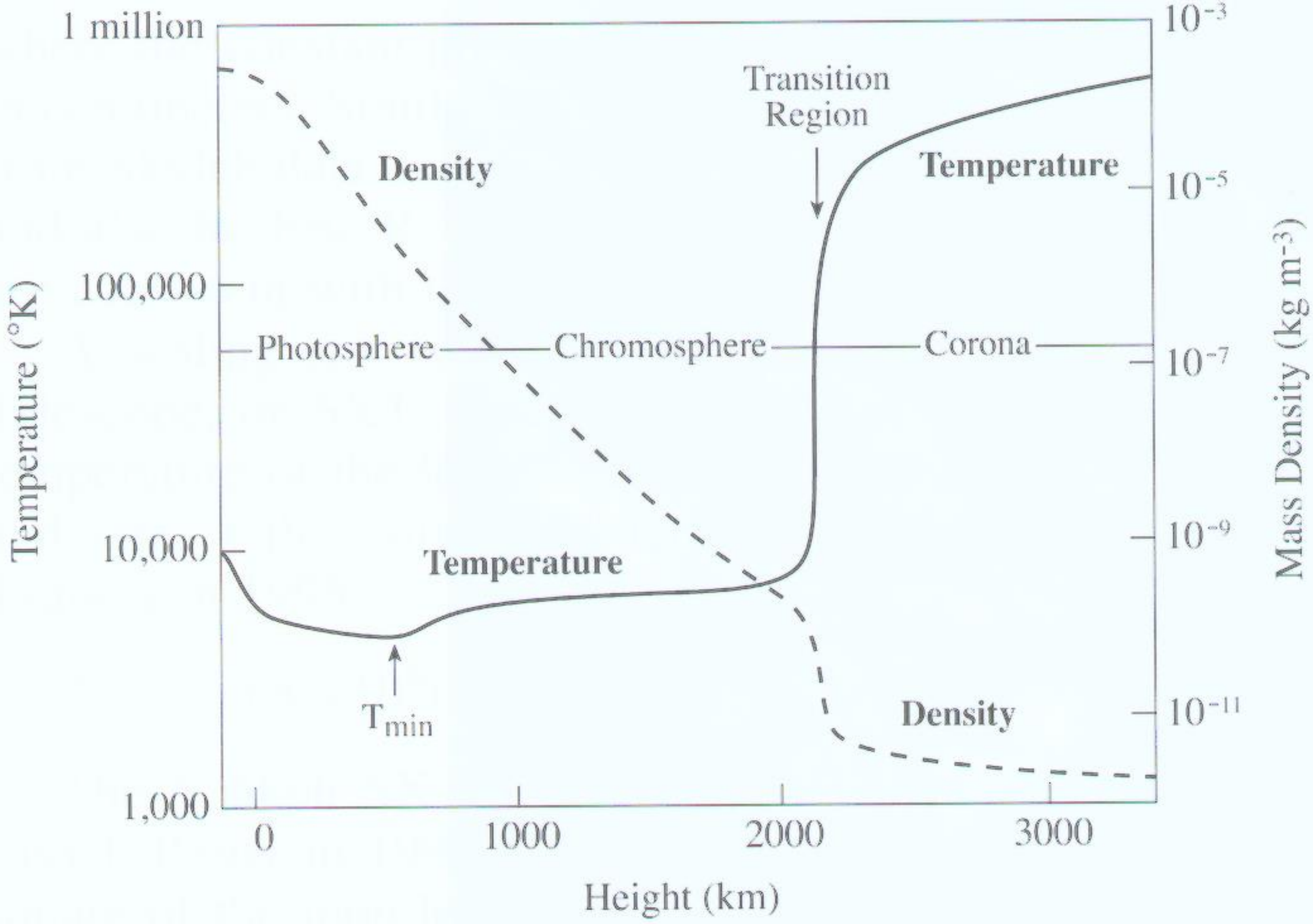
Form of Thermal Conduction:

$$\mathbf{C} = \nabla \cdot \mathbf{F}_c$$

$$\mathbf{F}_c = -\kappa_0 T^{5/2} \nabla T$$

In 1-dimension (along a loop), this is:

$$F_c = -\kappa_0 T^{5/2} \frac{dT}{dz}$$



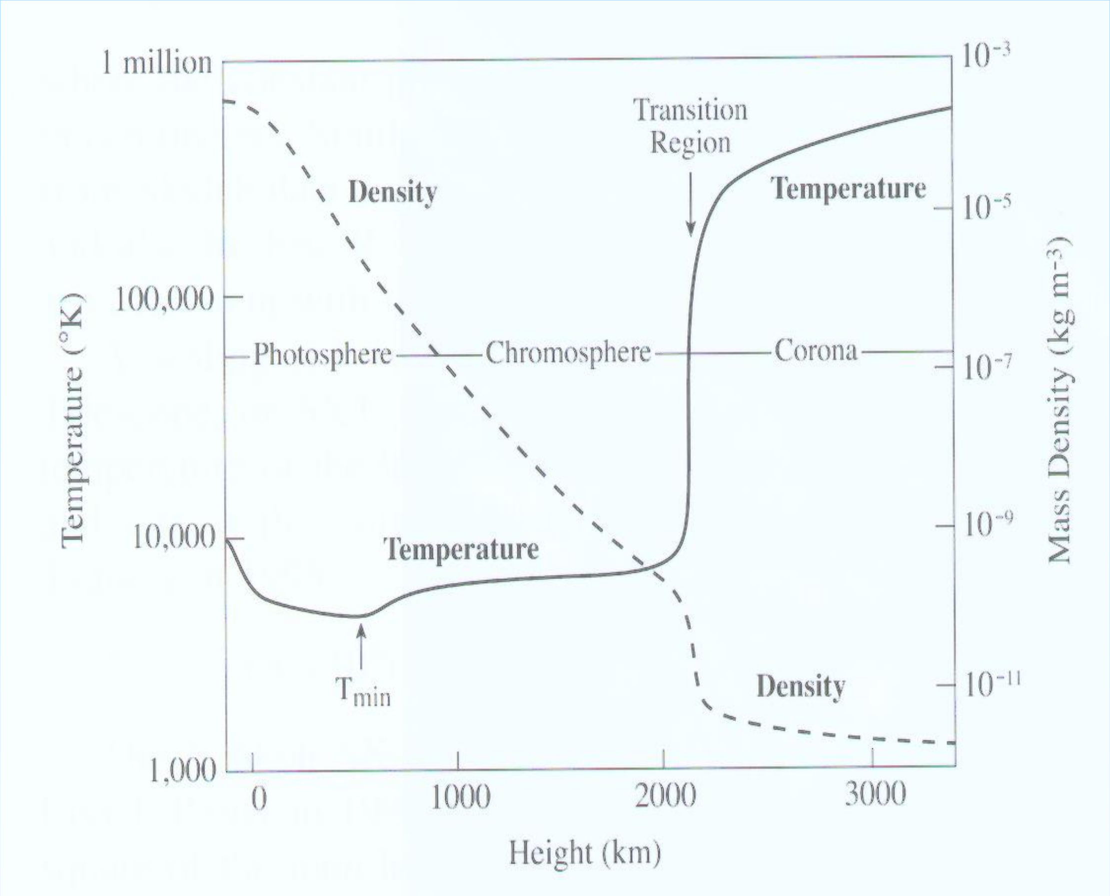
(From K. Lang: The Sun from Space, 2000)

$$H - R = C$$

At around T ~10^5 K:

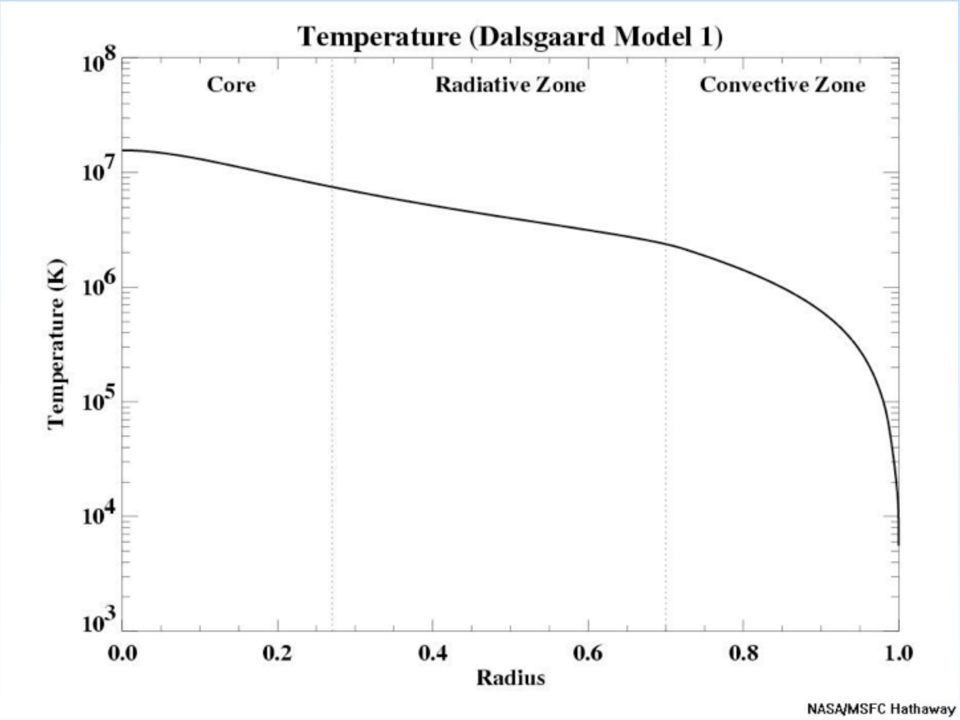
$$-R \approx C$$

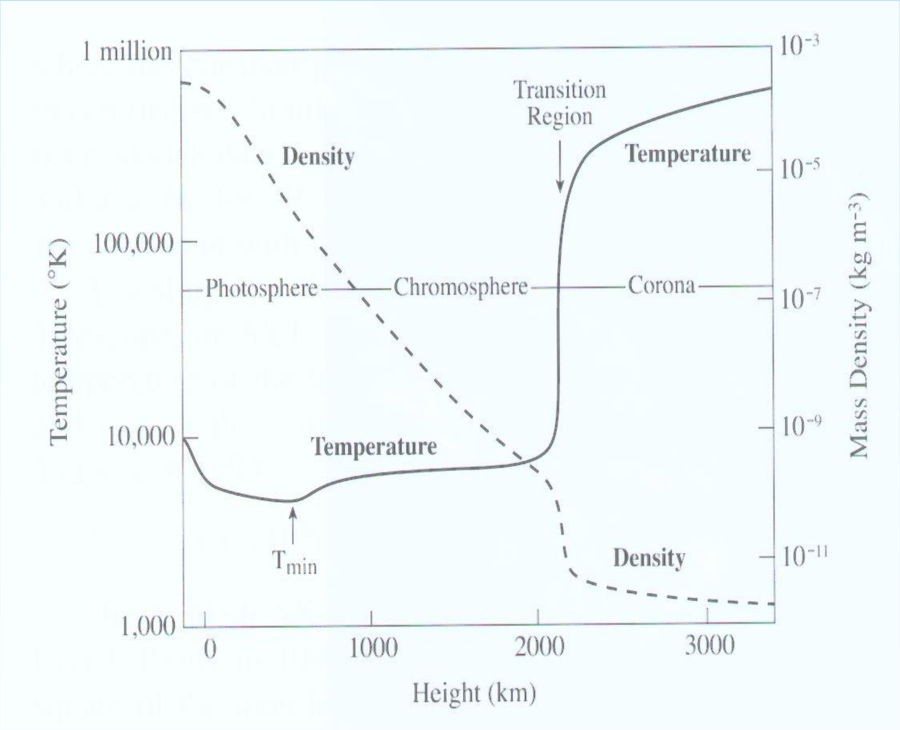
$$R \approx \frac{d}{dz}\left[\kappa_0 T^{5/2}\frac{dT}{dz}\right]$$



Strong radiation in this temperature range means a steep temperature gradient is needed for energy balance. This leads to a “thin” transition region.

The Sun's Temperature Structure





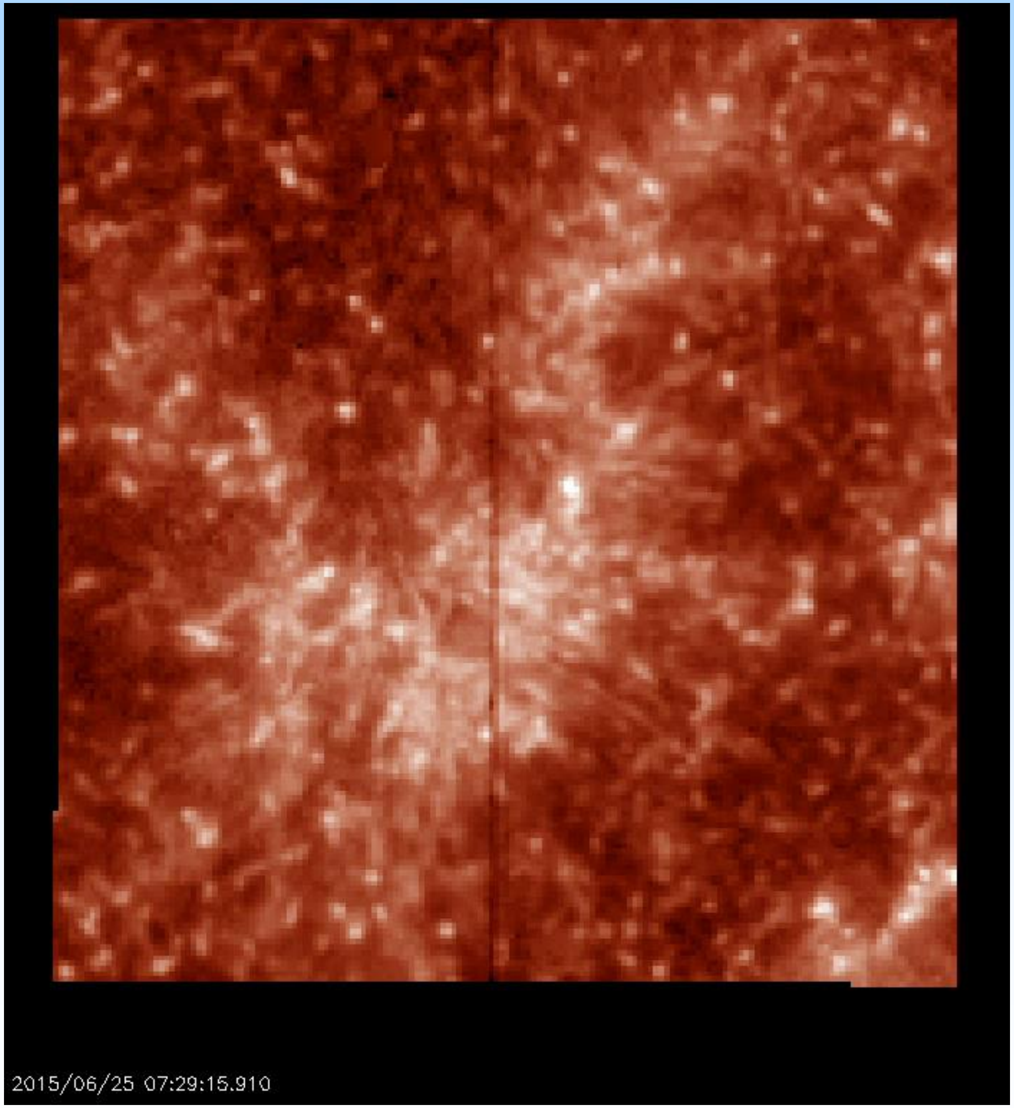
But, is this correct??

- (Just considering the atmospheric portion)
- There are many assumptions, including:
  - 1-dimensional calculations
  - Static atmosphere
  - Etc.

An example: The Transition Region:

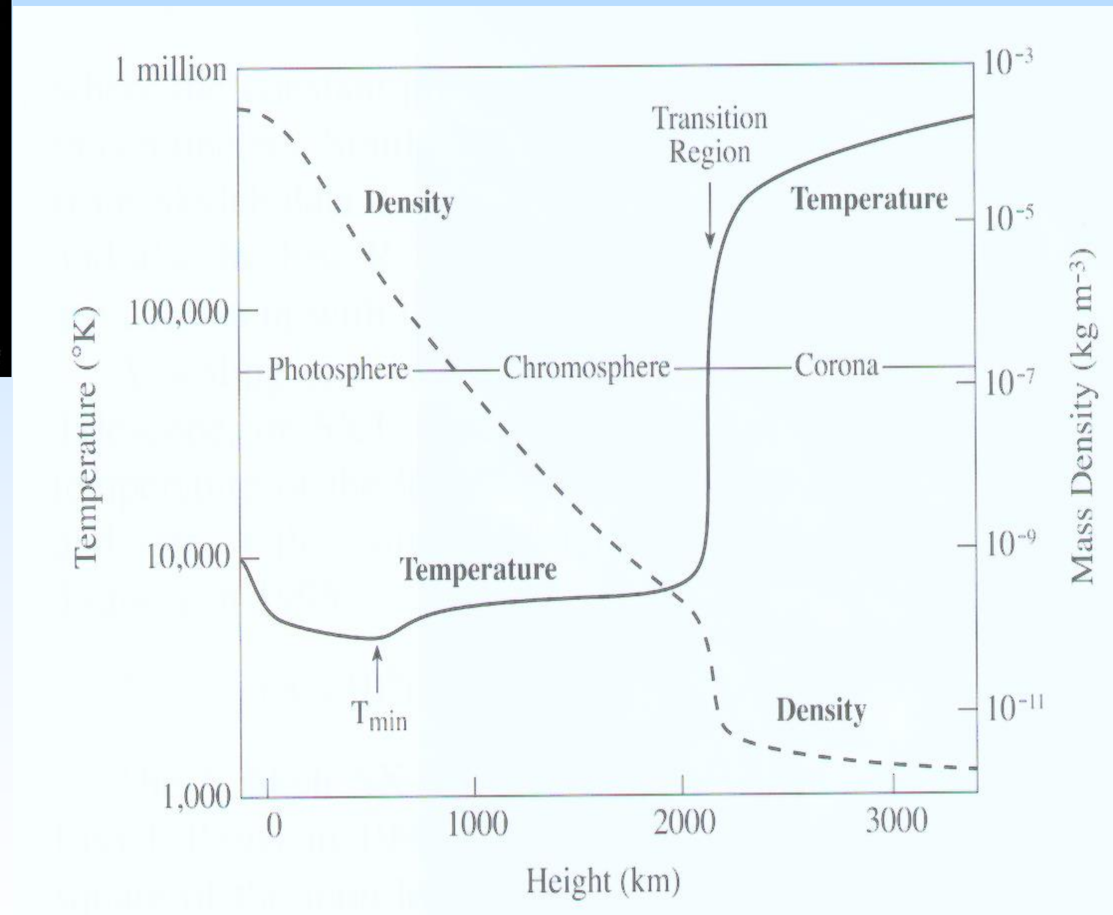
- Saw coronal movie earlier
- Now, with the IRIS satellite, can see the transition region

The “IRIS” satellite observes the transition region



Another example: Prominences/Filaments

Chromospheric material suspended in the corona



And the conclusion is...

- The derived atmospheric structure is "approximately" correct.
- It is a good starting point for considering solar phenomena.
- Have to keep in mind the limitations, based on what you are focusing on.
- Both the "approximate" temperature structure, and the "detailed" temperature structure, hold fascinating solar science questions (e.g coronal heating; prominence formation, stability, and instability).