

An Introduction to the Sun

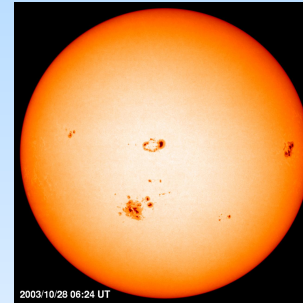
Dr. Alphonse Sterling
NASA/MSFC

Solar Physicist (“Astrophysicist”): Solar eruptions (prominences, flares & CMEs), spicules (chromospheric jets), coronal jets.
Yohkoh, Hinode satellites (including operations).

Solar Interior and Atmosphere(s)

The Outer layers (Atmospheres) of the Sun:

- Photosphere



- Chromosphere



- Corona



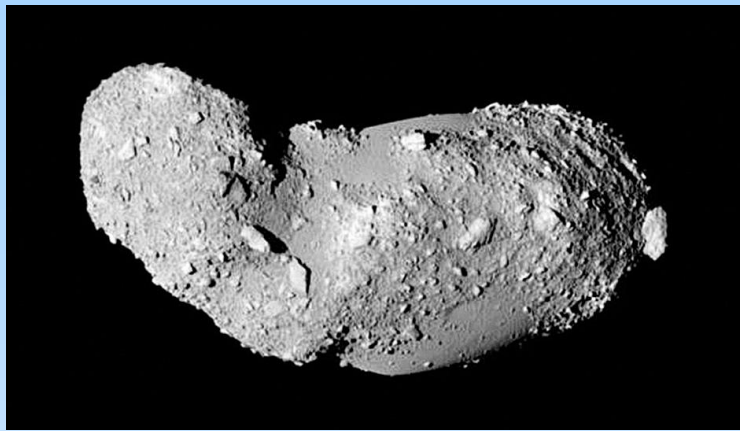
Formation of the Sun

Initially, have a blob of gas...

...and gravity:

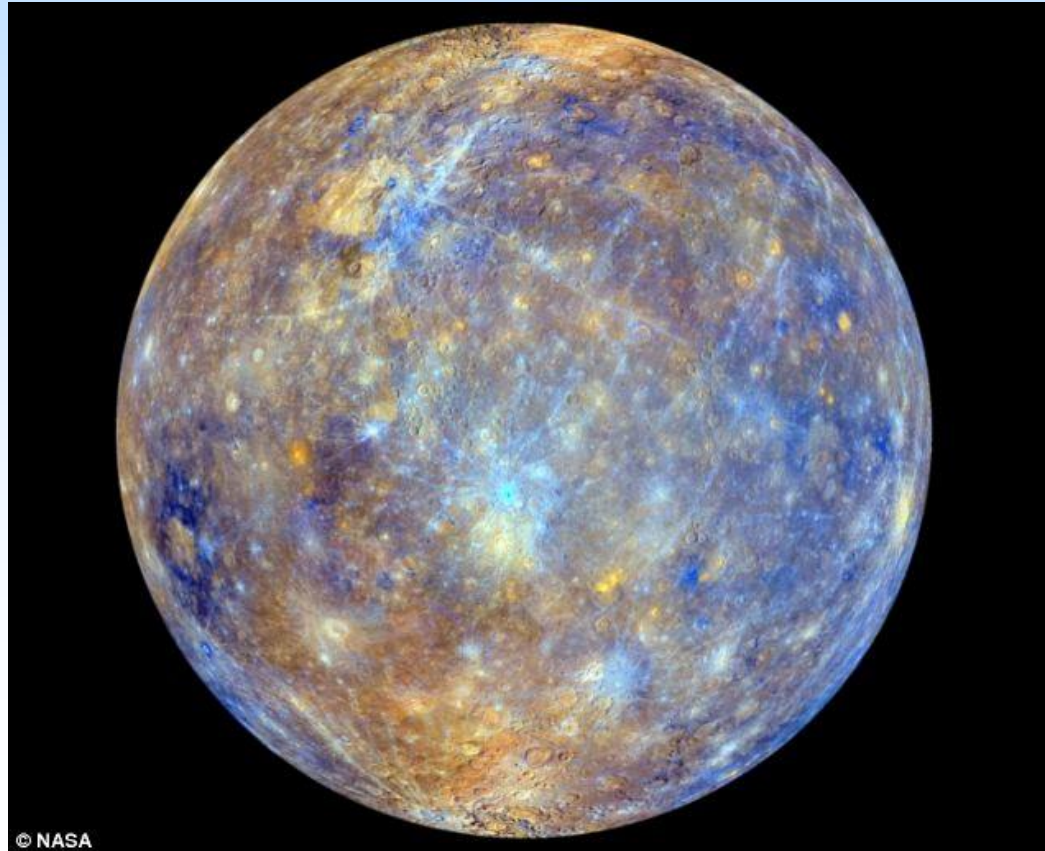
$$F = \frac{GMm}{r^2}$$

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



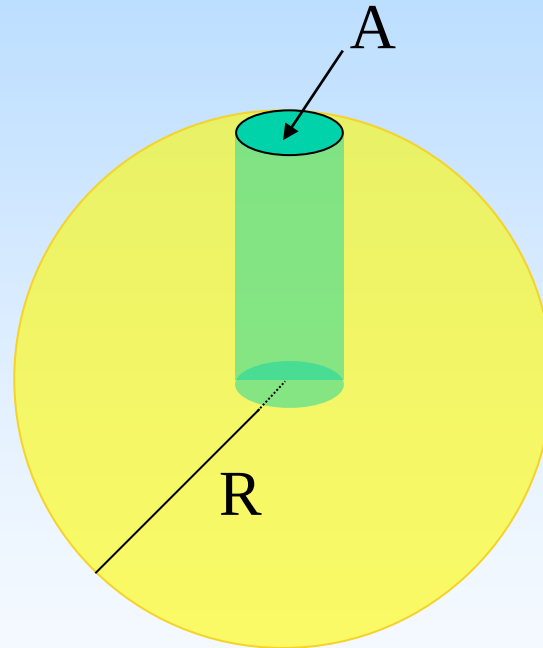
Length ~ 0.5 km
(Itokawa, from Hayabusa)

Diameter ~ 5000 km
(Mercury, from
Messenger)



Interior Temperature Structure

Sun's Central Core Temperature (Estimate)



Sun's Central Core Temperature (Estimate)

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

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

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

- $T = 1 \cdot 10^7 \text{ K}$

m, A, ρ = column mass, area, ave density

R, M = solar radius, mass

F = column force

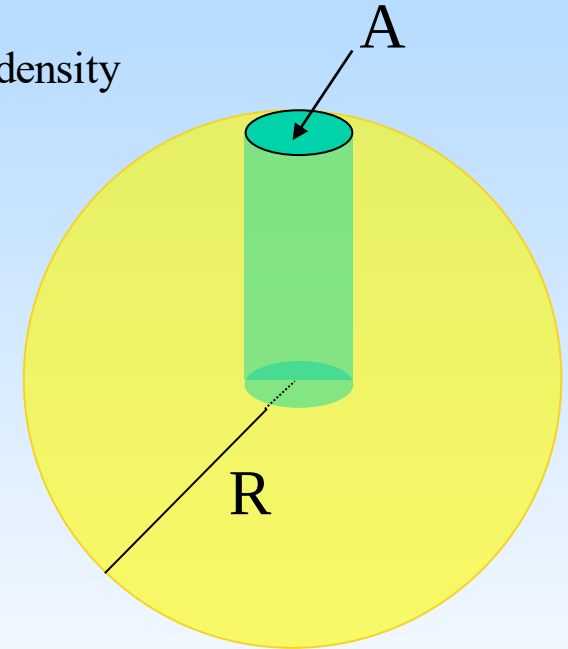
G = gravitational constant

P, T = solar center pressure,
temperature

N = number of column particles

k = Boltzmann's constant

m_H = hydrogen mass



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

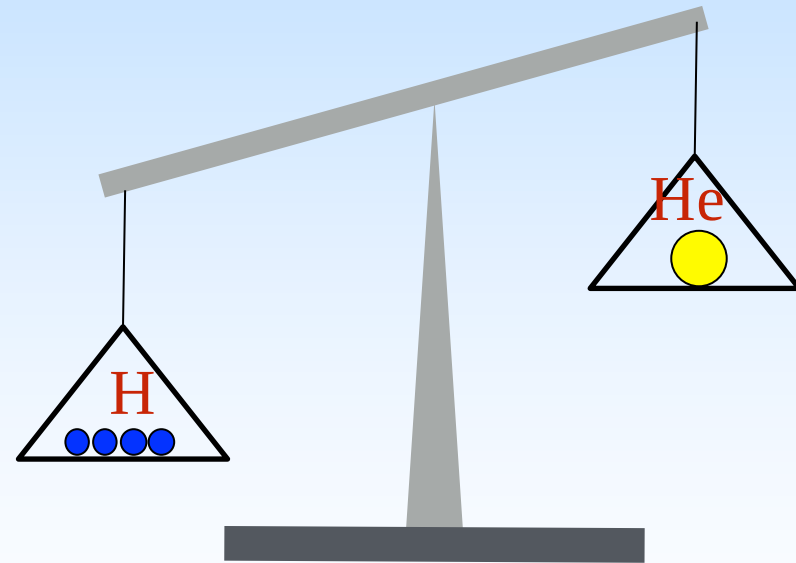
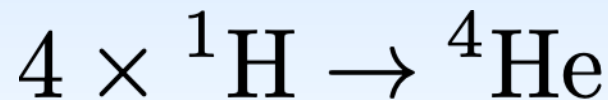
=> Solar lifetime of $\sim 3 \times 10^7$ years

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:

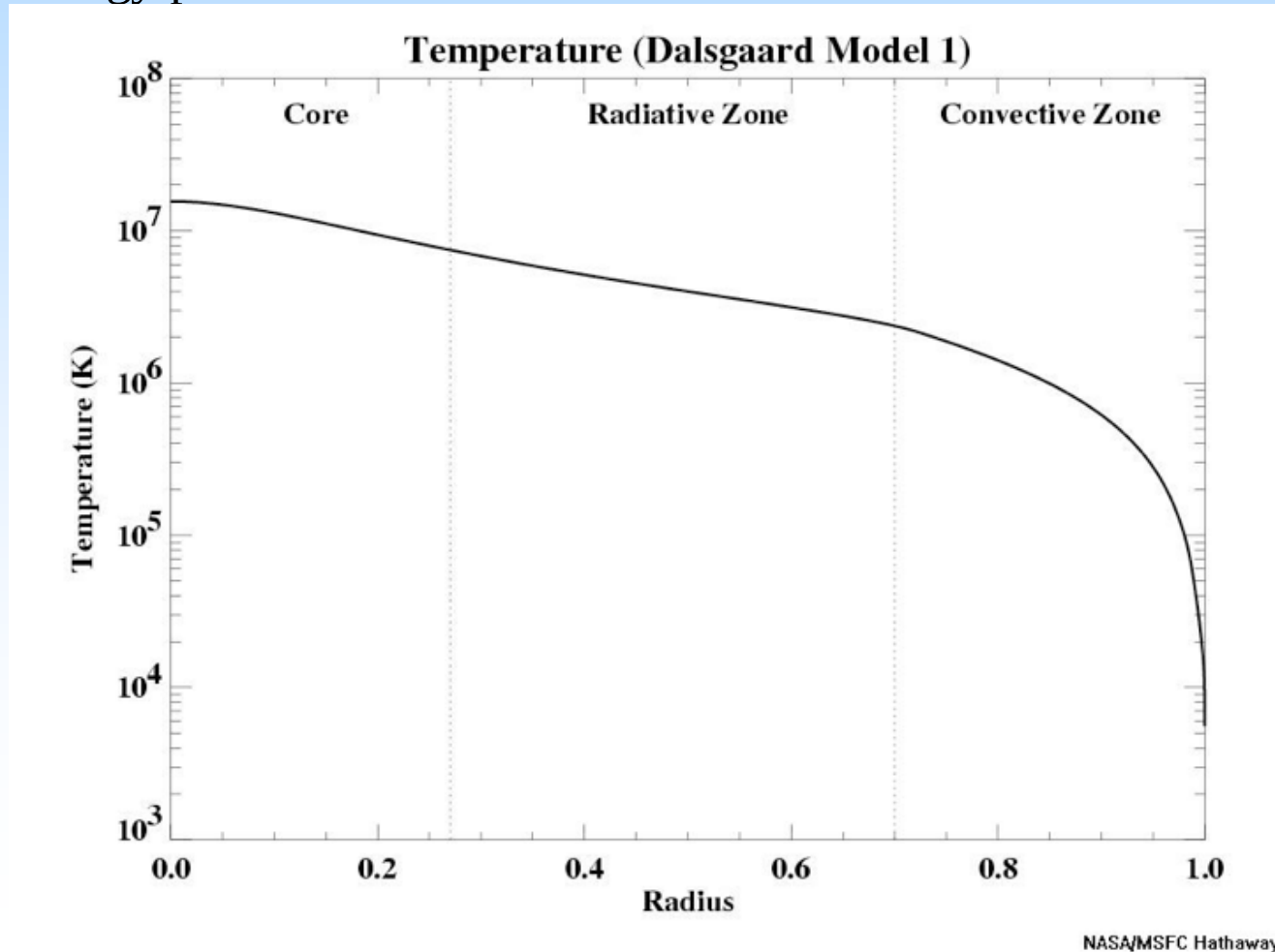


Mass “mismatch” of 0.0285 amu $\sim 5 \times 10^{-26}$ g...

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

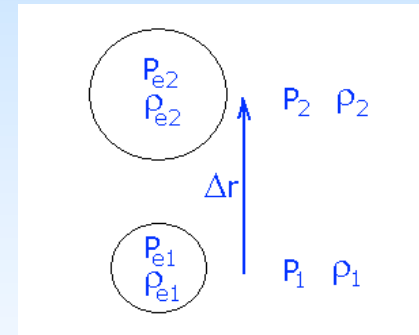
Get the full structure by solving equations for:

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

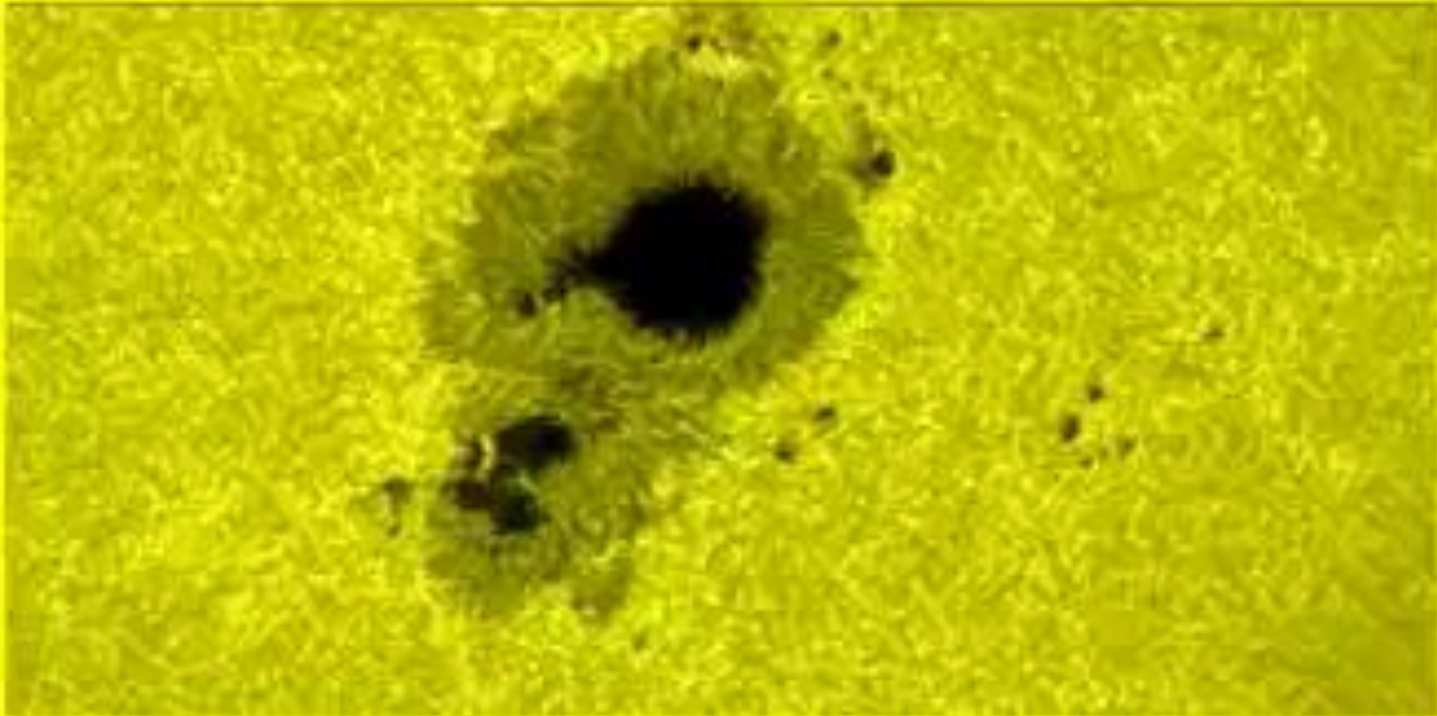


- Convective instability sets in when:

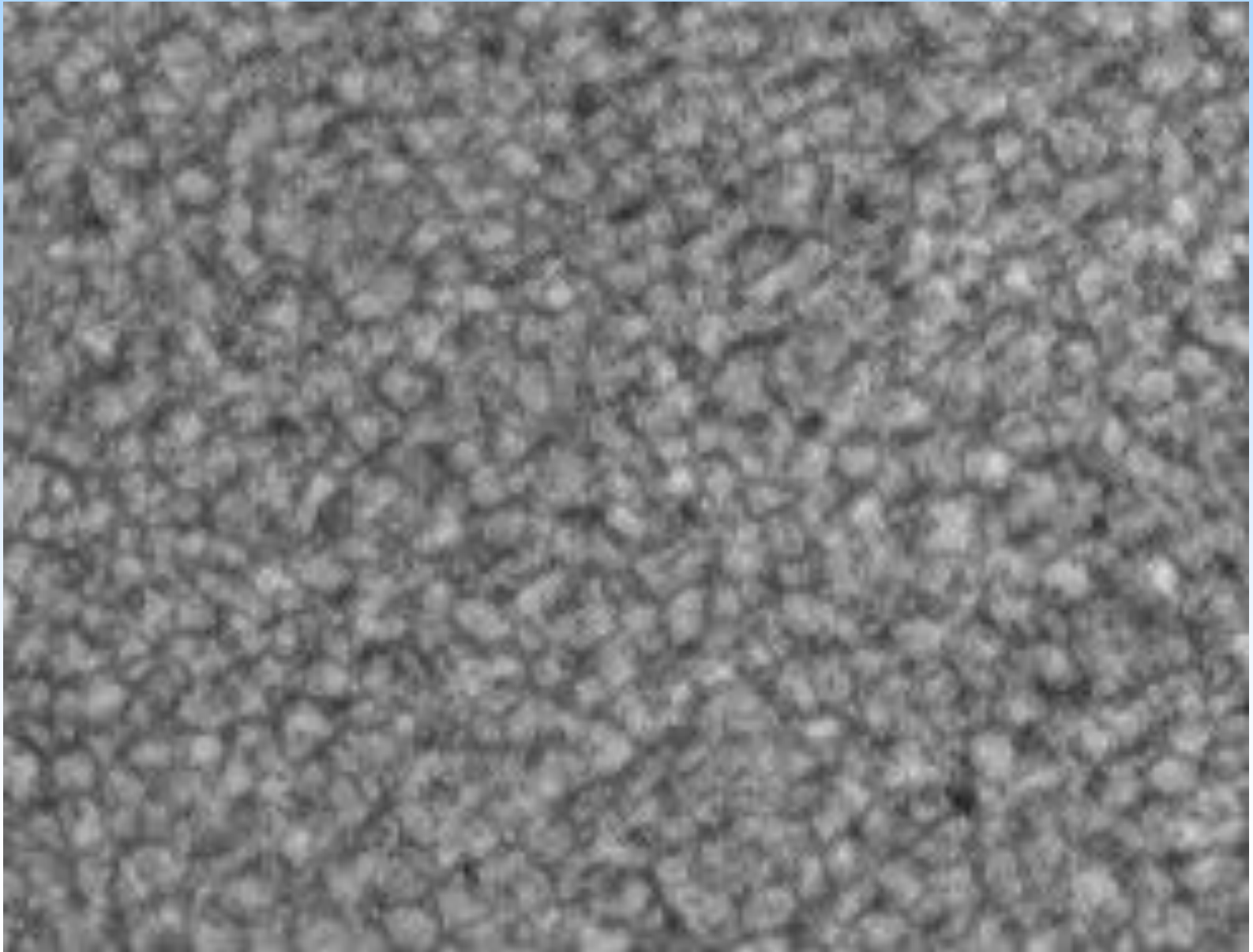
$$\left| \frac{dT}{dr} \right|_{outside} > \left| \frac{dT}{dr} \right|_{adiabatic}$$



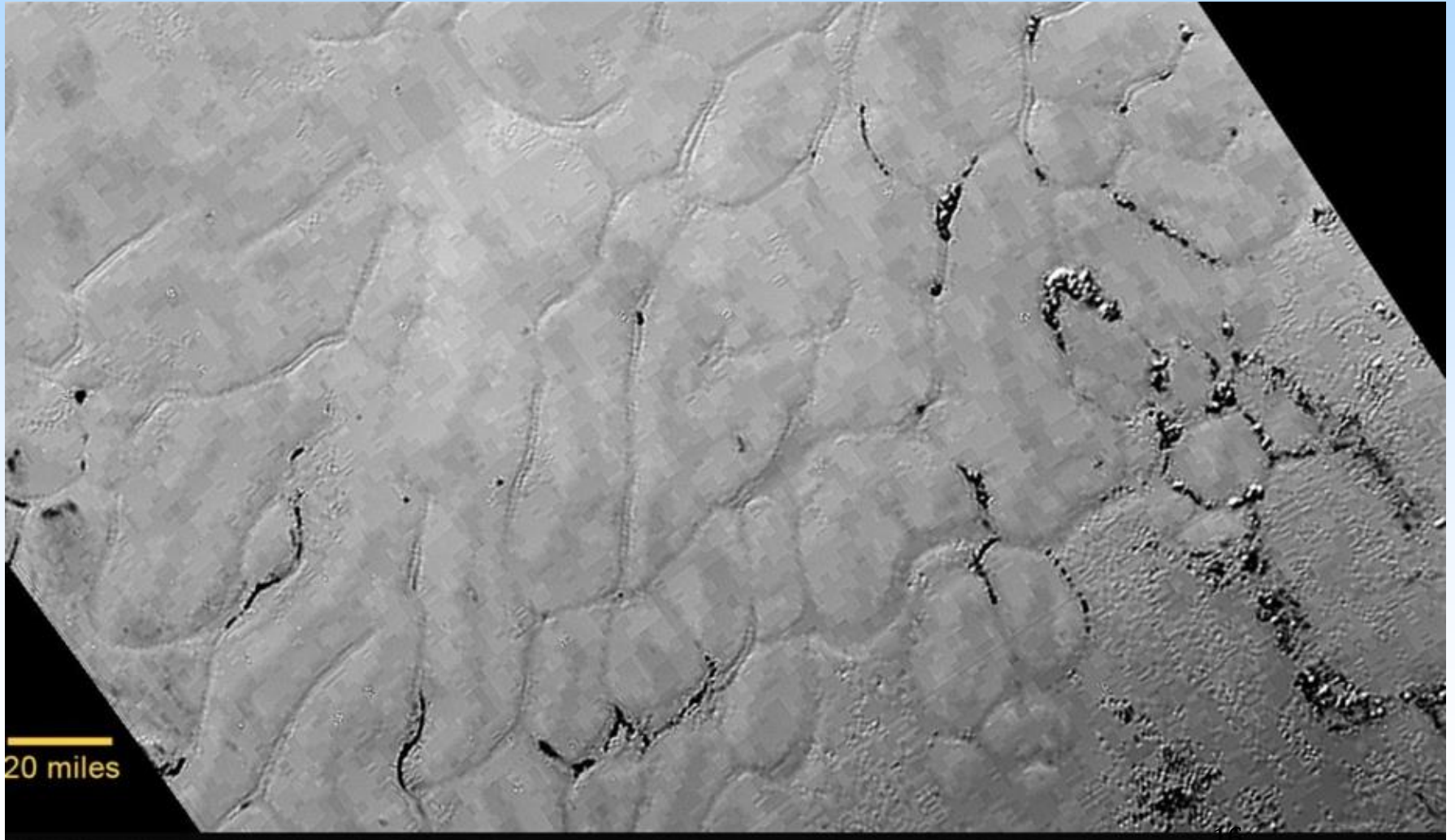
Hinode SOT Granulation Movie

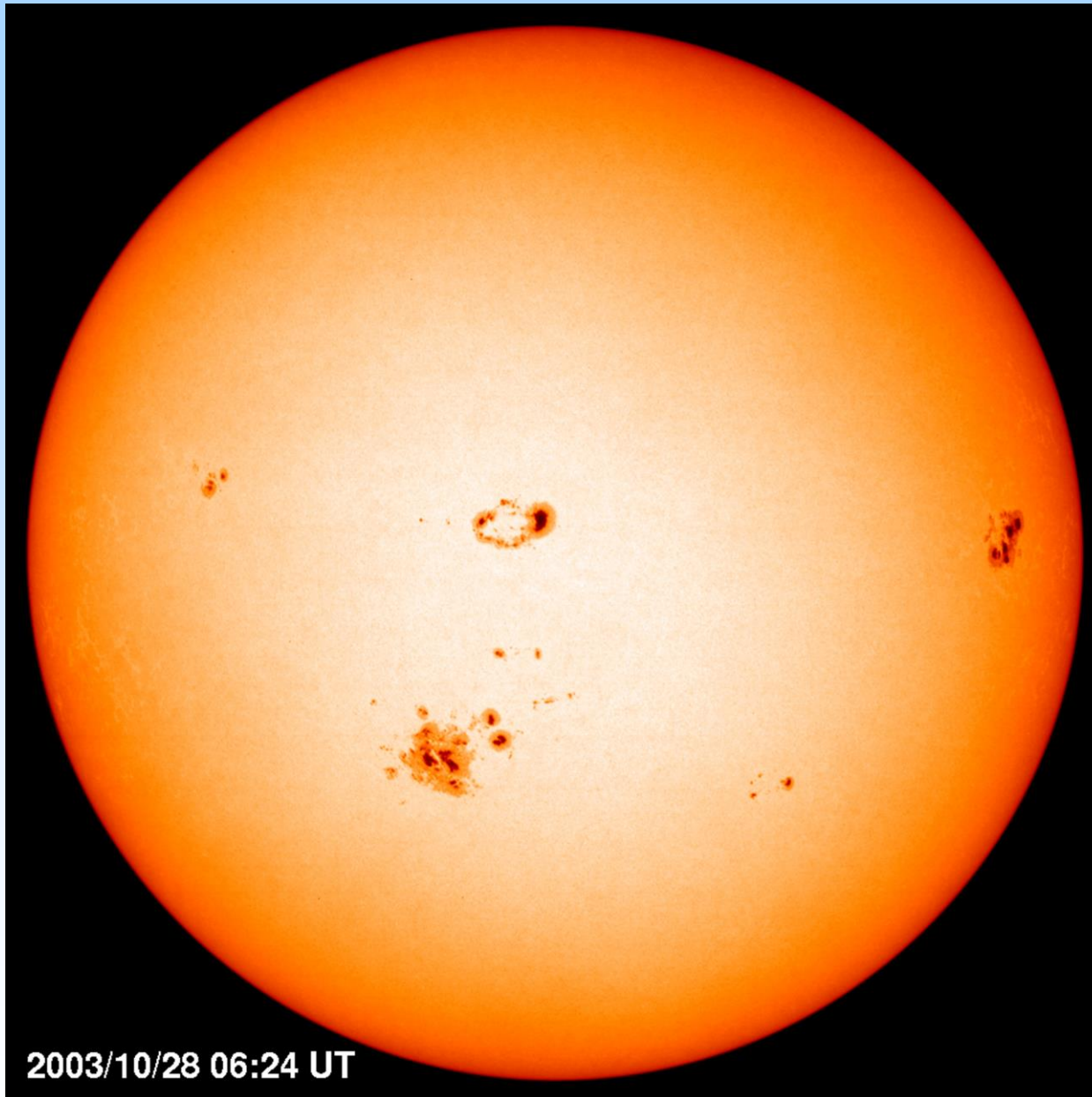


BBSO Granulation (near IR; 60 min)



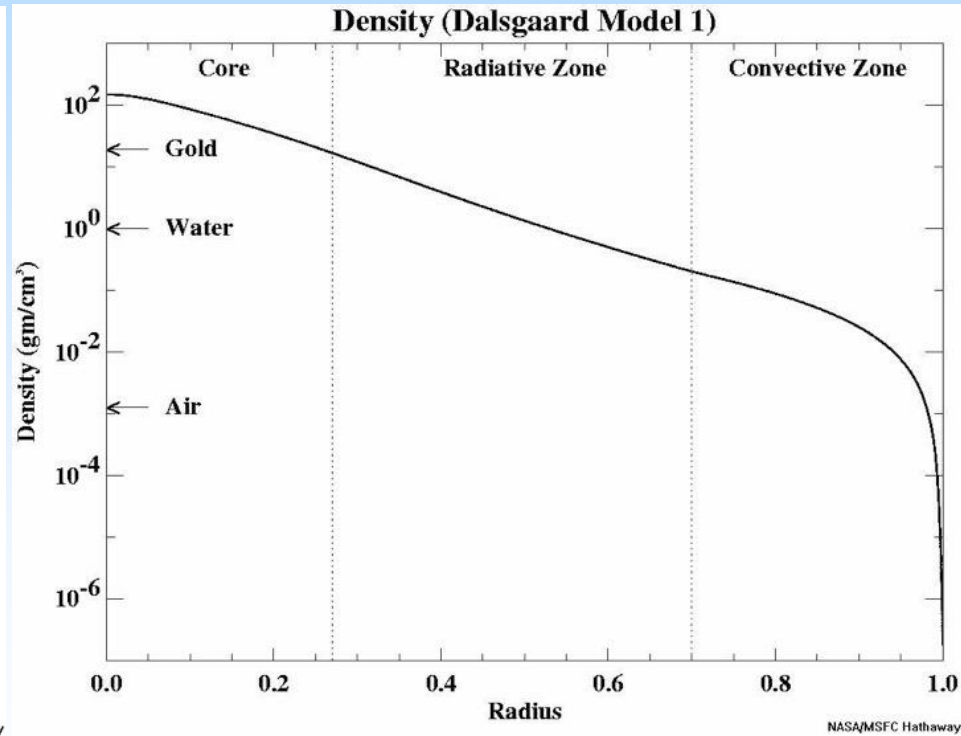
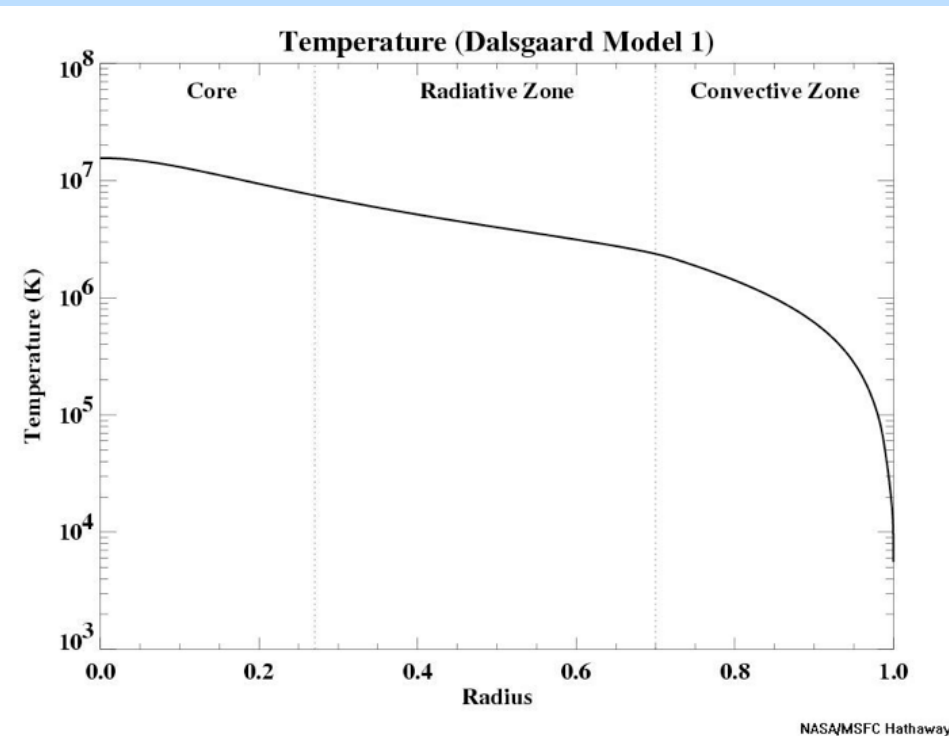
Convection on *Pluto* too??





The Photosphere

The Solar Interior's Temperature Distribution



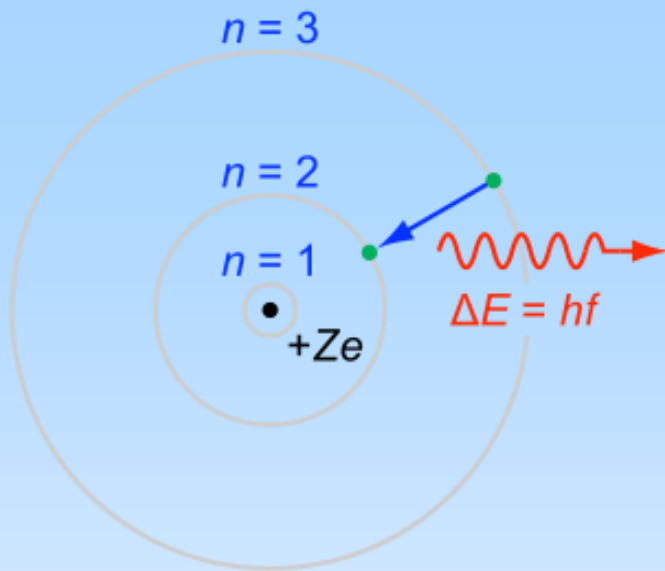
The Outer Solar Atmosphere

(First, an overview)

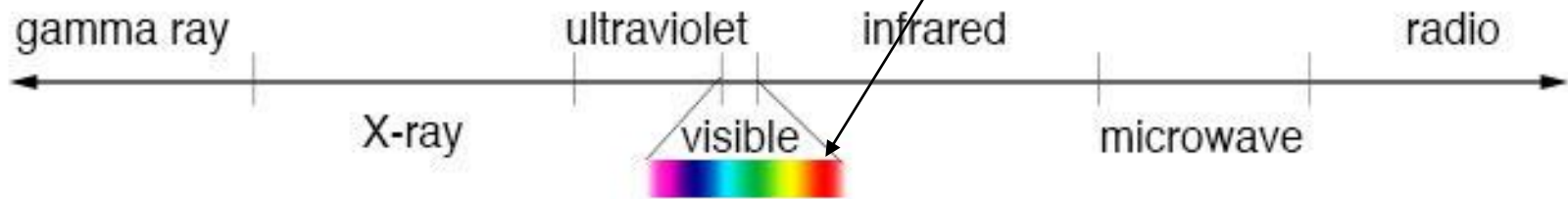


Alphonse Sterling, 2016 Mar 9, Indonesia
ZenithStar 66 + EOS700D, 1/1000 s

Chromosphere

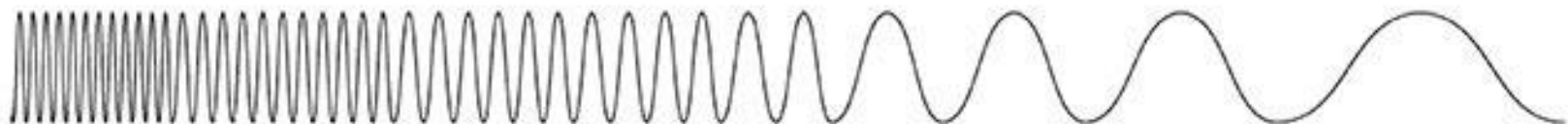


H-alpha ($H\alpha$) transition in hydrogen atom; 656.3 nm.

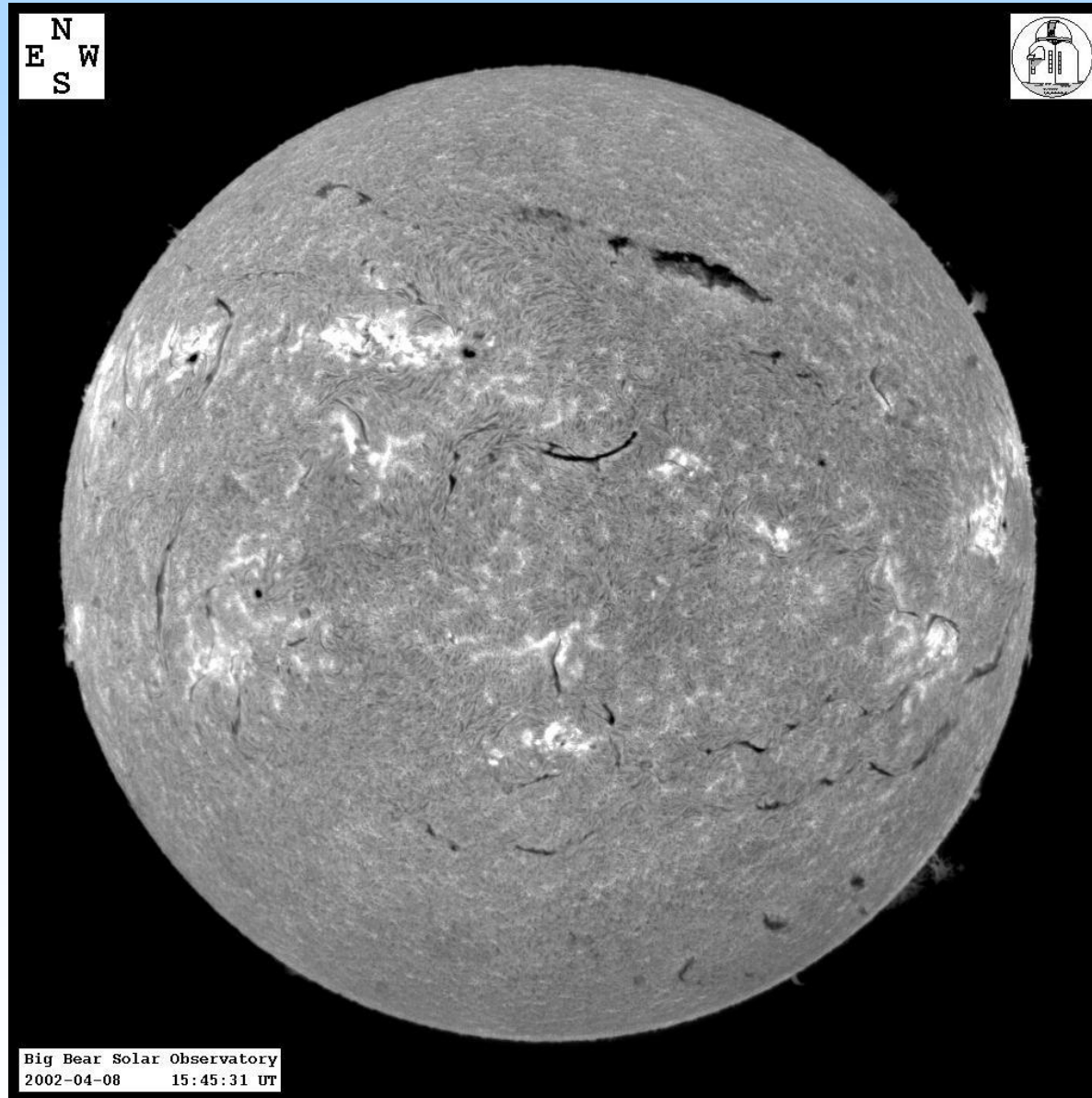


shorter wavelength
higher frequency
higher energy

longer wavelength
lower frequency
lower energy



Chromosphere in H α

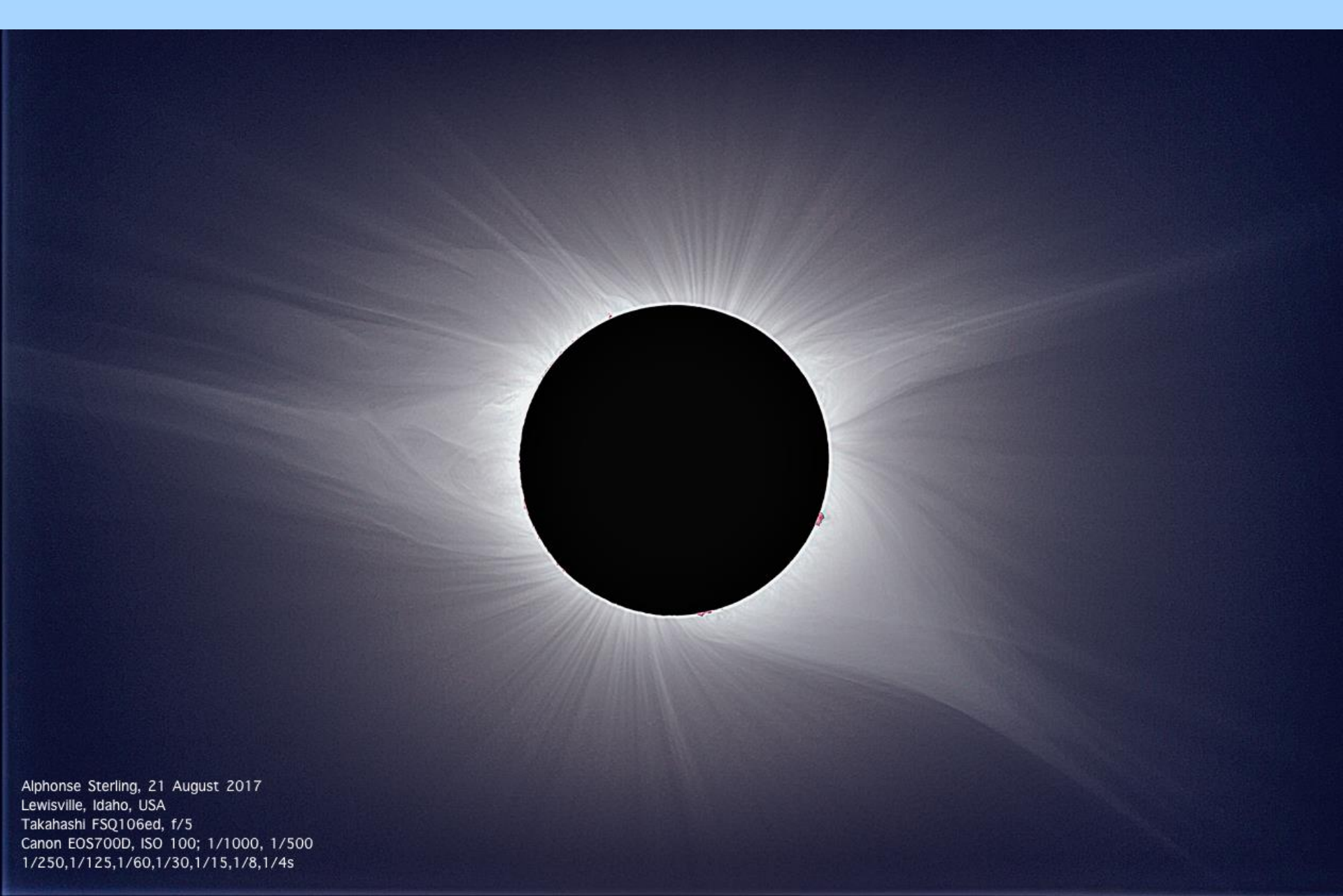


Solar Flare

1971 October 10

Big Bear Solar Observatory

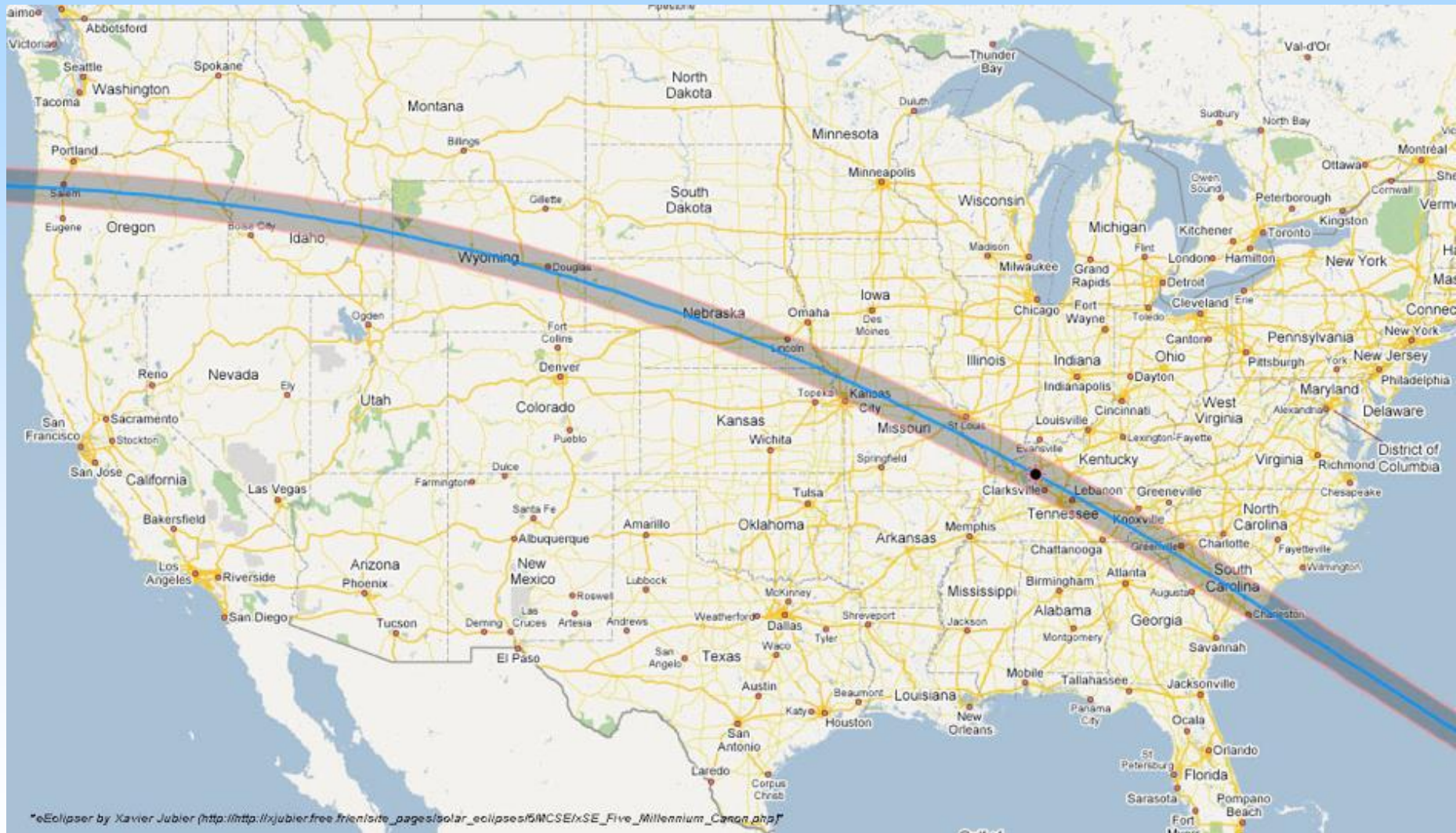




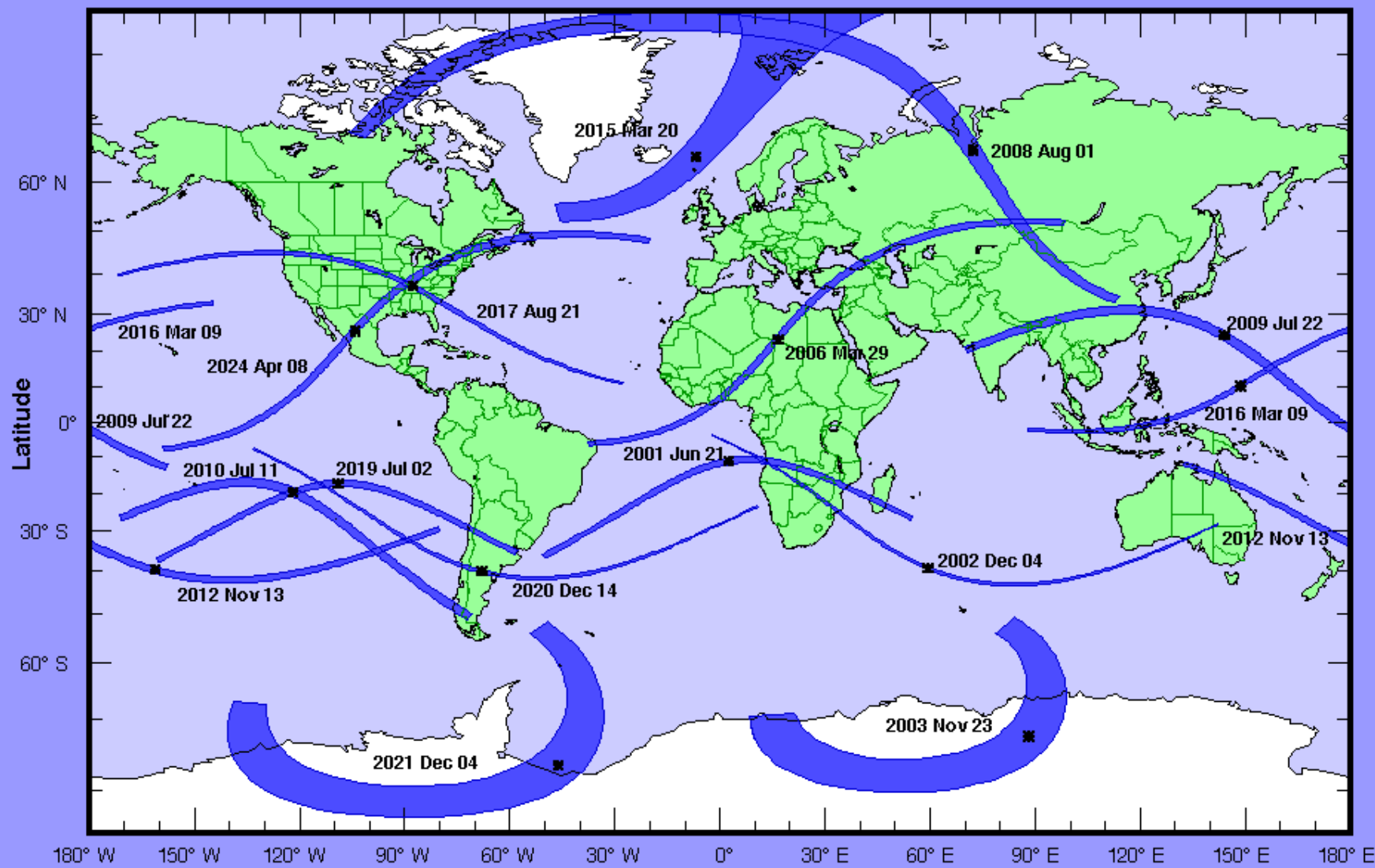
Alphonse Sterling, 21 August 2017
Lewisville, Idaho, USA
Takahashi FSQ106ed, f/5
Canon EOS700D, ISO 100; 1/1000, 1/500
1/250, 1/125, 1/60, 1/30, 1/15, 1/8, 1/4s

Corona – The Sun's outermost atmosphere

August 21, 2017 Total Solar Eclipse Path

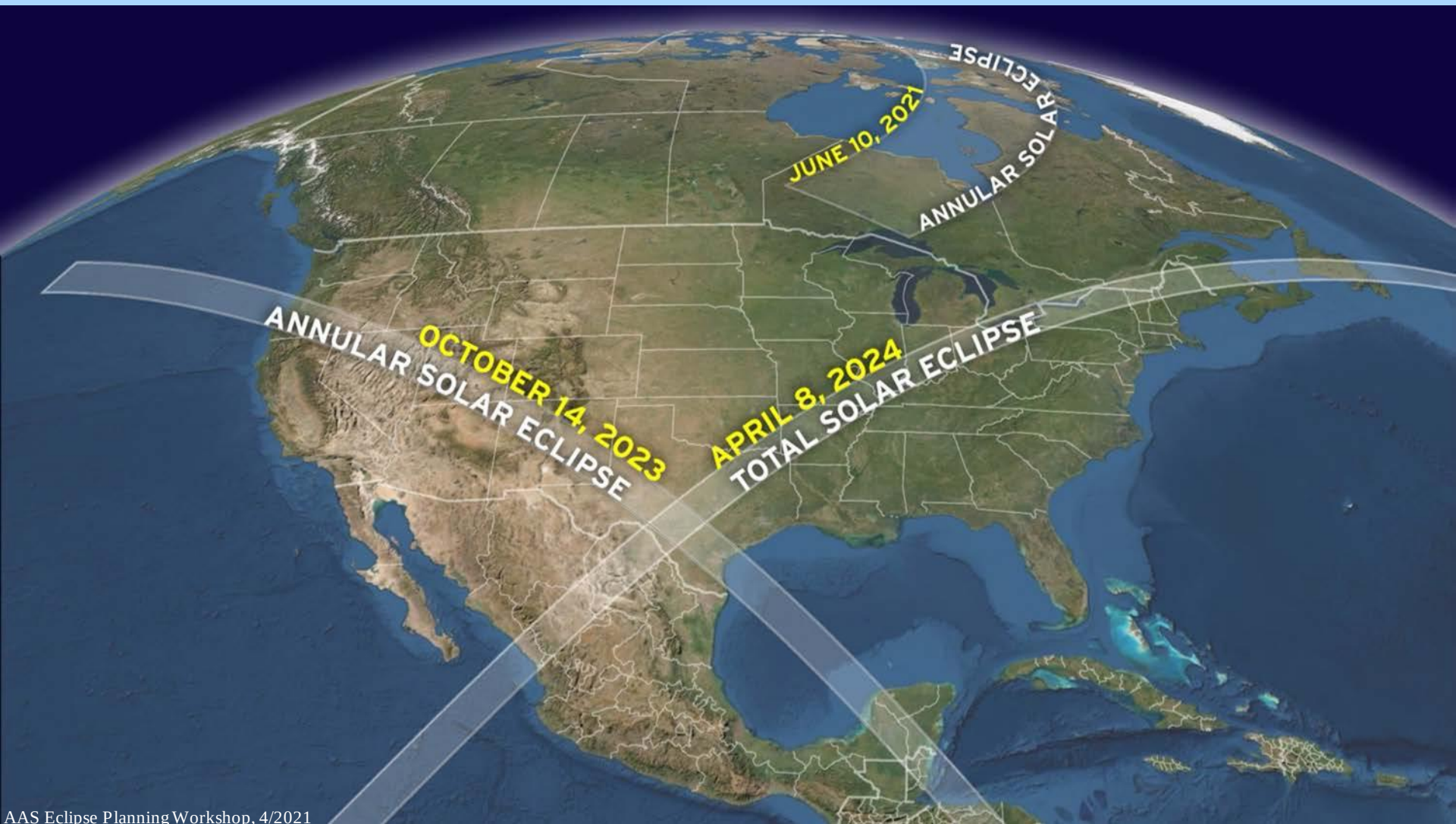


Total Solar Eclipse Paths: 2001–2025



- Total Eclipse
- Annular Eclipse
- Hybrid Eclipse





AAS Eclipse Planning Workshop, 4/2021



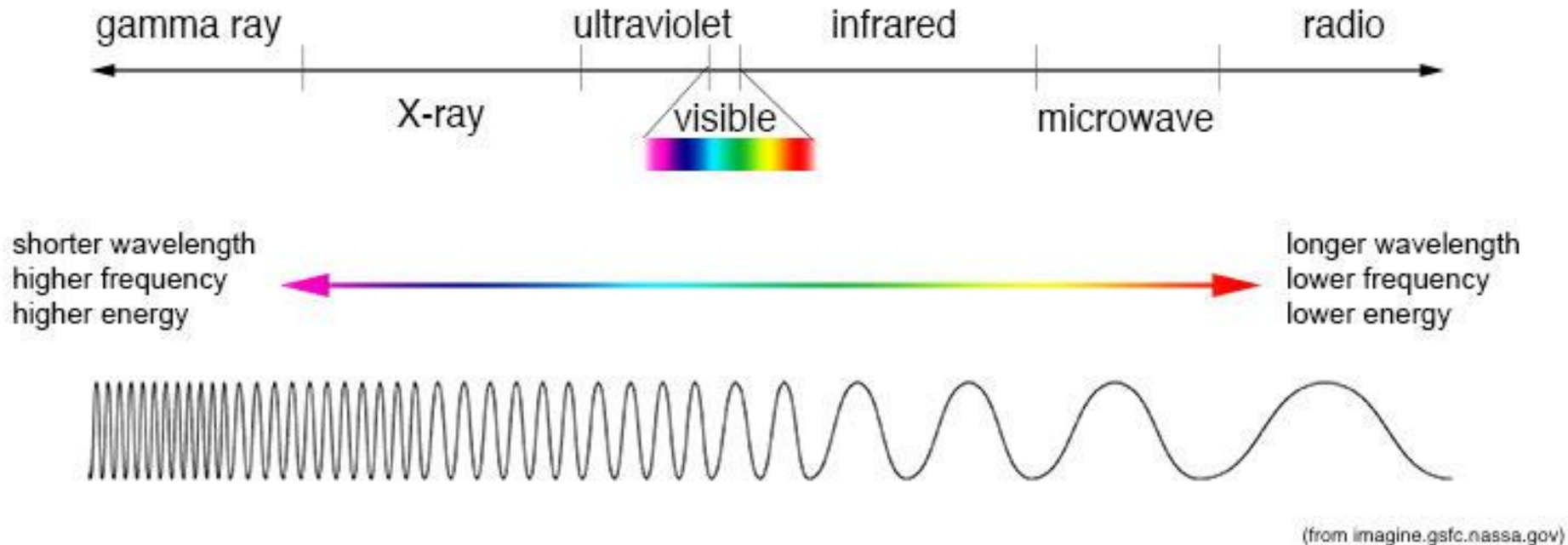
20 May 2012 22:34:57+-5s UT
FSQ106ED f/5, EM11, EOS500D, 100, 1/125
ISAS, Sagamihara, Kanagawa, Japan
Alphonse Sterling

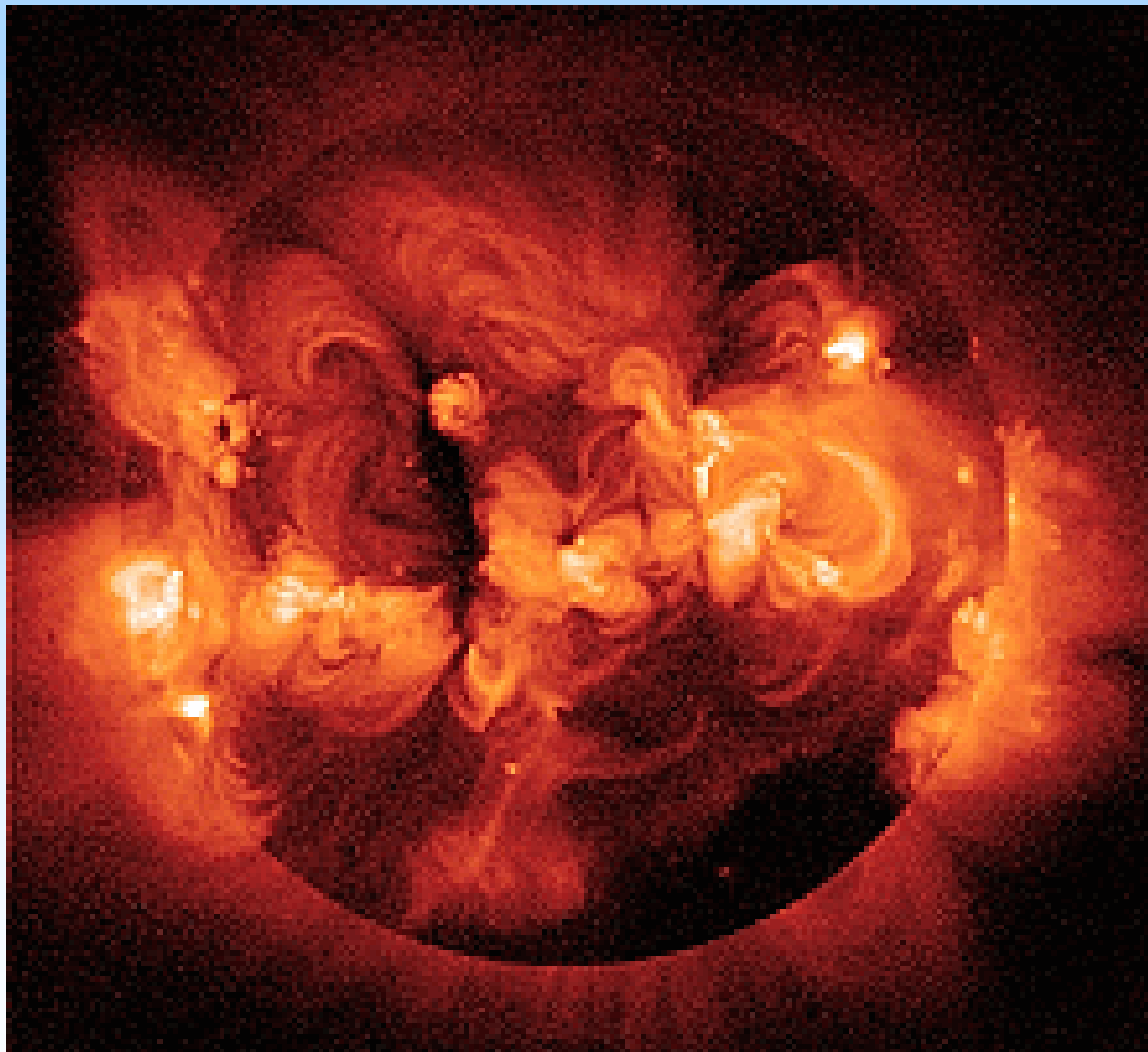


20 May 2012 22:37:33+-5s UT
FSQ106ED f/5, EM11, EOS500D, 100, 1/250
ISAS, Sagamihara, Kanagawa, Japan
Alphonse Sterling

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

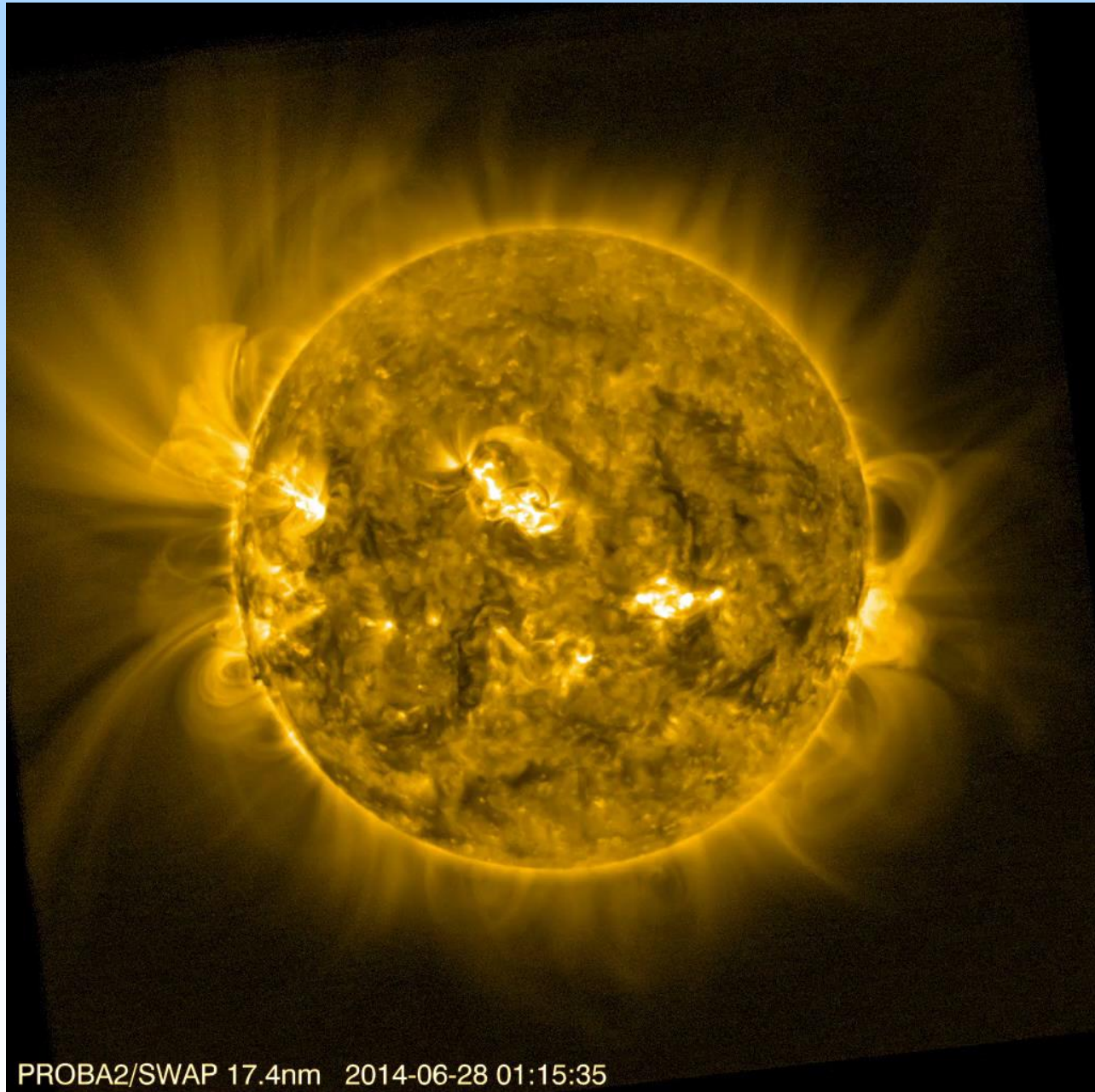
The Electromagnetic Spectrum





NASA

The Corona from Yohkoh/SXT

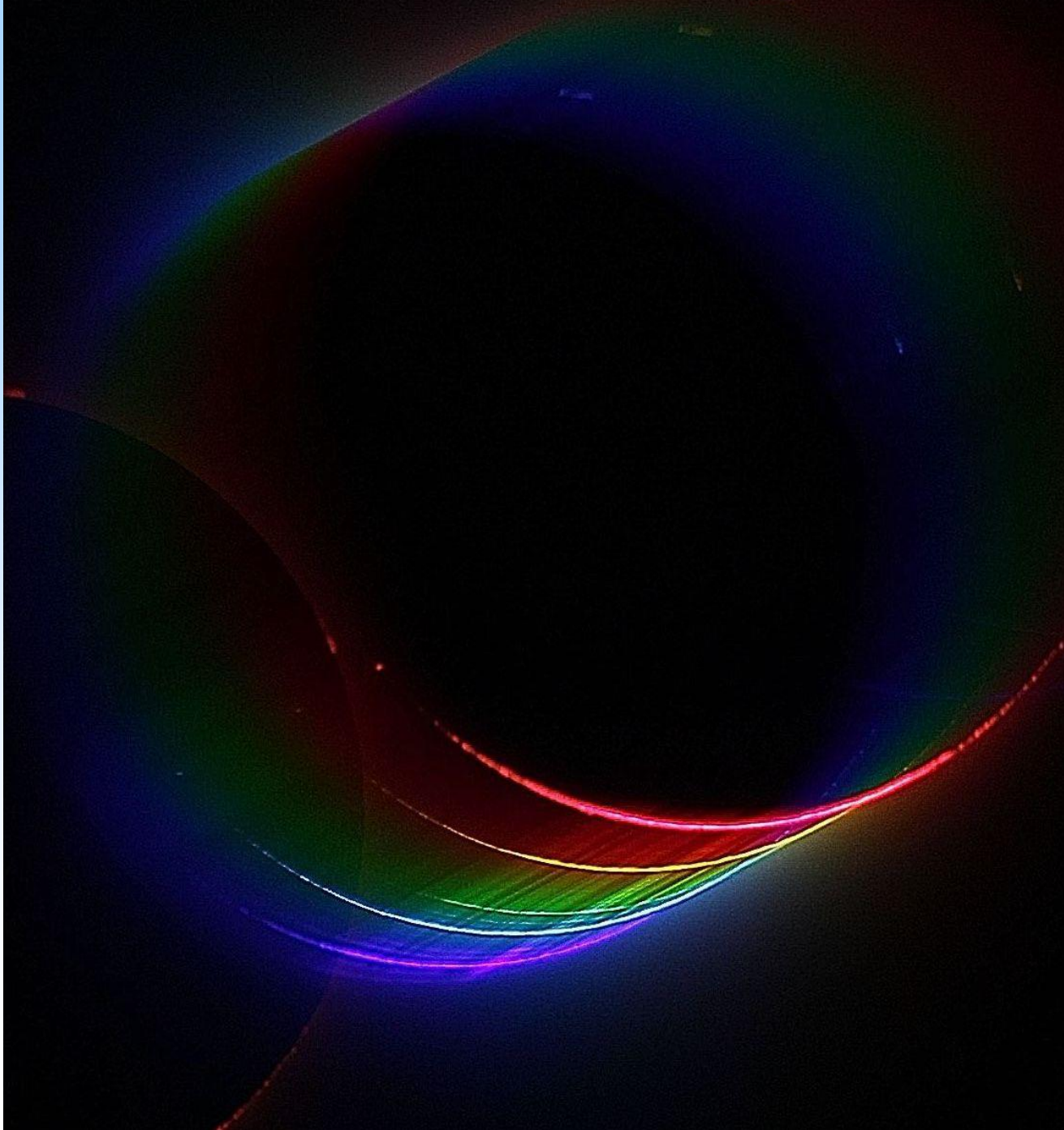


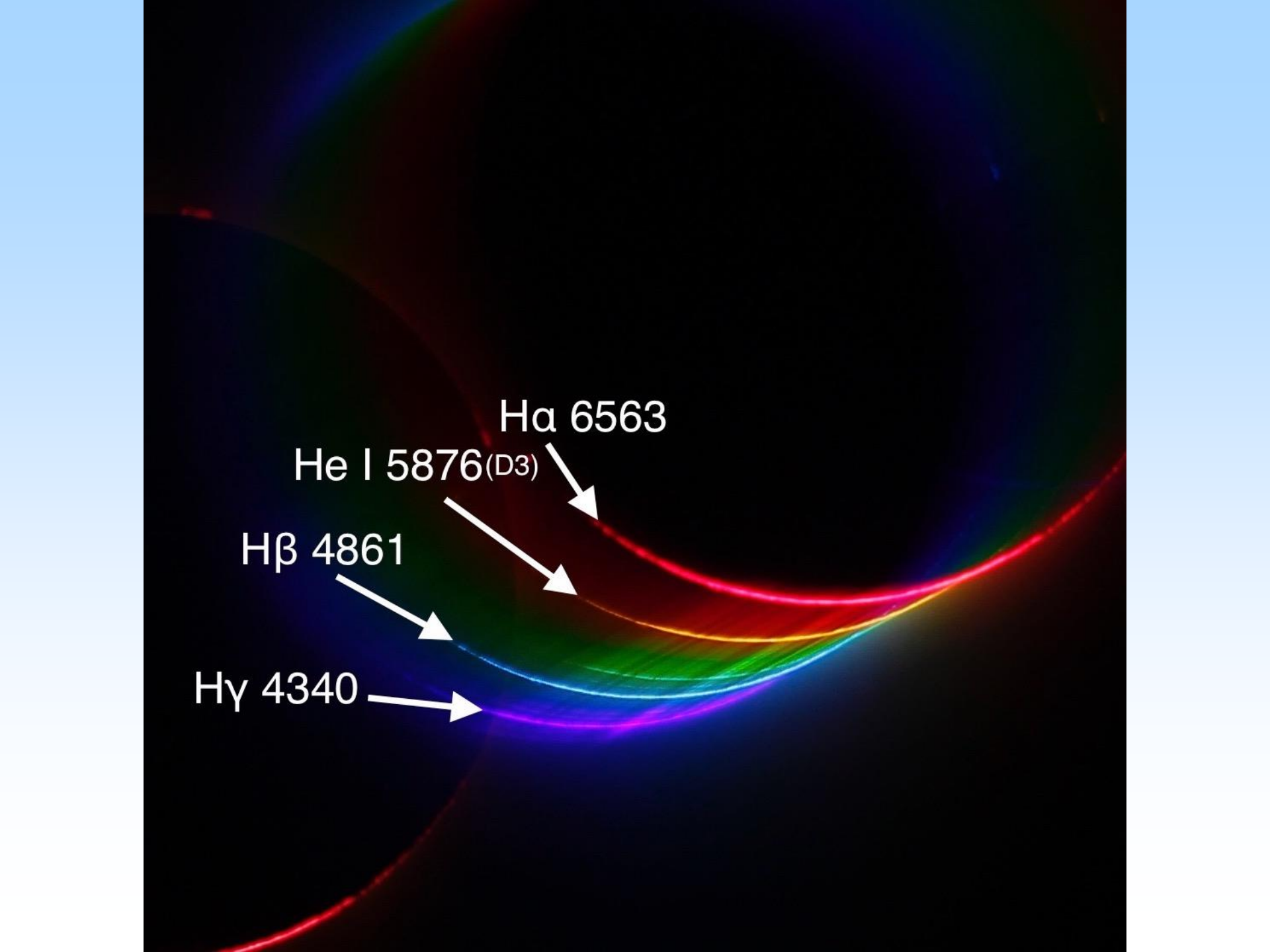
PROBA2/SWAP 17.4nm 2014-06-28 01:15:35

Atmosphere's Temperature Structure

The Corona

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





A photograph of a celestial object, likely a nebula, showing a spectrum of light. The spectrum is a curved band of colors, with red at the top and blue at the bottom. Several specific emission lines are labeled with white text and white arrows pointing to them. The labels are: H α 6563, He I 5876(D3), H β 4861, and H γ 4340. The H α line is the most prominent, appearing as a bright red line. The He I line is a yellow-green line. The H β line is a bright blue-green line. The H γ line is a blue line.

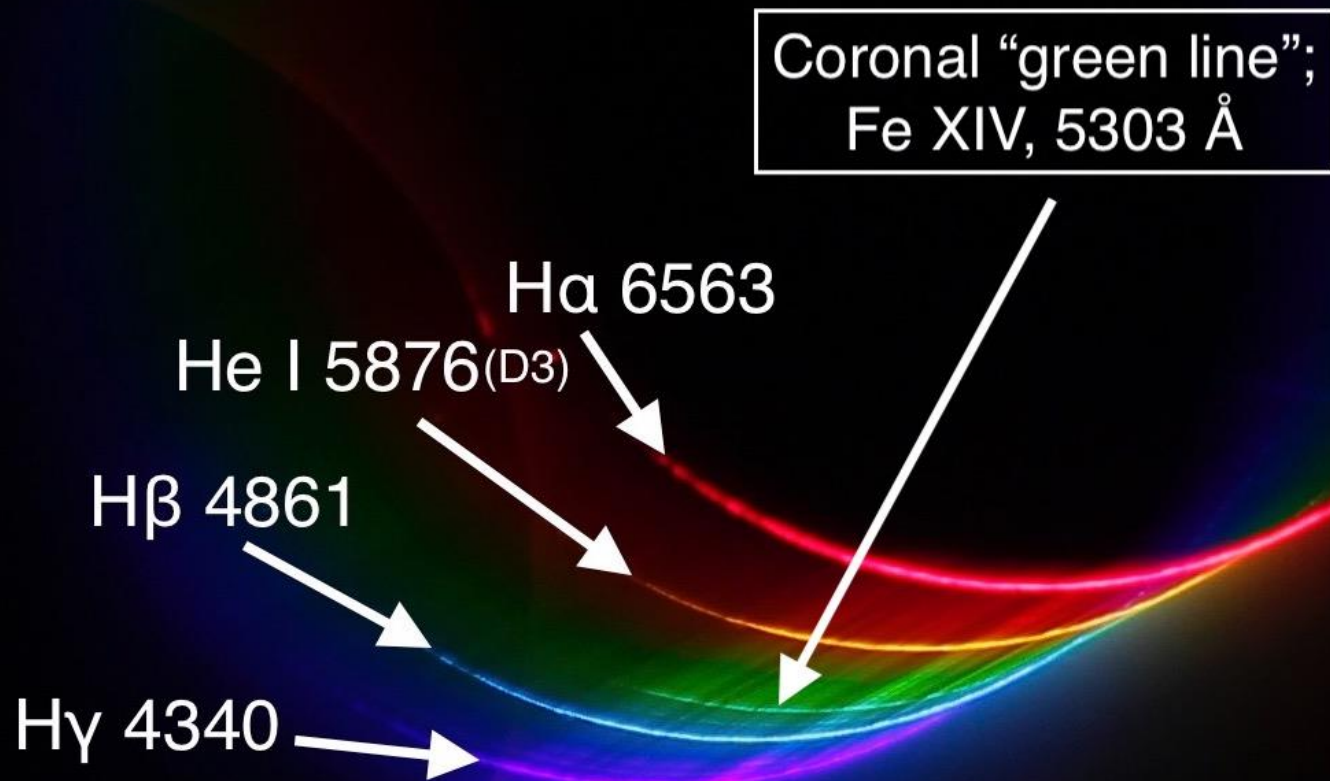
H α 6563

He I 5876(D3)

H β 4861

H γ 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

1 H hydrogen 1.007 94(7) Atomic Number Symbol Name Standard Atomic Weight																	
3	4											5	6	7	8	9	10
Li	Be											B	C	N	O	F	Ne
lithium	beryllium											boron	carbon	nitrogen	oxygen	fluorine	neon
11	12											13	14	15	16	17	18
Na	Mg											Al	Si	P	S	Cl	Ar
sodium	magnesium											aluminum	silicon	phosphorus	sulfur	chlorine	argon
19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
potassium	calcium	scandium	titanium	vanadium	chromium	manganese	iron	cobalt	nickel	copper	zinc	gallium	germanium	arsenic	selenium	bromine	krypton
37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
rubidium	strontium	yttrium	zirconium	niobium	molybdenum	technetium	ruthenium	rhodium	palladium	silver	cadmium	indium	tin	antimony	tellurium	iodine	xenon
55	56	57-71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86
Cs	Ba	La-Lu	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
caesium	barium	lanthanoids	hafnium	tantalum	tungsten	rhenium	osmium	iridium	platinum	gold	mercury	thallium	lead	bismuth	polonium	astatine	radon
87	88	89-103	104	105	106	107	108	109	110	111							
Fr	Ra	Ac-Lr	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg							
francium	radium	actinoids	rutherfordium	dubnium	seaborgium	bohrium	hassium	meitnerium	darmstadtium	roentgenium							
lanthanoids		57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	
		La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	
		lanthanum	cerium	praseodymium	neodymium	promethium	samarium	euroium	gadolinium	terbium	dysprosium	holmium	erbium	thulium	ytterbium	lutetium	
actinoids		89	90	91	92	93	94	95	96	97	98	99	100	101	102	103	
		Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr	
		actinium	thorium	protactinium	uranium	neptunium	plutonium	americium	curium	berkelium	californium	einsteinium	fermium	mendelevium	nobelium	lawrencium	

NASA/CXC/SAO

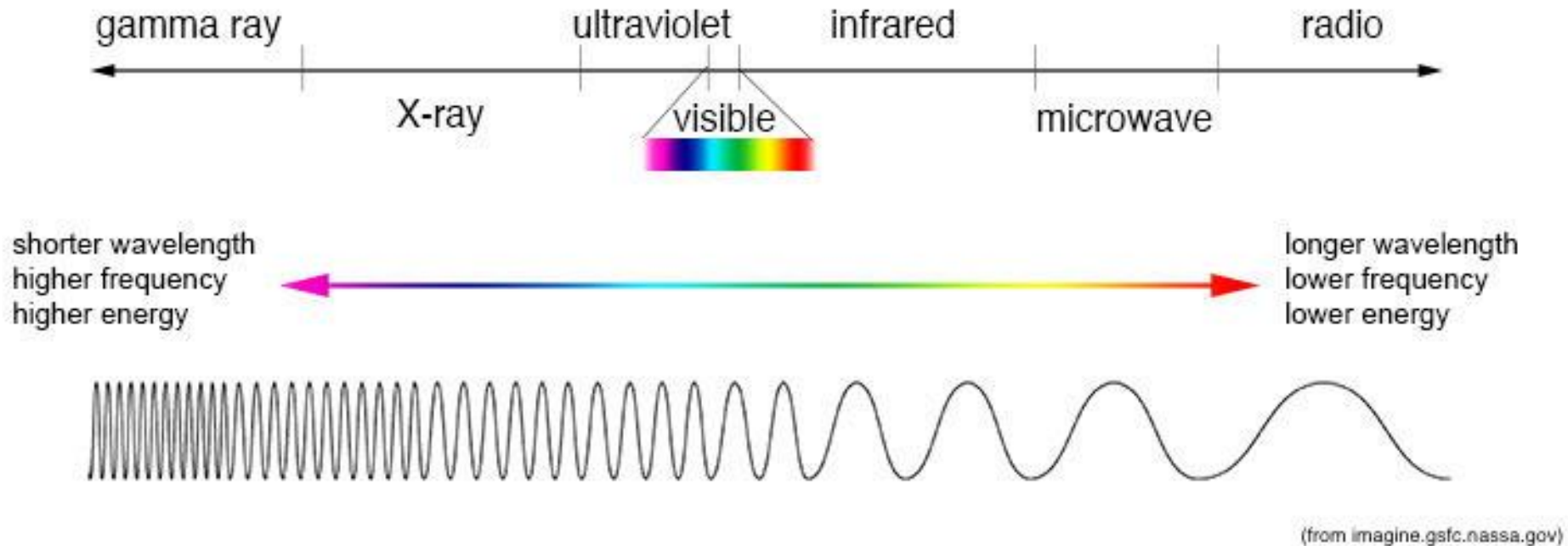
The Corona: Continued...

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

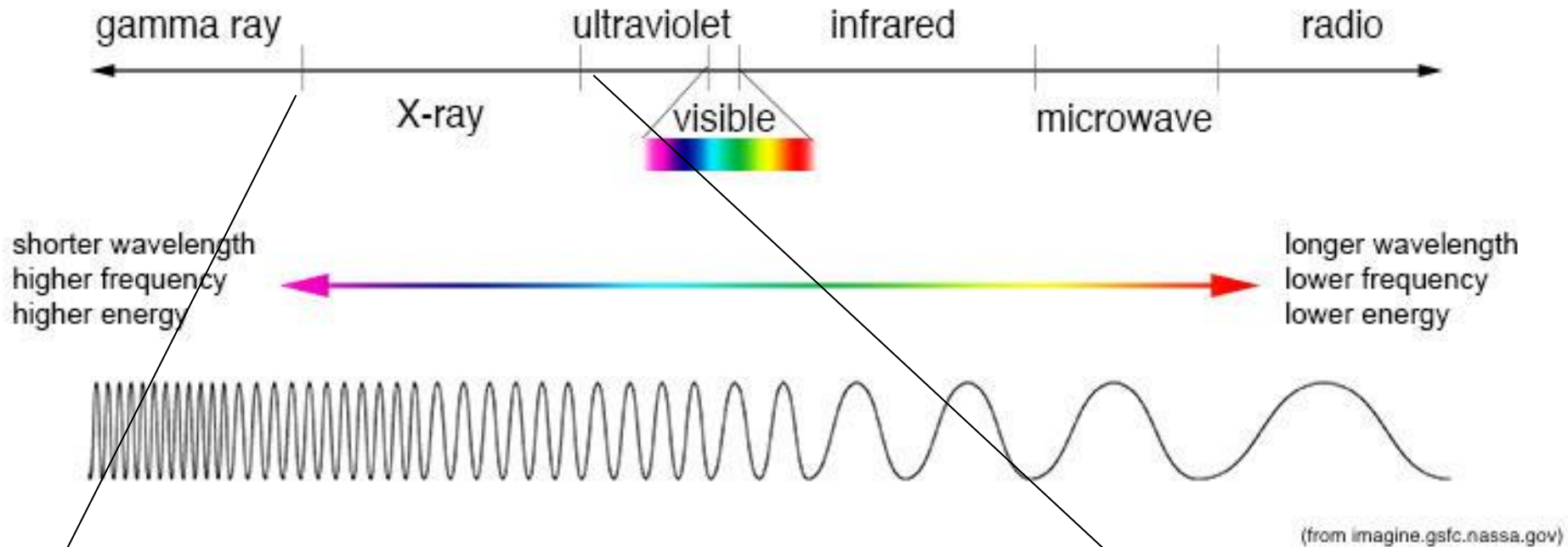
So this was a sloooooow process: 1869 eclipse observations, and 1939~1943 explanation!!

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

The Electromagnetic Spectrum



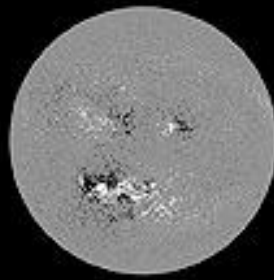
The Electromagnetic Spectrum



Hard X-ray ($\sim 1\text{--}0.1 \text{ \AA}$); Soft X-ray ($\sim 10\text{--}1 \text{ \AA}$); Extreme UV ($\sim 1000\text{--}100 \text{ \AA}$)



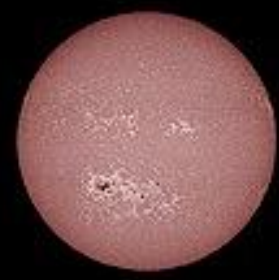
HMI Dopplergram
Surface movement
Photosphere



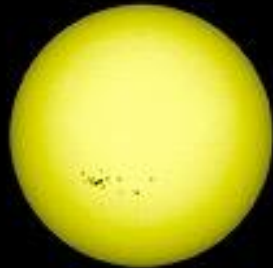
HMI Magnetogram
Magnetic field polarity
Photosphere



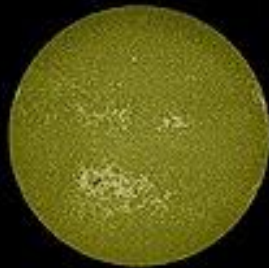
HMI Continuum
Matches visible light
Photosphere



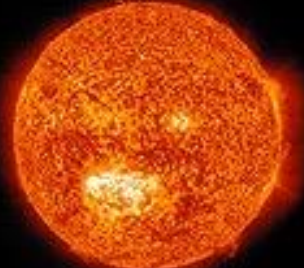
AIA 1700 Å
4500 Kelvin
Photosphere



AIA 4500 Å
6000 Kelvin
Photosphere



AIA 1600 Å
10,000 Kelvin
Upper photosphere/
Transition region



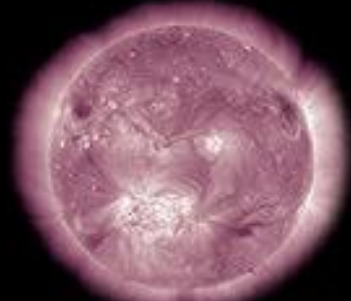
AIA 304 Å
50,000 Kelvin
Transition region/
Chromosphere



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.

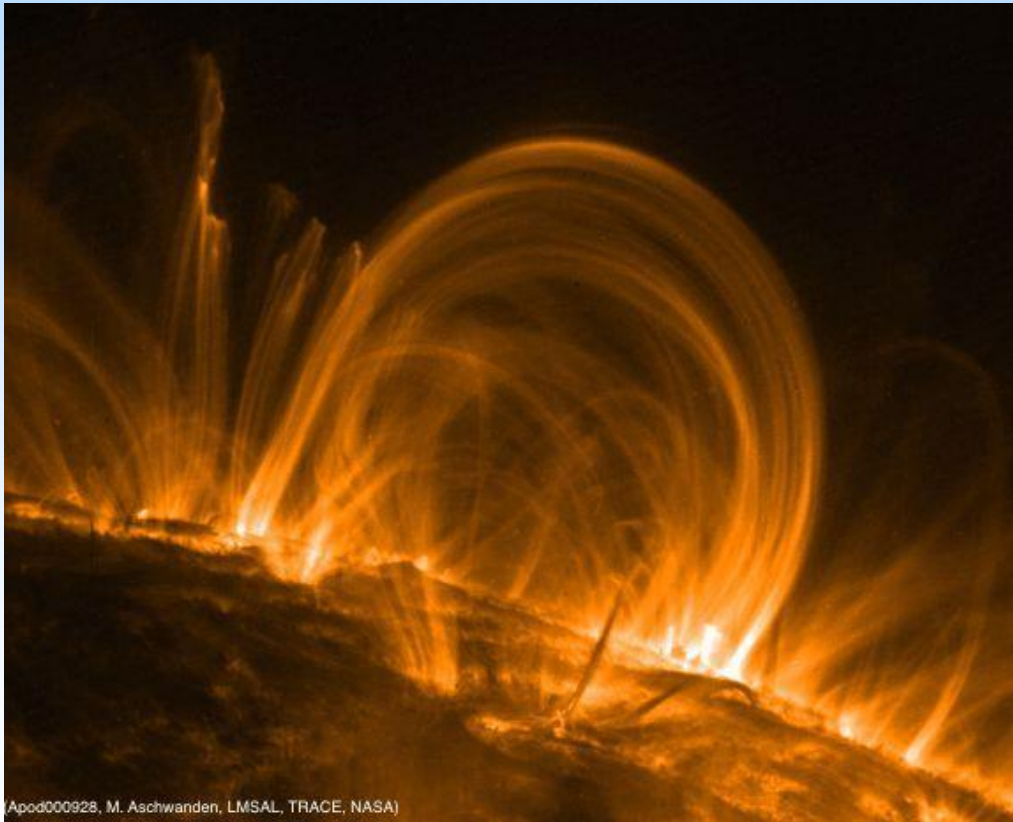
First question: What makes the corona hot??

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.)

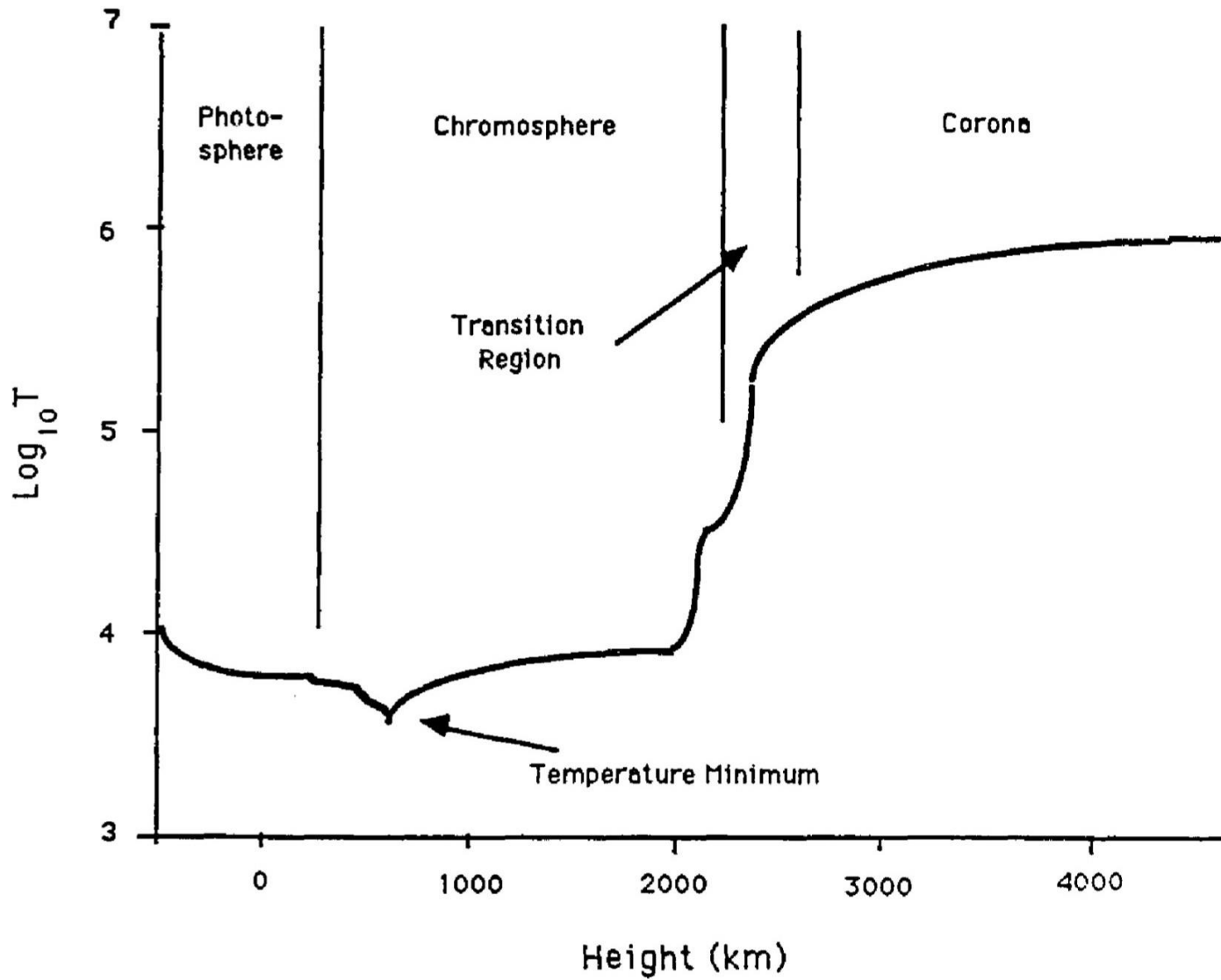
Form of Thermal Conduction:

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

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

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

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



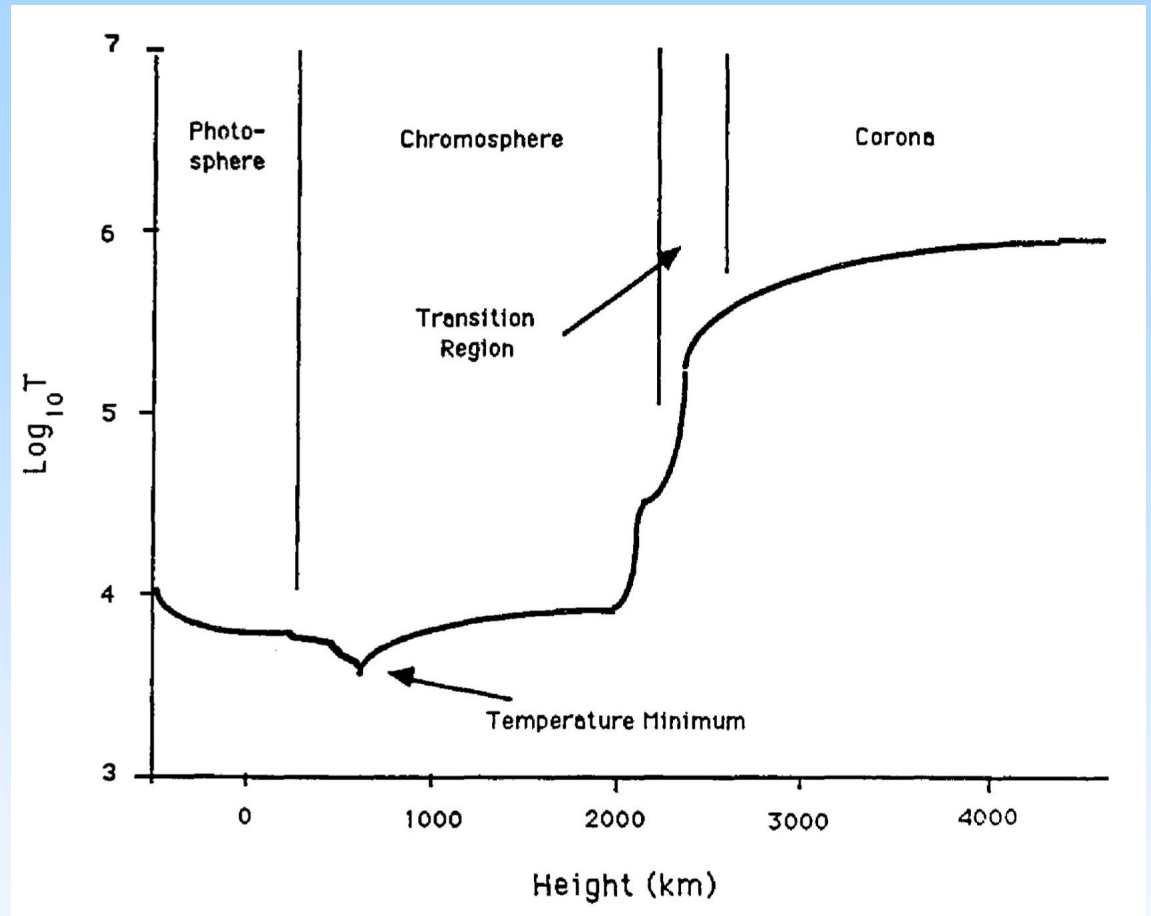
(Sterling, 1988)

$$H - R = C$$

At around $T \sim 10^5$ K:

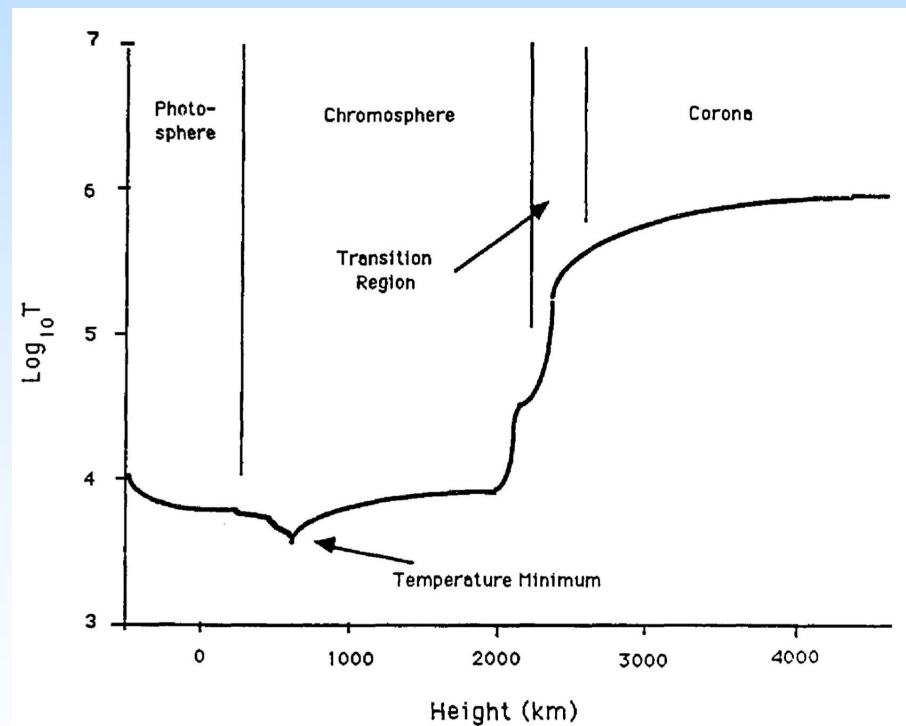
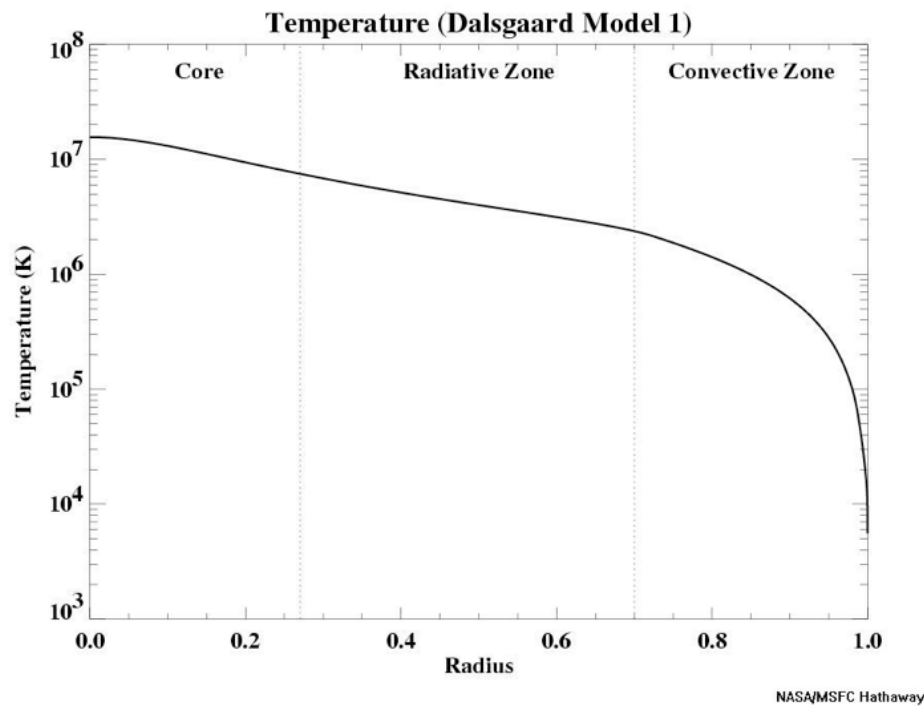
$$-R \approx C$$

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



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



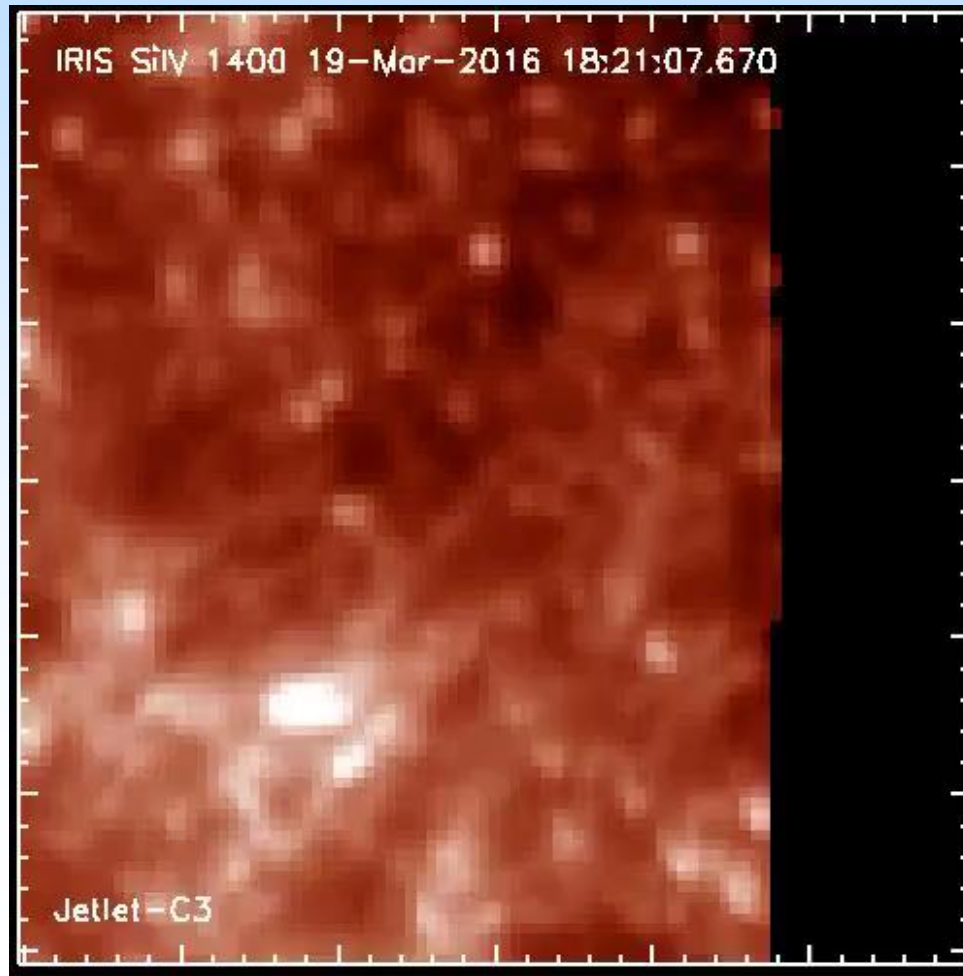
But, is this correct??

- (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

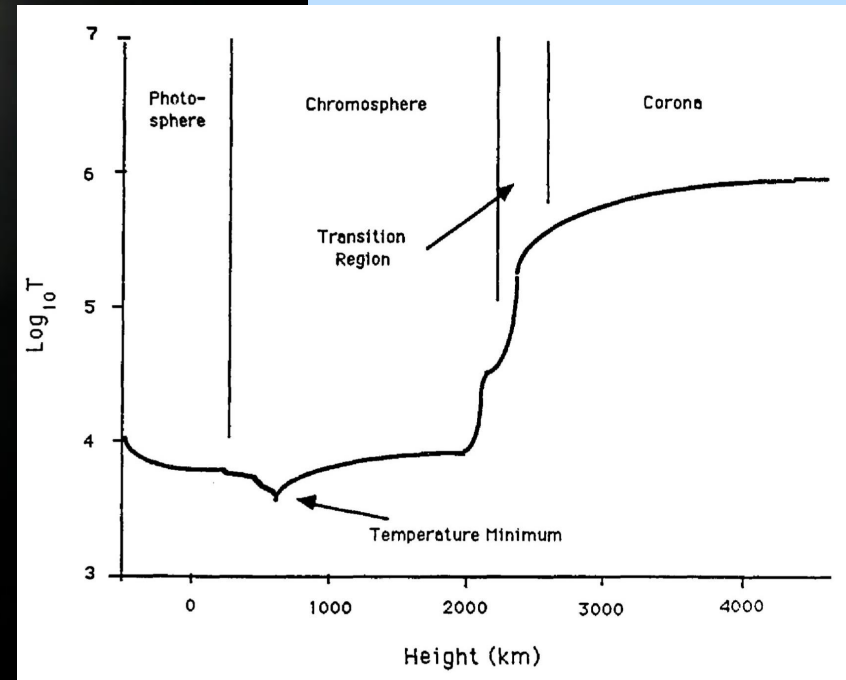
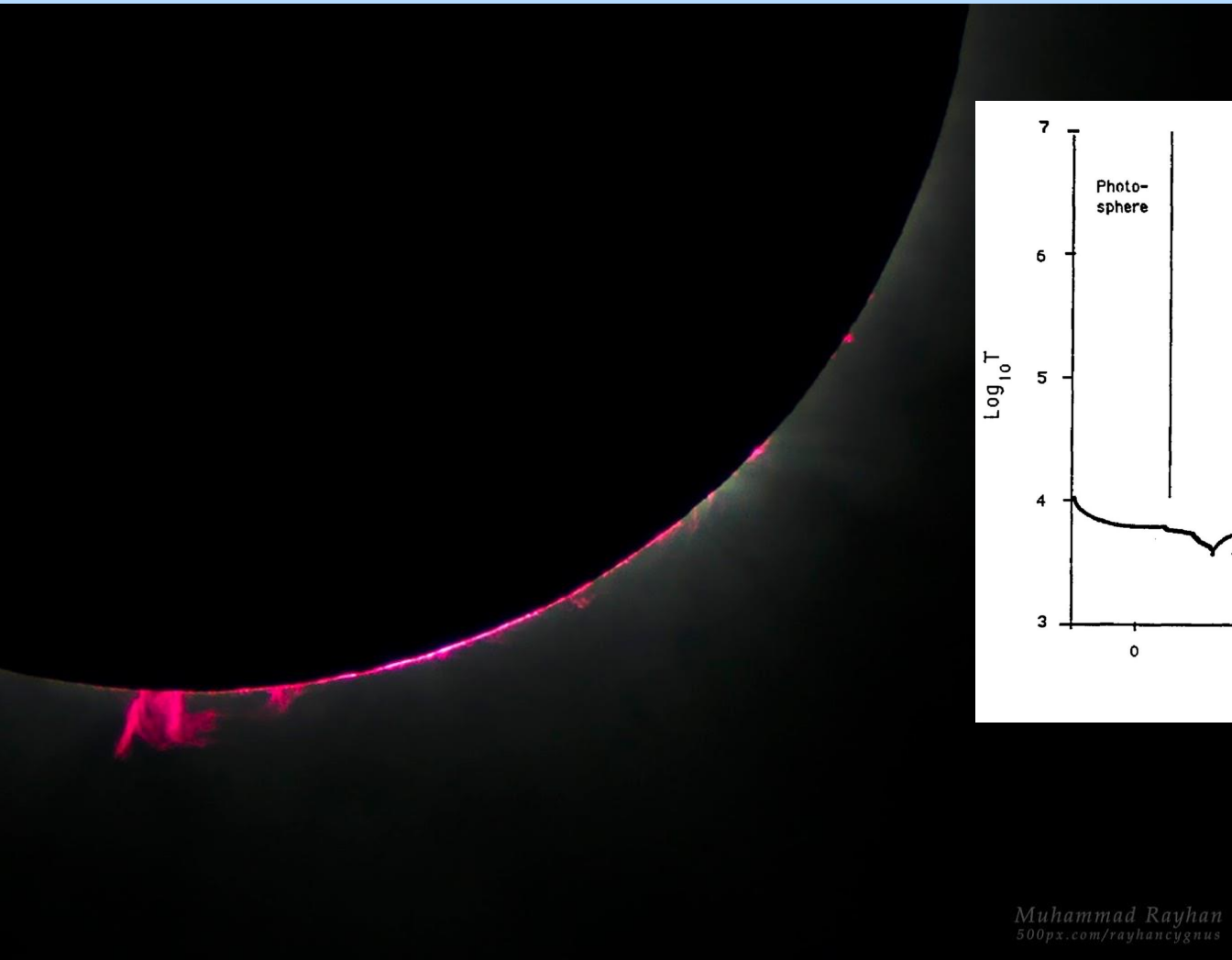
The “IRIS” satellite observes the transition region, and finds it to be highly dynamic. It’s not static, like in the simplest models!



(Panesar et al. 2018)

Another example: Prominences/Filaments

Chromospheric material suspended in the corona

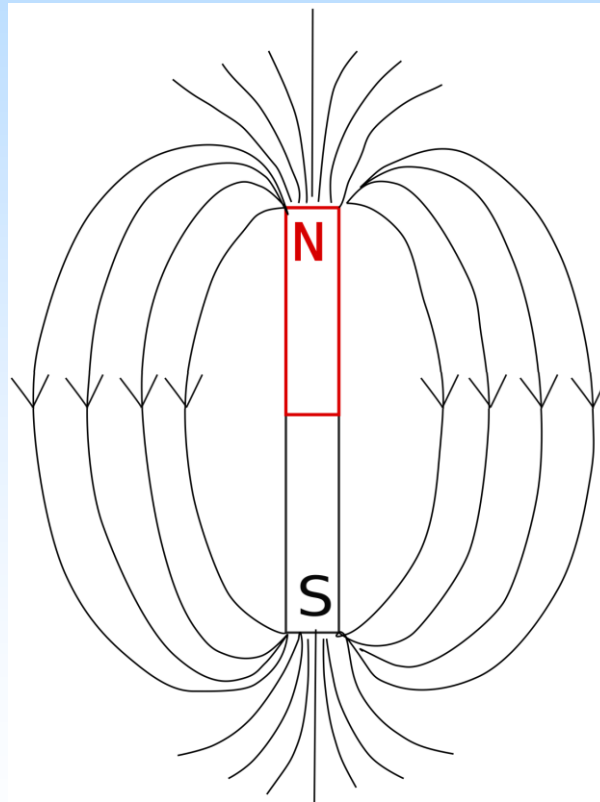


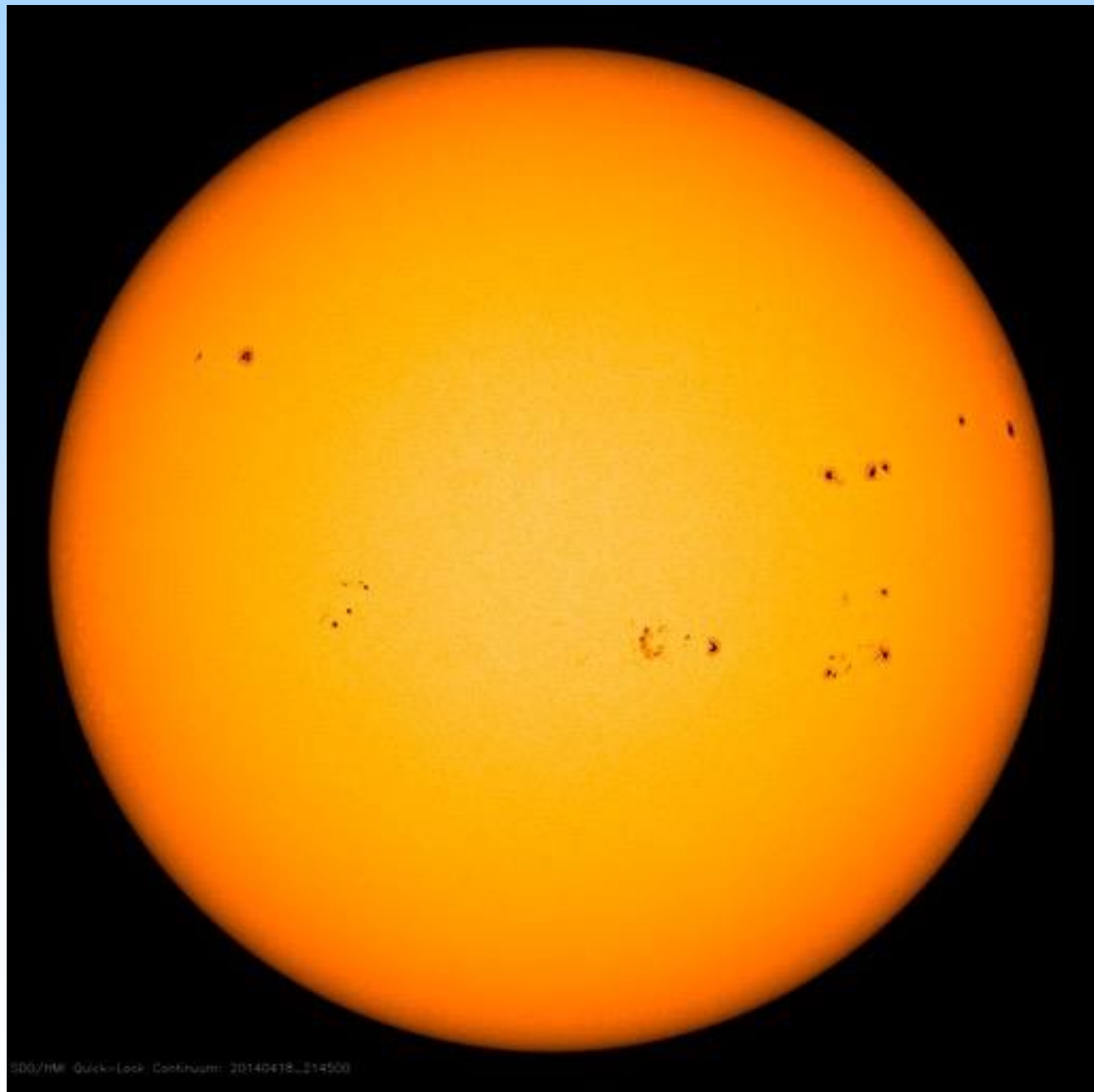
And the conclusion is...

- 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).

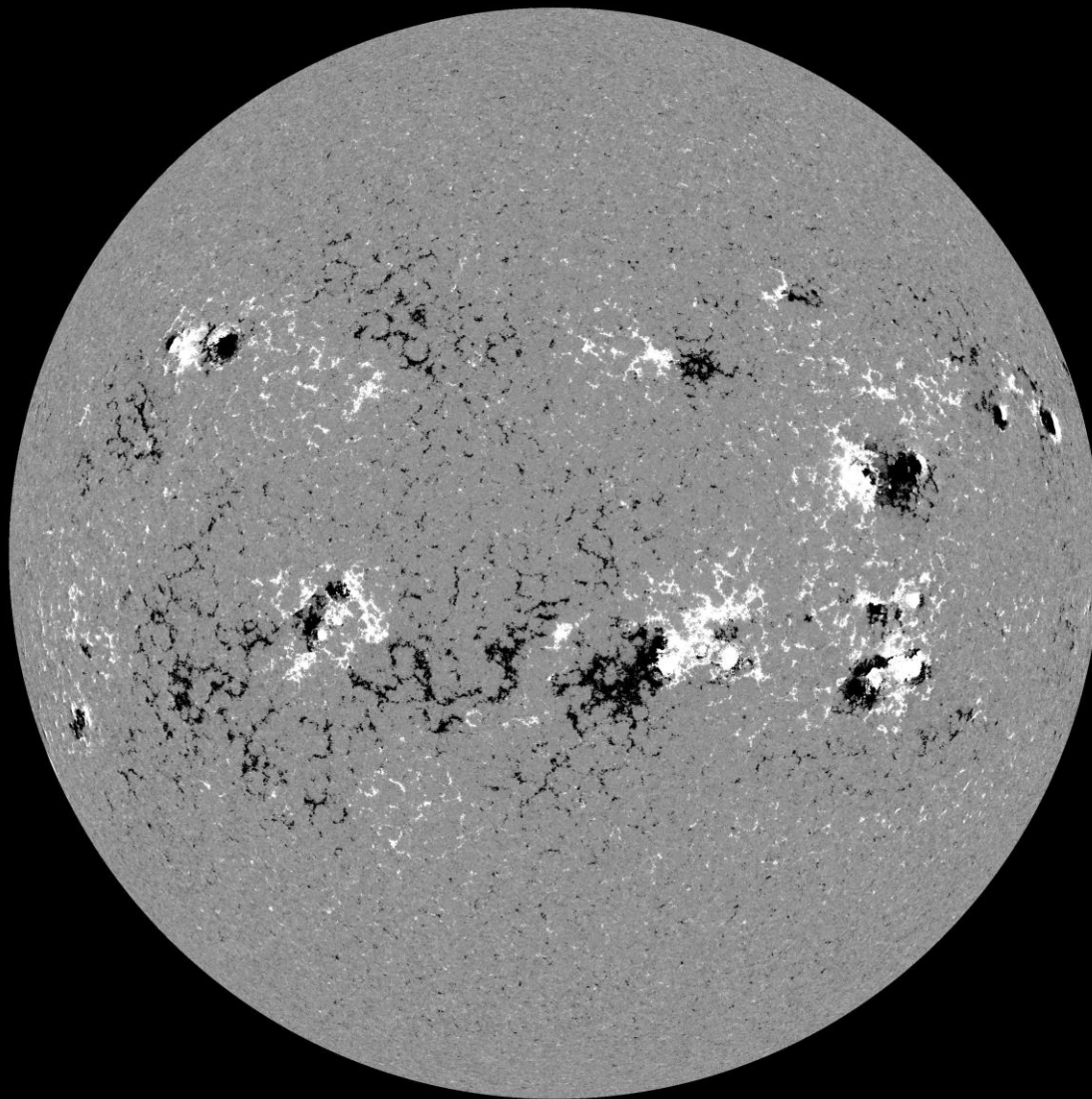
The Magnetic Sun, and Atmospheric Dynamics

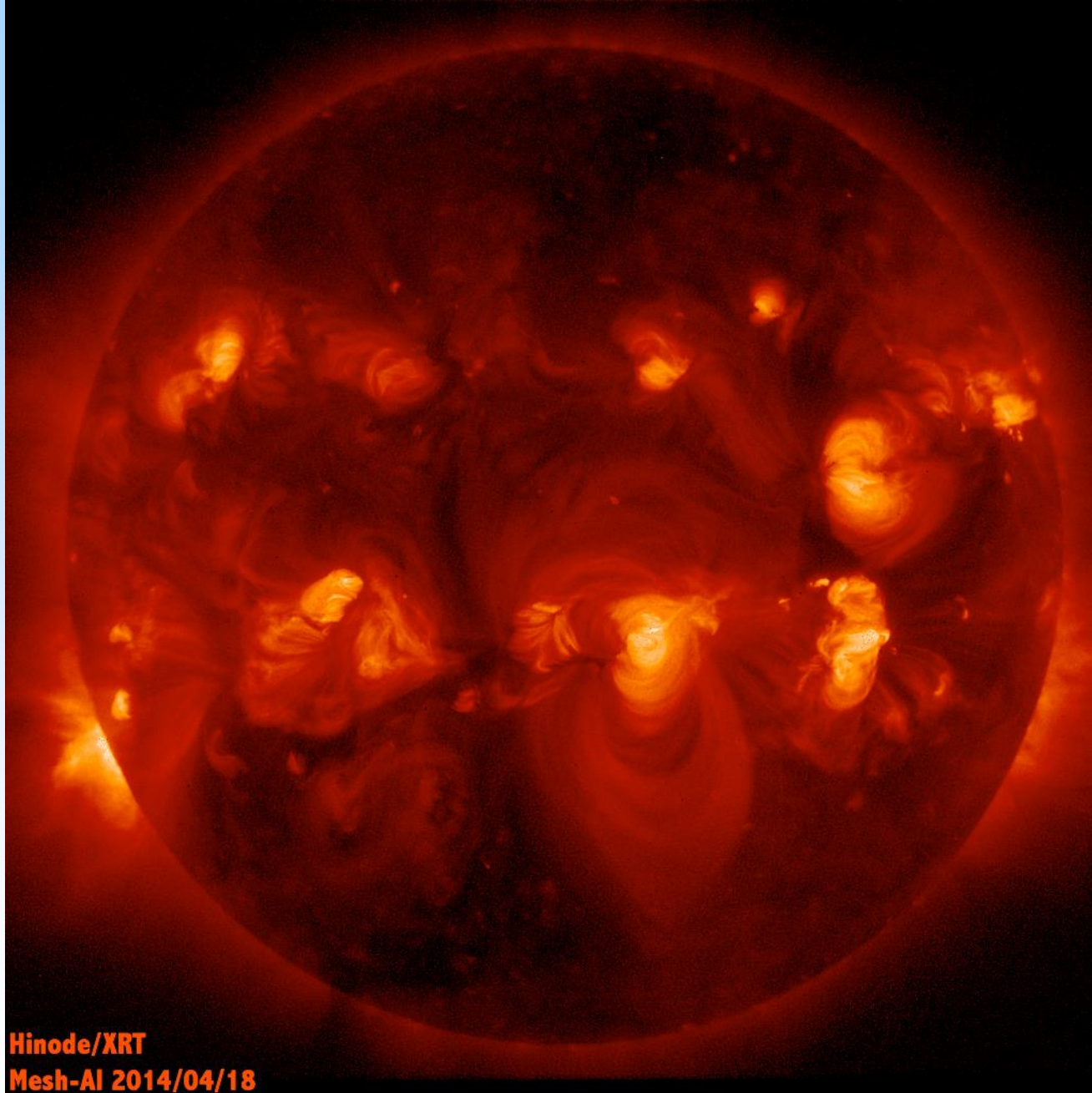
Magnetism is responsible for many of the changing features of the Sun.





SDO/HMI Quick-Look Continuum: 20140418_214500

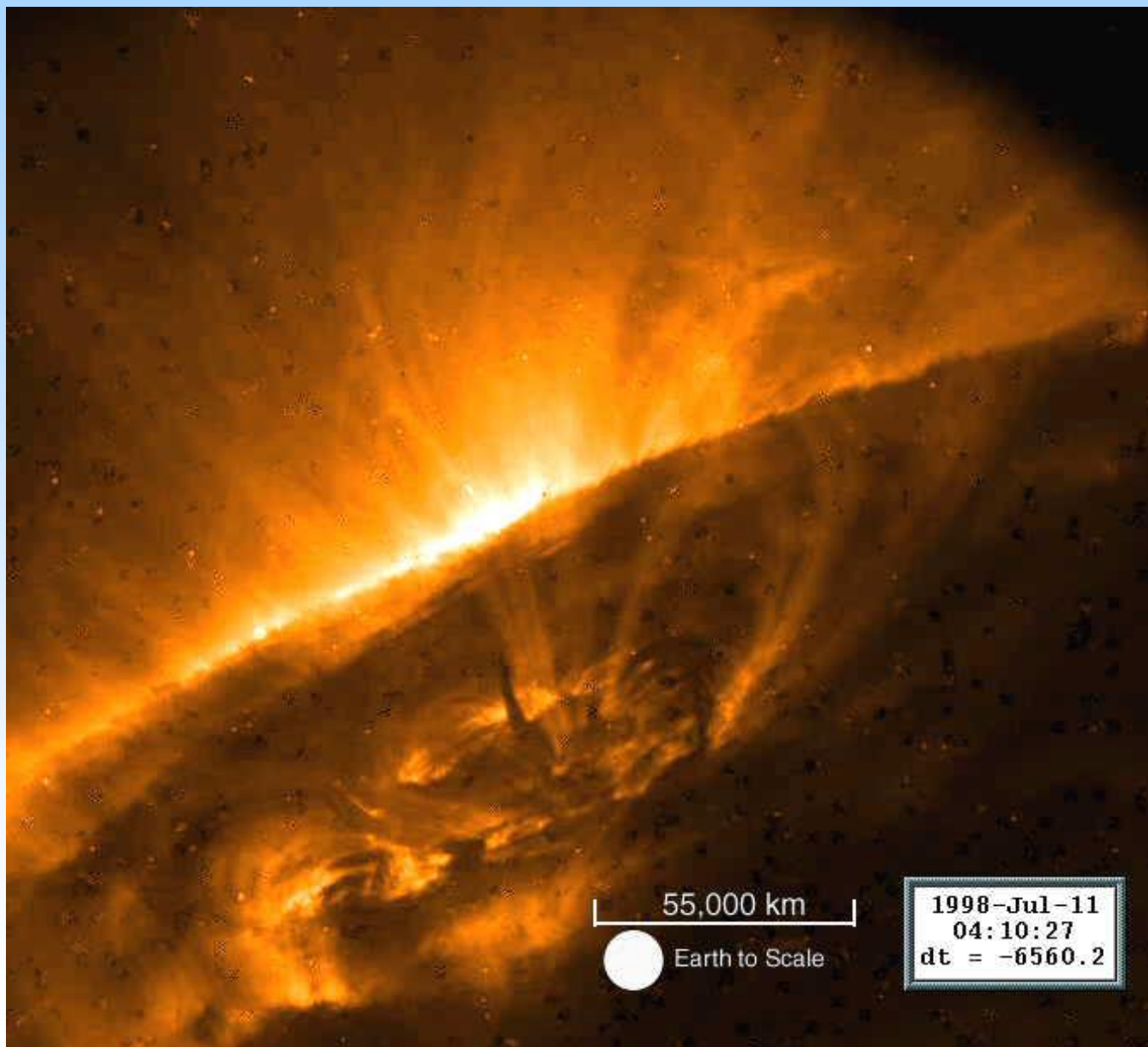




Hinode/XRT

Mesh-AI 2014/04/18

Solar Eruptions

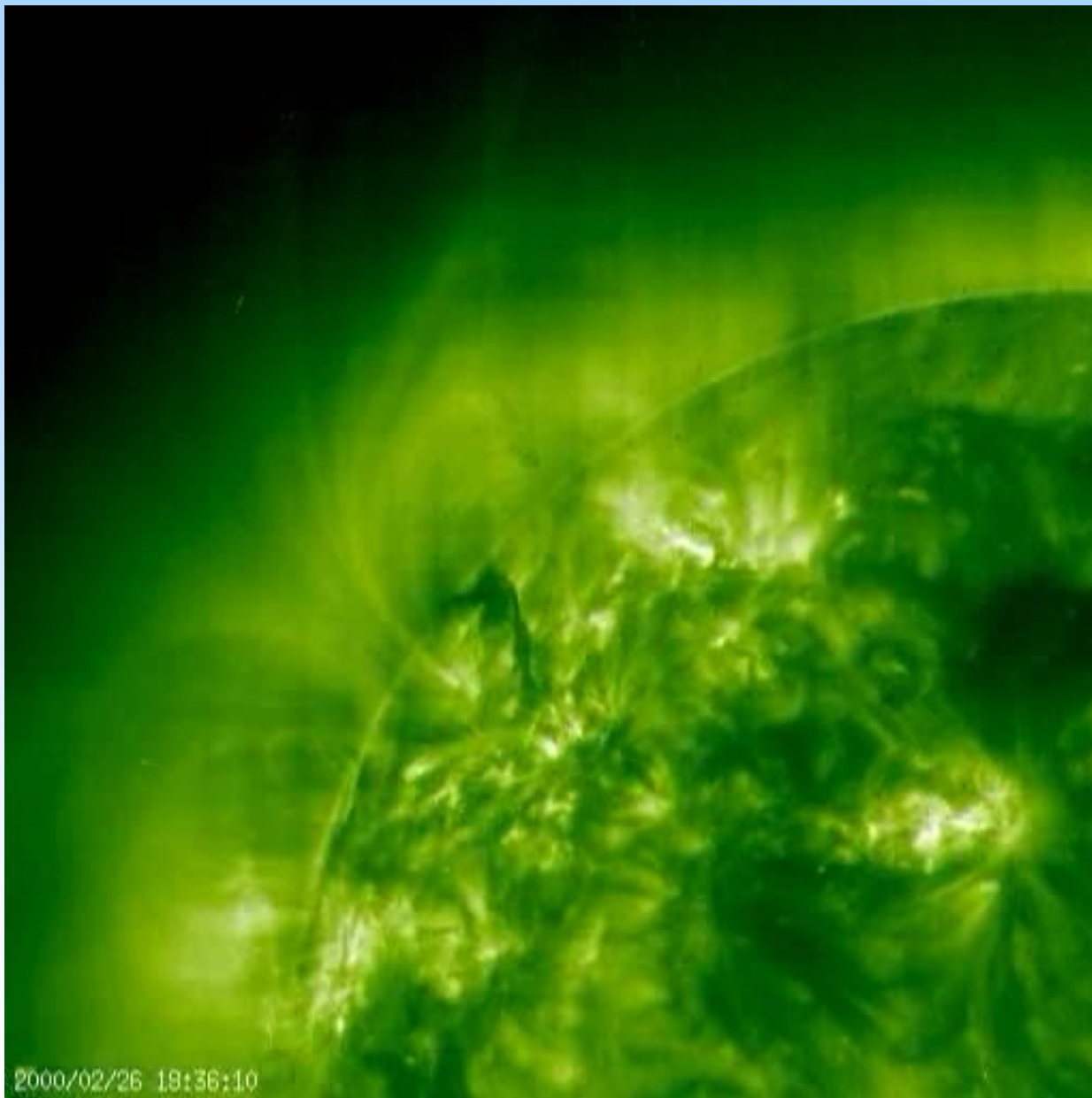


55,000 km

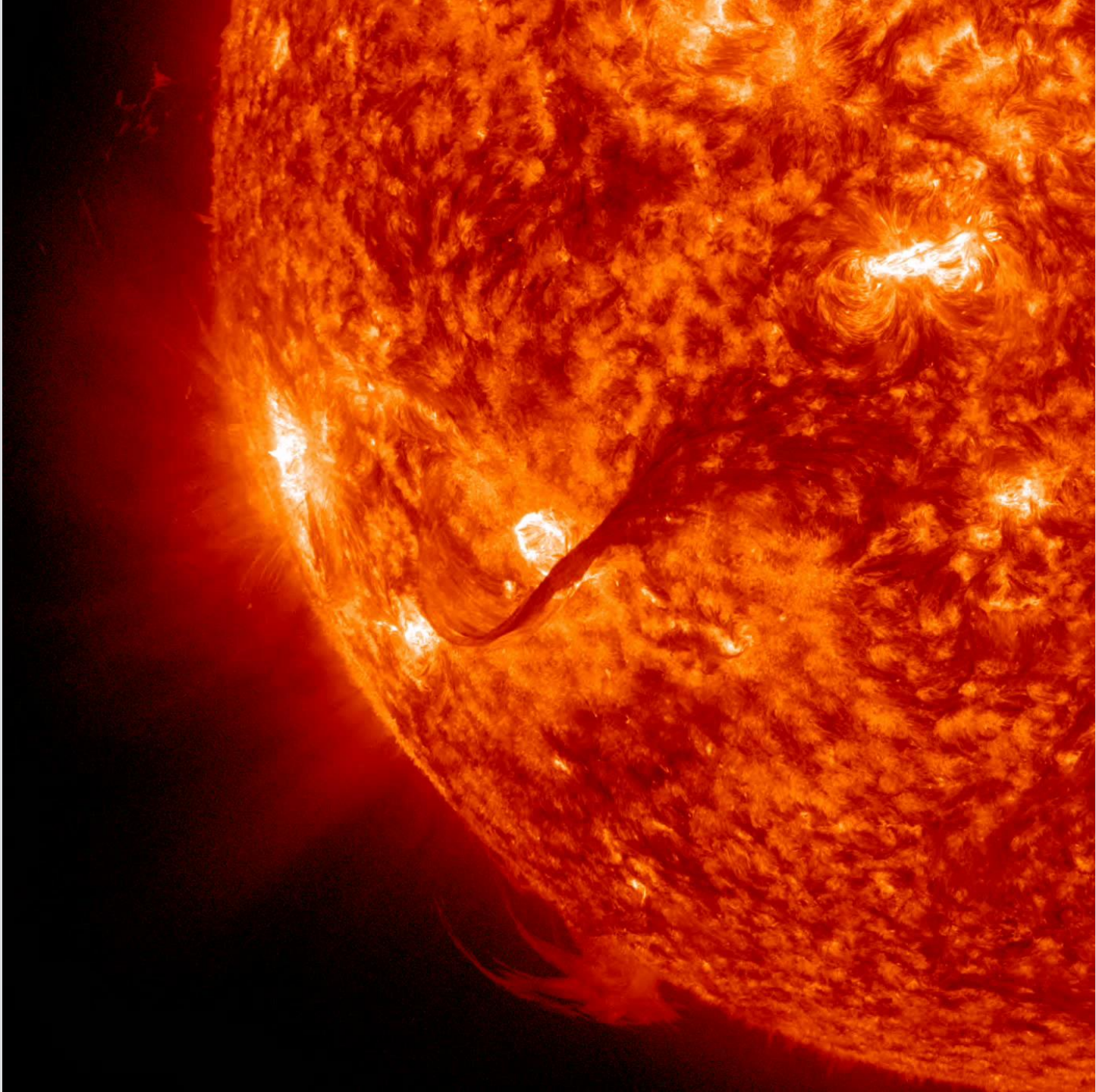


Earth to Scale

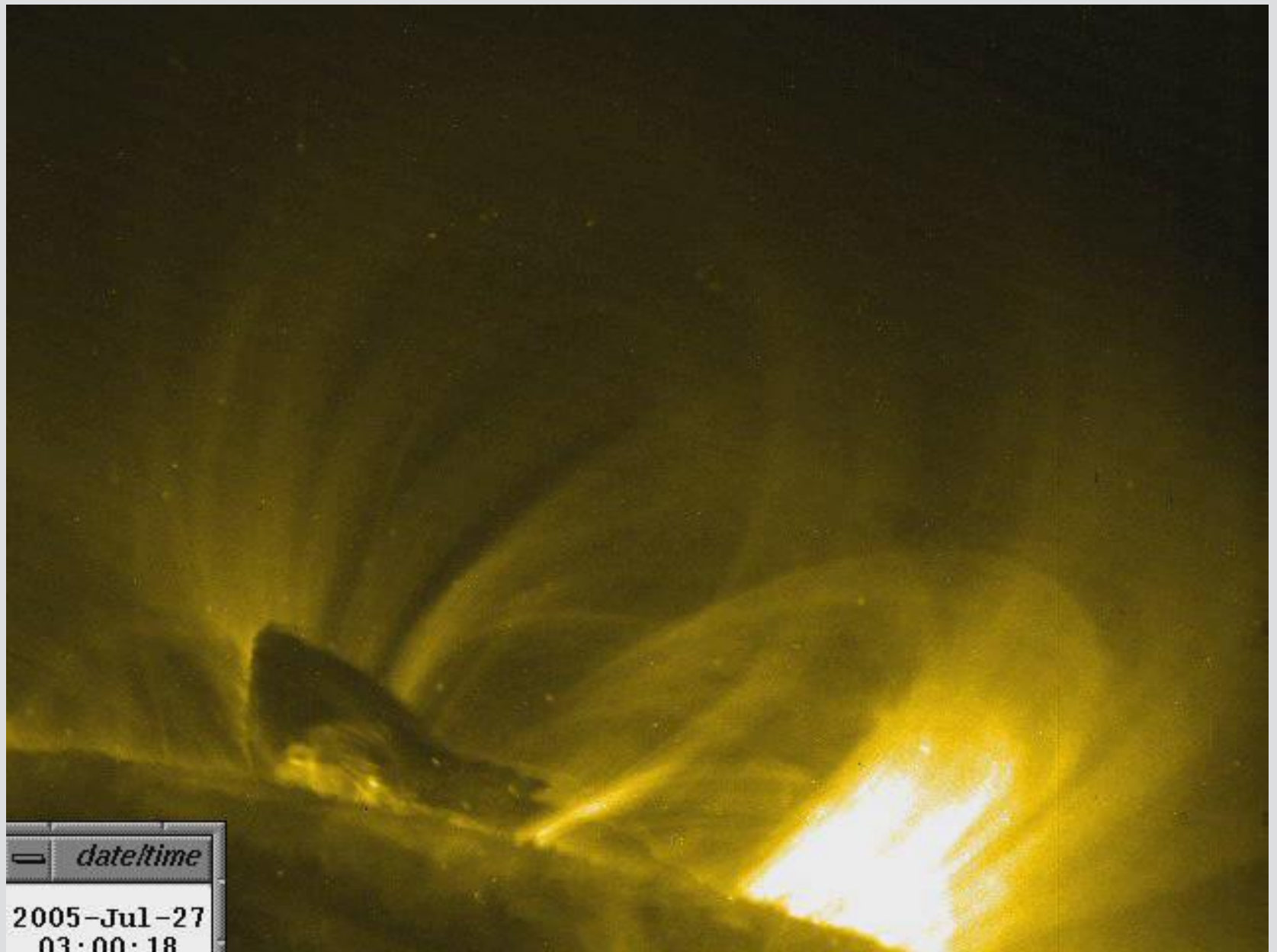
1998-Jul-11
04:10:27
dt = -6560.2

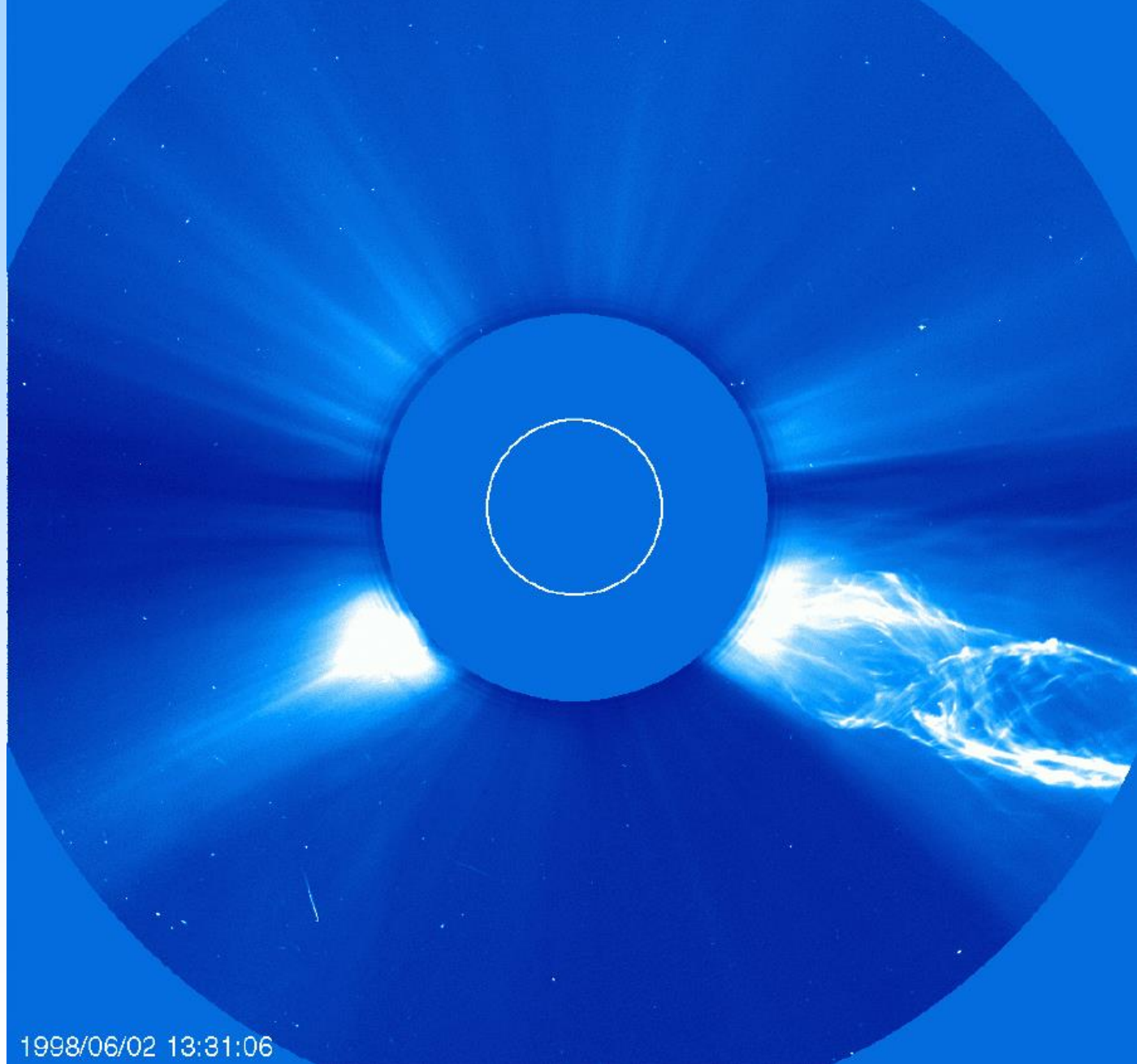


(Sterling & Moore 2004)

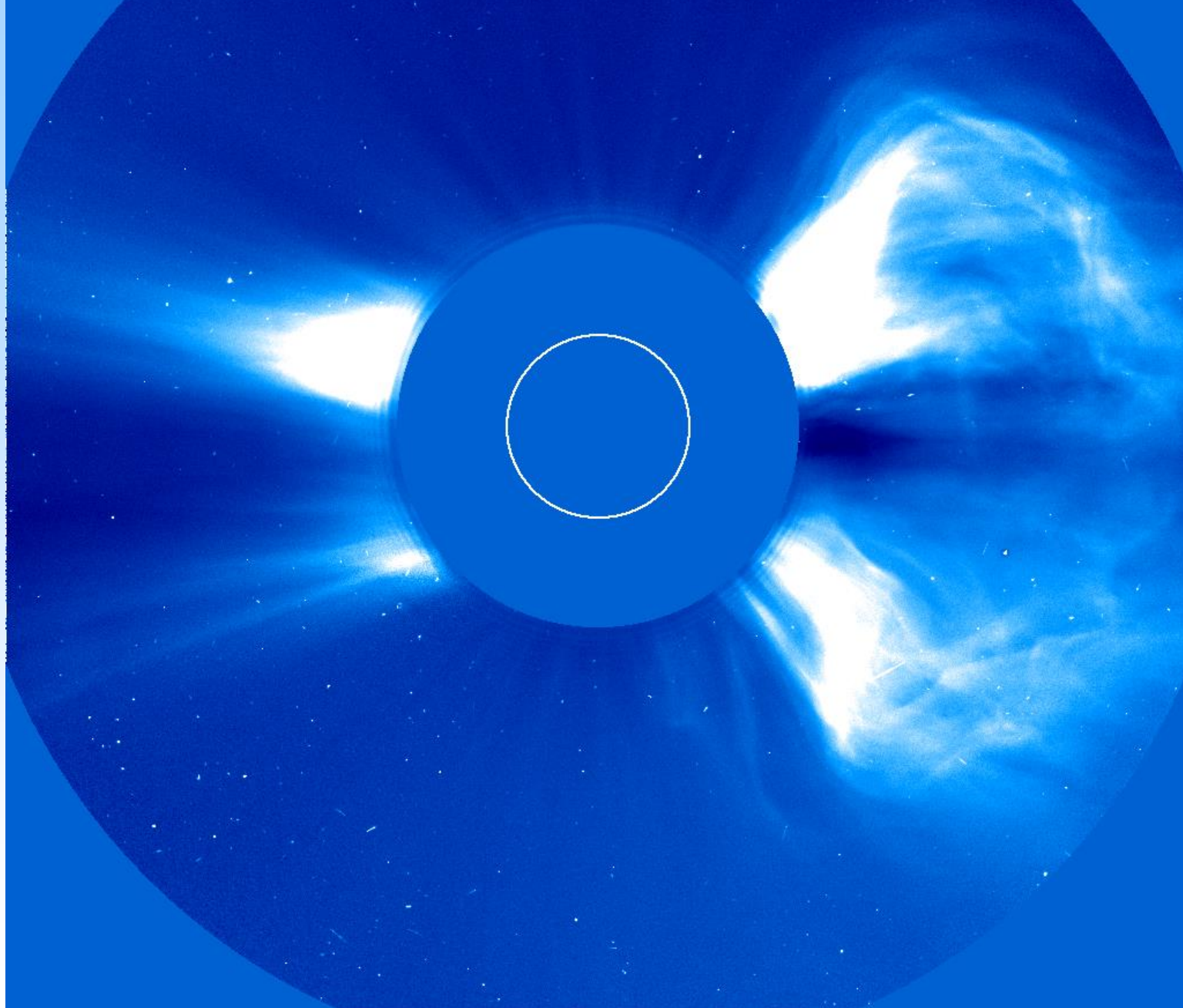


(TRACE 171)

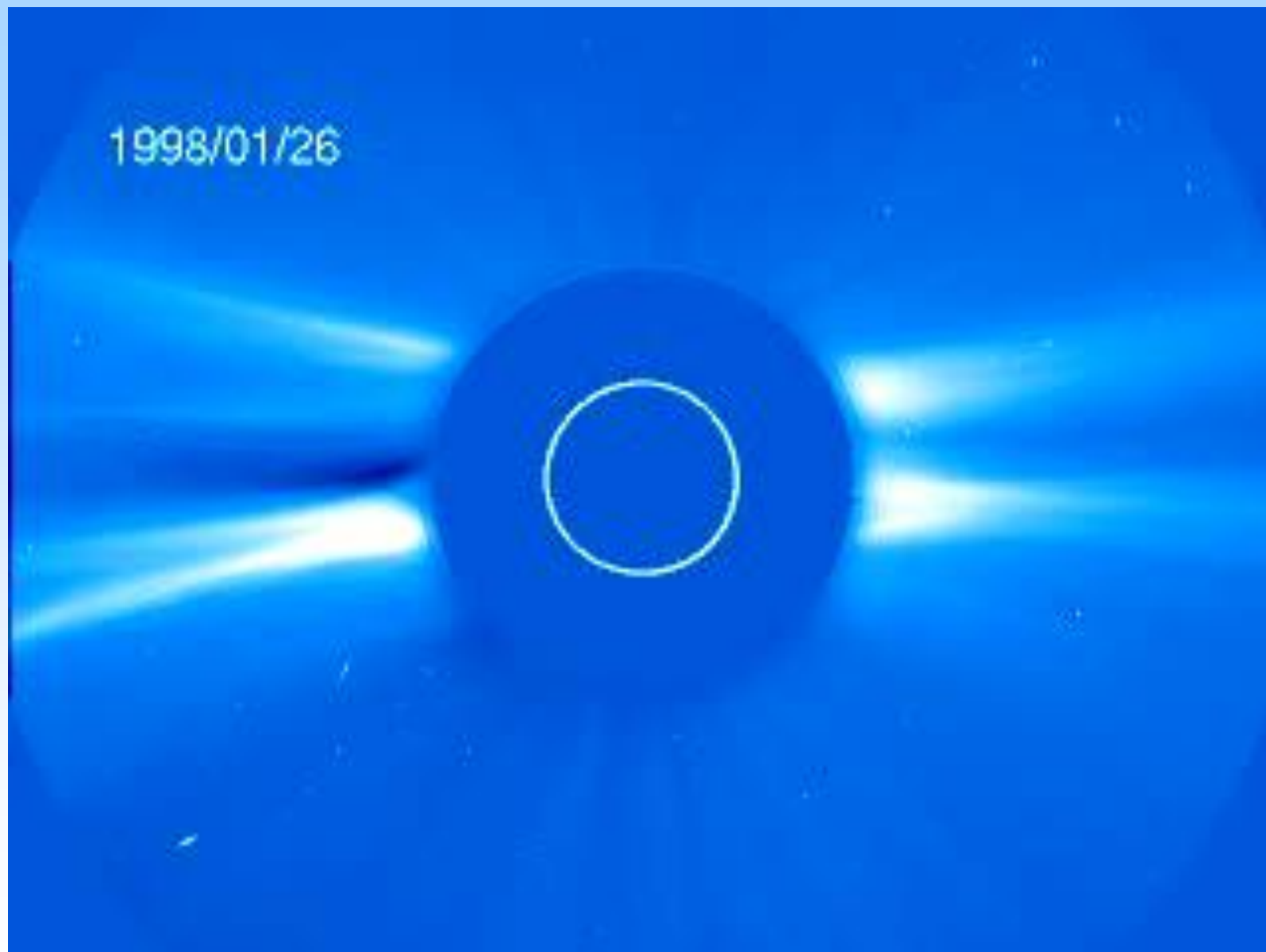


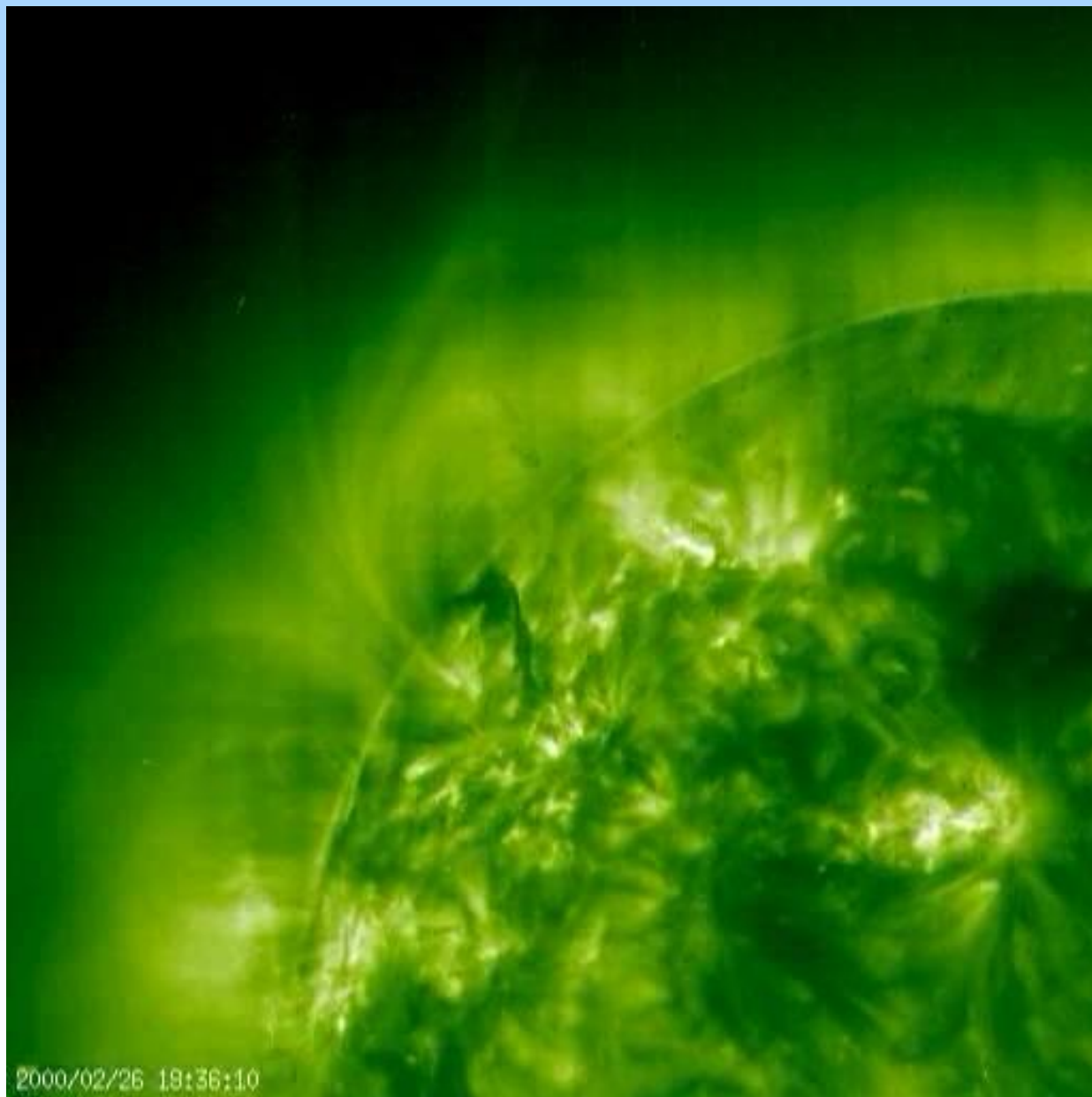


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Summary

- General structure of the Sun is well understood.
- There are still fundamental questions that remain to be resolved. Two that I have touched on here are:
 - Coronal heating: The mechanism must be magnetic, but how the magnetic energy is converted to thermal energy is still vigorously debated.
 - How does energy build up and violently release to cause solar eruptions, leading to flares and CMEs?
 - And there are many others!

Image:
Alphonse Sterling
21 August 2017,
Lewisville, Idaho