Chap 14: The Sun – A Typical Star

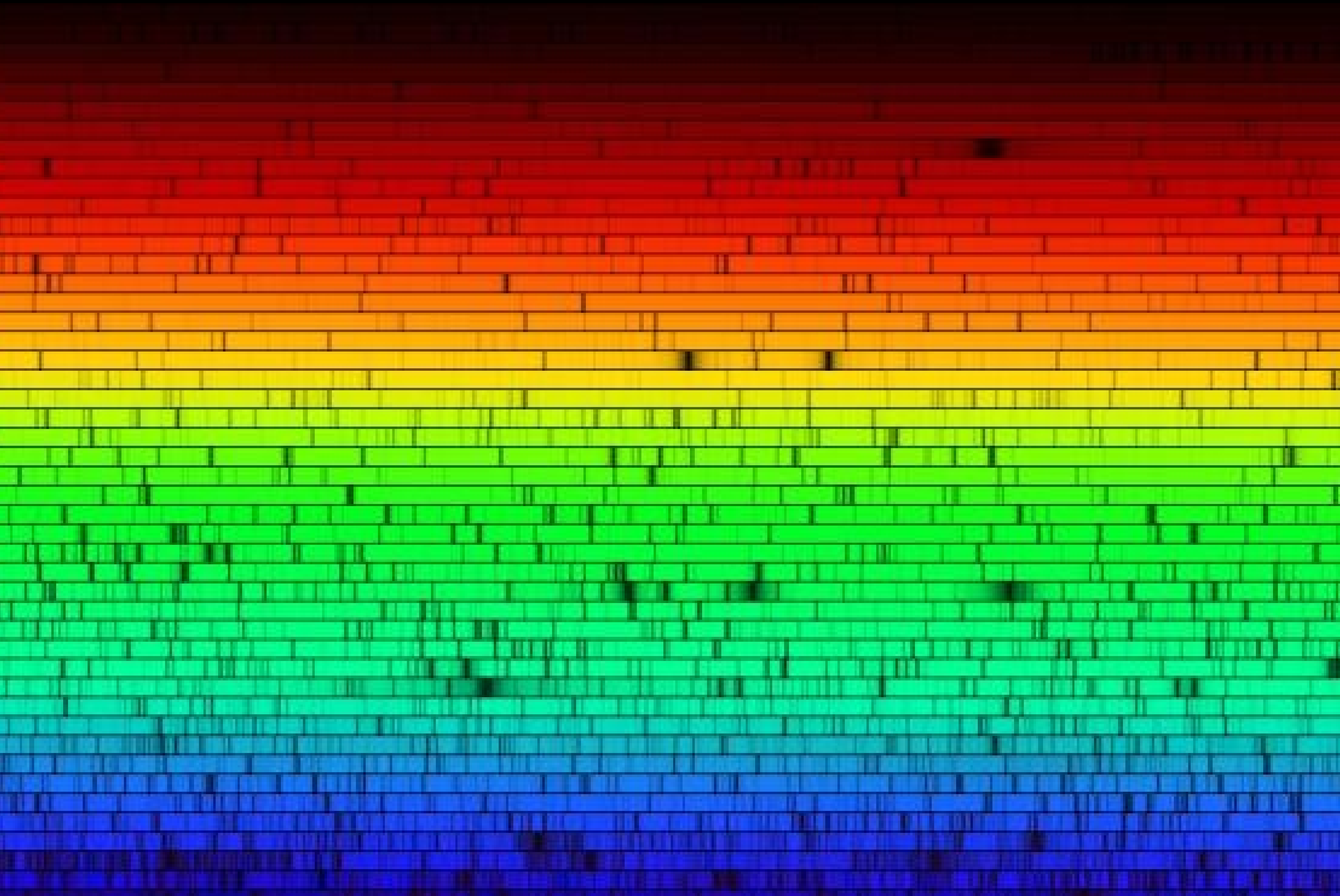
Here's the Story I'll Unfold for you…

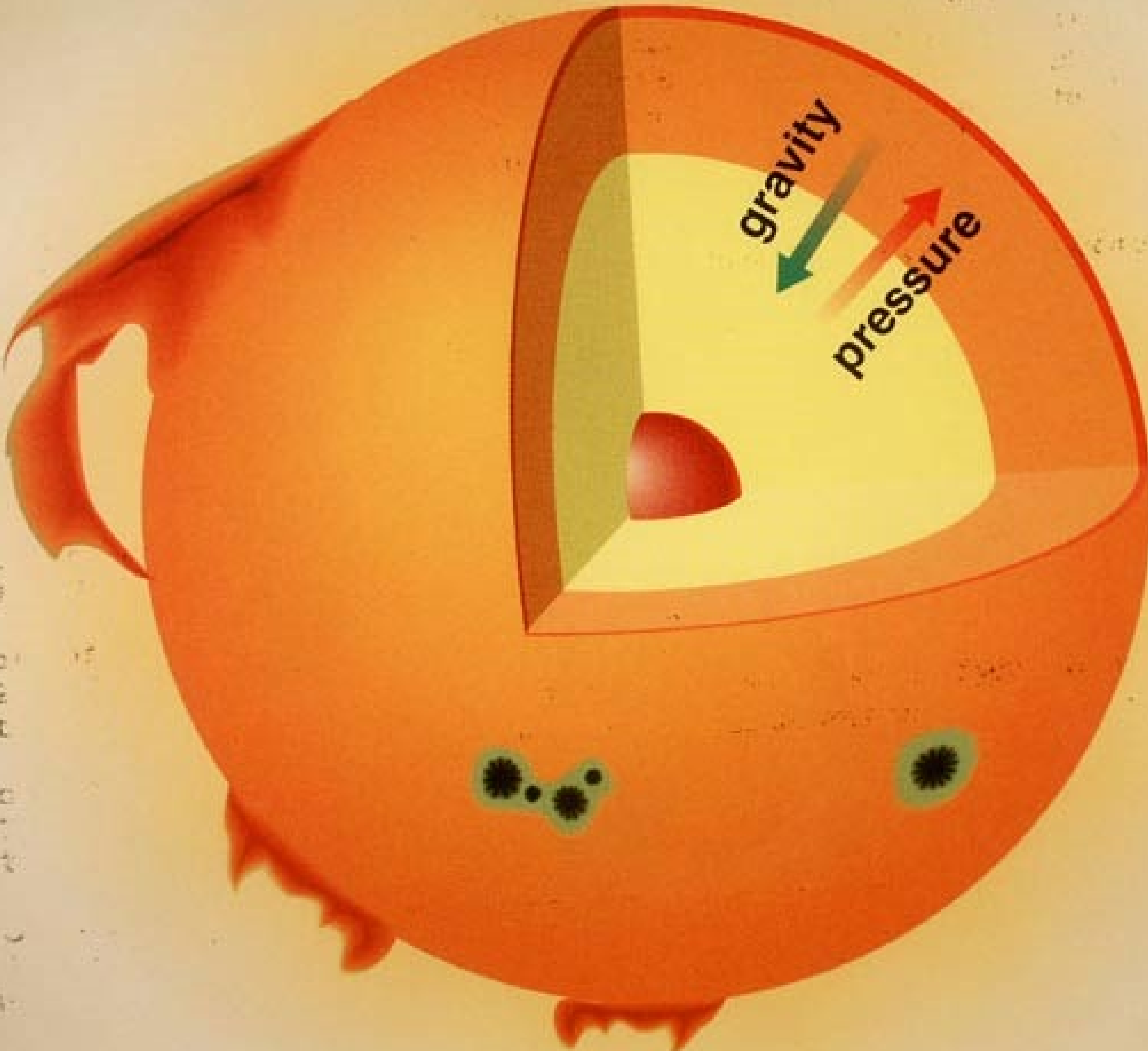
- What's it made of?
- A star: self-supporting partially ionized gas balancing gravity w/ pressure
- Nuclear fusion and how it powers the sun
- The layers of the sun; core, radiative zone, convective zone, photosphere, chromosphere, and corona
- Sunspots and magnetic fields, the sunspot cycle
- Solar activity and how it influences the Earth

What's it Made of?

- Basically, it's made of a little of ***everything, all the periodic table elements***
- But mainly hydrogen (~74%) and helium (~24%). And only a few percent the entire rest of the periodic table…

Eschelle spectrograph of solar spectrum




gravity
pressure

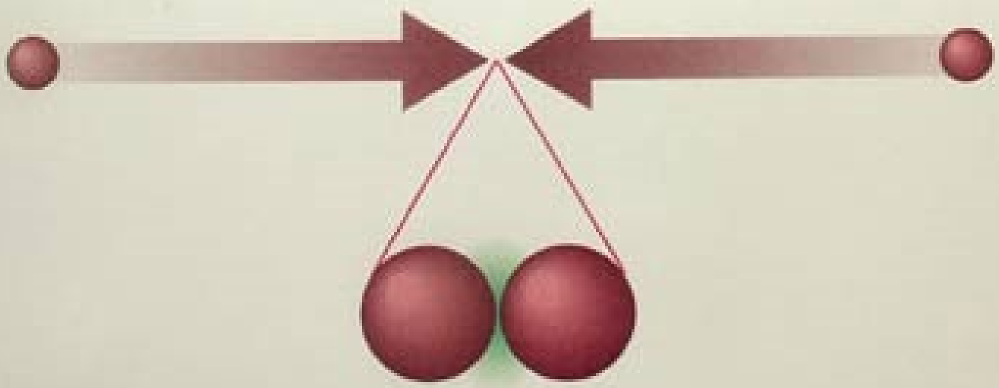
The Sun is a Star: A Balance between Gravity and Pressure

- It's self-balancing, because….
- **Higher fusion rate** would expand the core and with it the rest of the star, lowering core's density and hence its self-gravity, pressure, and temperature. And **thus lowering the fusion rate**. And vice versa

The Sun – Nuclear Power'ed

- **Core:** T~14M Kelvin, some high speed protons moving so fast they approach to within 10^{-13} cm, leading to hydrogen fusion into helium. ~10 million K minimum temperature for any significant hydrogen fusion, steeply rising with temperature
- **Fusion:** the Strong Nuclear Force overcomes EM repulsion of protons, binding protons and neutrons into heavier nuclei (for sun: H into Helium)

At low speeds, electromagnetic repulsion prevents the collision of nuclei.

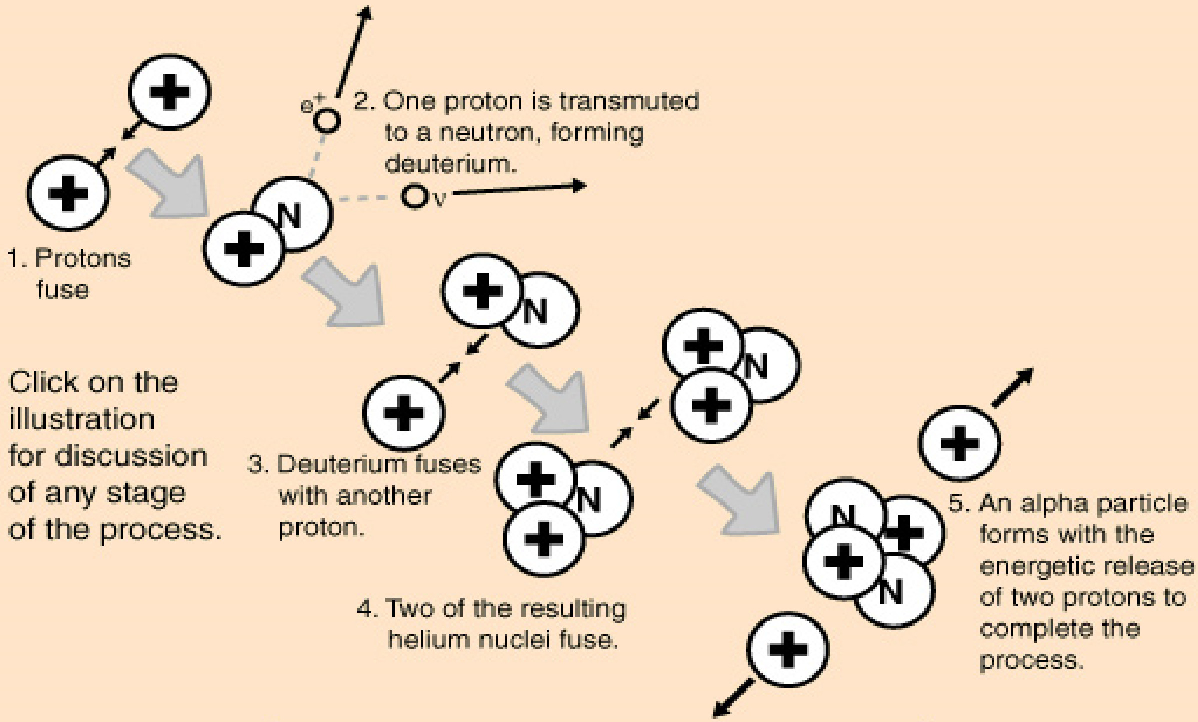


At high speeds, nuclei come close enough for the strong nuclear force to bind them together.

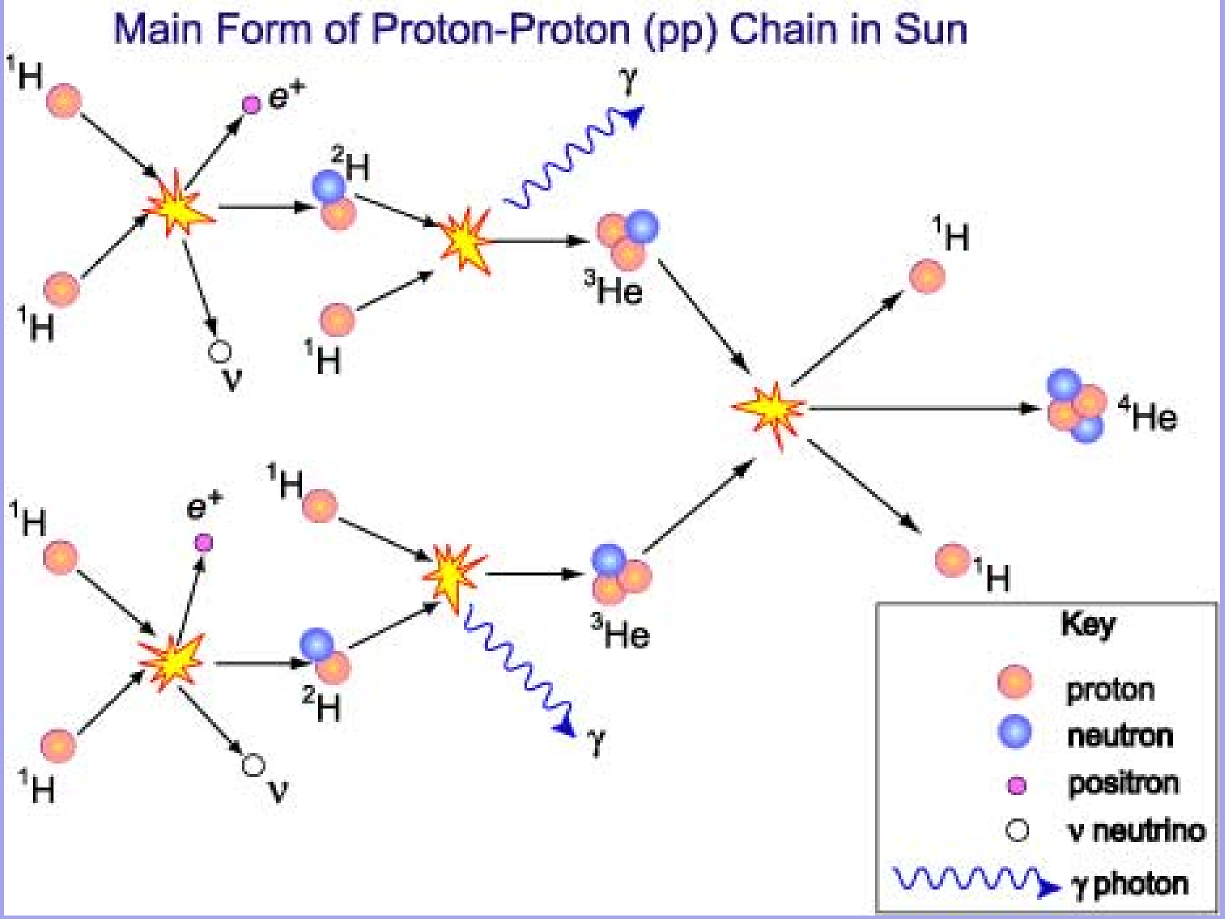
This is the basic reaction, but some amounts of energy also come from other possible branches, involving Lithium etc.

Proton-Proton Fusion

This is the nuclear fusion process which fuels the Sun and other stars which have core temperatures less than 15 million Kelvin. A reaction cycle yields about 25 MeV of energy.



Some details of the nuclear reactions involved



- Six protons are used in the series of reactions but two are released back. Other products include the He-4 nucleus, 2 neutrinos, 2 high-energy gamma photons and 2 positrons. Each of these products carries some of the energy released from the slight reduction in total mass of the system.

$$4\text{H-1} \rightarrow \text{He-4} + 2e+ + 2\nu + 2\gamma$$

- The 2e+ (positrons) quickly annihilate with electrons, 2e+ + 2e- = 4γ. Adding in the 2γ from the He3 creation reaction, gives a net production of 6 gamma rays for each helium atom produced (source: Australia National Telescope Facility, outreach program)
- About 2% of the energy released in the pp chain is carried away by neutrinos.

What Nuclear Reactions Power Stars?

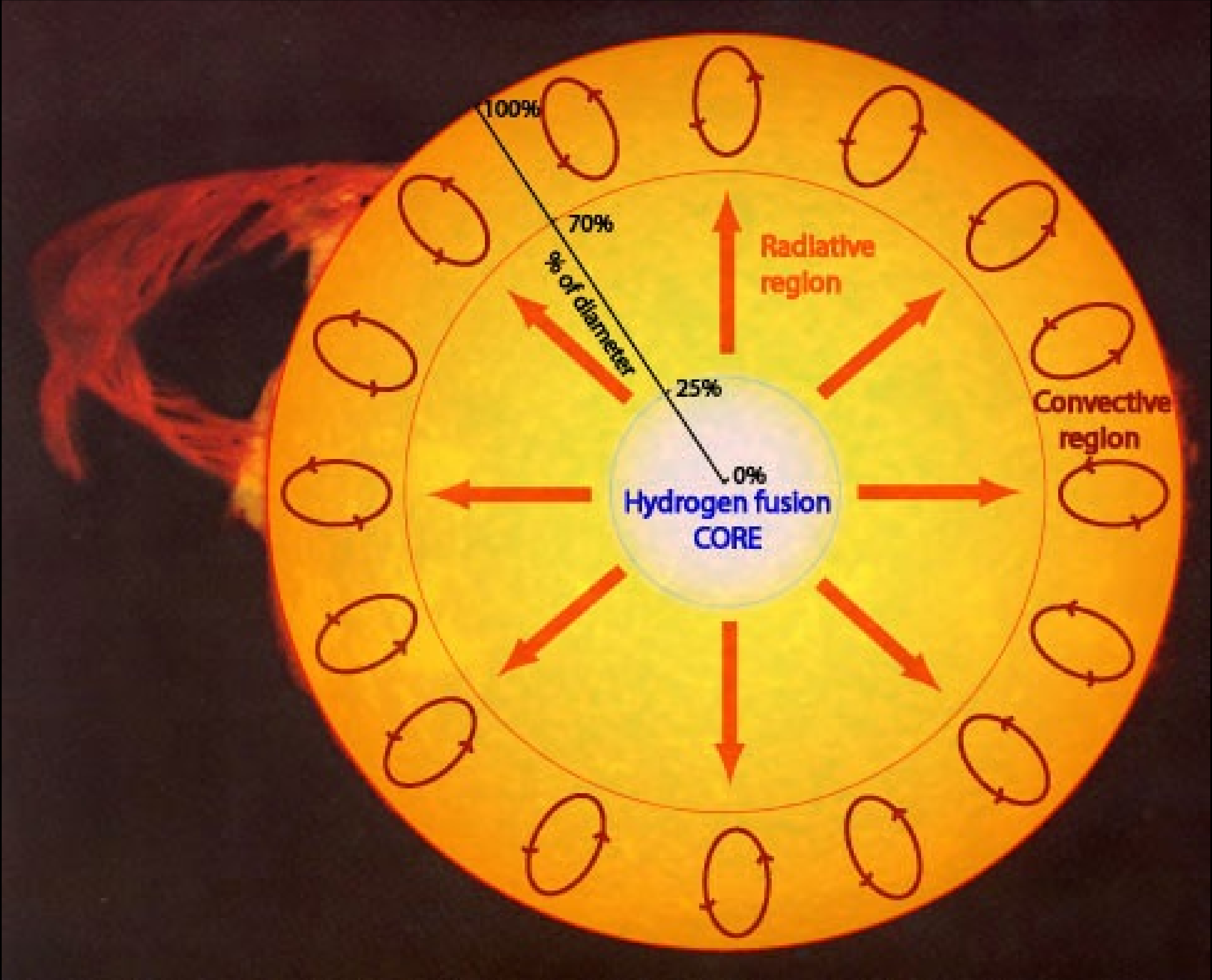
- Lower mass stars like the sun, it's variations on the "Proton-Proton Chain" which is effective at lower temperatures (<15 million K)
- For higher mass, higher core temperature stars, another more complex reaction involving again a net of 4H going into 1 He4, but involving carbon, nitrogen and oxygen in intermediate steps (CNO cycle) produces most of the energy

Neutrinos Have Almost 0 chance of interacting with other matter

- So nearly all neutrinos created in the core escape unscathed, arriving at Earth.
- Now, there is a very tiny chance of interaction, by the Weak Force, and because the flux of solar neutrinos is SO vast, we <u>do</u> detect neutrinos, and they give us key information about the nuclear reaction details in the sun's core.
- Clever way to see the invisible core!

The Layers of the Sun

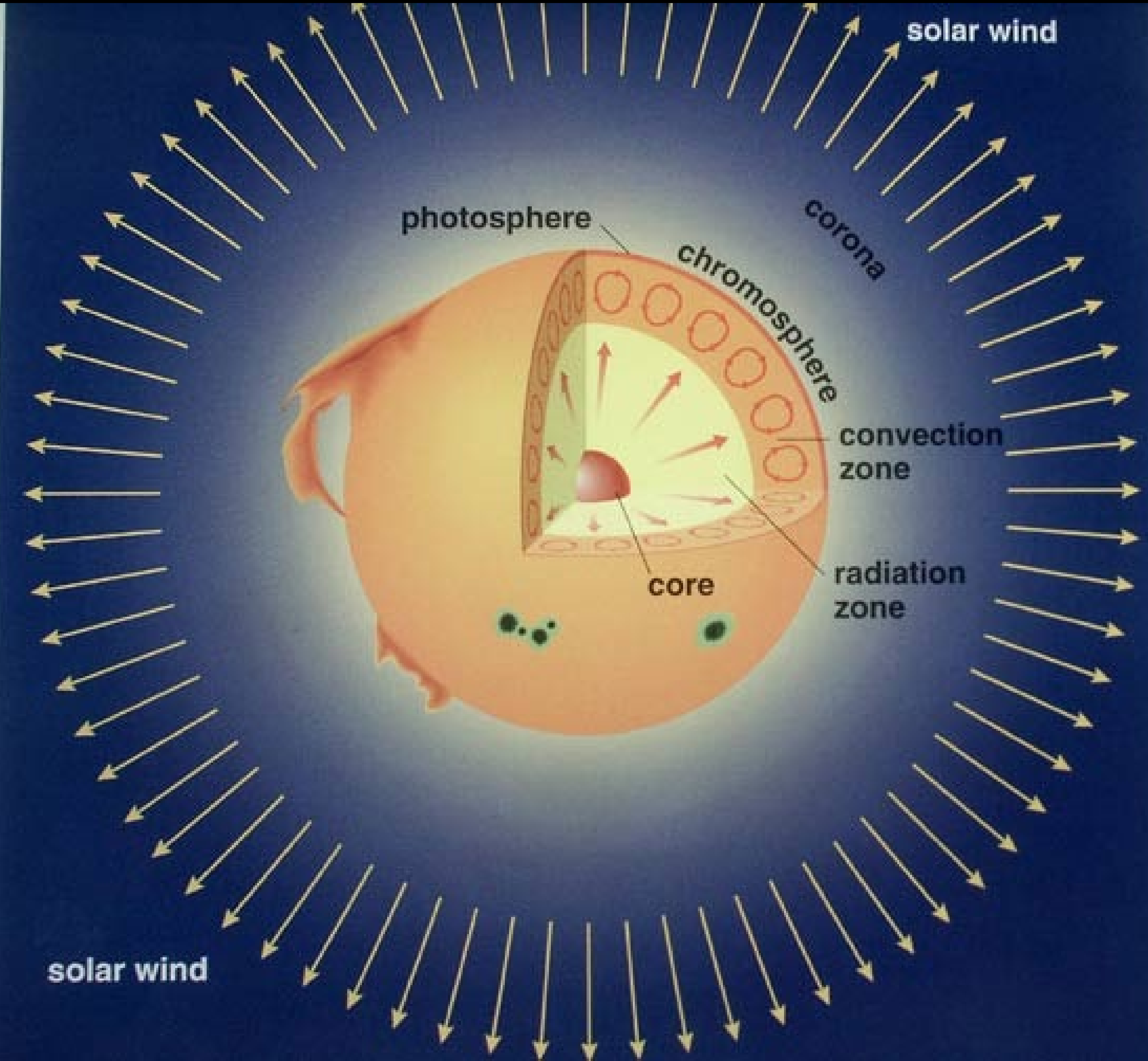
- **Core** = where temperature exceeds fusion point (10 million Kelvin)
- **Radiative Zone** = nothing much goes on here. It just acts as an obstacle course for the photon energy; scattering off charged particles, imparting some of their energy to the particles, and random-walking their way upward.
- Recall that when charged particles scatter off of each other, that is an acceleration (or deceleration) and this disturbs the electromagnetic field, creating waves…. Photons
- So, the number of photons is not "conserved" in this migration of photon heat from their creation in the core outward to the surface. In fact, the number of photons goes up just as the temperature goes down, by a factor of about 3000 in fact, from core to surface



100%
70%
% of diameter
25%
0%
Radiative region
Convective region
Hydrogen fusion CORE

Above the Radiative Zone

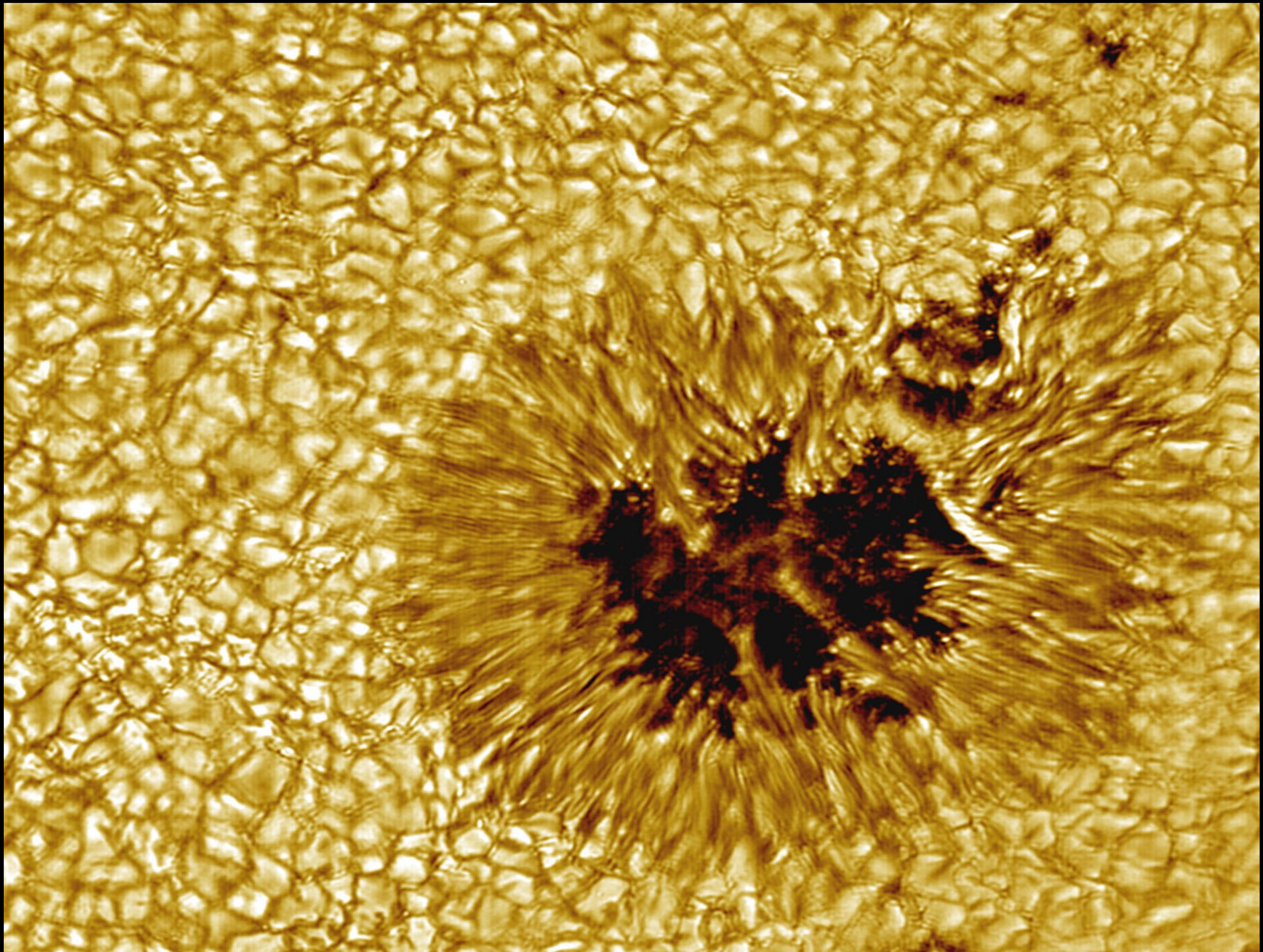
- **Convection Zone** = temperature gradient is so steep that photon diffusion can't carry the heat outward fast enough. The rising temperature expands the gas, lowering density and causing it to rise (helium-balloon-like) to the surface, where it cools, gets denser, and falls back down to get reheated and start all over again. Think – soup cooking on a stove.
- **Photosphere** = visible surface. 5,800 K This is where the mean free path now gets so long the material is transparent above here. This fuzzy layer is only a few hundred kilometers thick. It is the coolest place in or on the sun!


solar wind
photosphere
corona
chromosphere
convection zone
core
radiation zone
solar wind

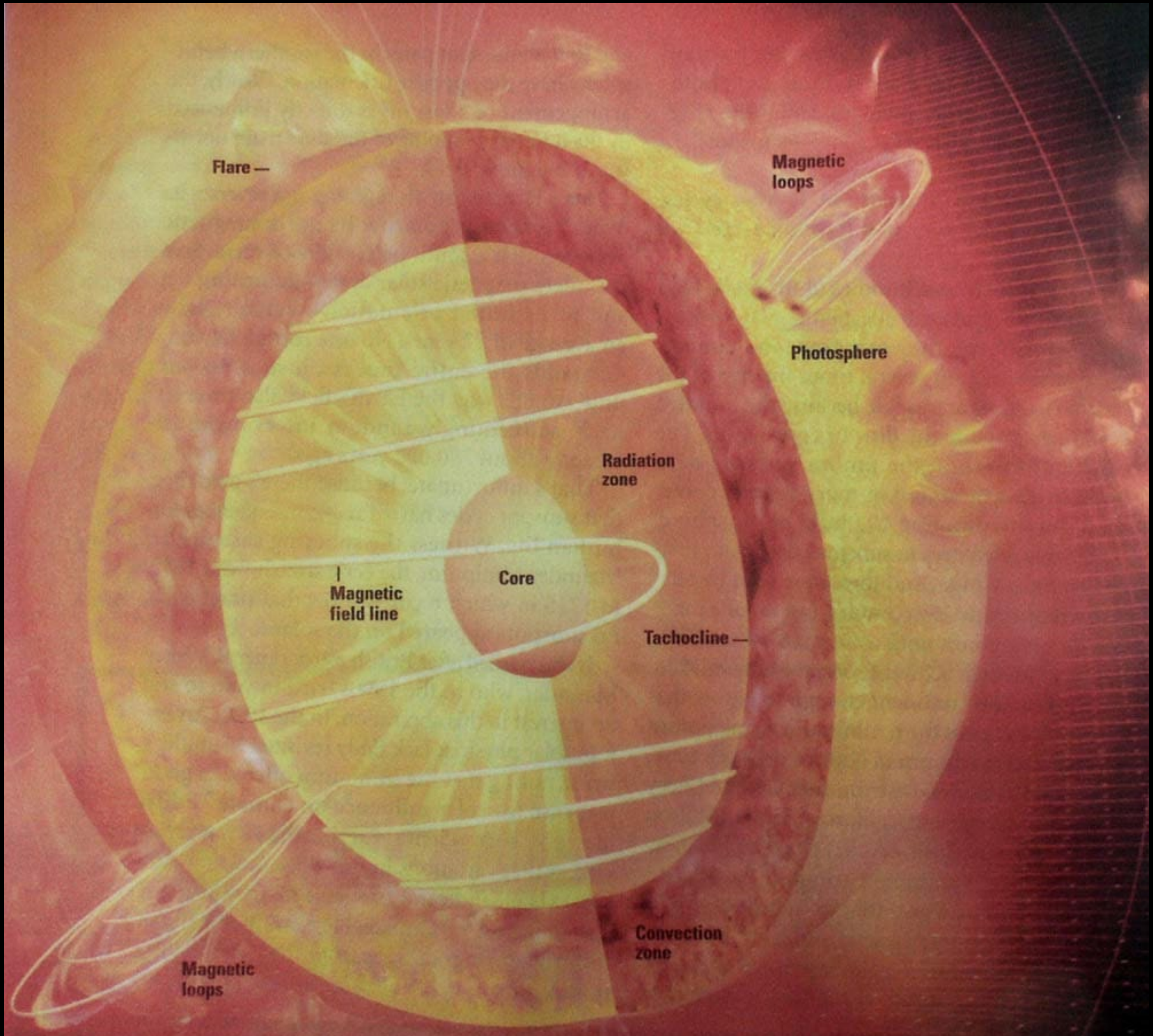
What Does the Photosphere Show?

- There's two more layers which are transparent, but let's pause on the photosphere for now
- There's lots to learn about the physics of the sun by examining it's "surface" – the photosphere…
- The photosphere is the top of the convection zone, and convective motion is obvious in **time lapse images**

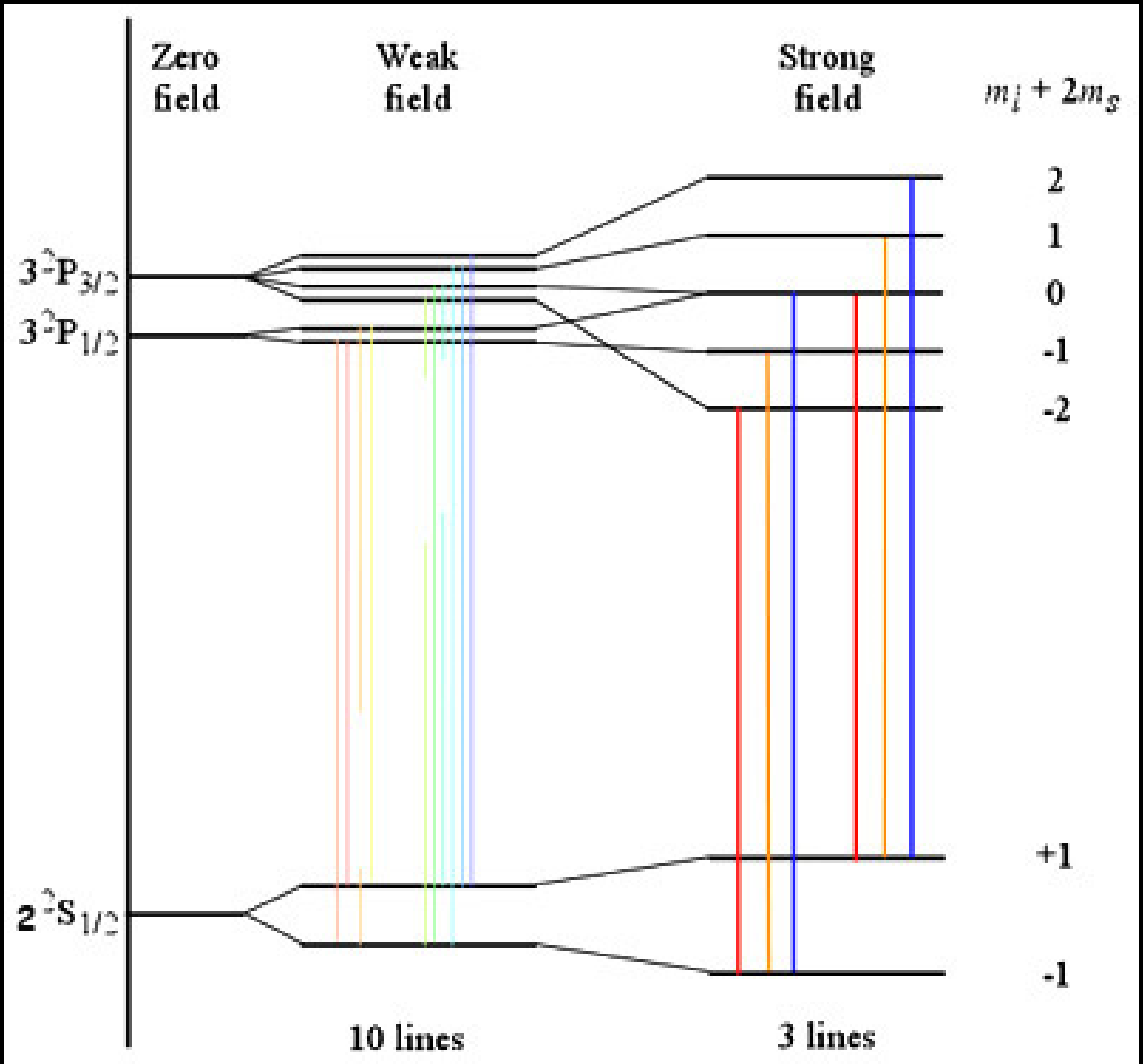
Solar Granulation Shows Visually the Tops of the Convection Cells in the Photosphere. Each of these is about the size of Texas



The Solar Dynamo: Differential Rotation twists and stretches magnetic field lines just like you add energy to rubber bands by stretching them. Over time, these emerge on the surface as **sunspots**…

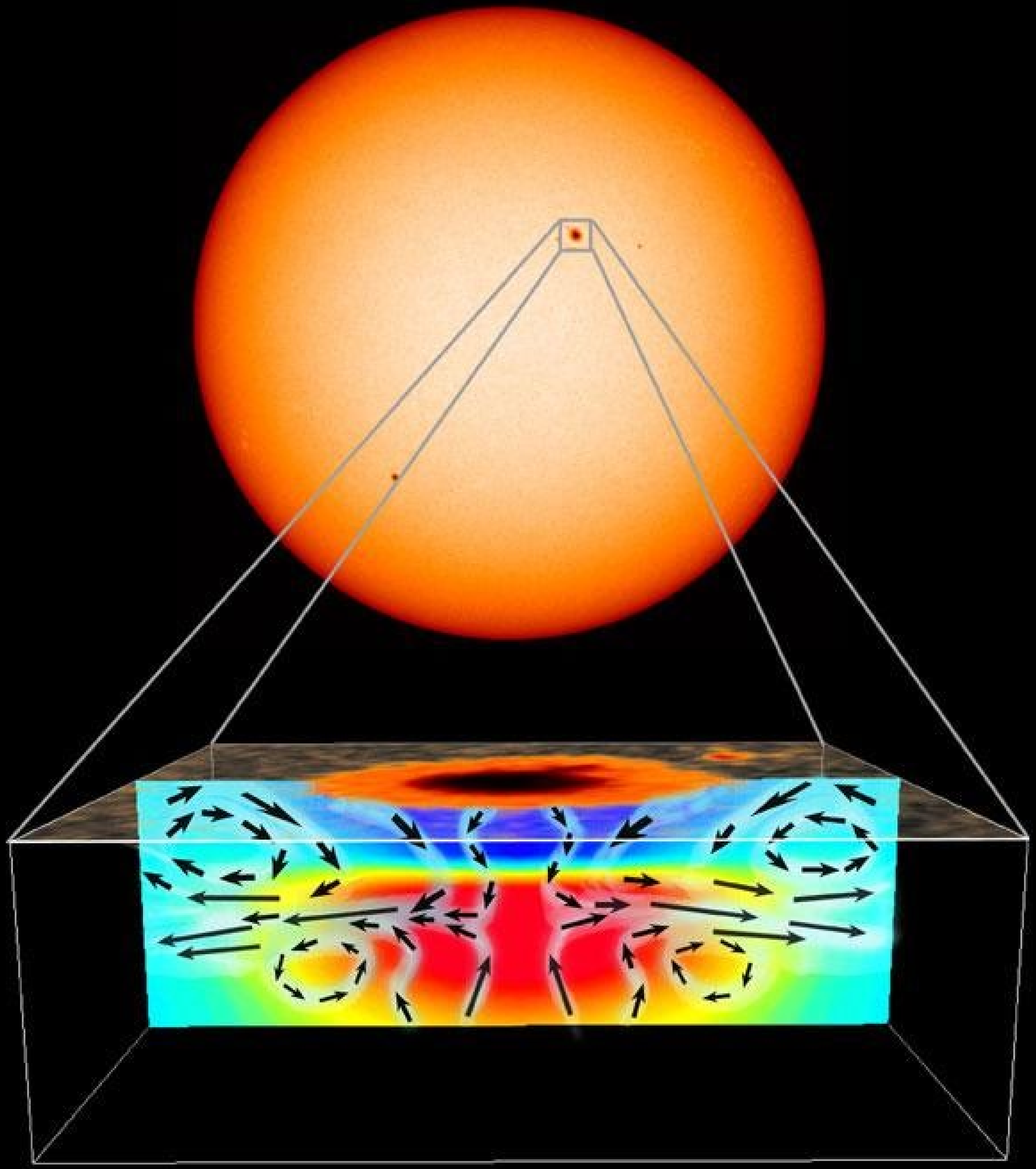


Spectrum of a sunspot shows each absorption line is split into several lines = <u>The Zeeman Effect</u>, due to the presence of a Magnetic Field. Remember there's splitting, but not the details below

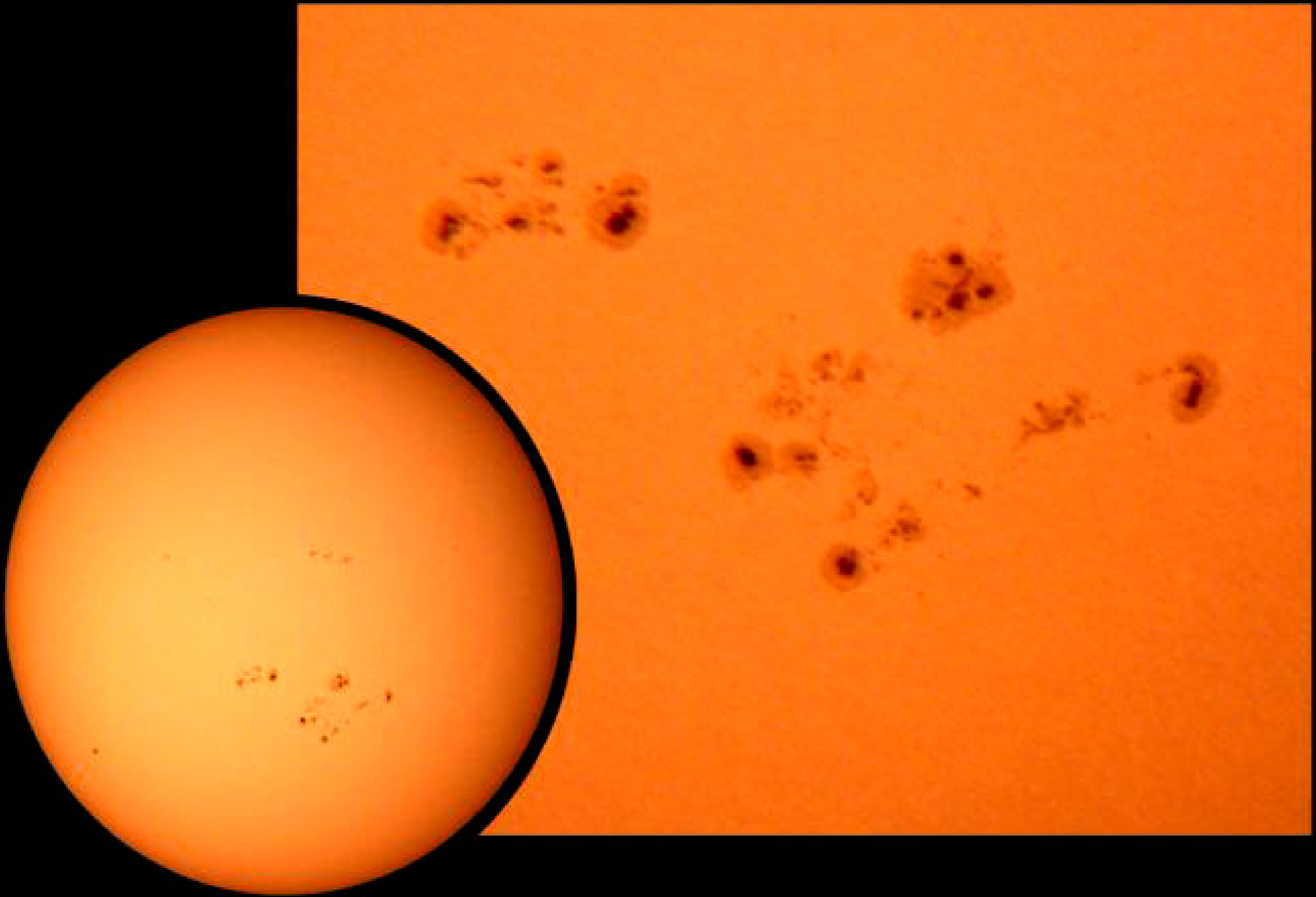


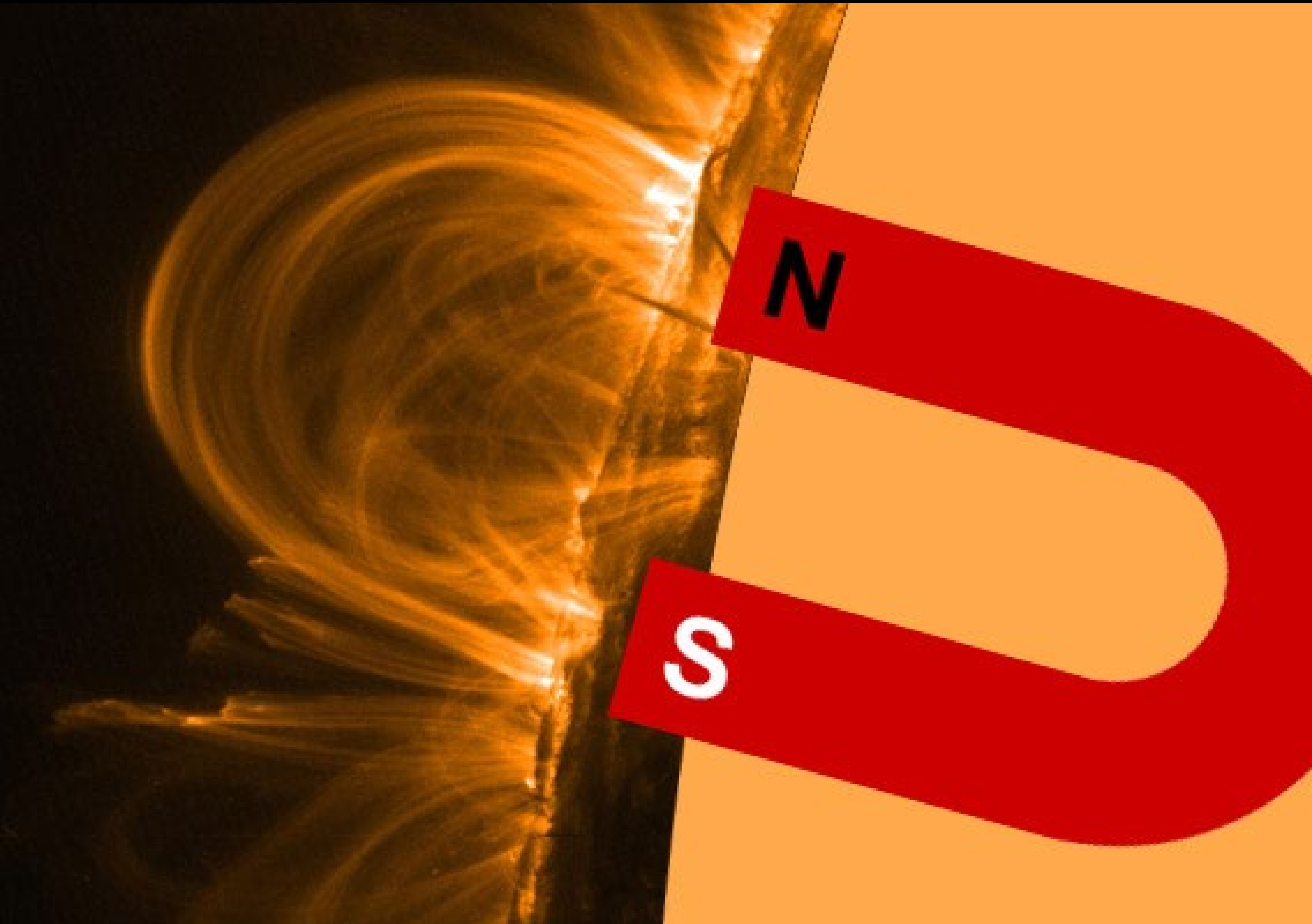
Sunspots

- **Why does a Magnetic Field make a dark spot…?**
- Charged particles in a magnetic field feel a force sideways to their motion, binding the gas to the field.
- Where the sun’s magnetic field is concentrated it inhibits the normal convective flow of hot material from below. So the material sits on the surface, and cools off as it radiates to the sky.
- Sunspots are like “magnetic scabs” of gas unable to be recirculated to lower, hotter levels. They are bound to the magnetic fields in the photosphere, cooling as they radiate to the cold universe, and hence cooling and darkening.
- Temperature drops from 5,800K down to as low as 3,000K, which cuts the brightness to ~1/15 of normal and makes area look very dark by comparison.



Sunspots usually occur in groups





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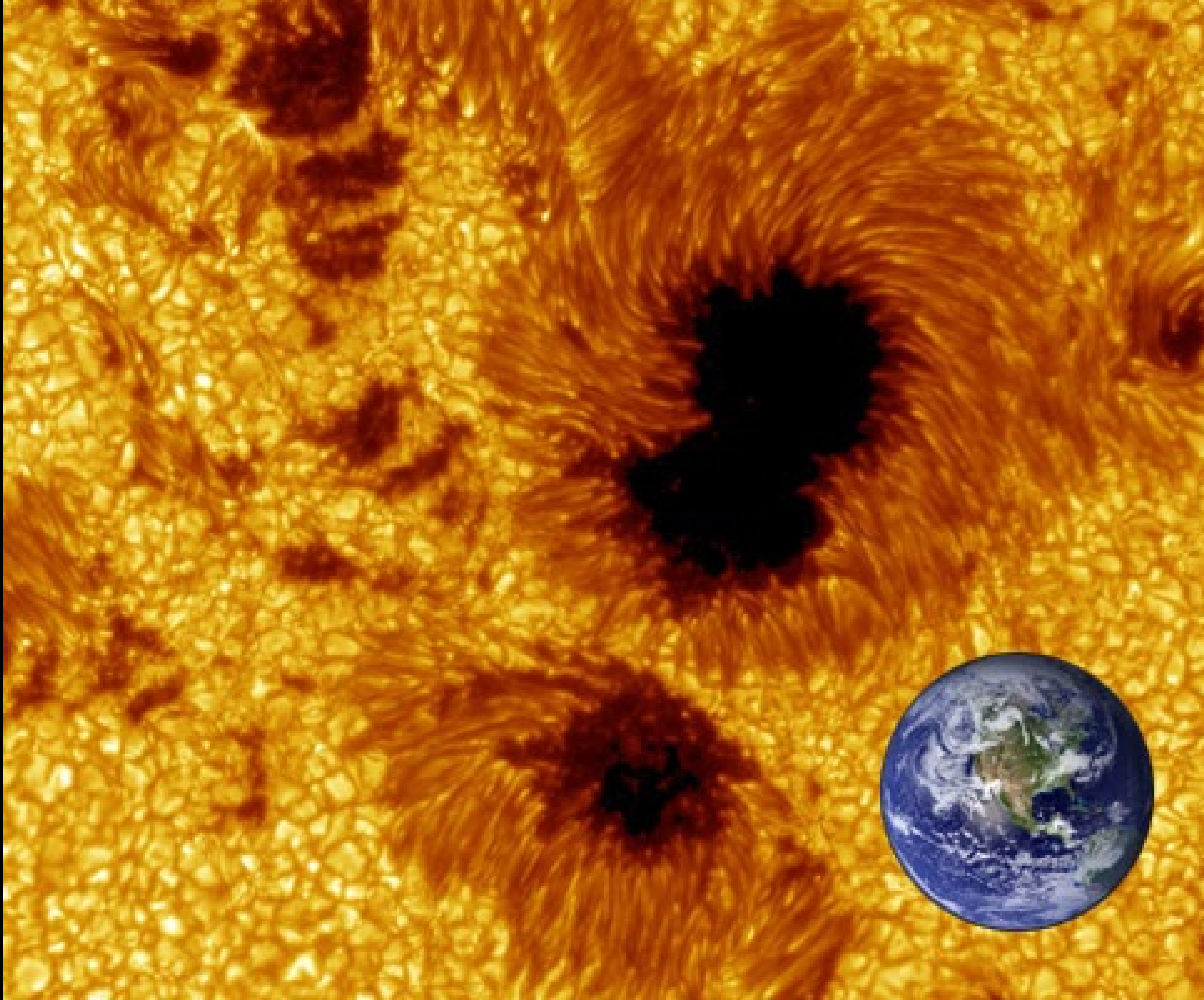
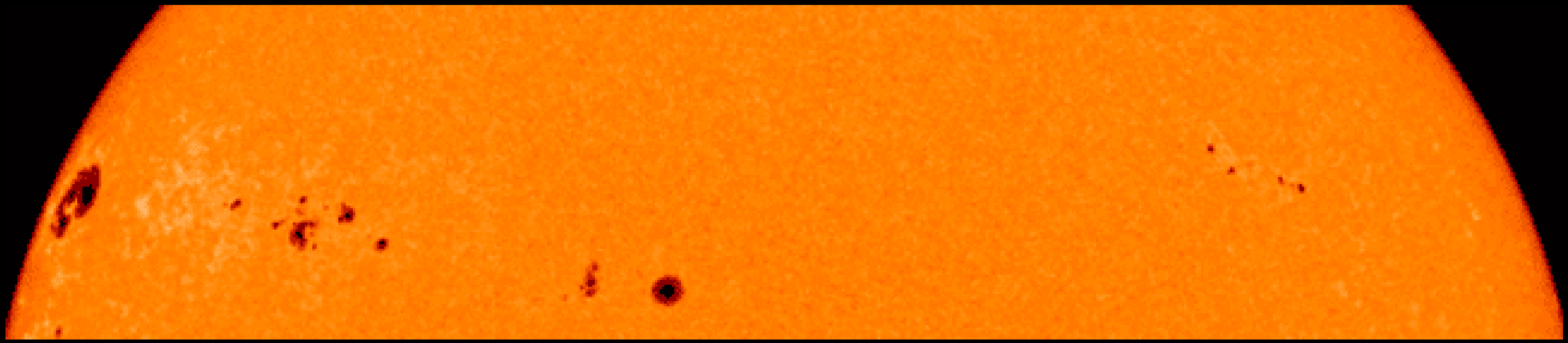
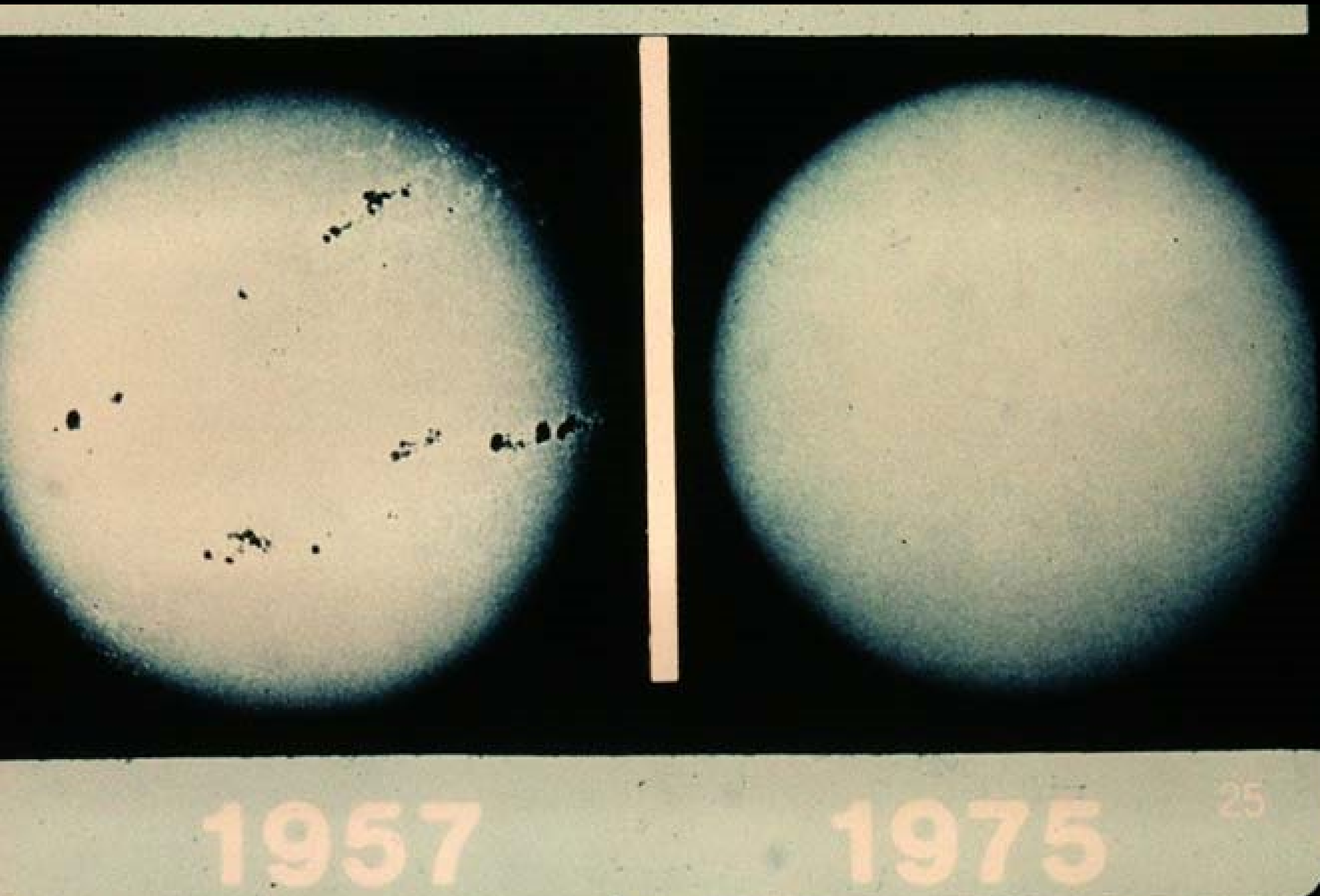


Do Sunspots Make the Sun Dimmer?

- **No**. The energy unable to get out at a sunspot because of the twisted magnetic fields disrupting convection, finds its way out in surrounding areas. In fact, the magnetic field energy created actually makes the sun a bit BRIGHTER with higher solar activity.
- These surrounding areas are called ***Plages***
- Here's a black/white picture up close…




1957
1975
25

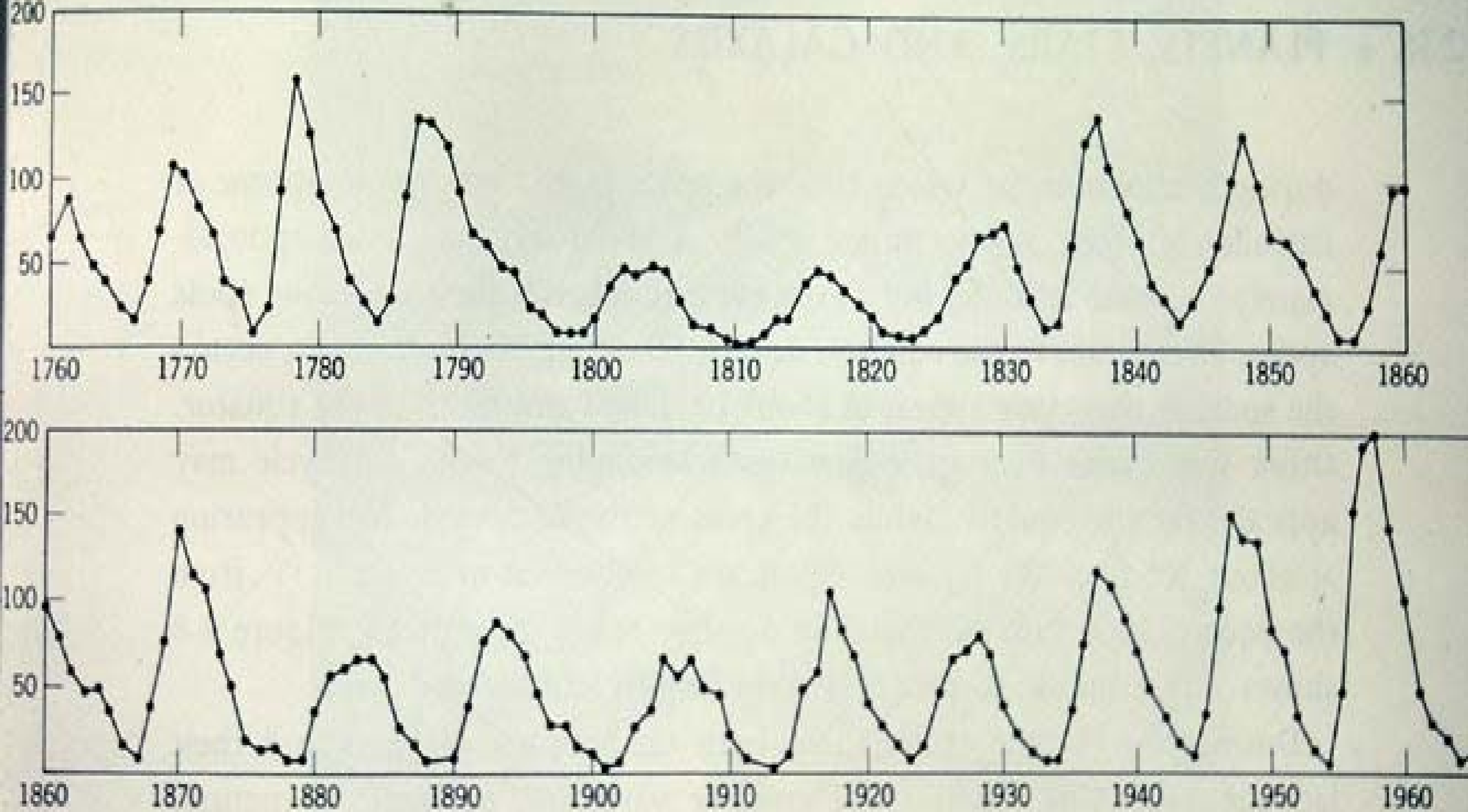
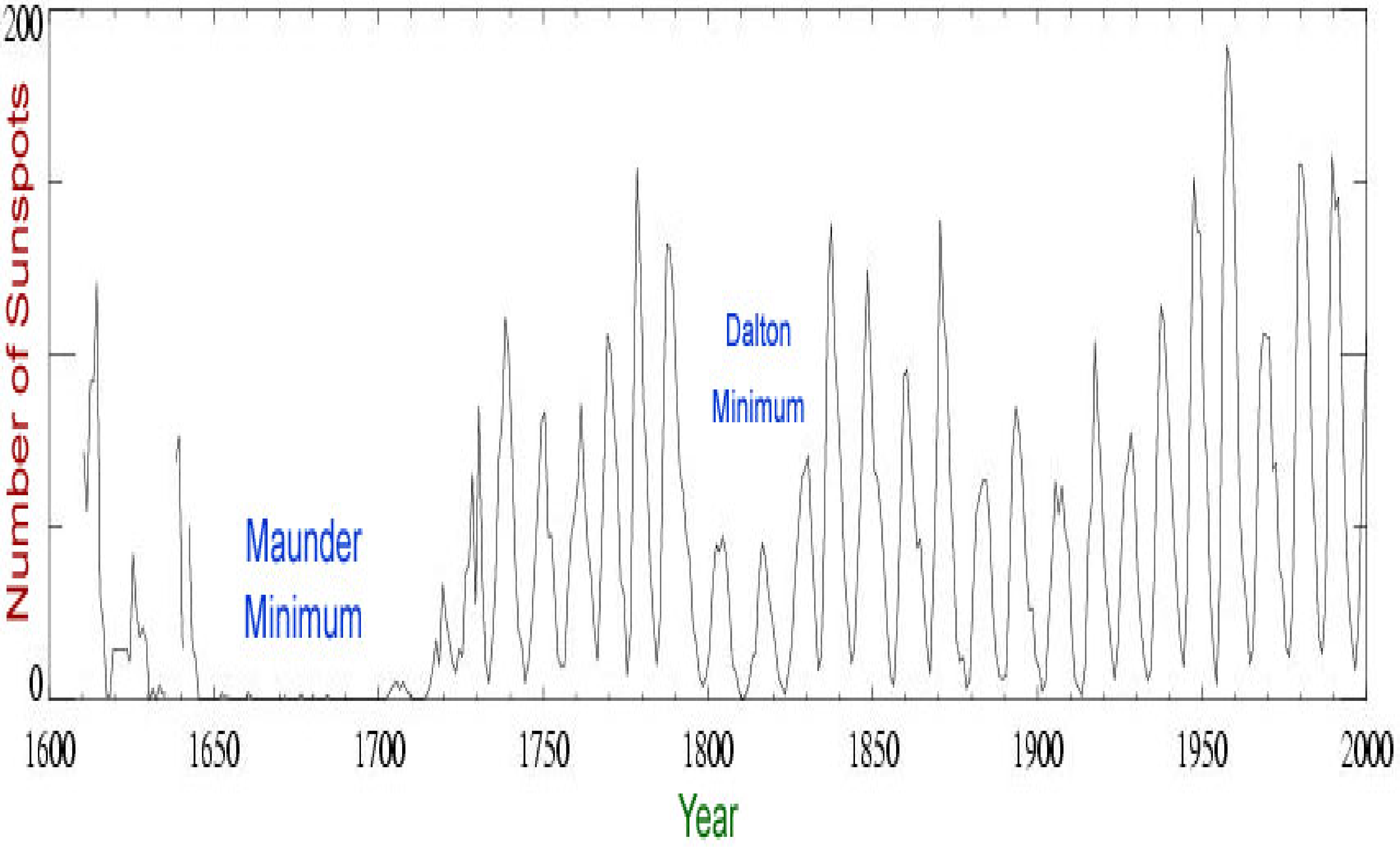


Figure 9-7

The sunspot cycle. The variations in the number of sunspots since 1760. The records before 1860 are not very reliable for they were not kept systematically.

Since the dawn of the telescope – Sunspot number averaged per year



How Does The Solar Cycle Affect Earth?

- Two important ways…
- **1.** Climate. We have seen that lower solar activity goes with lower average temperatures on Earth
- **2.** The solar wind creates ***aurorae*** when it strikes the Earth's atmosphere

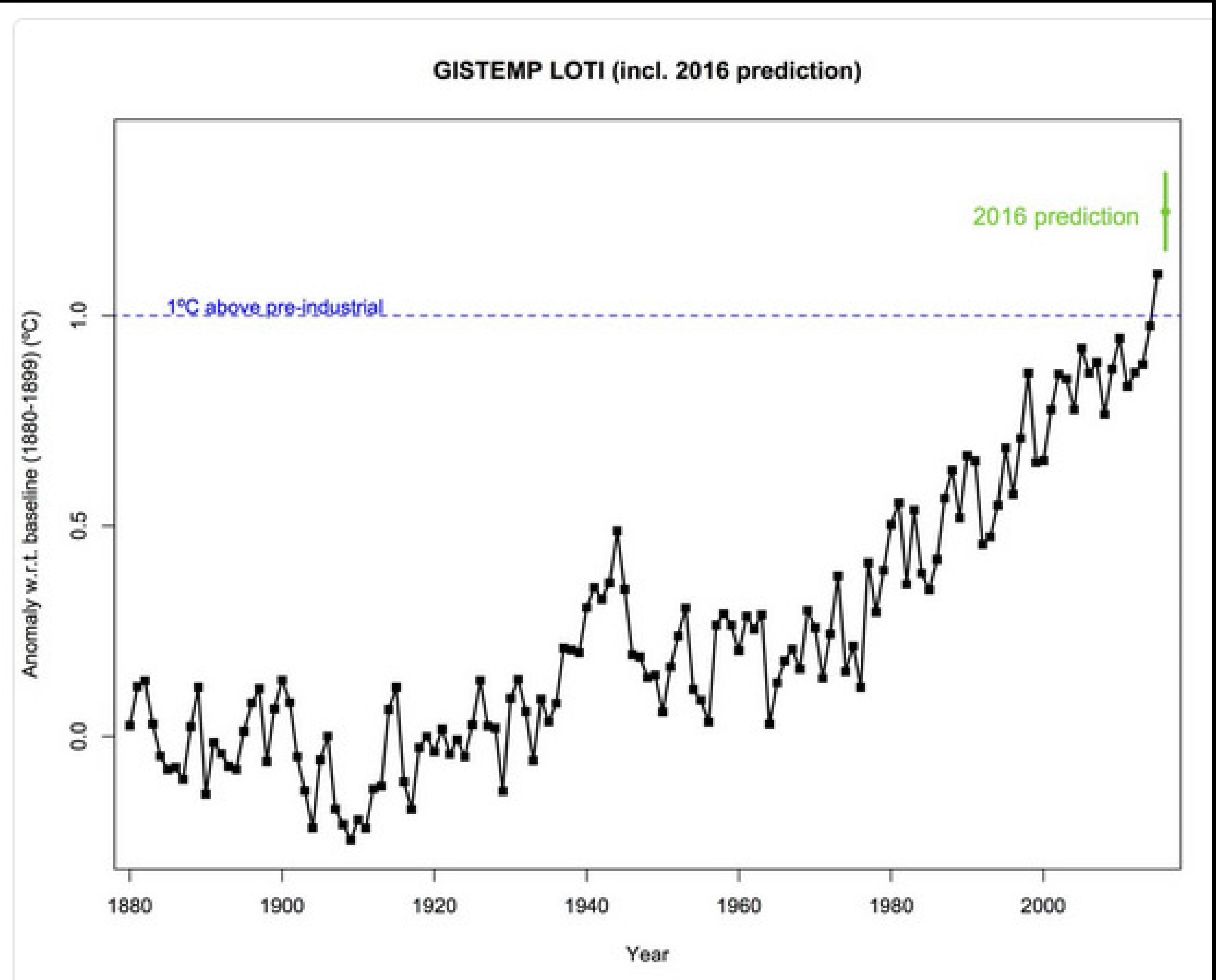
How Does Solar Activity Change Earth Temperatures?

- By itself, by not very much!
- **Lower solar activity -> Lower solar luminosity**. This is because magnetic field energy is being turned into thermal energy (the highest entropy form of energy).
- The luminosity effect is only about 0.1% between solar cycle max and min. The climate record shows a bit stronger effect at the great Maunder Minimum, but other things were going on then which can help explain the cooler climate then.
- Also, even slight cooling can be amplified if there is more ice created at the poles, which reflect sunlight better than ice-less ground.

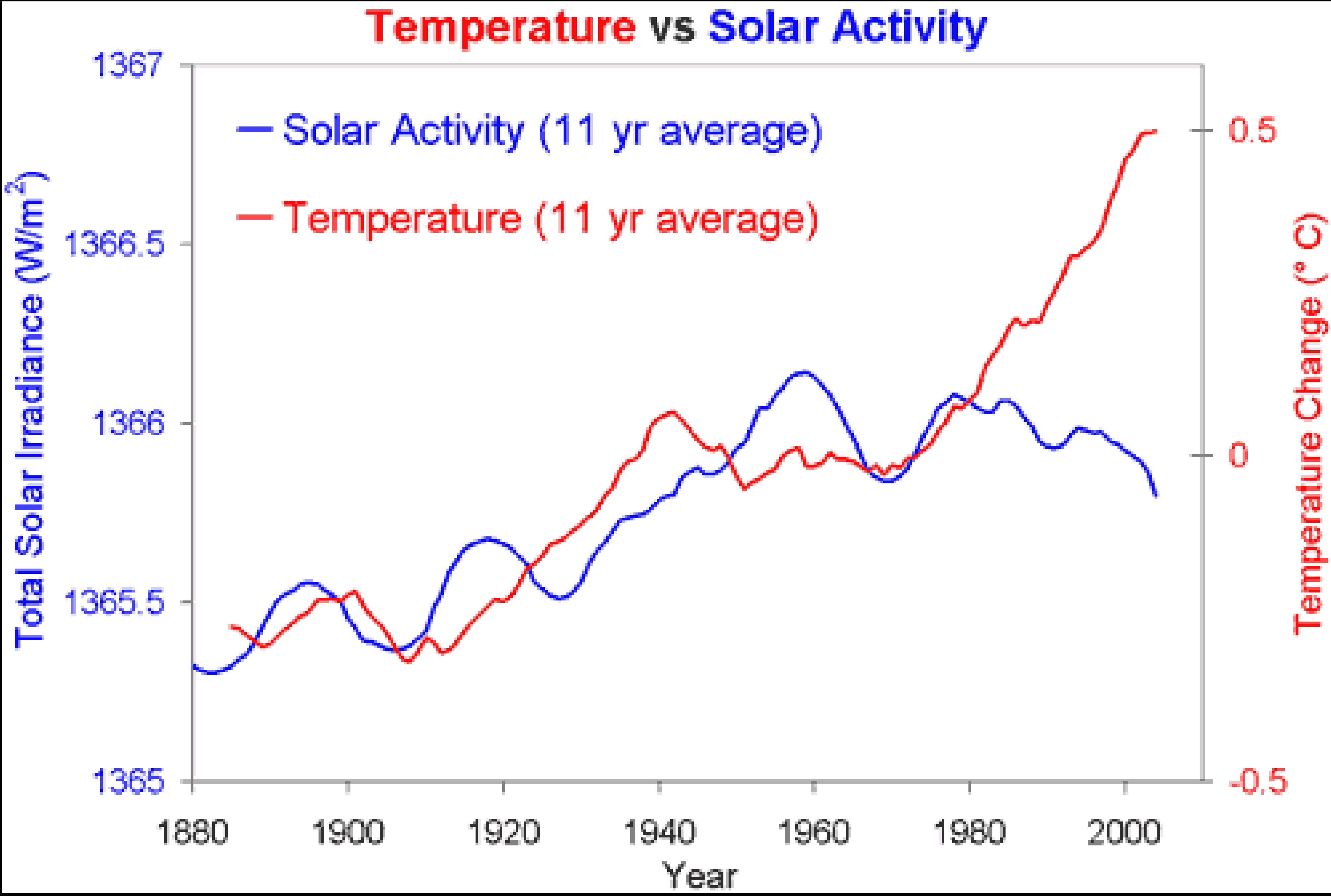
Could Solar Activity Explain Current Climate Change?

- **The science is clear…. NO**. In recent decades, climate change has become so dramatic and so accelerated that it far exceeds any historical correlation between solar activity and temperatures.
- **Even more: the sun's luminosity is actually very slightly decreasing while Earth temperatures rise rapidly, over the past 60 years.**
- Current climate change is being driven by human activities; mostly CO2 emissions generating enhanced Greenhouse Effect warming.
- For more on that, consider taking **Astro 7 "Planetary Climate Science"**, which covers in detail the science of climate and also current climate change on Earth.

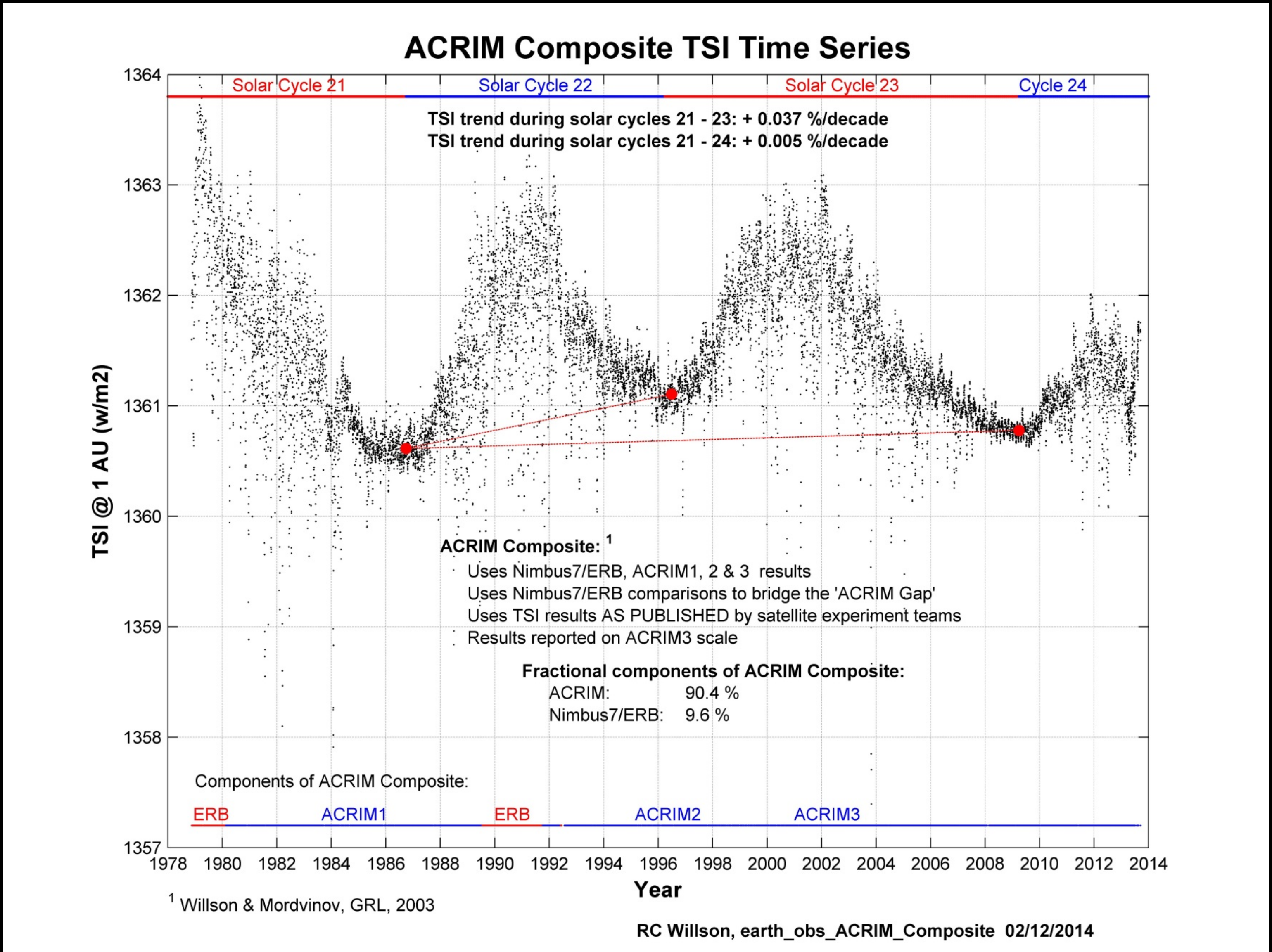
Global Temperatures are Skyrocketing; but not solar activity



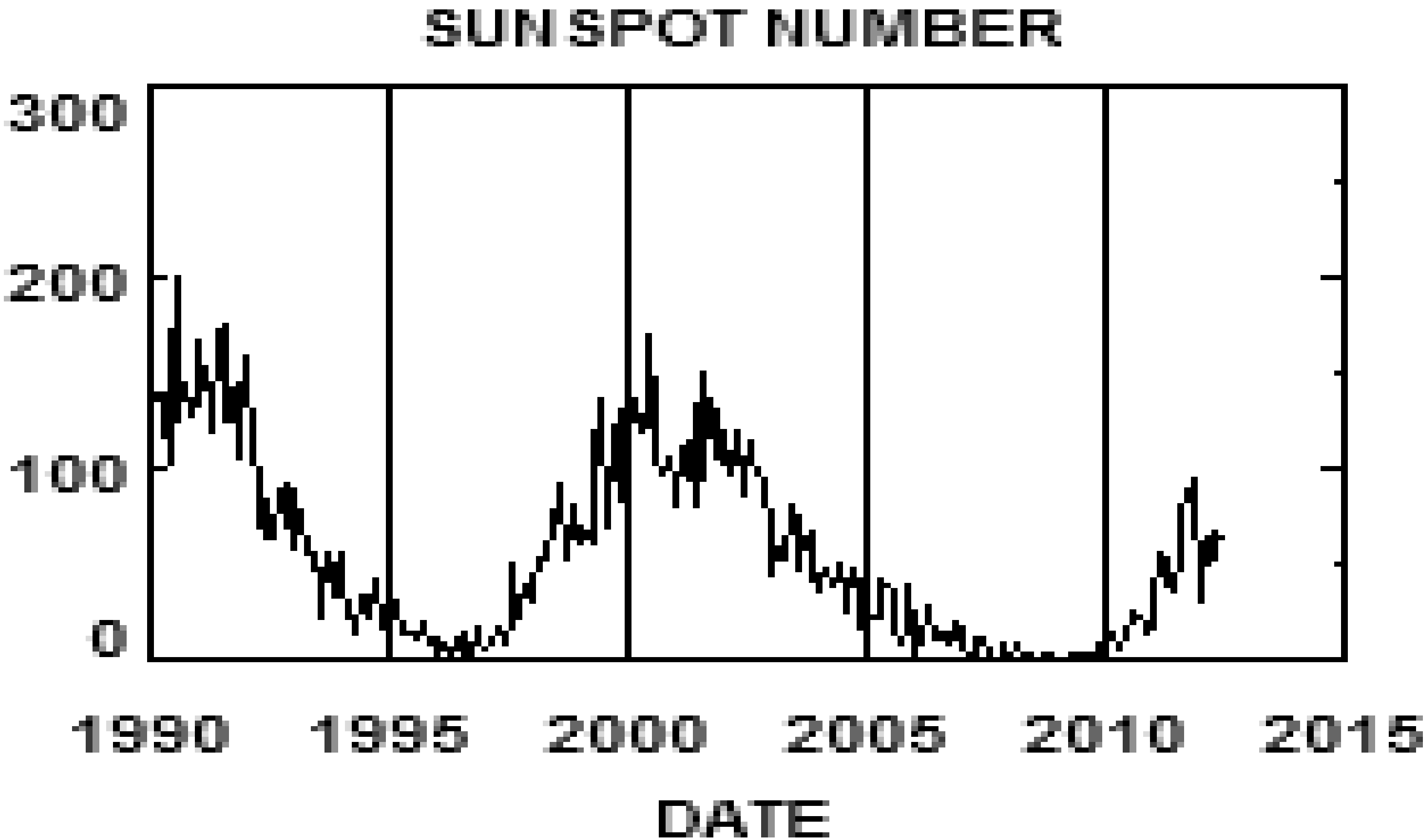
Global Average Earth Surface Temp vs. Solar Luminosity



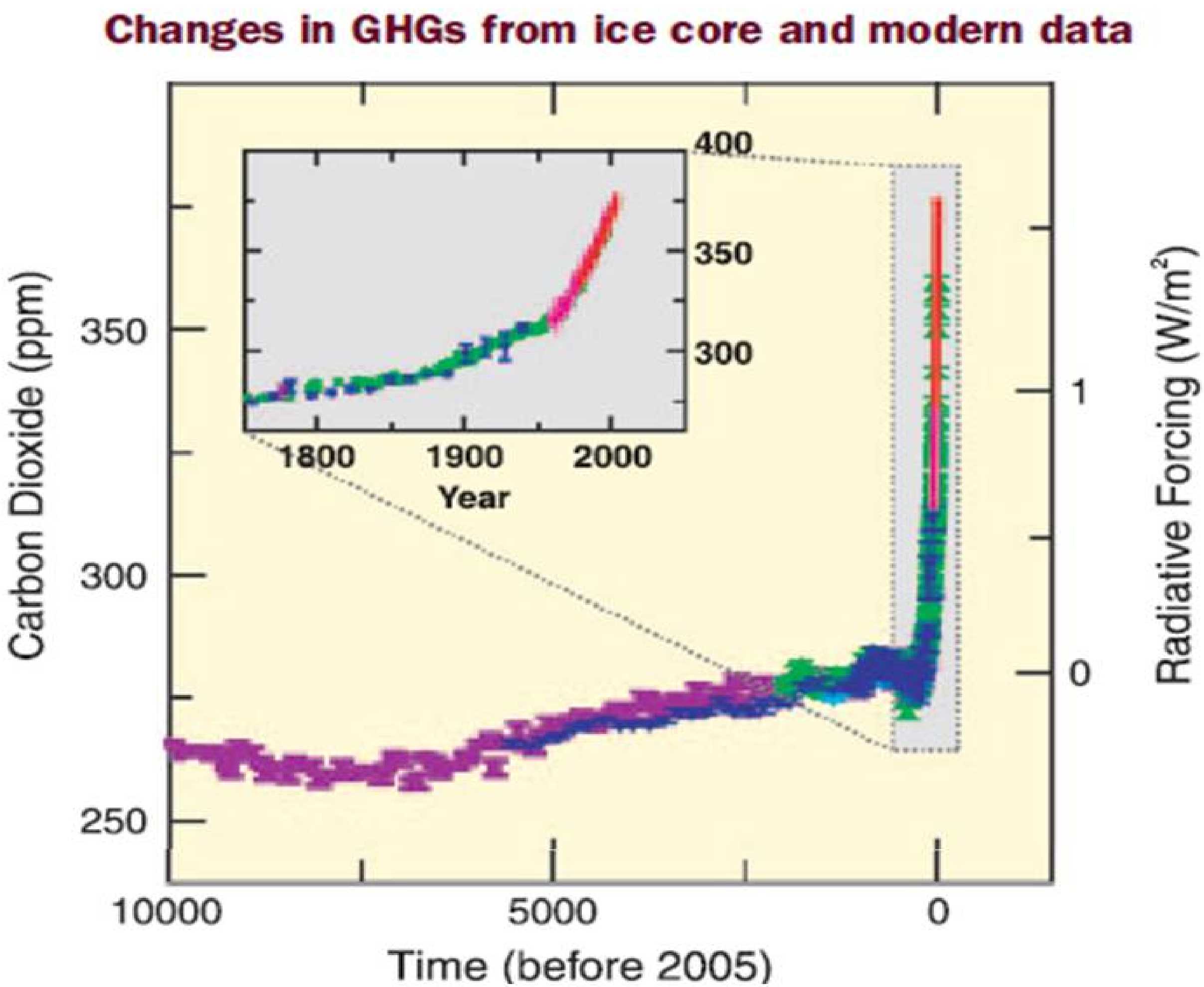
Total Solar Irradiance, Past 60 Years, Trending Down



Sunspot Number a good proxy for solar luminosity, also trending down

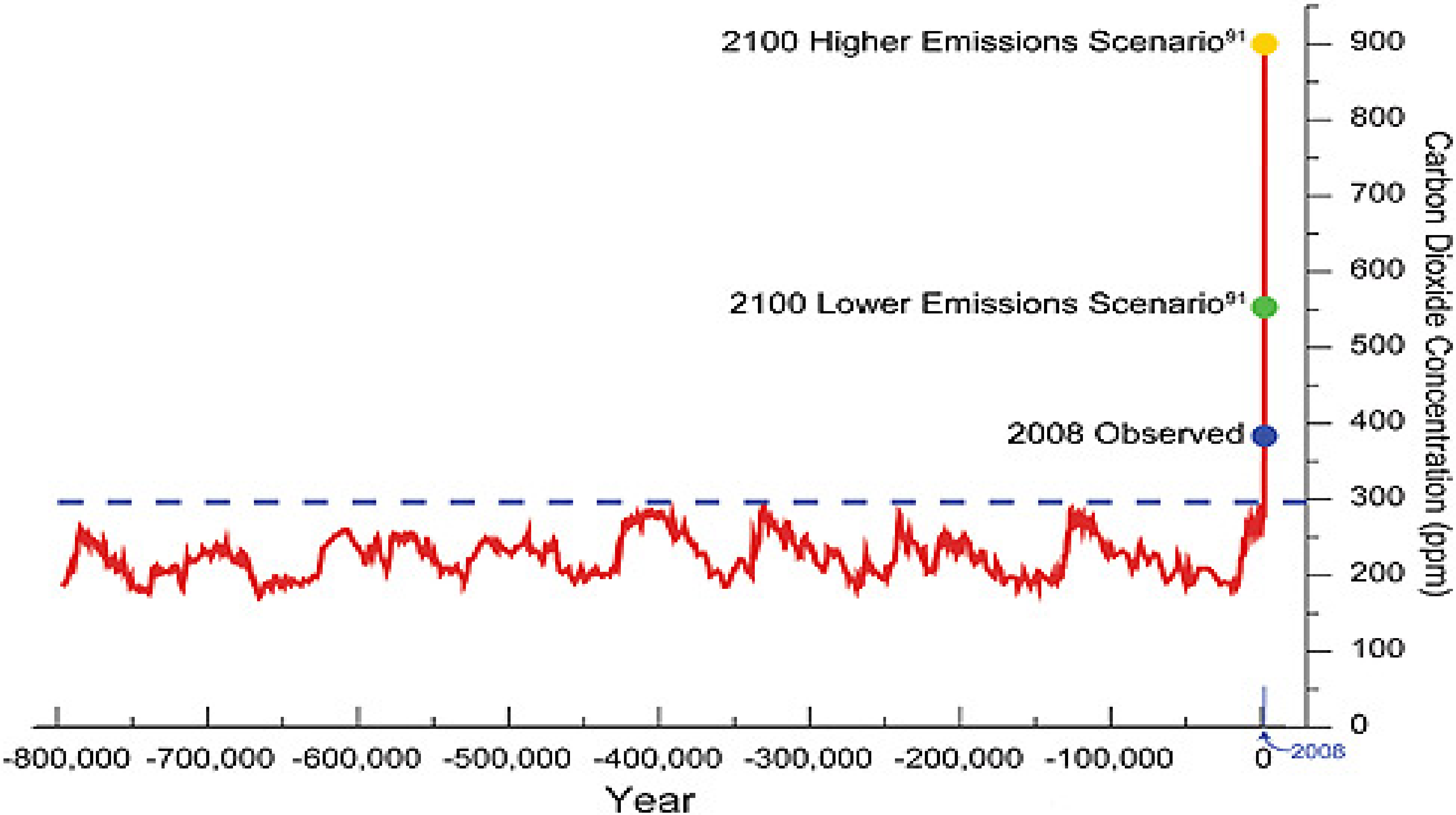


It's Greenhouse Gases (CO_2 mostly) that are causing global warming



http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr.pdf p. 38

Fig. 2.3 Axis label moved to fit bottom of this picture.

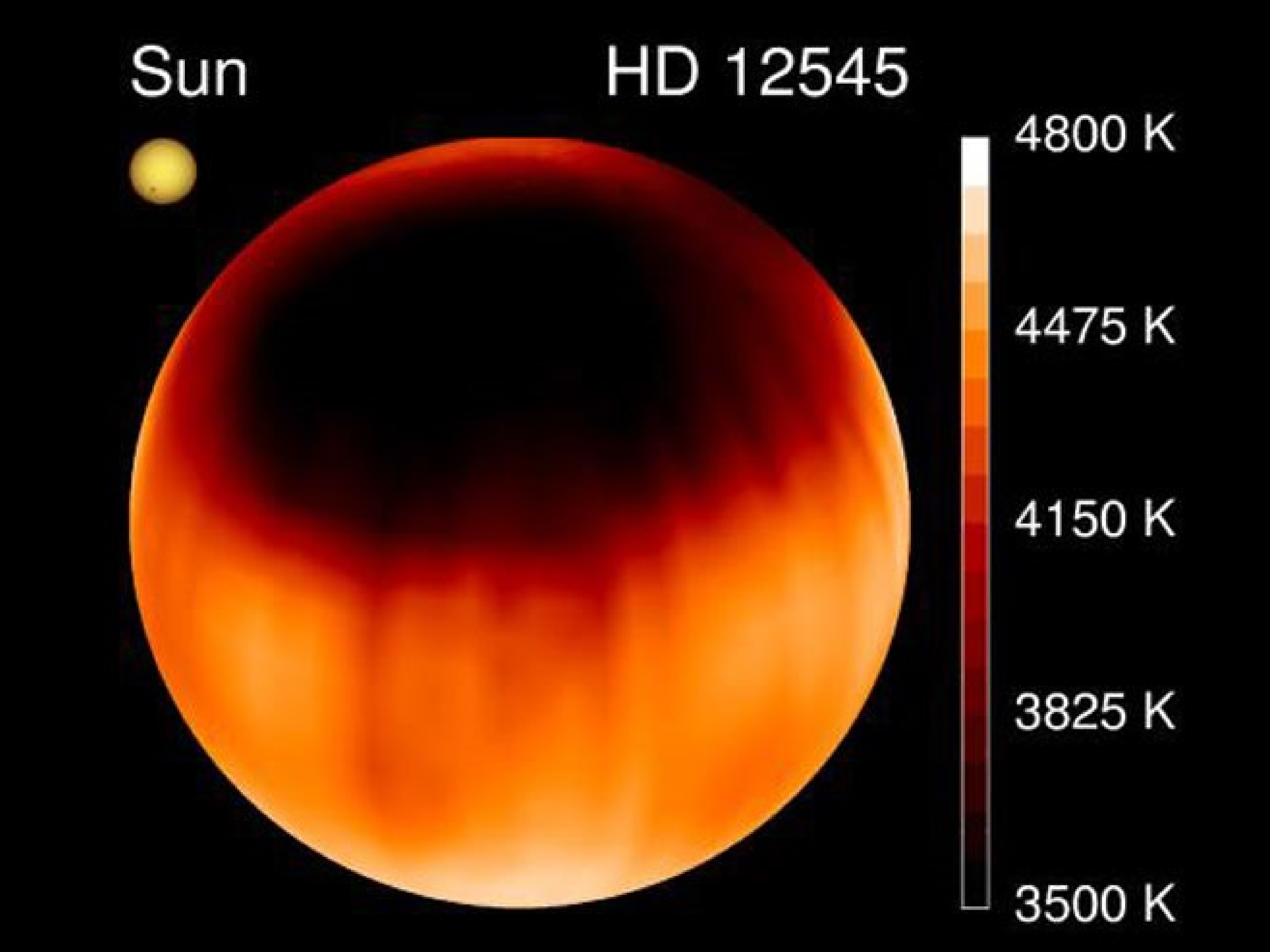


Lüthi *et al.*; Tans; IIASA[2]

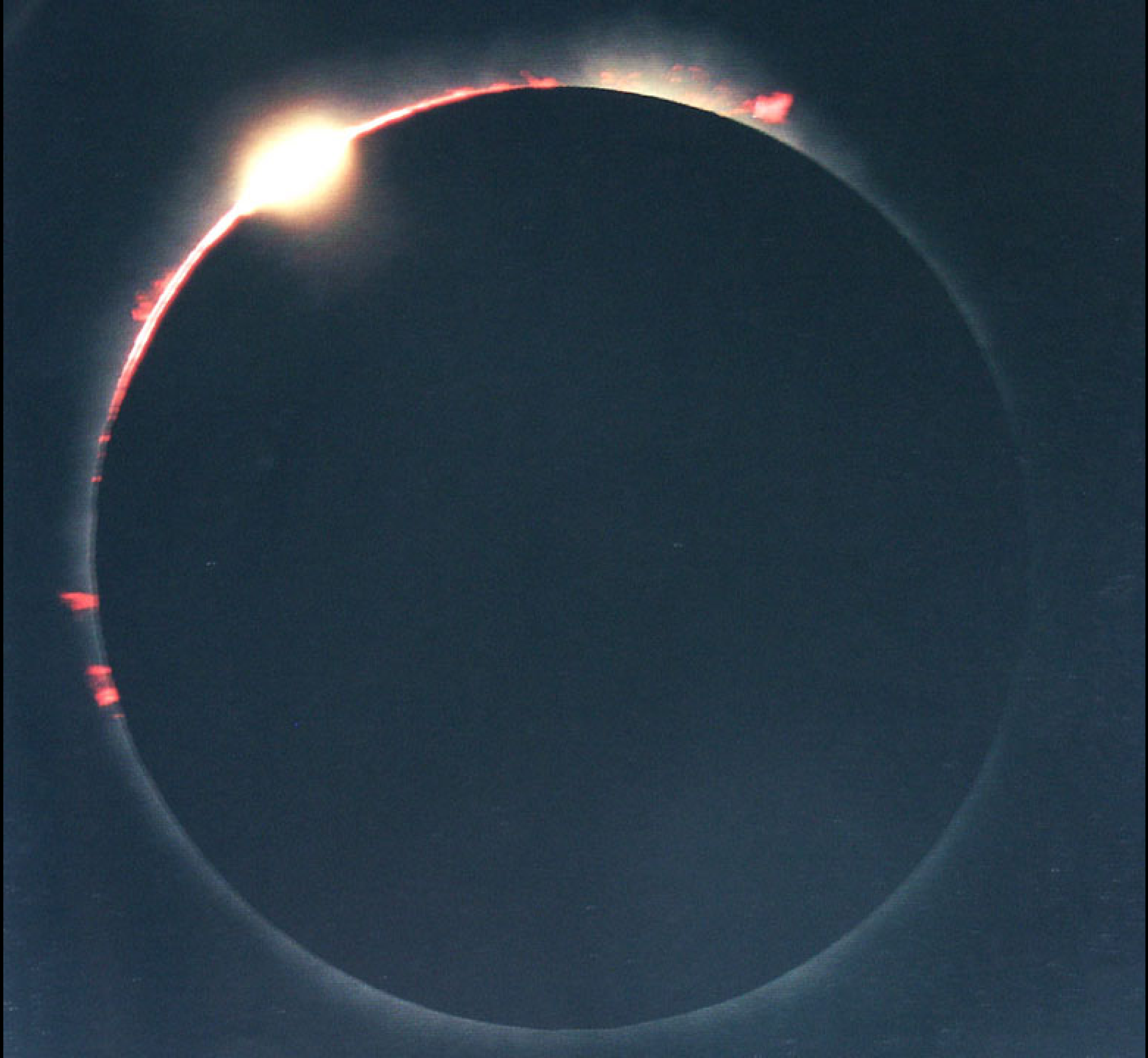
Analysis of air bubbles trapped in an Antarctic ice core extending back 800,000 years documents the Earth's changing carbon dioxide concentration. Over this long period, natural factors have caused the atmospheric carbon dioxide concentration to vary within a range of about 170 to 300 parts per million (ppm). Temperature-related data make clear that these variations have played a central role in determining the global climate. As a result of human activities, the present carbon dioxide concentration of about 385 ppm is about 30 percent above its highest level over at least the last 800,000 years. In the absence of strong control measures, emissions projected for this century would result in the carbon dioxide concentration increasing to a level that is roughly 2 to 3 times the highest level occurring over the glacial-interglacial era that spans the last 800,000 or more years.

The Sun isn't the only star showing magnetic fields and star spots

- Magnetic field activity on the sun is relatively mild compared to many stars, even stars of similar mass and surface temperature.
- By far the most dramatic example of star spots is HD 12545 – a chromospherically active star which has had huge spots in the past – star spots discovered right here at Cabrillo Observatory!


Sun
HD 12545
4800 K
4475 K
4150 K
3825 K
3500 K

The 10,000K chromosphere – red from H-alpha emission



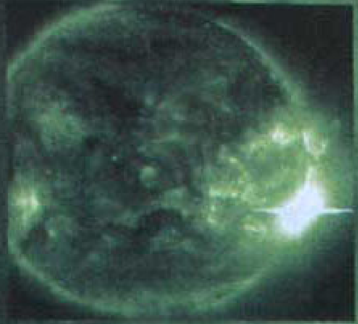
The Corona, 2 million K, at Solar Activity Maximum


©2001 F. Espenak, www.MrEclipse.com

The Solar Corona

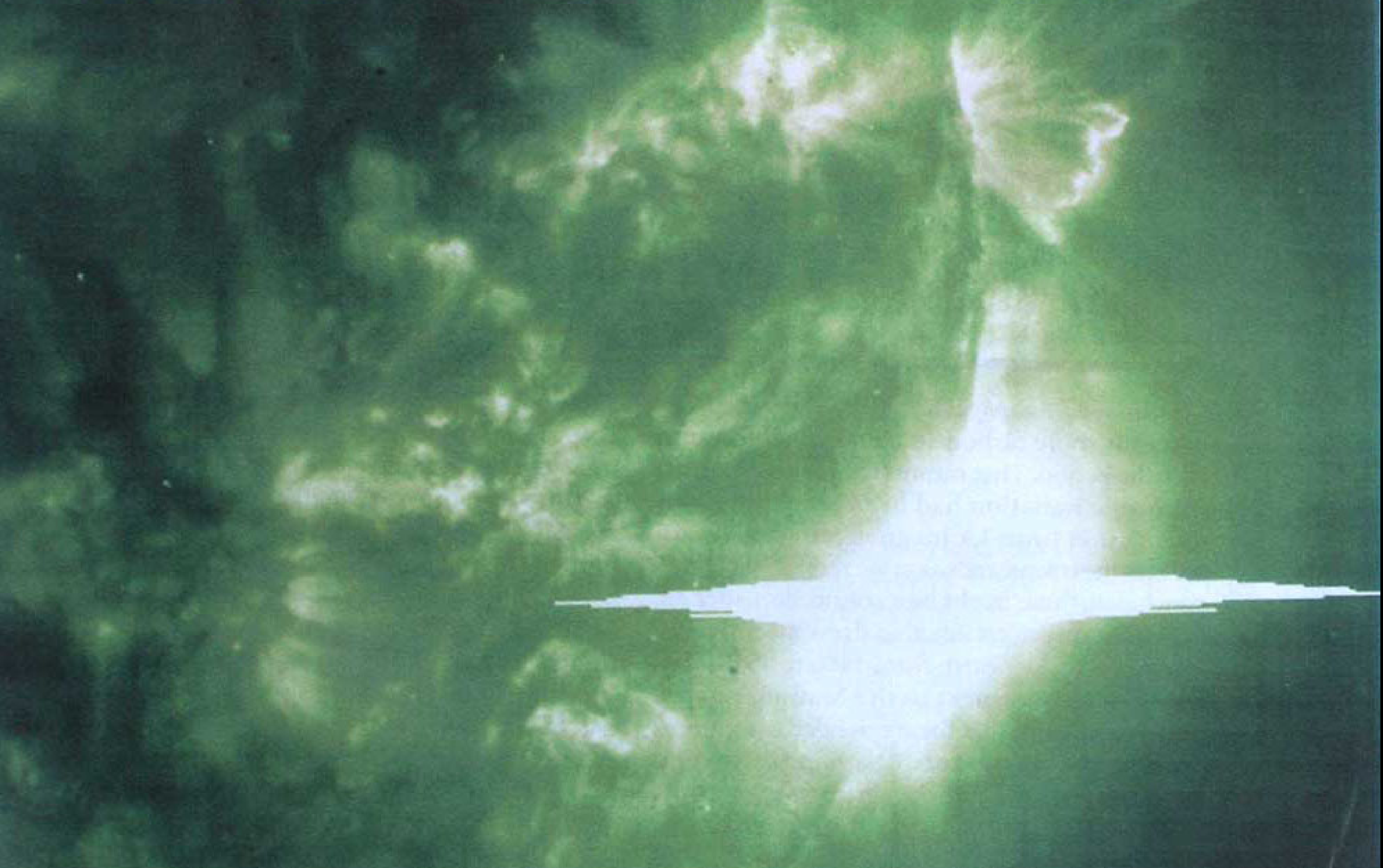
- The corona, at 2 million Kelvin, means the protons and electrons and helium nuclei are moving at speeds of order 100 km/sec. That's far above the escape velocity of the sun.
- So the corona is continually evaporating these particles away from the sun. It's the **solar wind**, and typical of all stars.
- It's thin, so it's dim, and only visible during total solar eclipses, and it white because these ionized particles will equally reflect all wavelengths from the sun beneath it.

11/2: Nearly rotated away from Earth, the spots keep firing flares and CMEs.

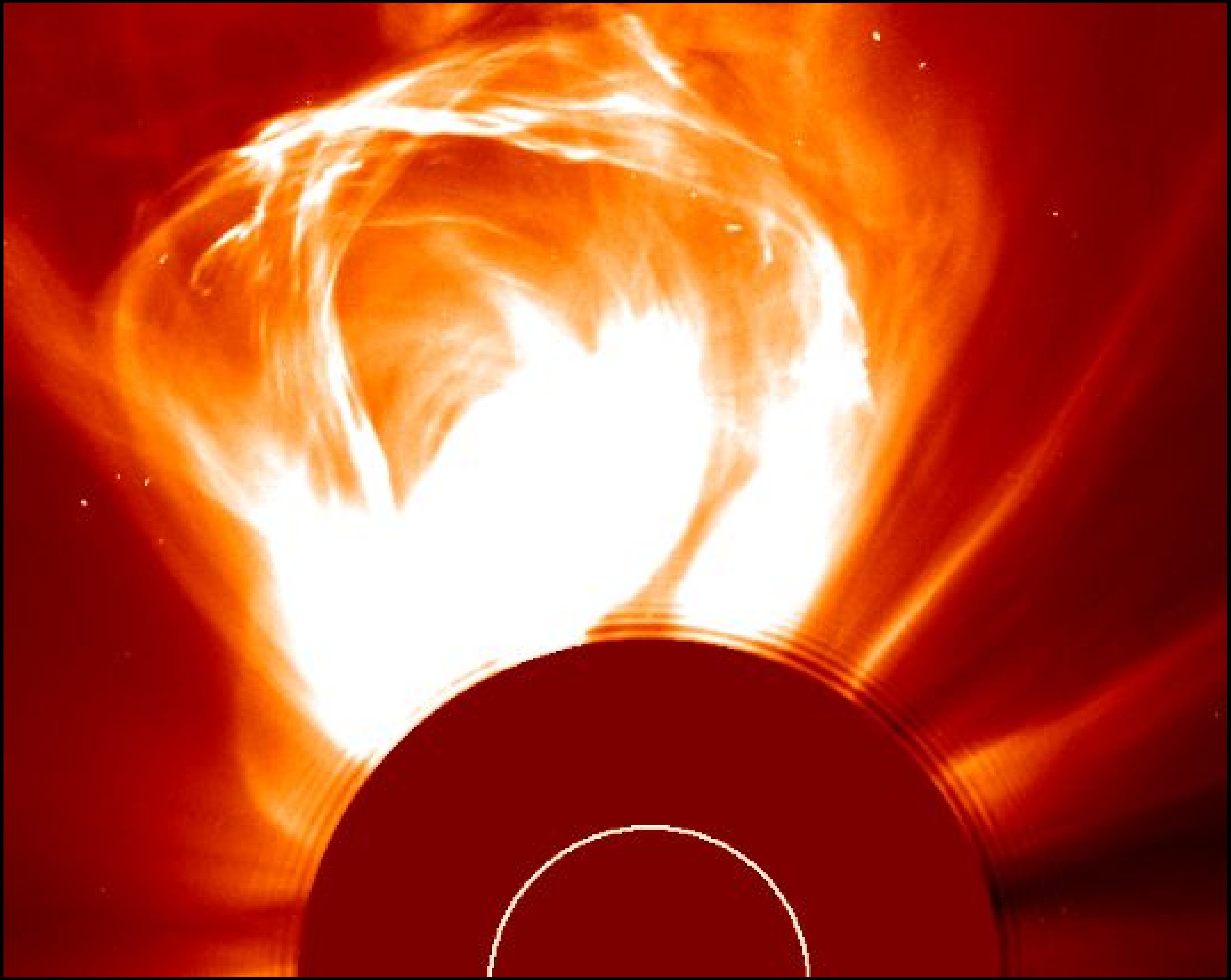


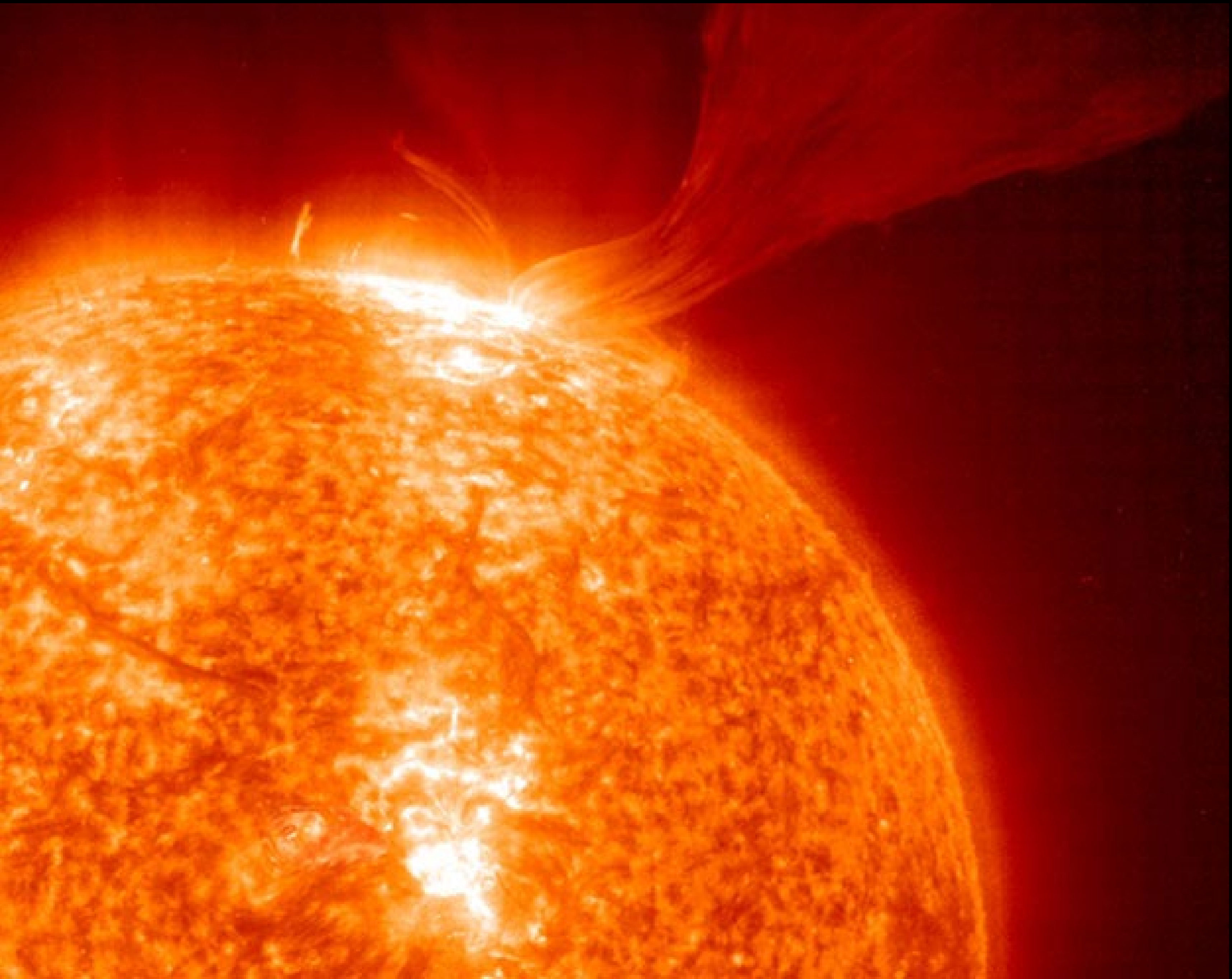
11/4: Most powerful flare on record blasts from same sunspot (enlarged below).

A fast-moving CME follows, but at an angle that only glances Earth.



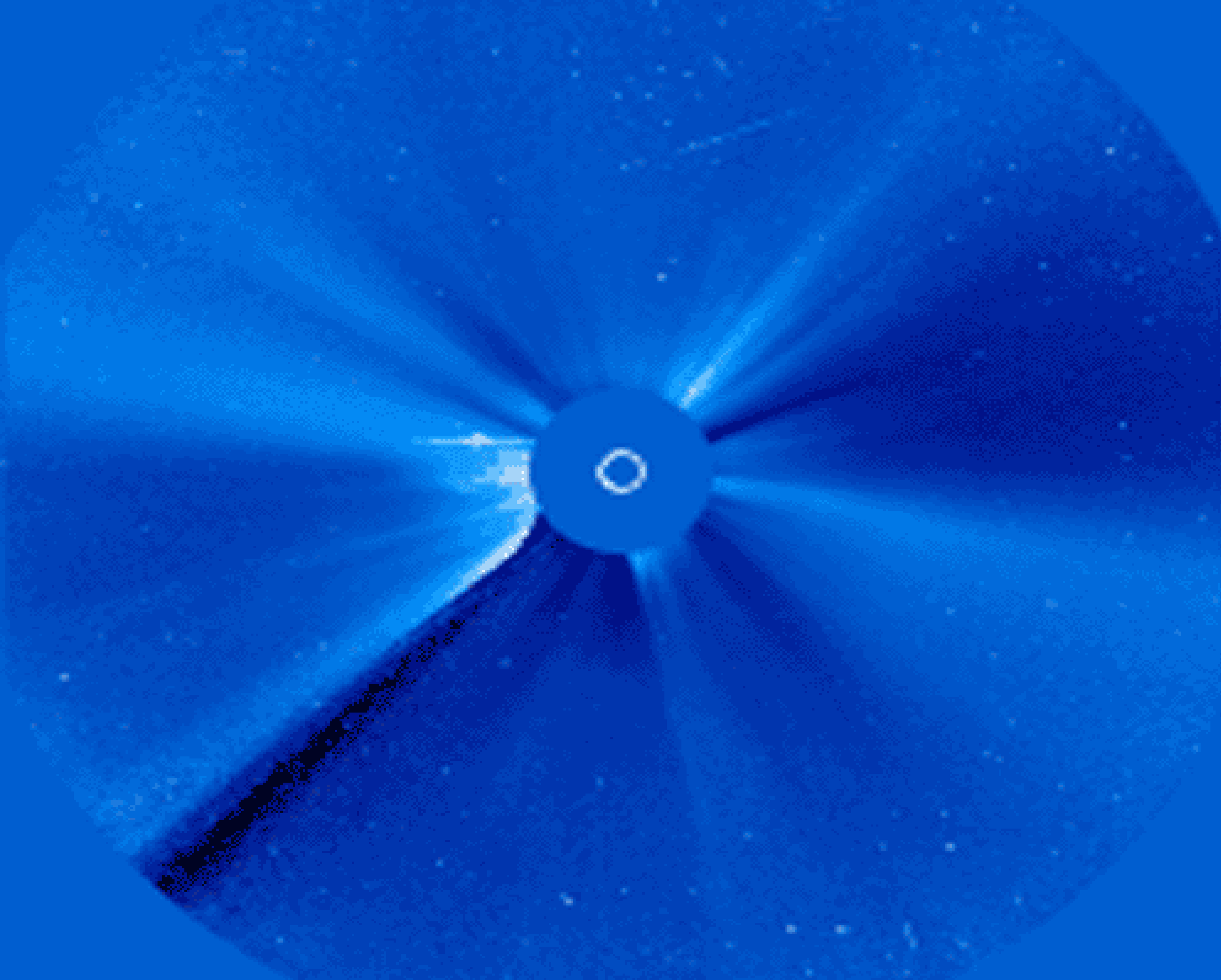
Coronal Mass Ejection, from Solar Flares

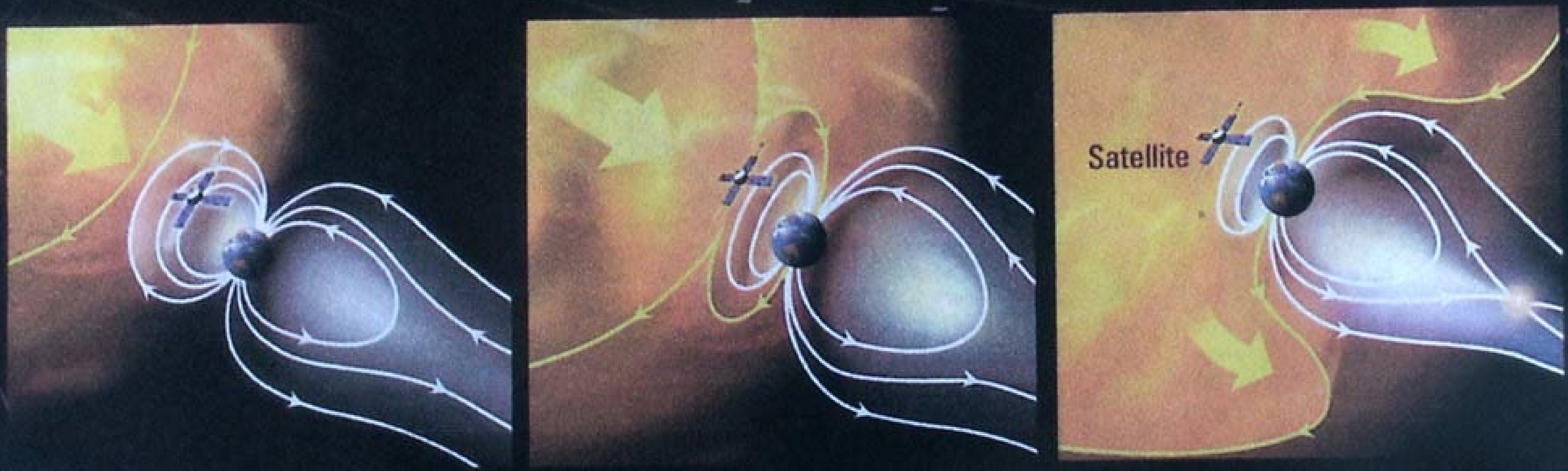




Video Images of Solar Activity

- Convection on photosphere (0:34)
- --Solar Flares, CME's, Solar Polarity Sectors (1m41s)
- NASA X-ray movie of solar surface (10 Meg; takes a while). Instead try the Wikipedia page which contains it

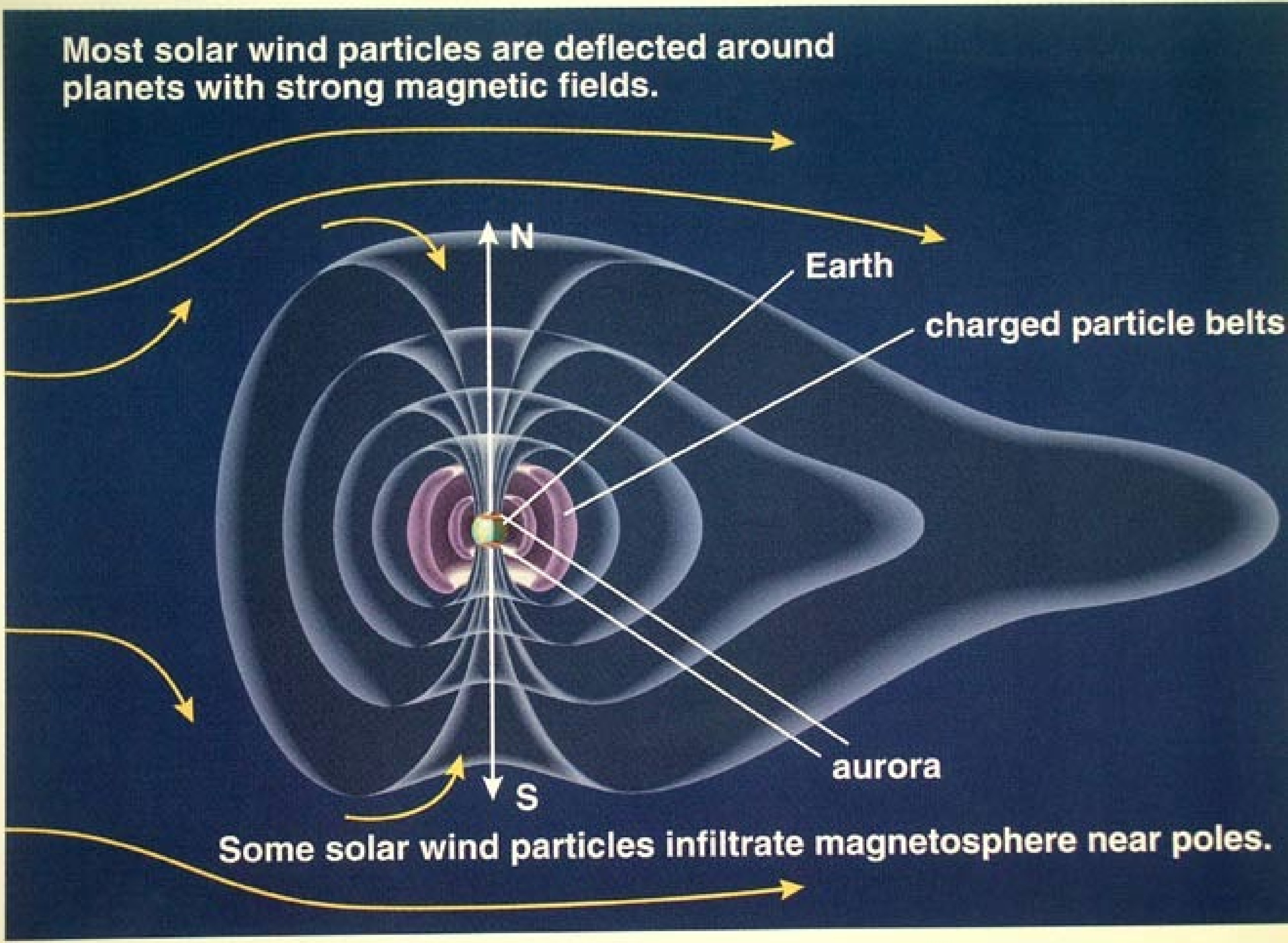


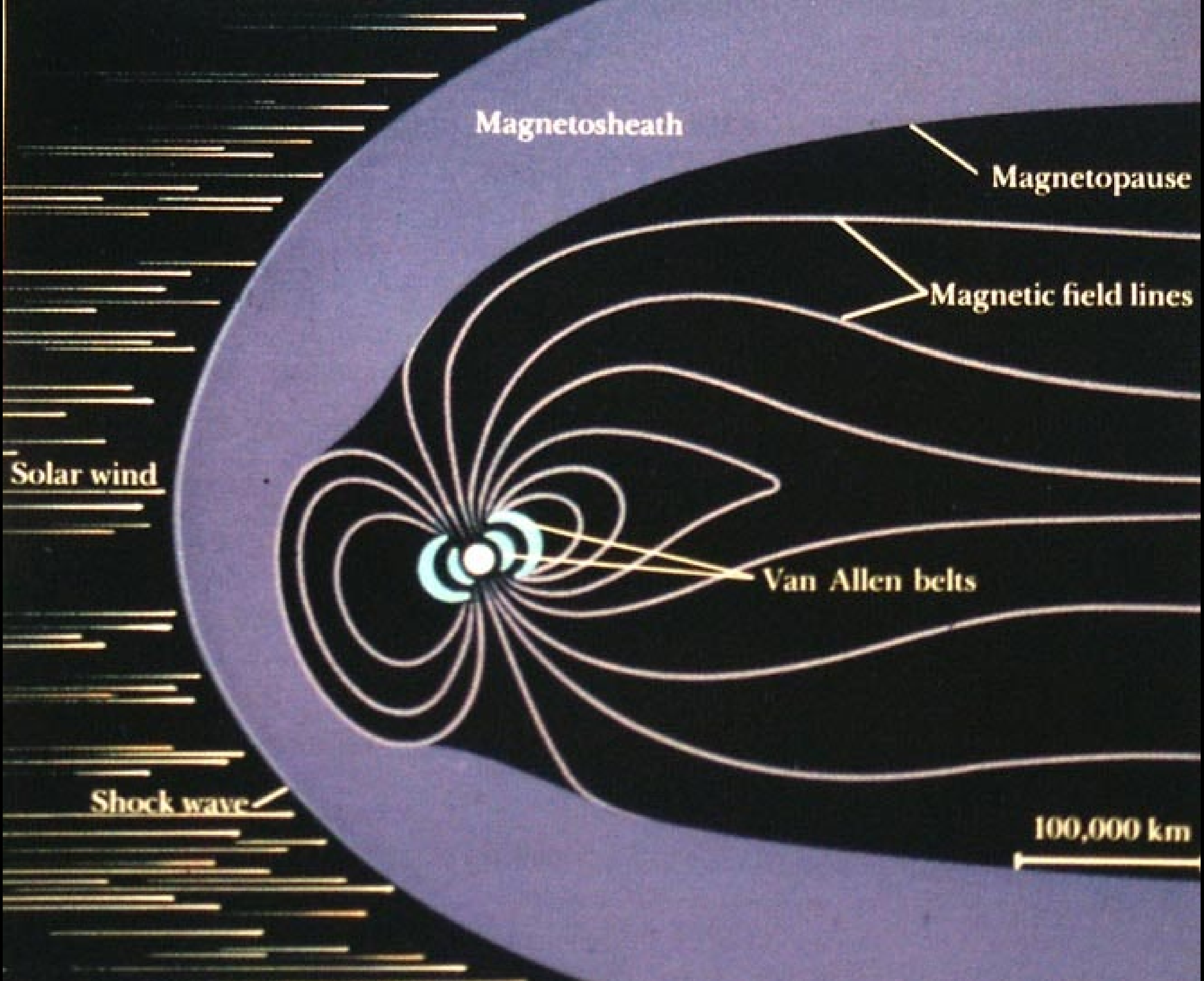


Earth Takes a Hit

It takes one to three days for a CME to reach us. SOHO and other satellites detect its liftoff, but not until about an hour before impact can we measure how bad it will be. In the worst case (above), a CME carries a southward magnetic orientation, the opposite of Earth's. Such a CME not only compresses our protective magnetosphere (exposing satellites to particles), it also links to our dayside magnetic field and peels back field lines. Then, at the nightside tail, Earth's lines reconnect, driving trillions of watts of power into the upper atmosphere.

ALLAGHER, L-3 COMMUNICATIONS GSI; PETER A. GILMAN, HAO/NCAR; CHARLES C. GOODRICH, BOSTON UNIVERSITY, CENTER FOR
G. LUHMANN, SPACE SCIENCES LABORATORY, UNIVERSITY OF CALIFORNIA, BERKELEY; JURI TOOMRE; MICHAEL WILTBERGER, HAO/NCAR


Most solar wind particles are deflected around planets with strong magnetic fields.
N
Earth
charged particle belts
aurora
S
Some solar wind particles infiltrate magnetosphere near poles.



Magnetosheath
Magnetopause
Magnetic field lines
Solar wind
Van Allen belts
Shock wave
100,000 km

The Genesis Mission

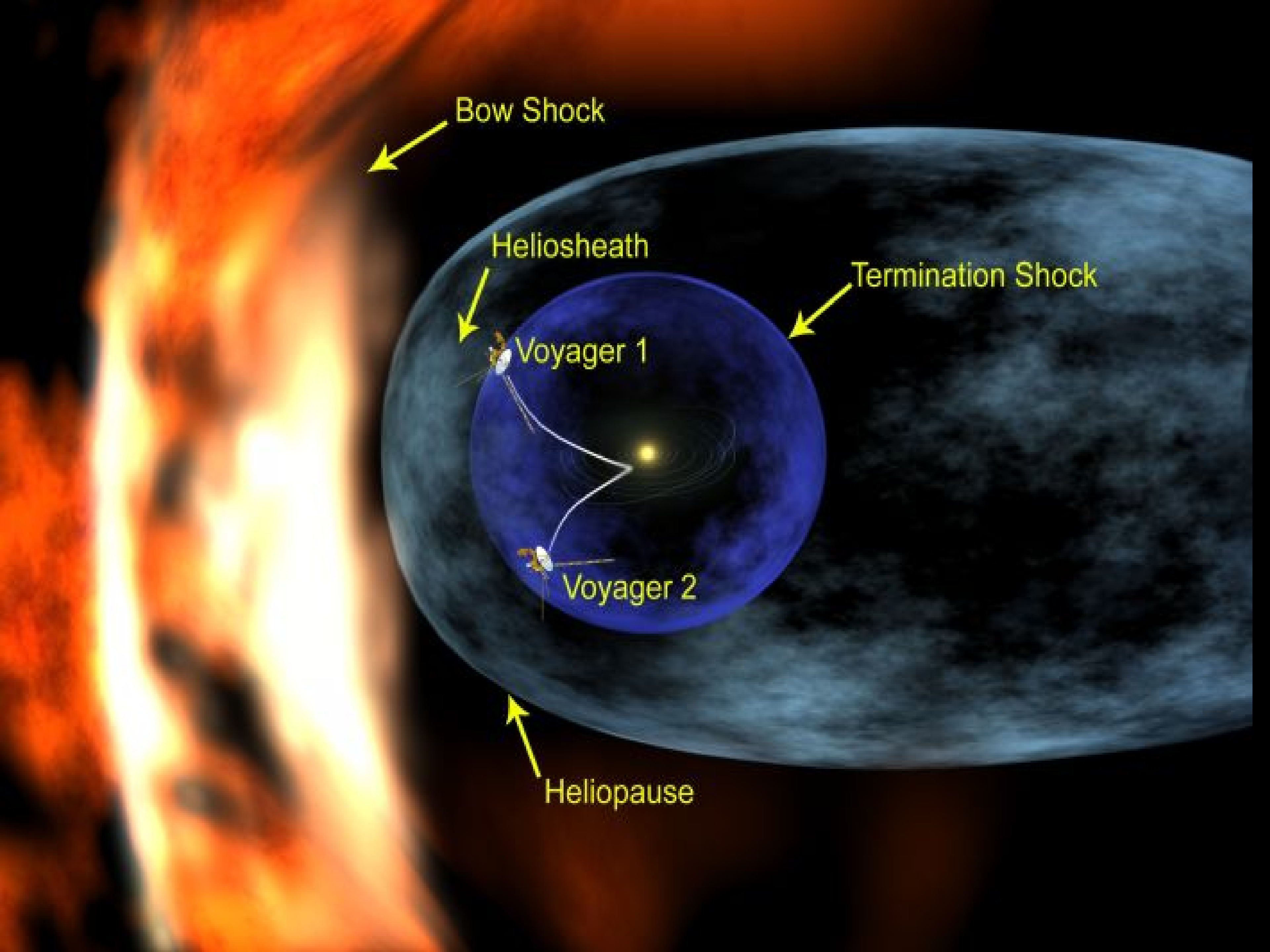
- (no, not the hokey StarTrek thing…)
- Spacecraft spent months out in interplanetary space, capturing particles from the solar wind and from interstellar space
- Then, brought them back to earth
- But, there was this ***parachute problem***…

Aurorae – GiNormous Flourescent Lights!

- Caused when high speed solar wind particles impact the Earth’s atmosphere
- Collisionally excites the nitrogen and oxygen atoms
- These atoms then de-excite (electrons fall back down through the energy levels) giving off photons
- Exactly the same as how flourescent lights work!

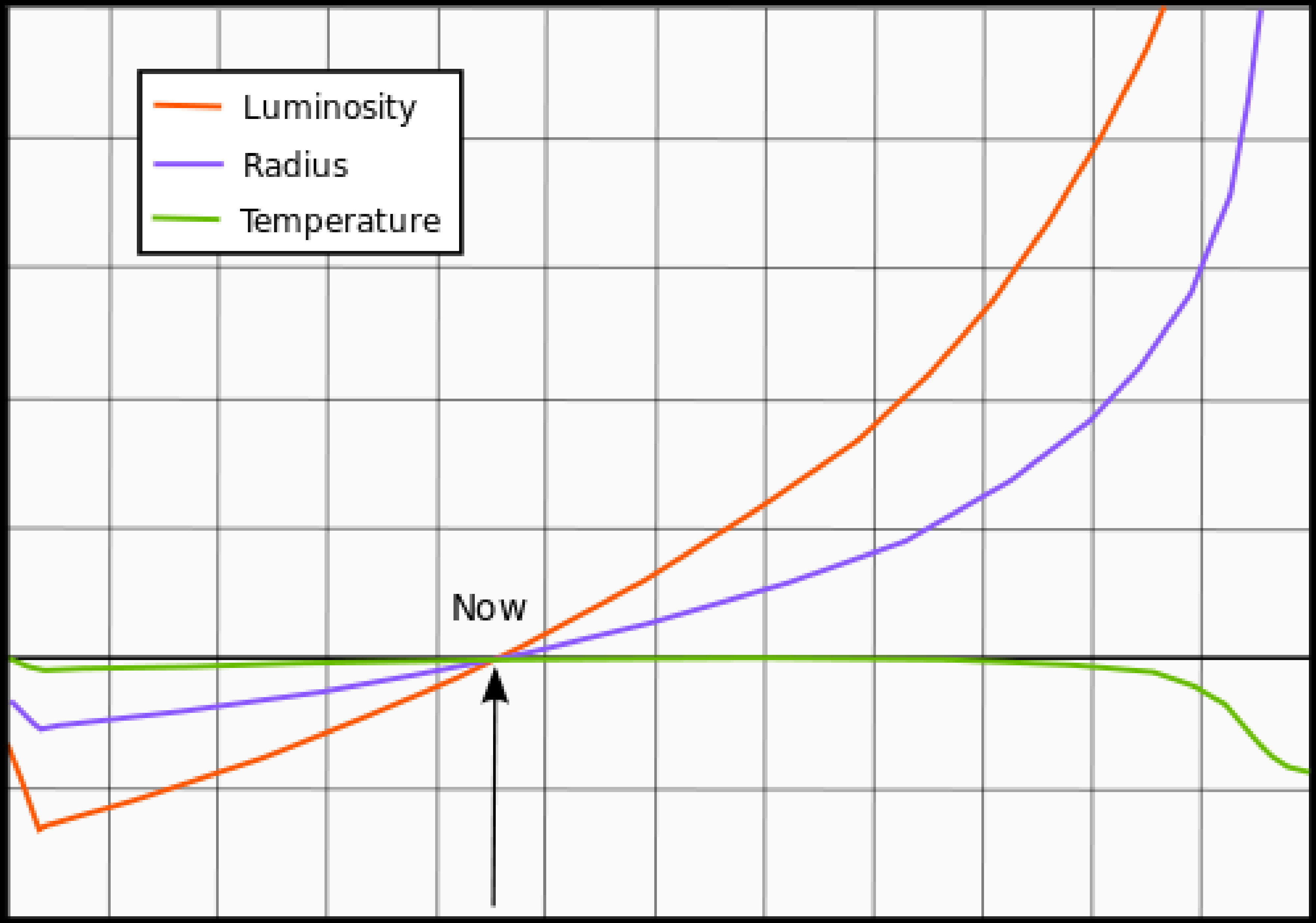

© Phil Hoffman

Comet NEAT, kinked tail. Comet tail ions feel the magnetic field discontinuities in coronal mass ejections


Bow Shock
Heliosheath
Termination Shock
Voyager 1
Voyager 2
Heliopause

Long Term Change…

- As the sun ages, its core collapses as hydrogen converts to helium, and this increases the gravity and pressure and fusion rate in the core
- So, the sun is getting more luminous, long term
- During the life of the solar system, the sun, now middle aged, has increased in luminosity by 25%, and close to 30% since it's minimum L soon after formation.



Luminosity
Radius
Temperature
Now

This Increasing Luminosity will Continue and even Accelerate.

- We have a couple hundred million years before it gets dangerously hotter for ***<u>this</u>*** reason.
- But longer term…

ew billion years from now, with atmosphere and ocean boiled away by a growing post-main-sequenc
ne to an end. Humankind — or whatever it has evolved into — may flourish elsewhere in the galax
The Last Three Minutes, we can't run forever. Painting © 1991 David A. Hardy/Astro Art.

We're All Doomed!

Key Points – The Sun

- Know the layers of the sun
- Magnetic fields cause splitting of spectral lines, allows us to measure them in the Universe – Zeeman Effect
- Sunspots; high magnetic field traps gas on photospheric surface, where it cools.
- Photosphere is the coolest layer of the sun
- Corona heated by magnetic field energy to ~million degrees, but very low density
- Hydrogen fuses to make helium in core, creating neutrinos, and photons, pressure to hold up sun against gravity, needs 10 million K
- Solar luminosity climbs slowly as it ages, same for all stars
- Higher solar magnetic activity -> higher solar luminosity, but very slight.
- Last 60 years, sun getting slightly dimmer
- Convection causes "granules" on the photosphere, several hundred km across convection cells