Chap 14: The Sun – A Typical Star

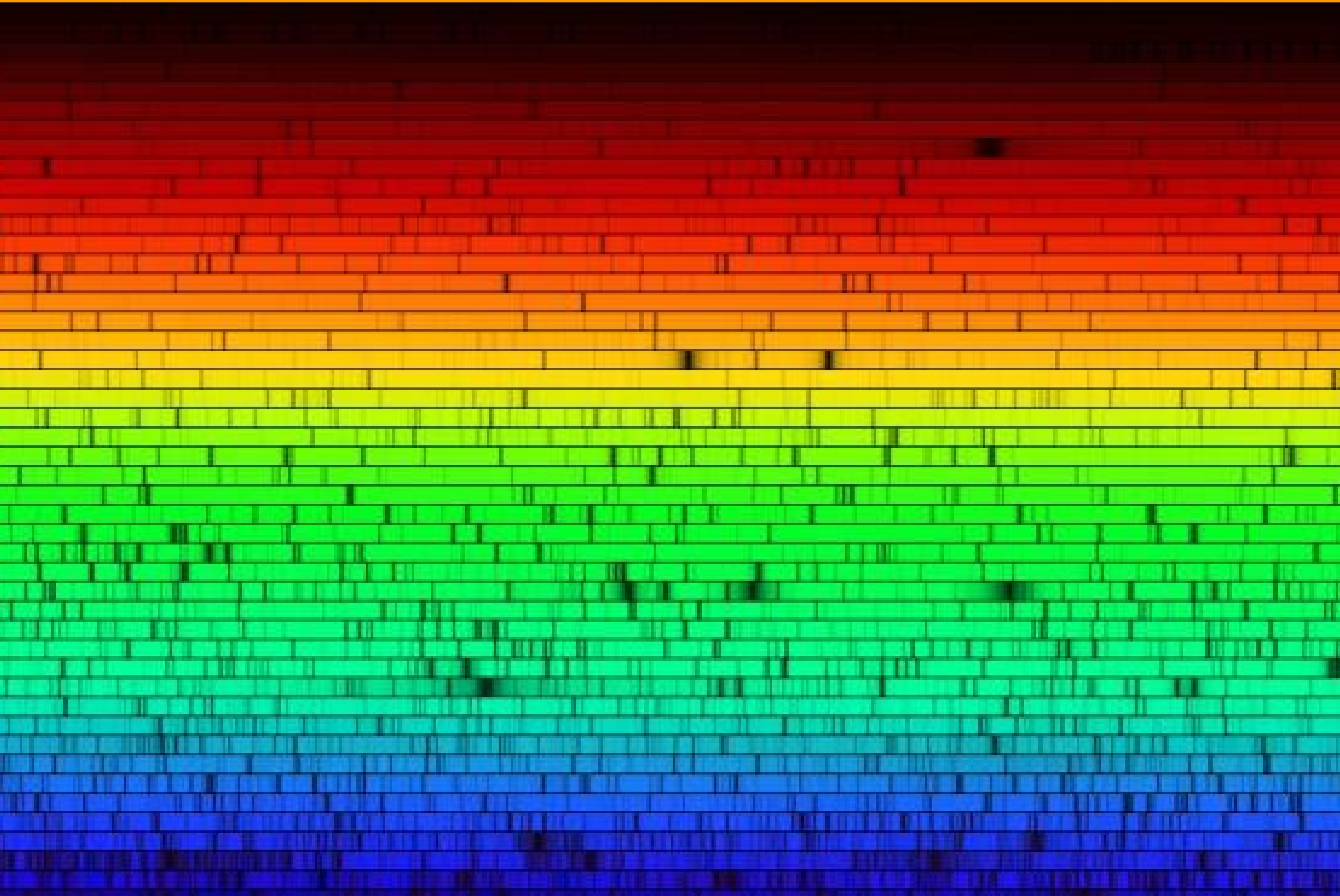
Here's the Story I'll Unfold for you…

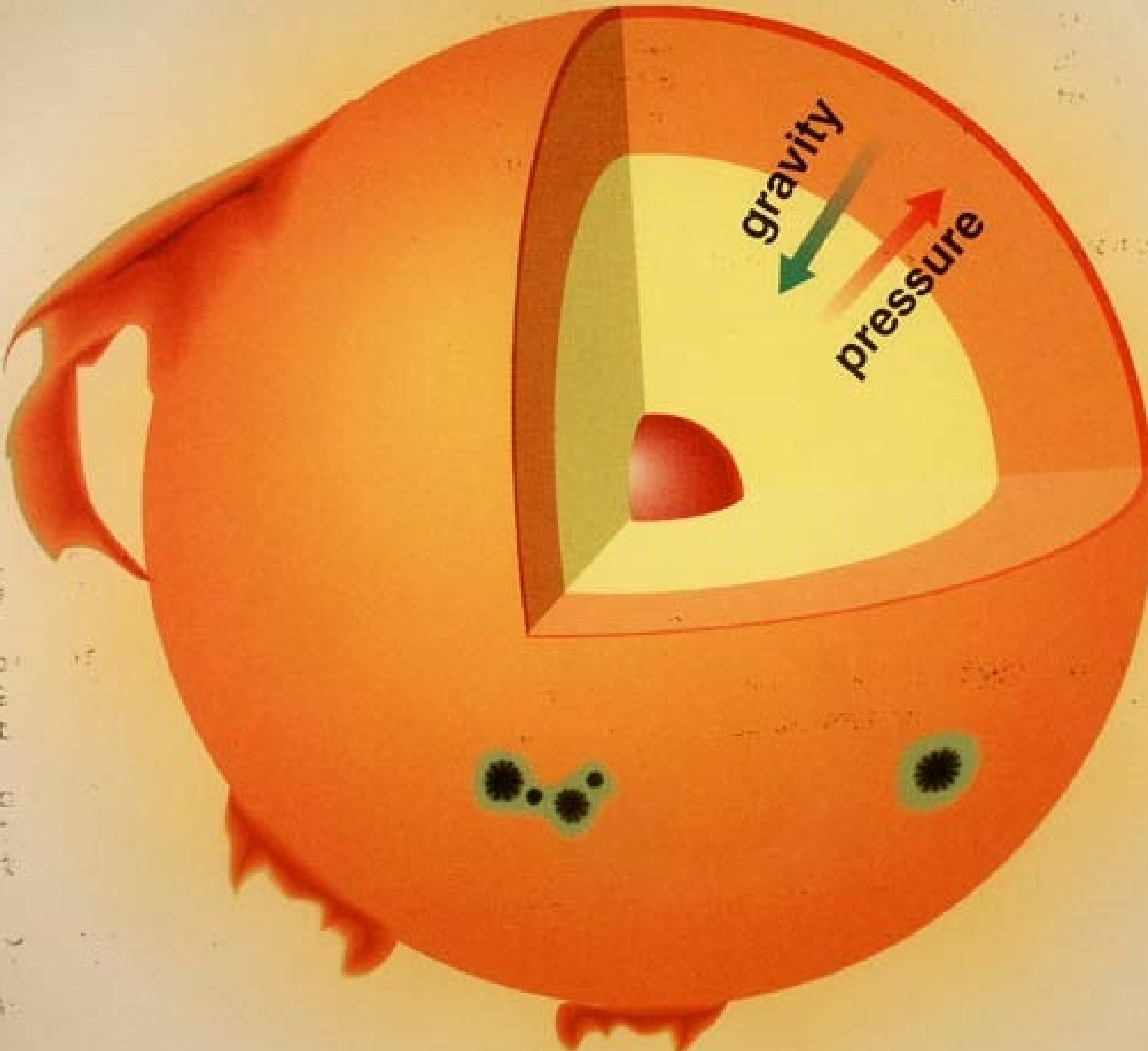
- What's it made of?
- A star: self-supporting partially ionized gas balancing gravity w/ pressure
- Nuclear fusion and how it powers the sun
- The layers of the sun; core, radiative zone, convective zone, photosphere, chromosphere, and corona
- Sunspots and magnetic fields, the sunspot cycle
- Solar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

An Eschelle spectrograph image of solar spectrum




gravity
pressure

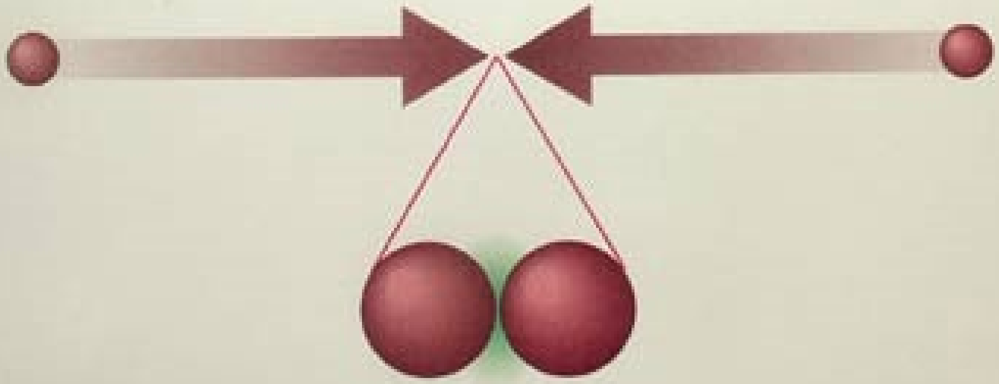
A Star: A Balance between Gravity and Pressure

- It's self-regulating, 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**.
- A "negative feedback" which gives stability

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 (attractive) overcomes electromagnetic repulsion of protons due to their having the same charge

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.

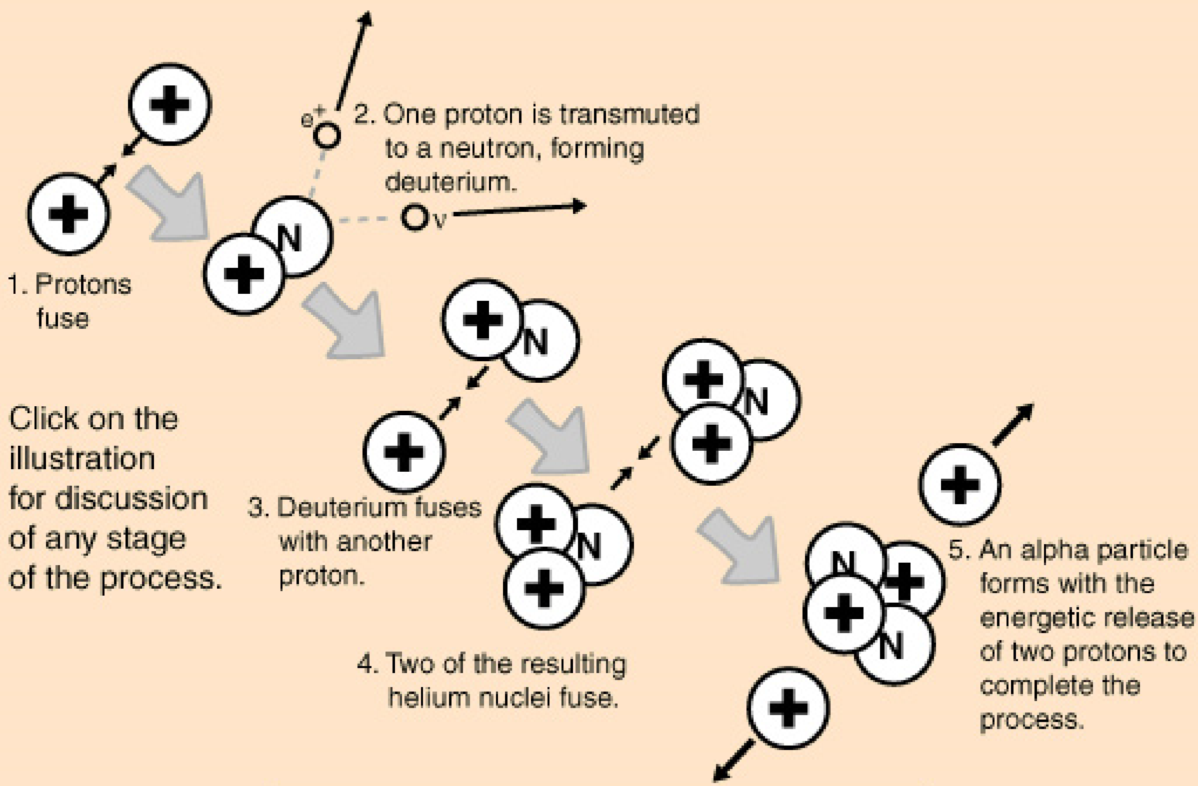
What Nuclear Reactions Power Stars?

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

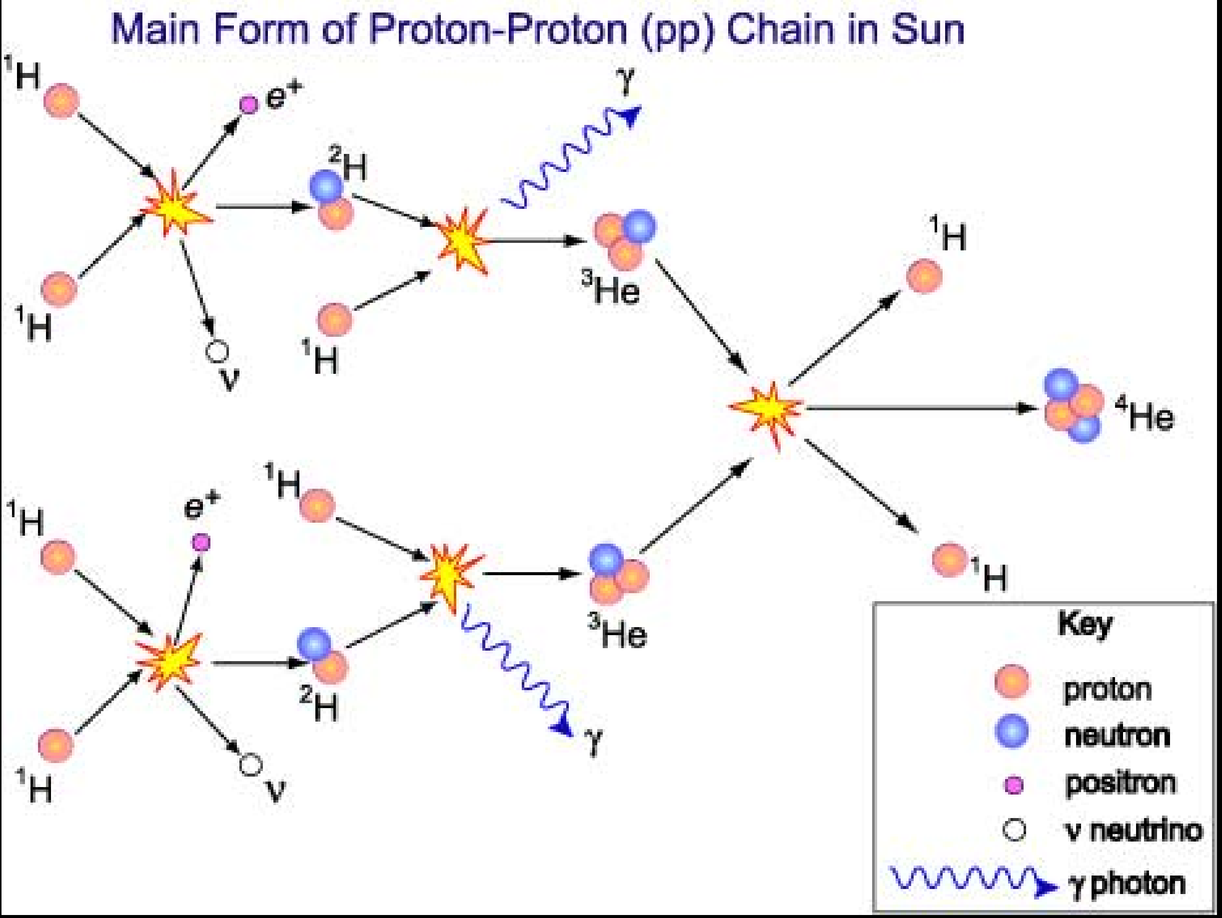
This is the basic reaction, but some amounts of energy also come from other possible branches, involving Lithium etc.

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.

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

- The 2e+ (positrons) quickly annihilate with electrons, 2e+ + 2e- = 4γ. Adding in the 2γ from the He^3 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.

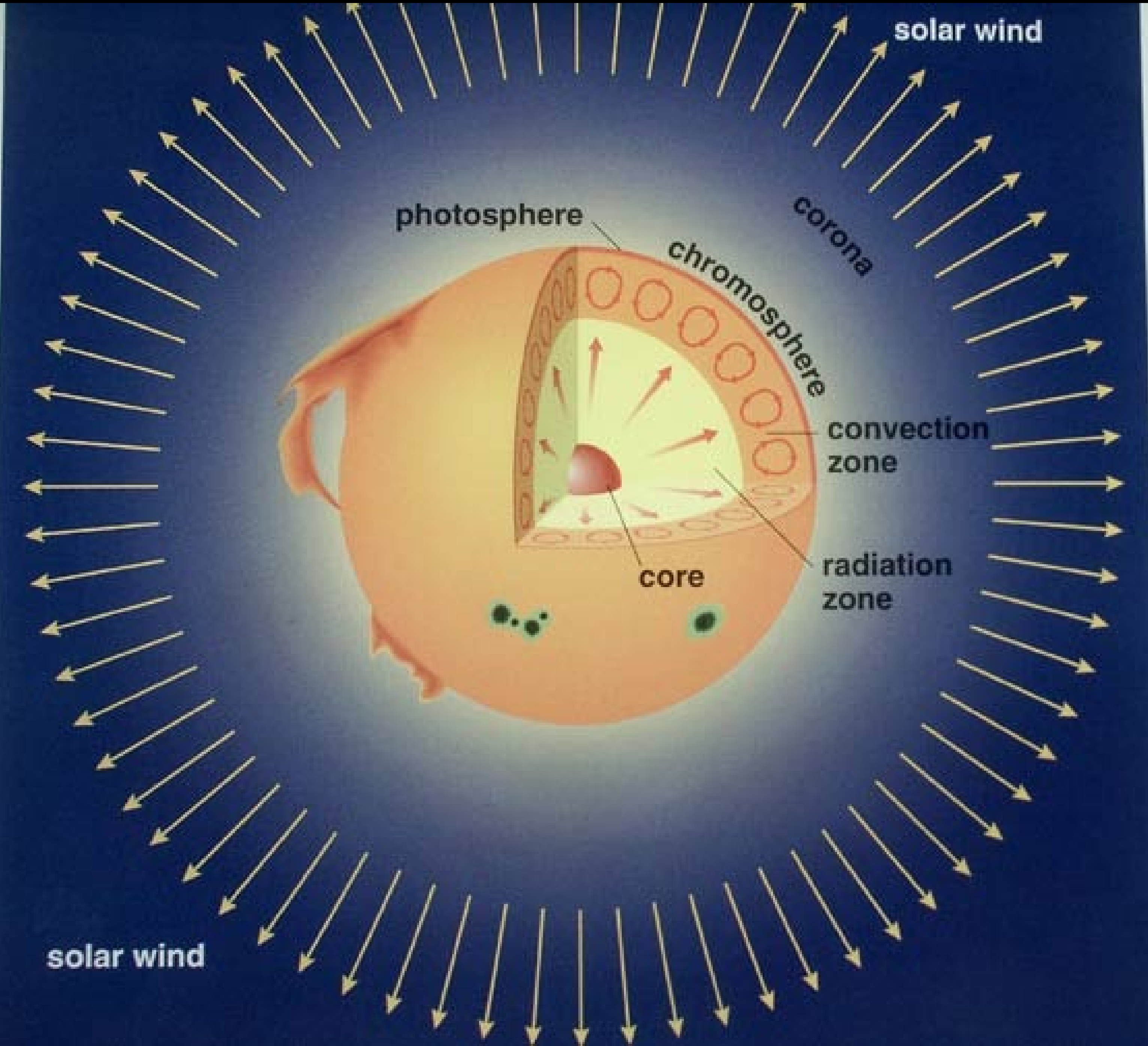
Neutrinos Have Almost 0 chance of interacting with other matter

- 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 do 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

- **1. Core** = where temperature exceeds fusion point (~10 million Kelvin)

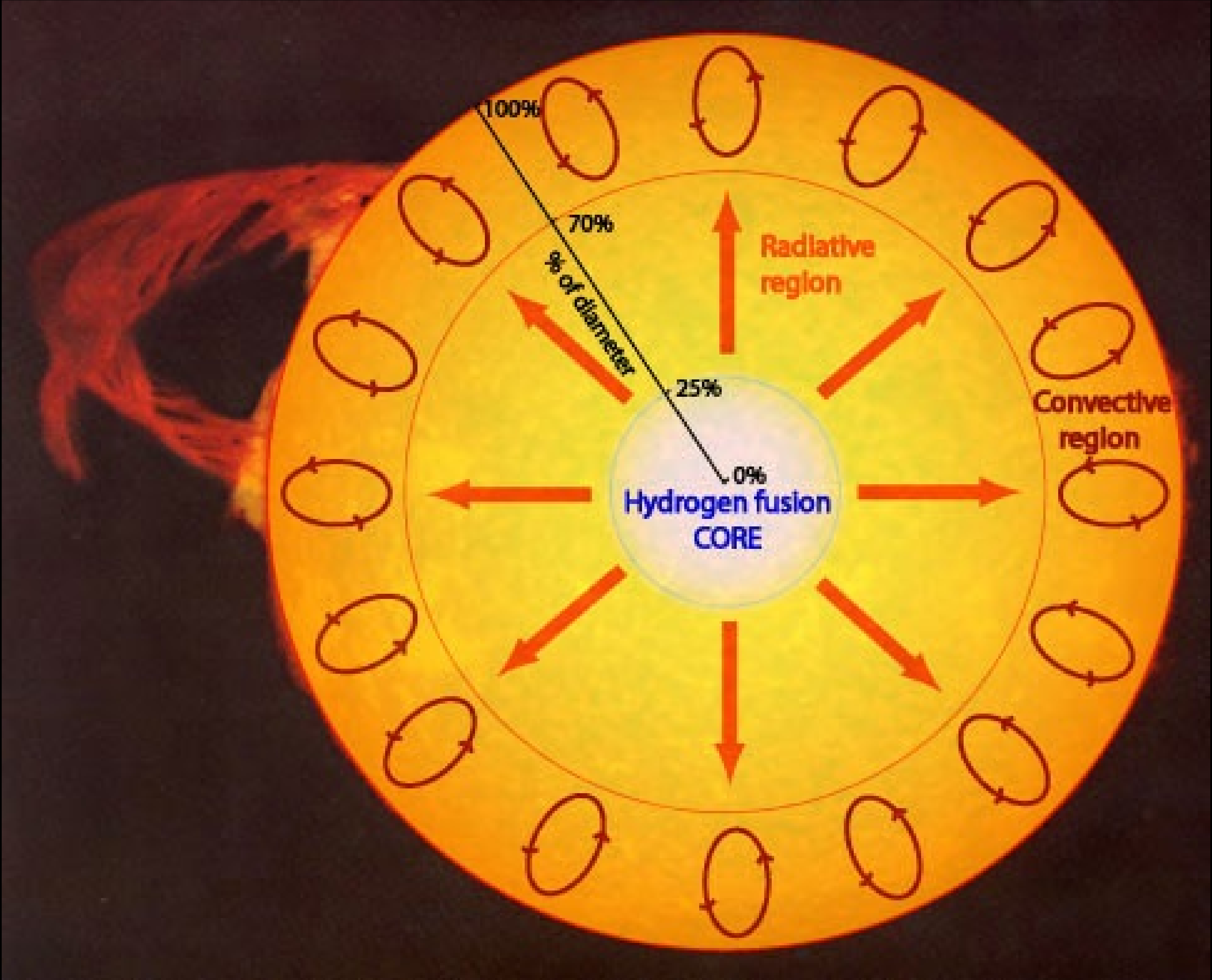
- **2. Radiative Zone** = nothing much goes on here. It just acts as an obstacle course for the photons, scattering off charged particles, imparting some of their energy to the particles, and random-walking their way upward.
- Recall that when charged particles scatter off of each other, that is an acceleration (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



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

Above the Radiative Zone

- **Convection Zone** = temperature gradient is so steep that photon diffusion can't carry the heat outward fast enough. So it builds up, and the rising temperature expands the gas, lowering its 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. 5,800K. 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!

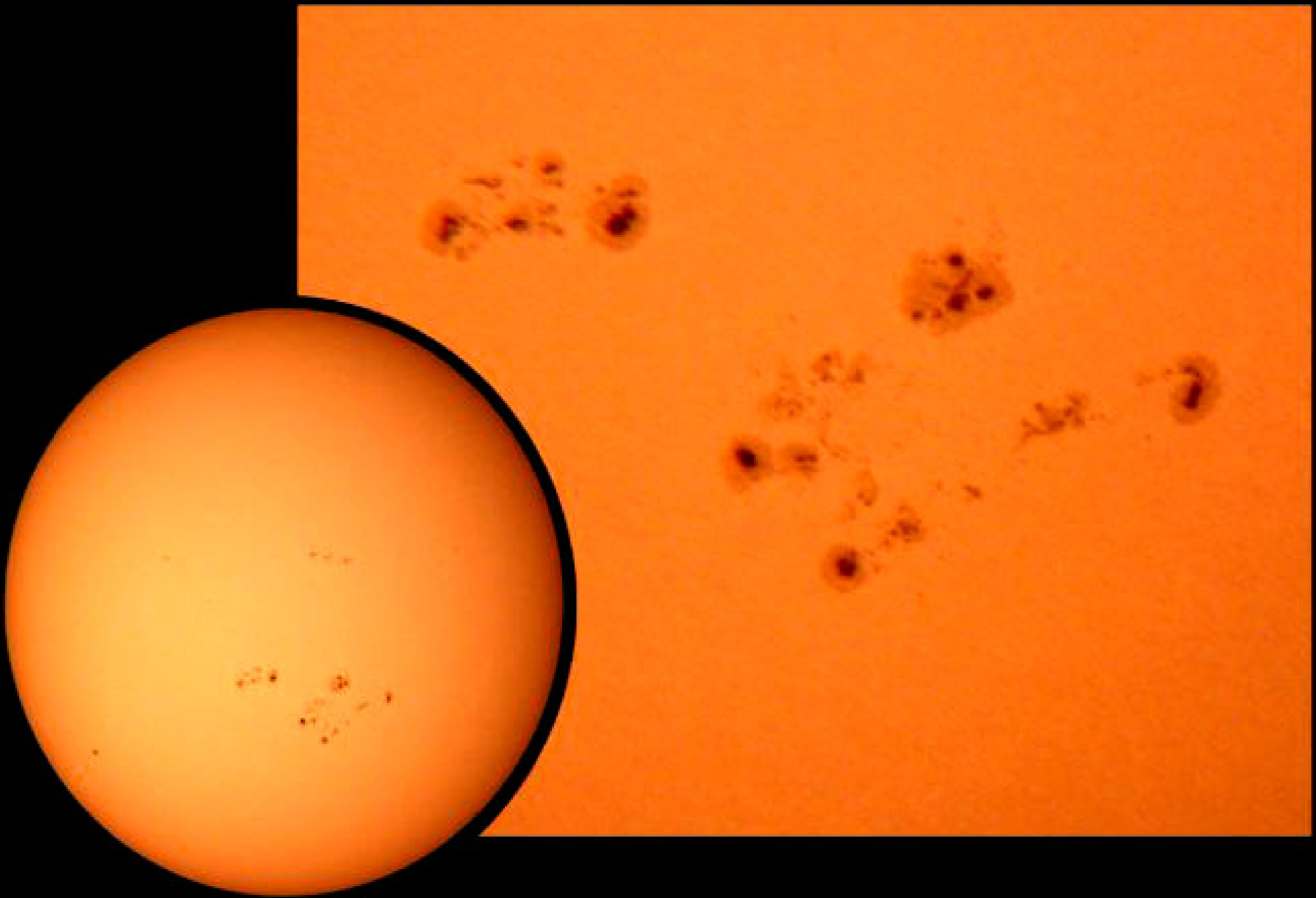


100%
70%
% of diameter
25%
0%
Radiative region
Convective region
Hydrogen fusion CORE

What Does the Photosphere Show?

- There's two more layers above the photoshopere 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 makes for Texas-sized "granules" as shown here in this 33sec video

Sunspots… Which usually occur in groups



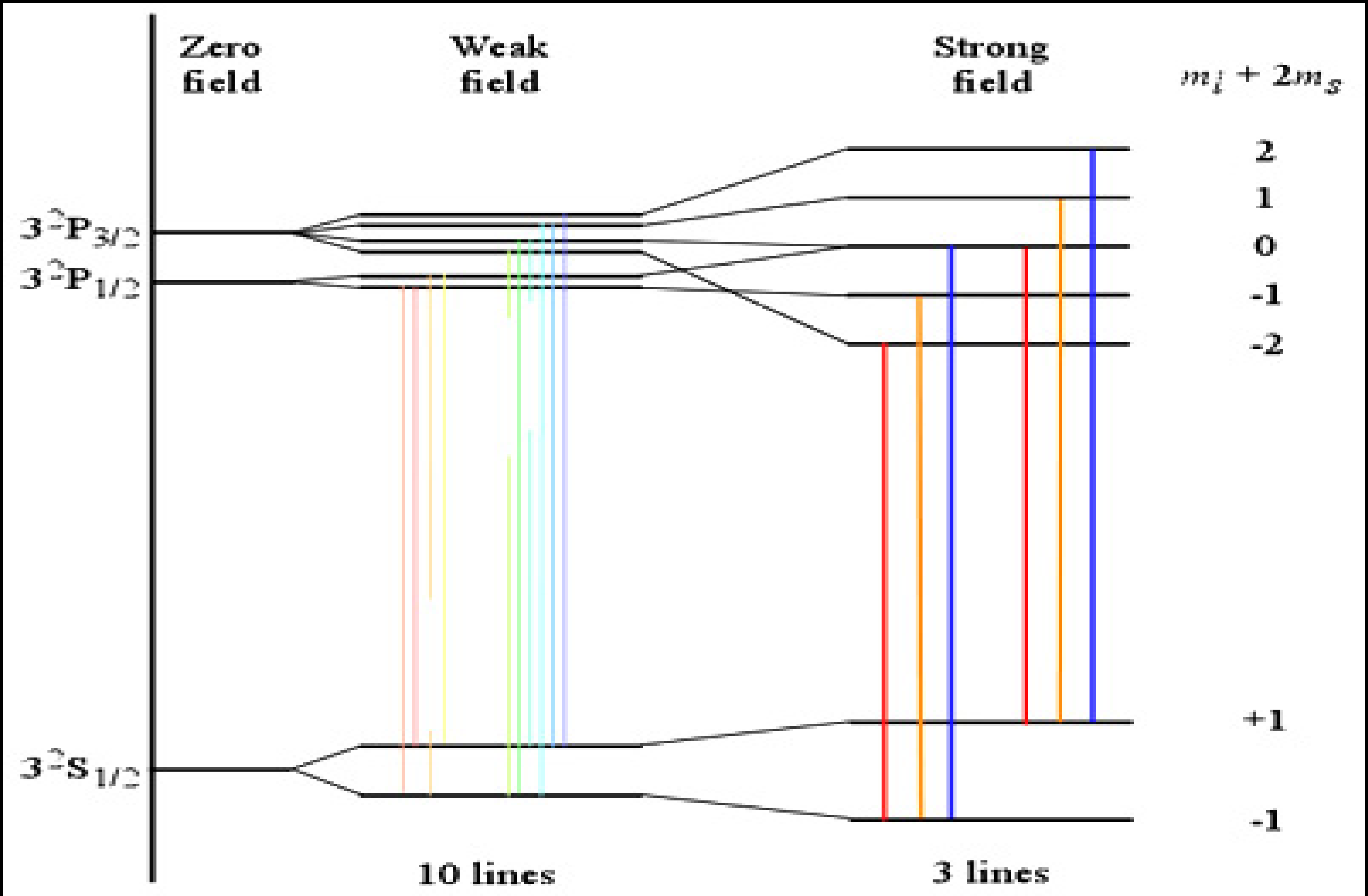
We Wondered… Why are the Sunspots Dark?

- The sun shows the classic spectrum of a thermal radiator, so if spots are darker, it must be because they are cooler.
- Sunspot cores are about 3,000K, or about half the temperature of surrounding photosphere.
- Since the radiation laws show that ½ the temperature means $(½)^4$ =1/16 of the light, they look pretty dark

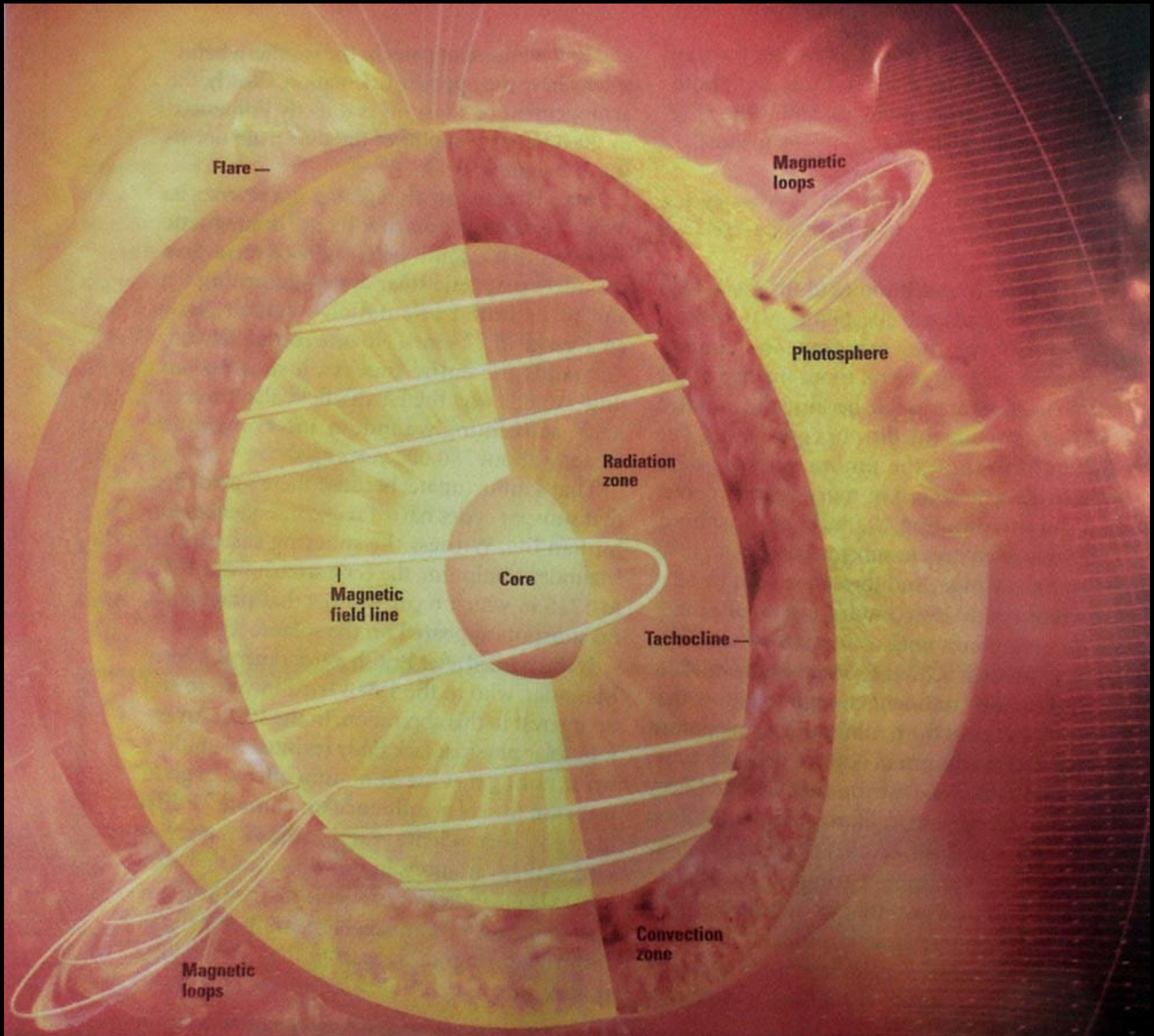
But WHY are the cooler?

- The next clue came when we took spectrograph images of sunspots, to see their spectral features
- The absorption lines showed a class splitting known since the 1800’s as the Zeeman Effect…

Spectrum of a sunspot shows each absorption line is split into several lines =The Zeeman Effect. Due to the presence of a Magnetic Field

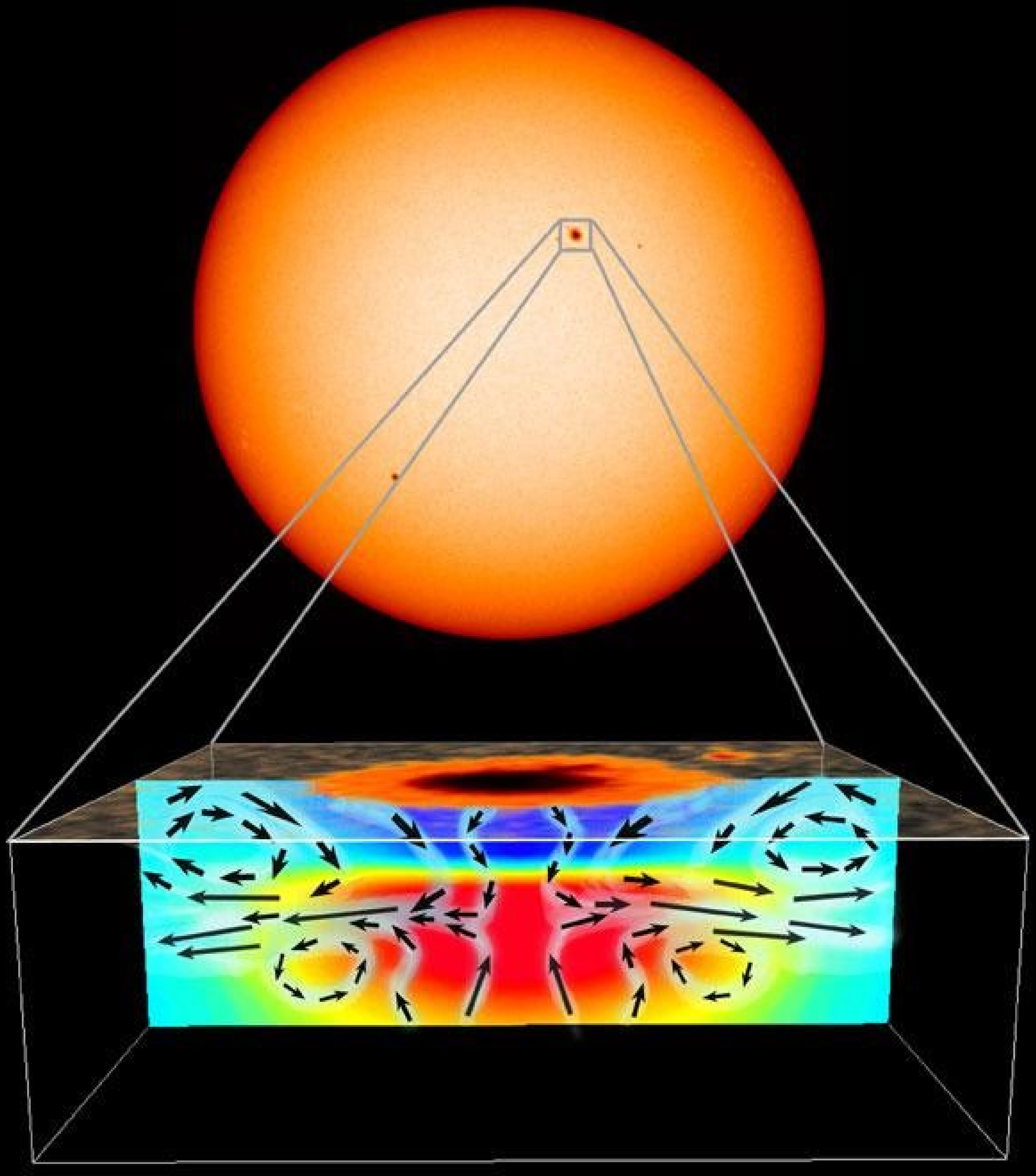


The Solar Dynamo: Differential Rotation twists and stretches magnetic field lines just like you add energy to rubber bands by stretching them. Over time, these emerge on the surface as…

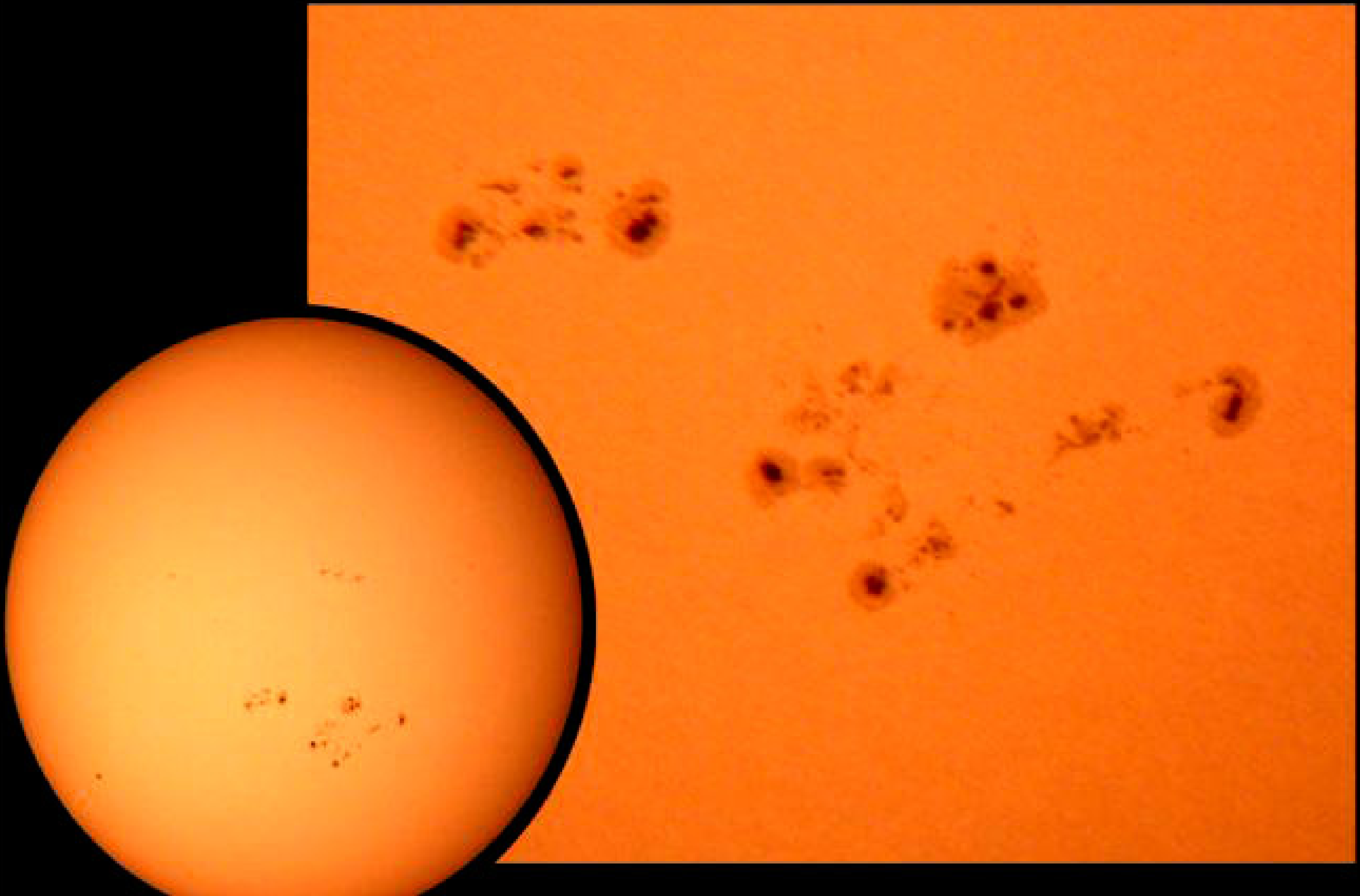


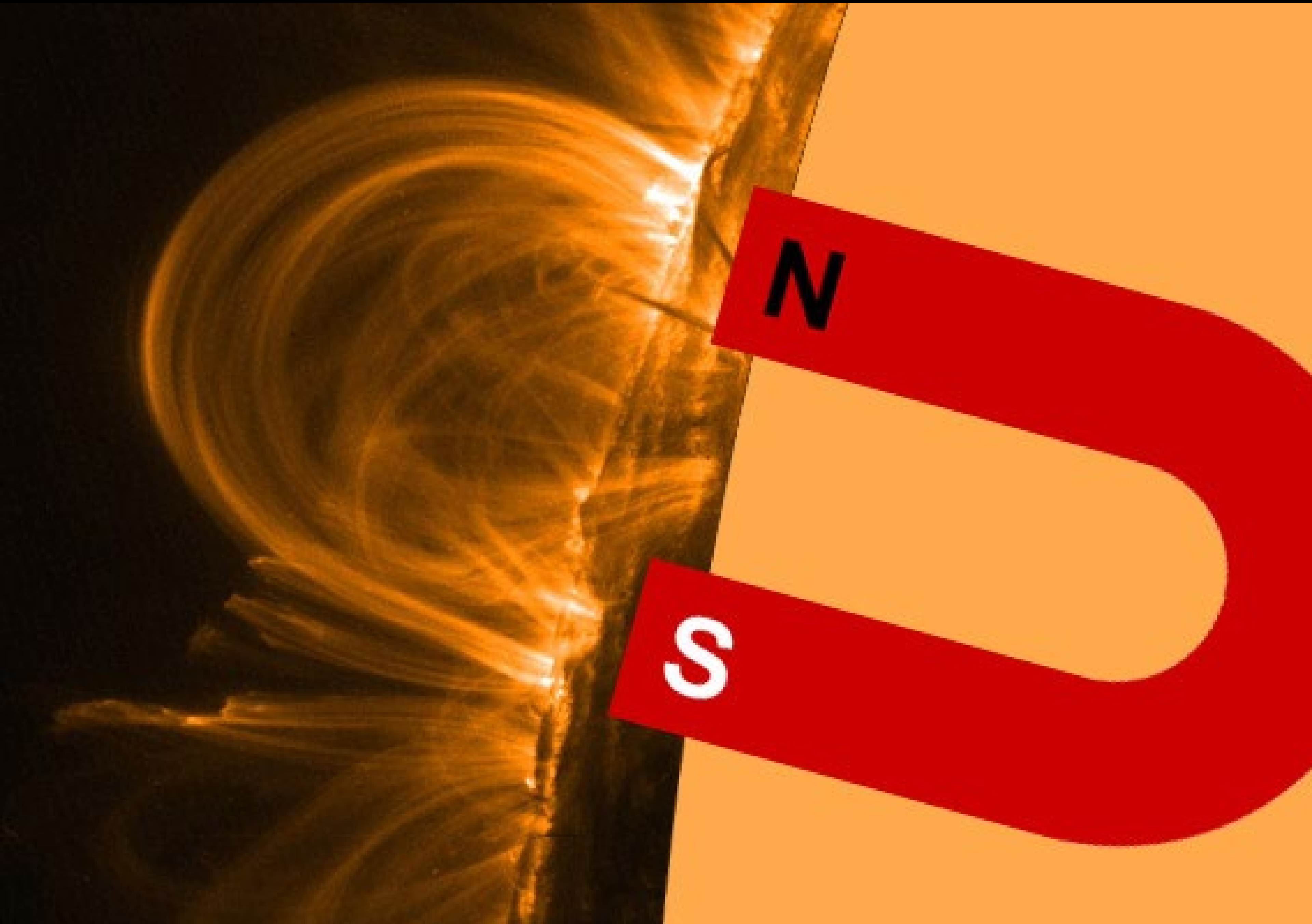
…Sunspots

- **How do magnetic fields create sunspots?**
- Charged particles in a magnetic field feel a force sideways to their motion, binding the gas to the field lines.
- So where the sun’s magnetic field is concentrated it inhibits the normal convective flow of hot material from below. The material gets locked by the magnetic fields to stay on the surface, where it cools as it radiates to space.
- 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
- Temperature drops from 5800K down to as low as 3,000K, which cuts the brightness to ~1/15 of normal and makes the area look very dark by comparison.
- Convection and solar granulation near a large sunspot (3min video) and simulation showing vertical motion (9 sec)



Sunspots occur in groups, defined by the bundle of magnetic field lines of like polarity

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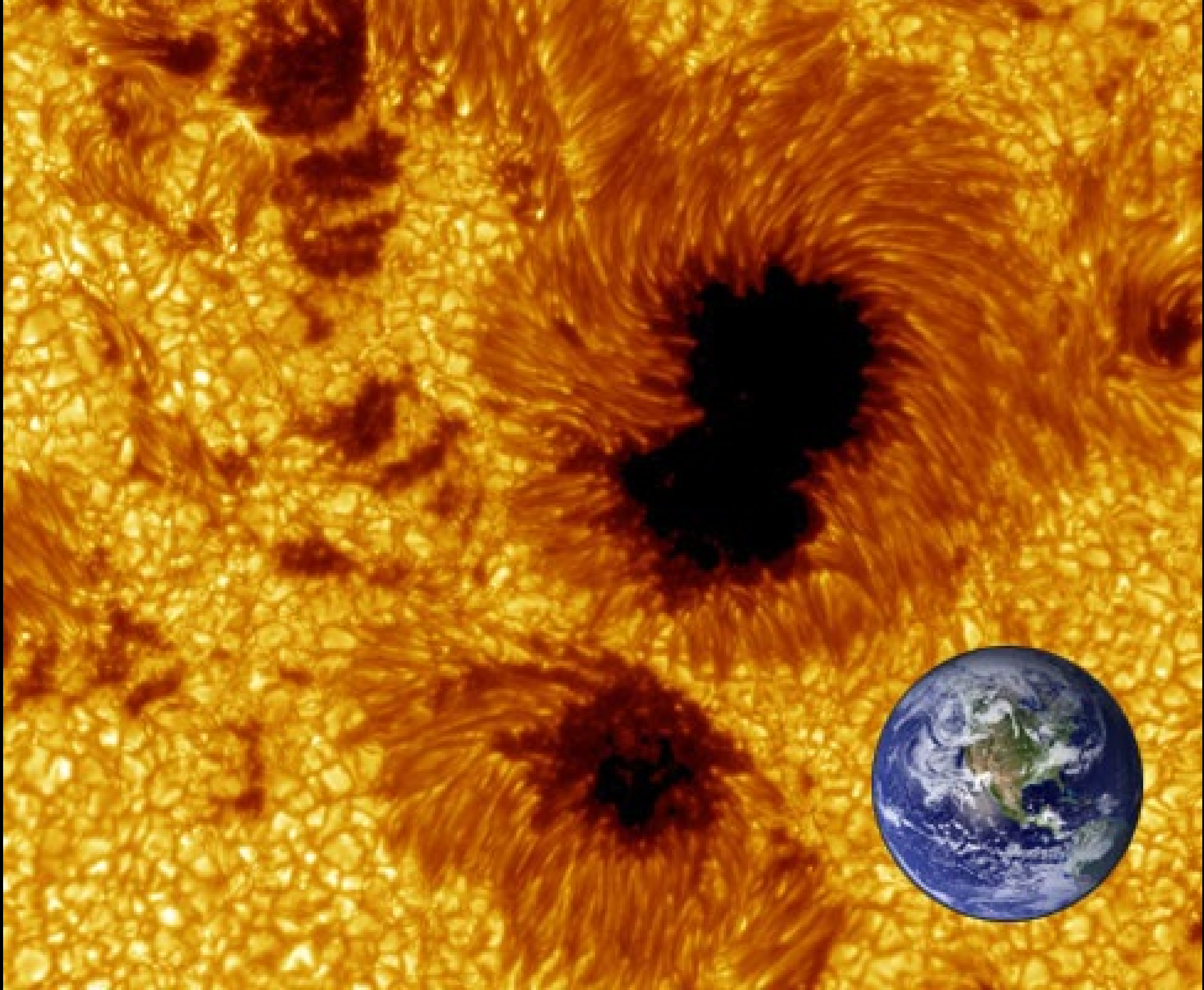
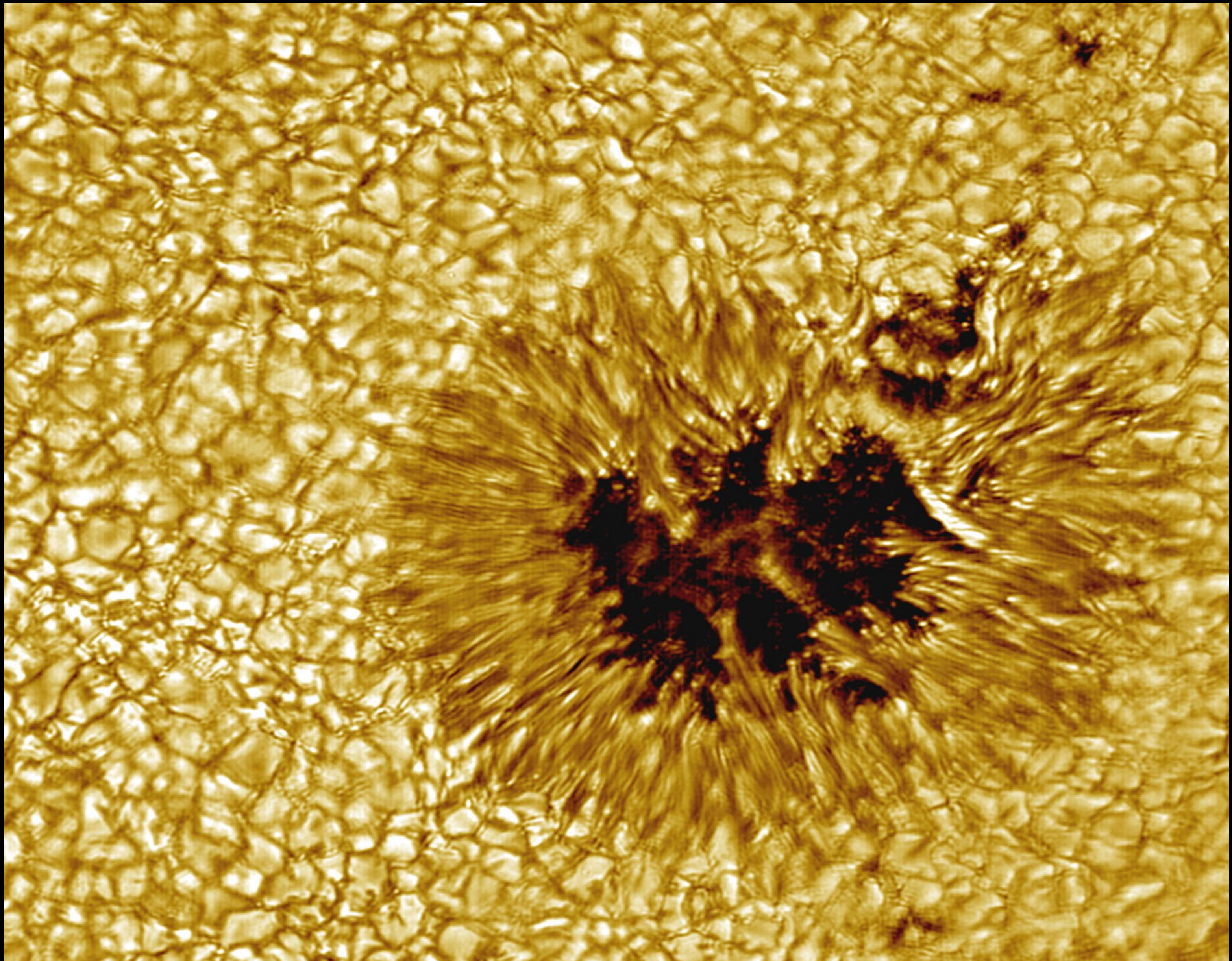


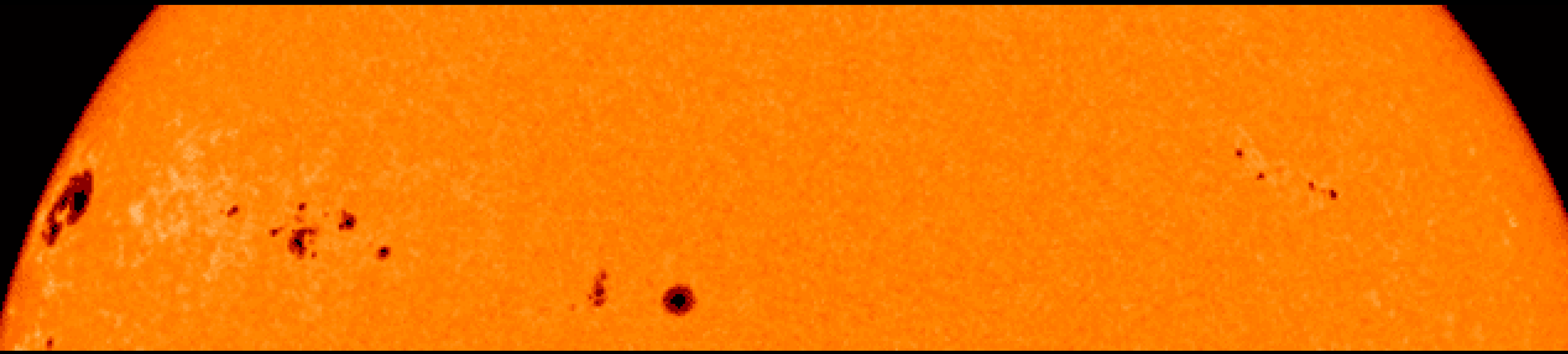
Solar “granulation” – directly shows us that the surface is experiencing convection



Do Sunspots Make the Sun Dimmer?

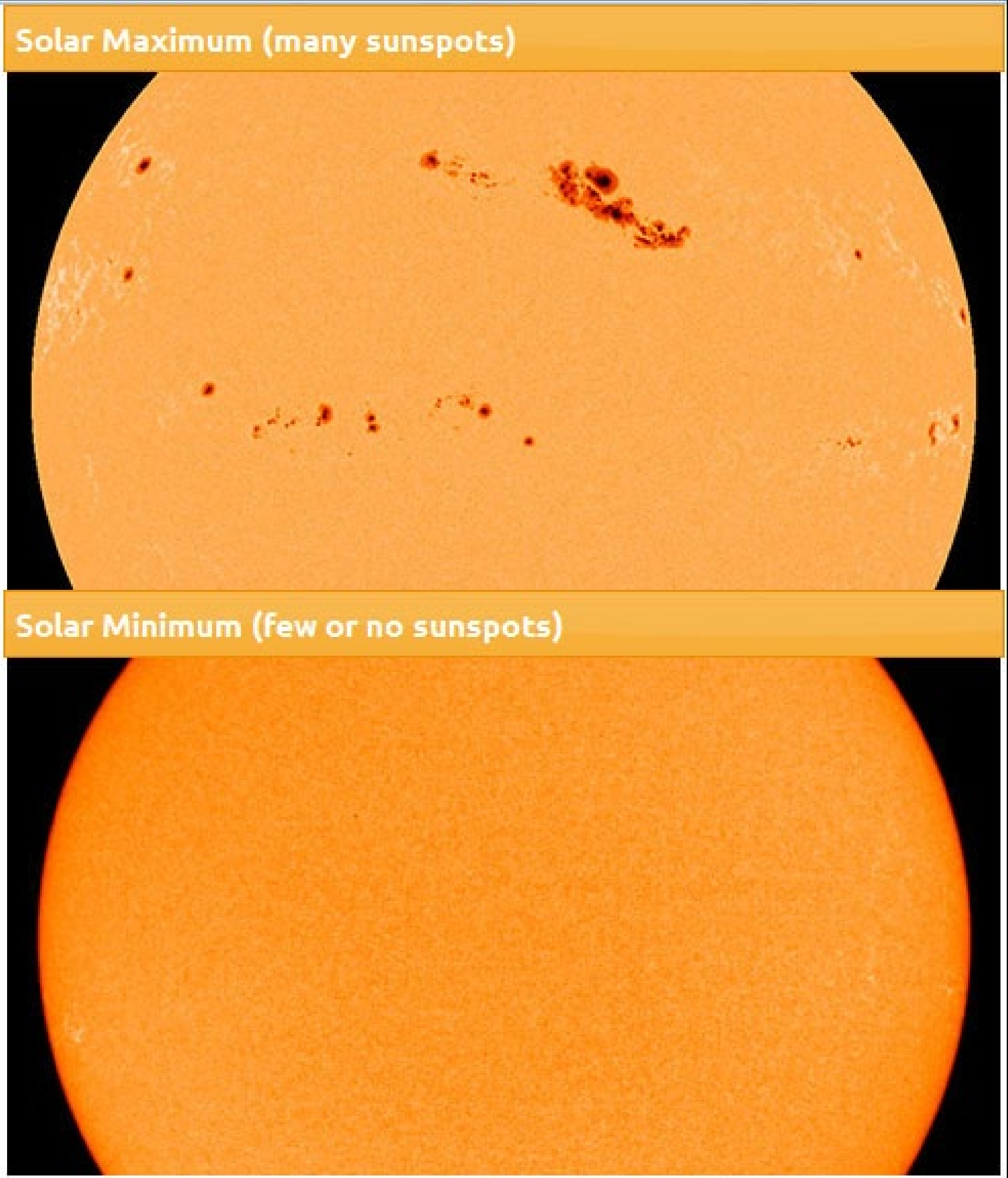
- **No**. The energy unable to get out at a sunspot because of the twisted magnetic fields disrupting convection, finds its way out in surrounding areas. In fact, the magnetic field energy created actually makes the sun a bit BRIGHTER with higher solar activity.
- These surrounding areas are called ***Plages***
- Here's a short video showing ***plages*** near the edge of the sun (where "limb darkening" naturally makes extra-bright areas easier to see)

Solar rotation. Note the “plages” of bright areas near the sunspots, especially easy when near the solar limb (edge)



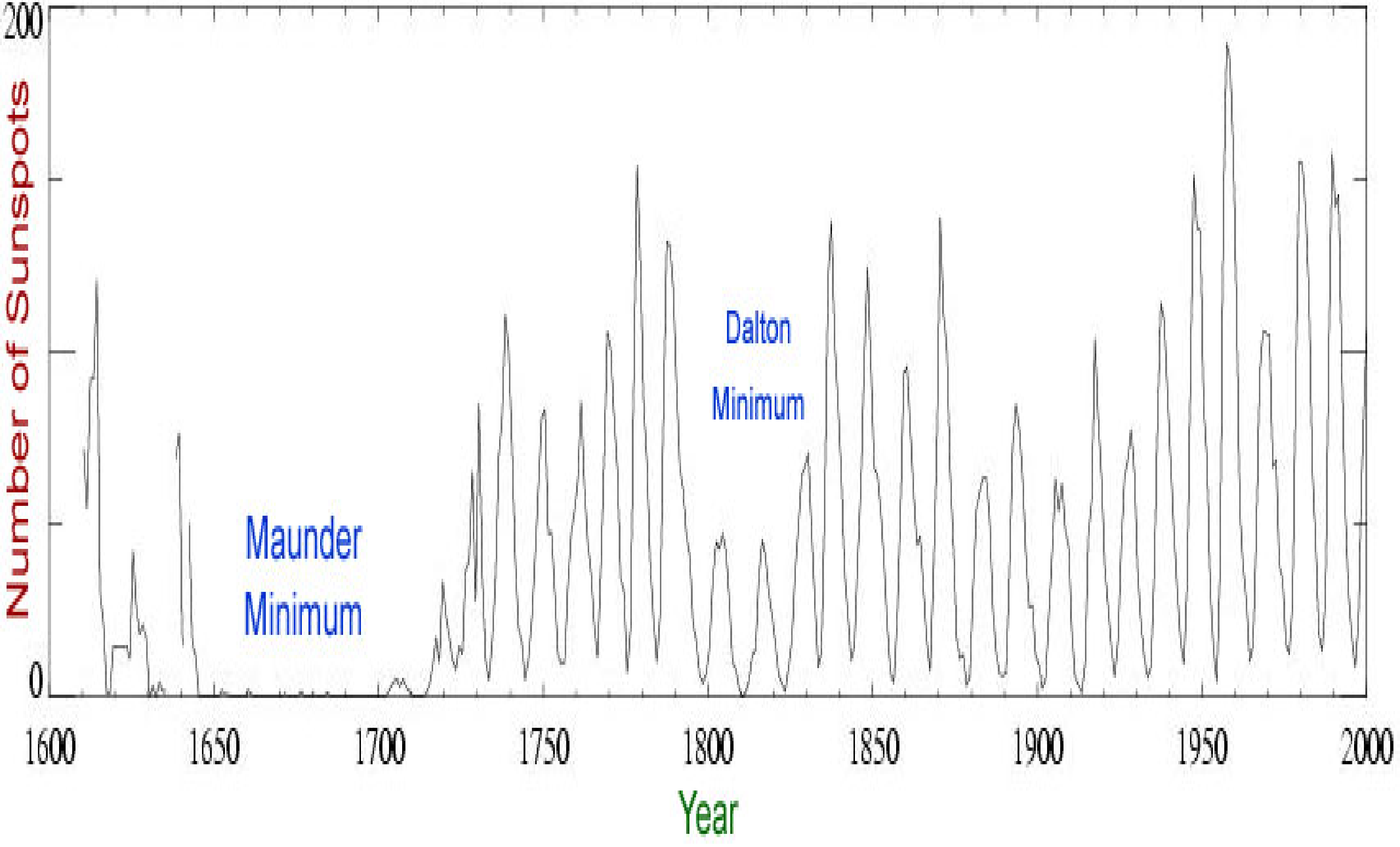
Sunspots Numbers on the Sun Follow an ~11 year cycle

- As the twisted magnetic field lines experience differential rotation inside the sun, they get stretched, twisted, rotational energy goes into the field, which slowly works it's way to the surface for a few years and we see lots of sunspots
- Then the magnetic field energy diffuses into heat and radiates away and the sun is quiet for a while, until the differential rotation has built up enough energy that the fields again burble to the surface. Takes about 11 years for a full cycle

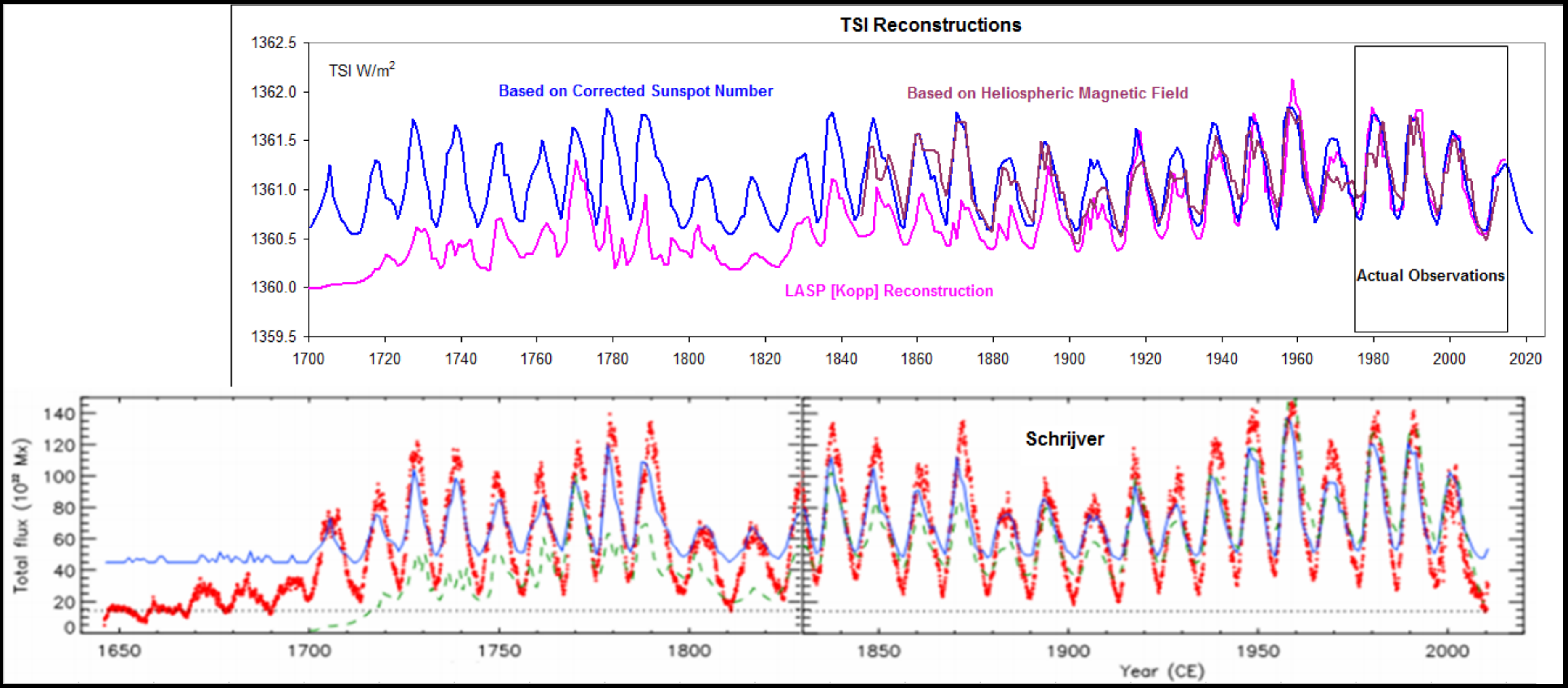


Sunspot cycle of ~11 years: Maximum (e.g. 2001 top) vs. Minimum (e.g. 2007 bottom)

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



But this is biased by inaccurate calibration of telescope *vs* sunspot number. Better: Use sunspot group counts. Then the trend in solar luminosity disappears, except 1650-1700 Maunder Minimum



Does The Solar Cycle Affect Earth?

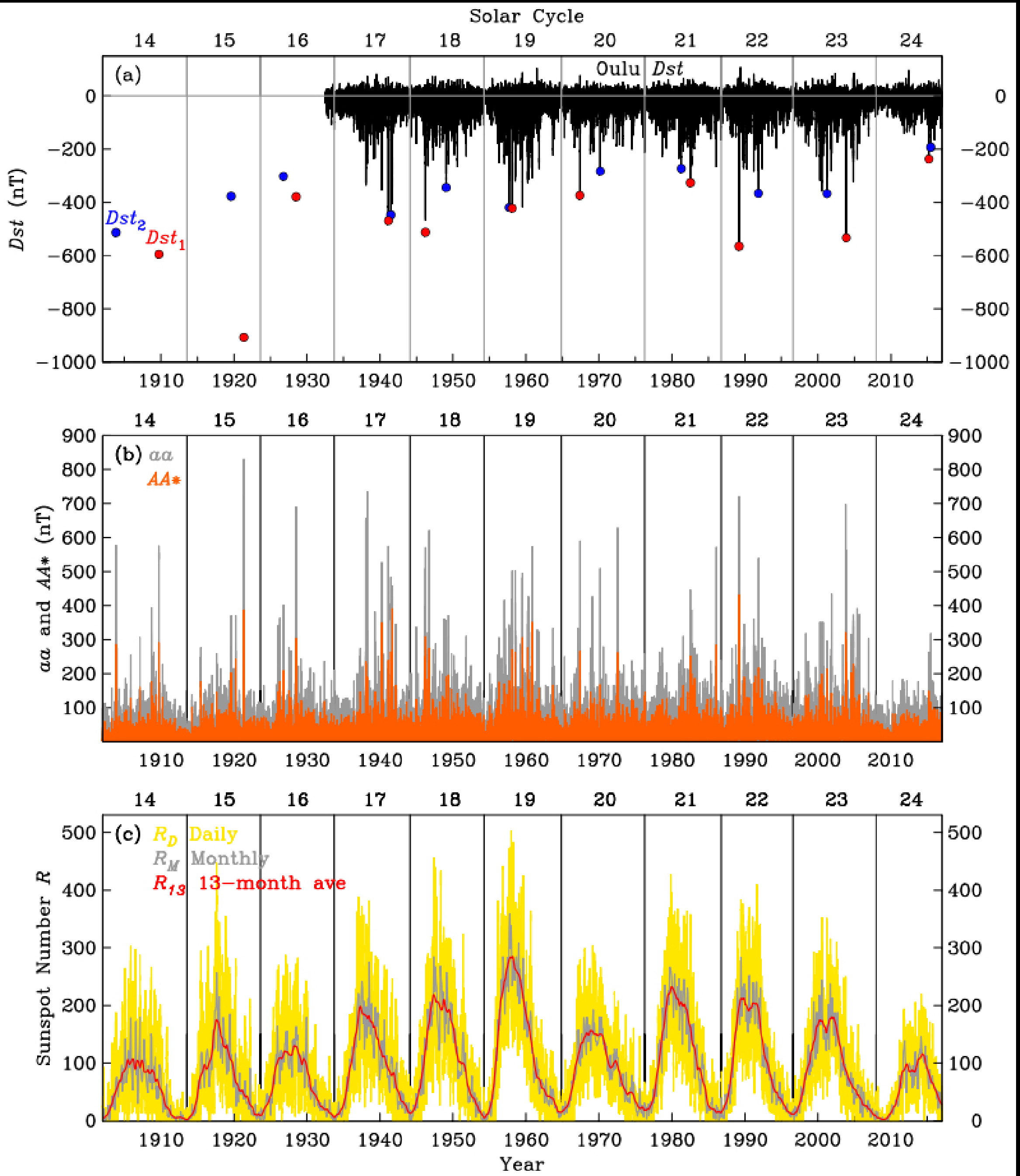
- **Yes, in three ways…**
- **1. Climate.** We have seen that lower solar activity (fewer sunspots) goes with slightly lower average temperatures on Earth
- **2.** The solar wind creates ***aurorae*** (more later)
- **3. GeoMagnetic storms**, which can wreck power grids
- First lets talk a bit about the climate effect…

How Does Solar Activity Change Earth Temperatures?

- By itself, by not very much!
- **<u>Lower solar activity -> Lower solar luminosity</u>**. Remember this!
- This is because magnetic field energy is being turned into thermal energy (the highest entropy form of energy).
- The luminosity effect is less than **0.1%** between solar cycle maximum to minimum. The climate record shows a bit stronger effect at the great Maunder Minimum of the late 1600's, but other things (exceptional volcanism, 20% die-off of human population and resulting re-forestation) were going on then which explain most of the cooler climate ("The Little Ice Age") then.
- Note; Even slight cooling or warming can be amplified if there is more/less ice created at the poles, which reflect sunlight better than ice-less dark ground.

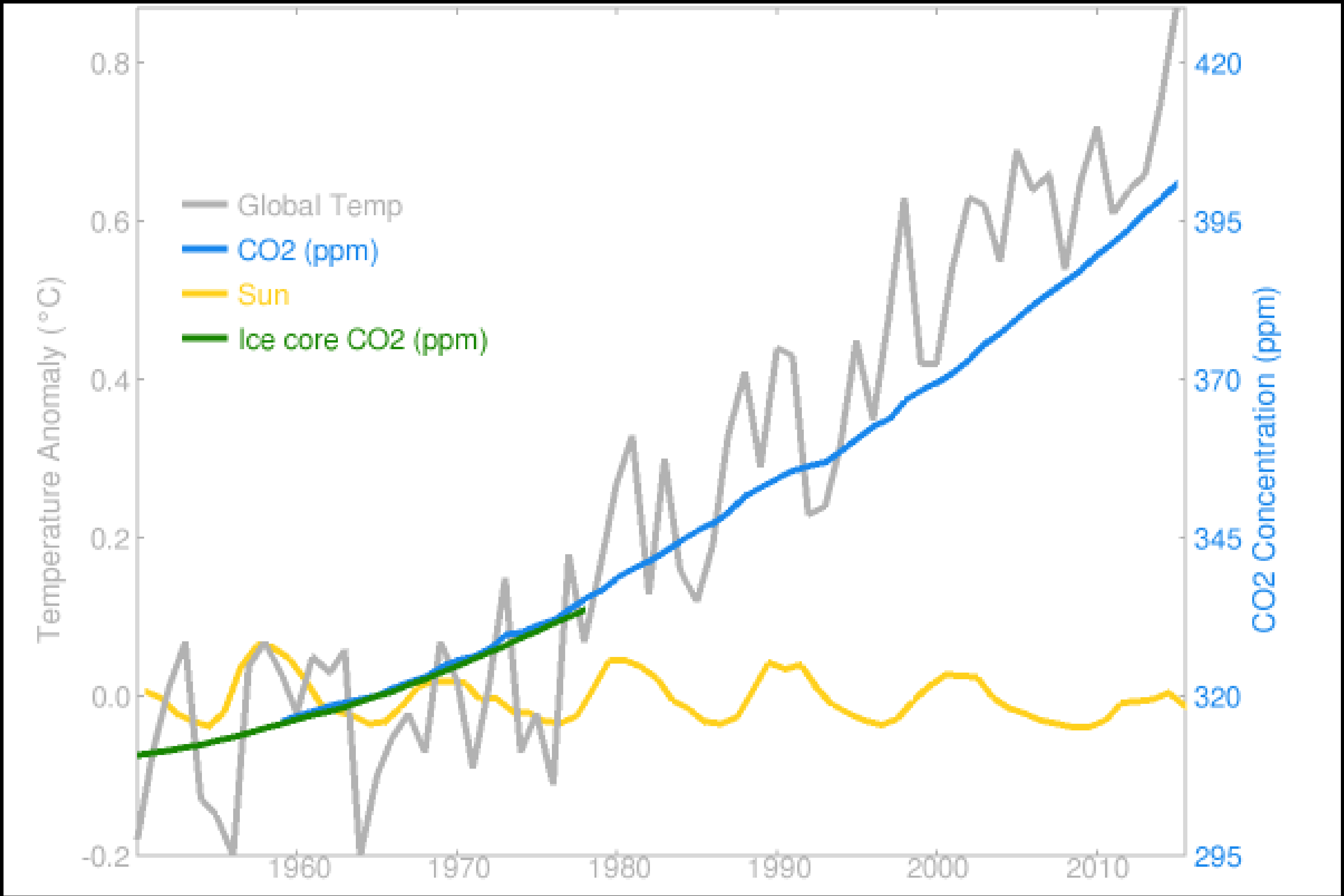
Could solar activity explain current climate change?

- **No.** Climate change has become so dramatic and so accelerated that it far exceeds any historical amplitude of solar luminosity with solar cycle Satellite data on solar luminosity confirm this.
- **In fact, Earth temperatures have been rising rapidly for the past 60 years: a time when the sun's luminosity has been DEcreasing.**
- Current climate change is being driven by human activities; mostly CO2 emissions, and partly methane emissions from our cattle, from positive feedback effects on Arctic ice, methane being released from the permafrost, and dramatic clear-cutting of ancient tropical forests mainly to make cattle ranches to support fast-food restaurants worldwide.

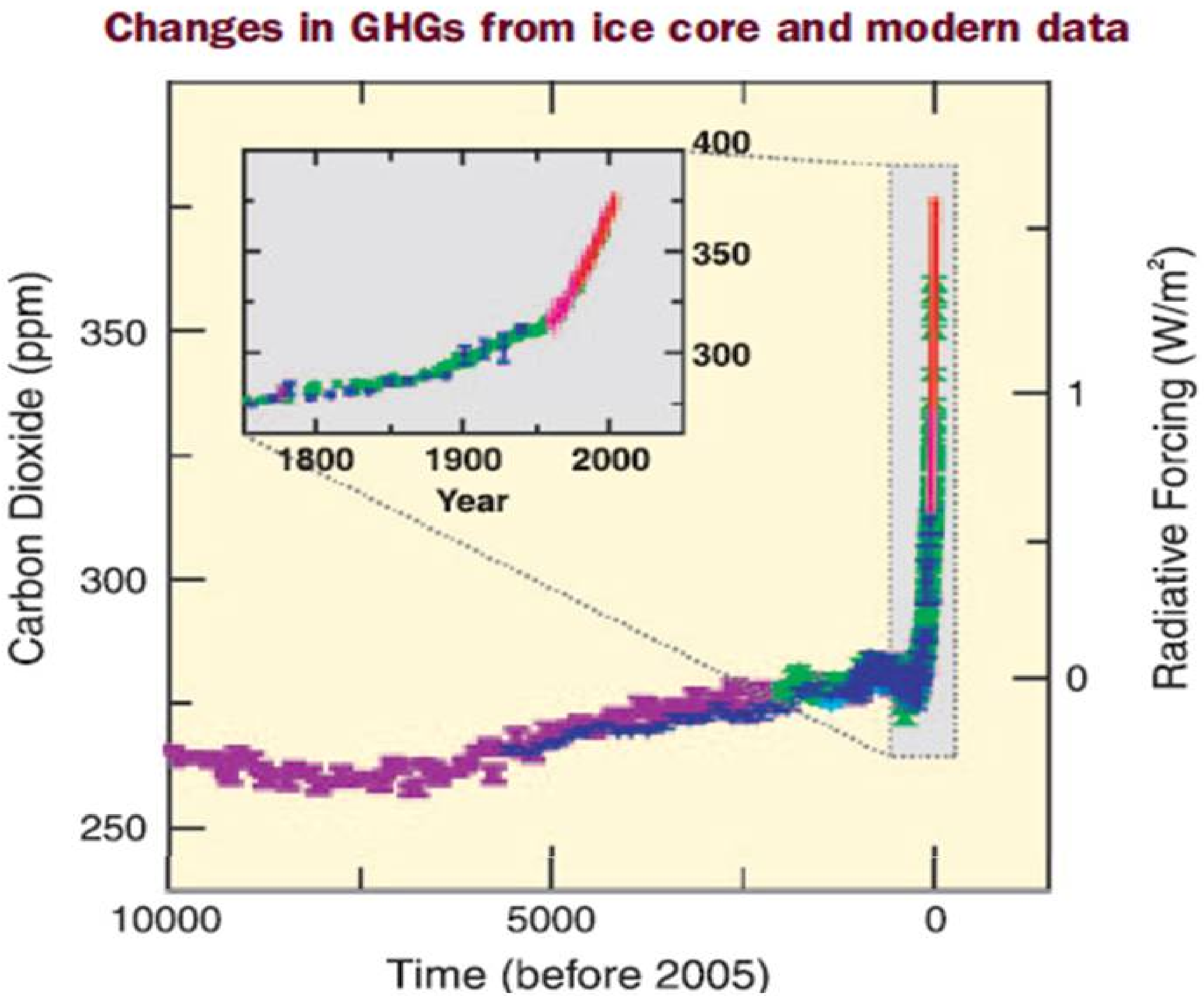


Sunspots - a good proxy for solar luminosity, also trending down since 1957.

CO2 levels are the primary forcing to Earth Climate.The Sun's luminosity has actually slightly DEcreased since the mid-20th century



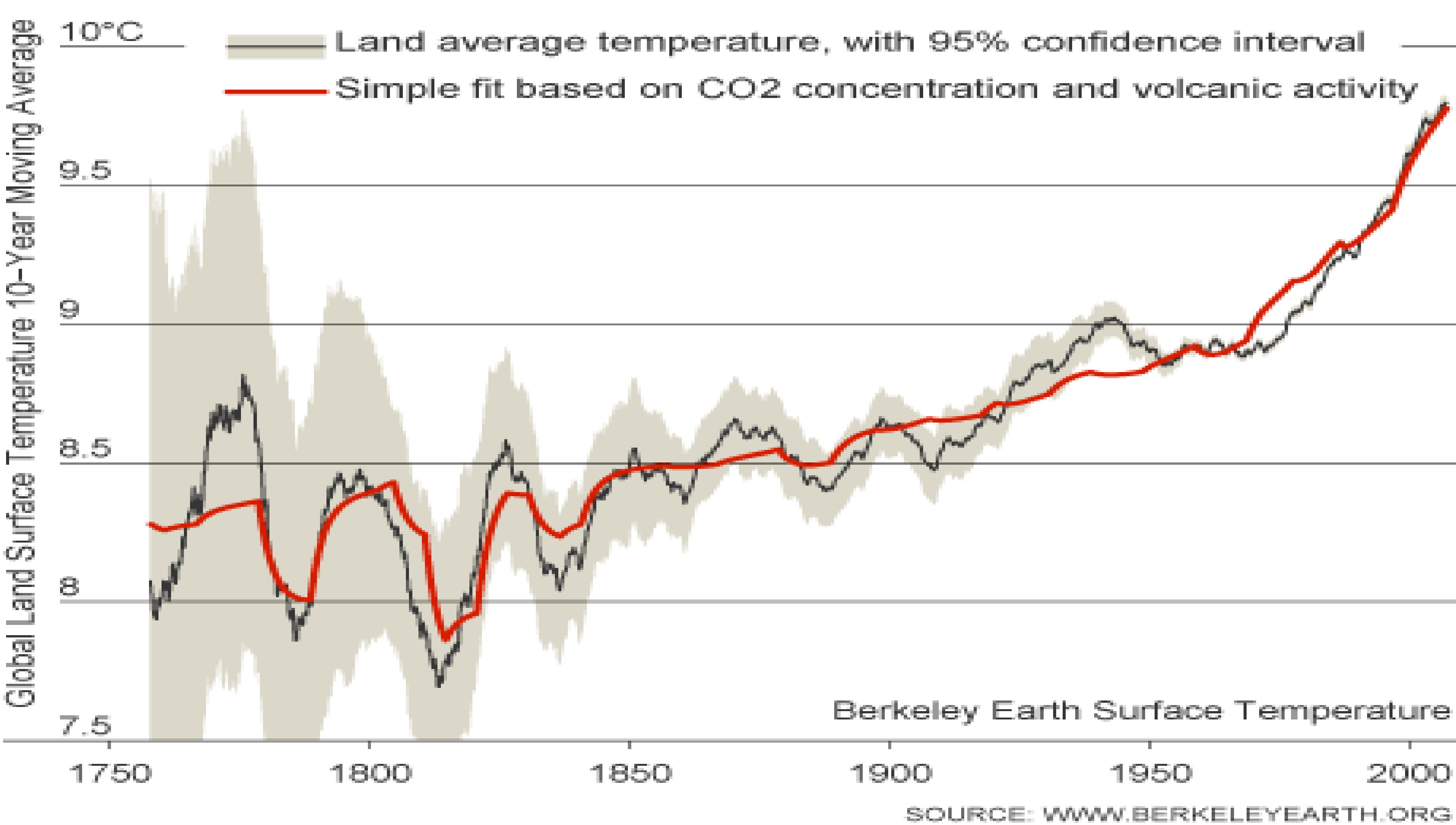
Human caused atmospheric Greenhouse Gases – Skyrocketing since we discovered Fossil Fuels



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.

Earth is heating up due to the Greenhouse effect from human-generated CO2, and feedbacks, not the Sun

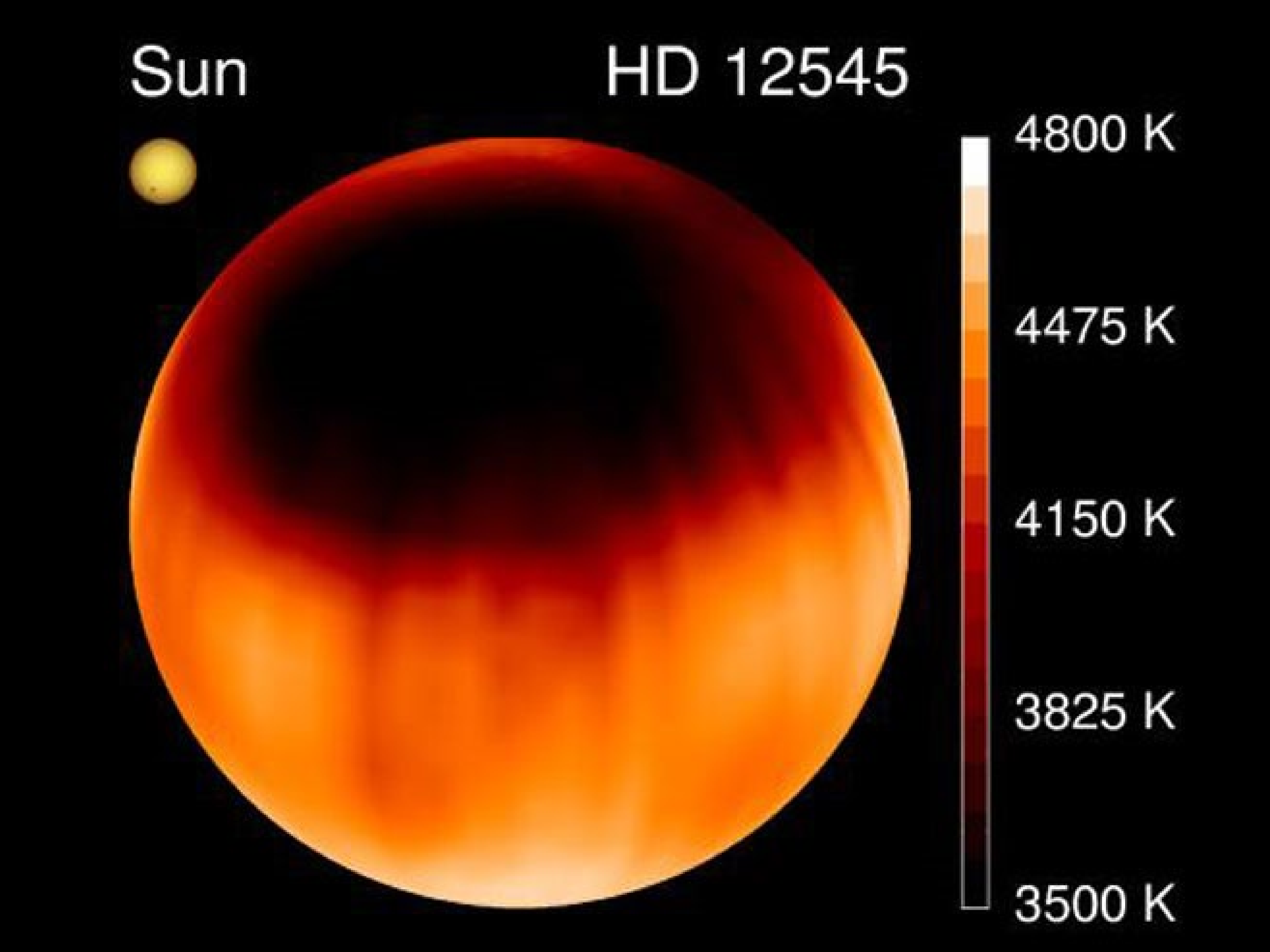


For more on Earth Climate and Climate Change, Take Astro 7

- OK, public service notice is now done.
- Back to the sun….

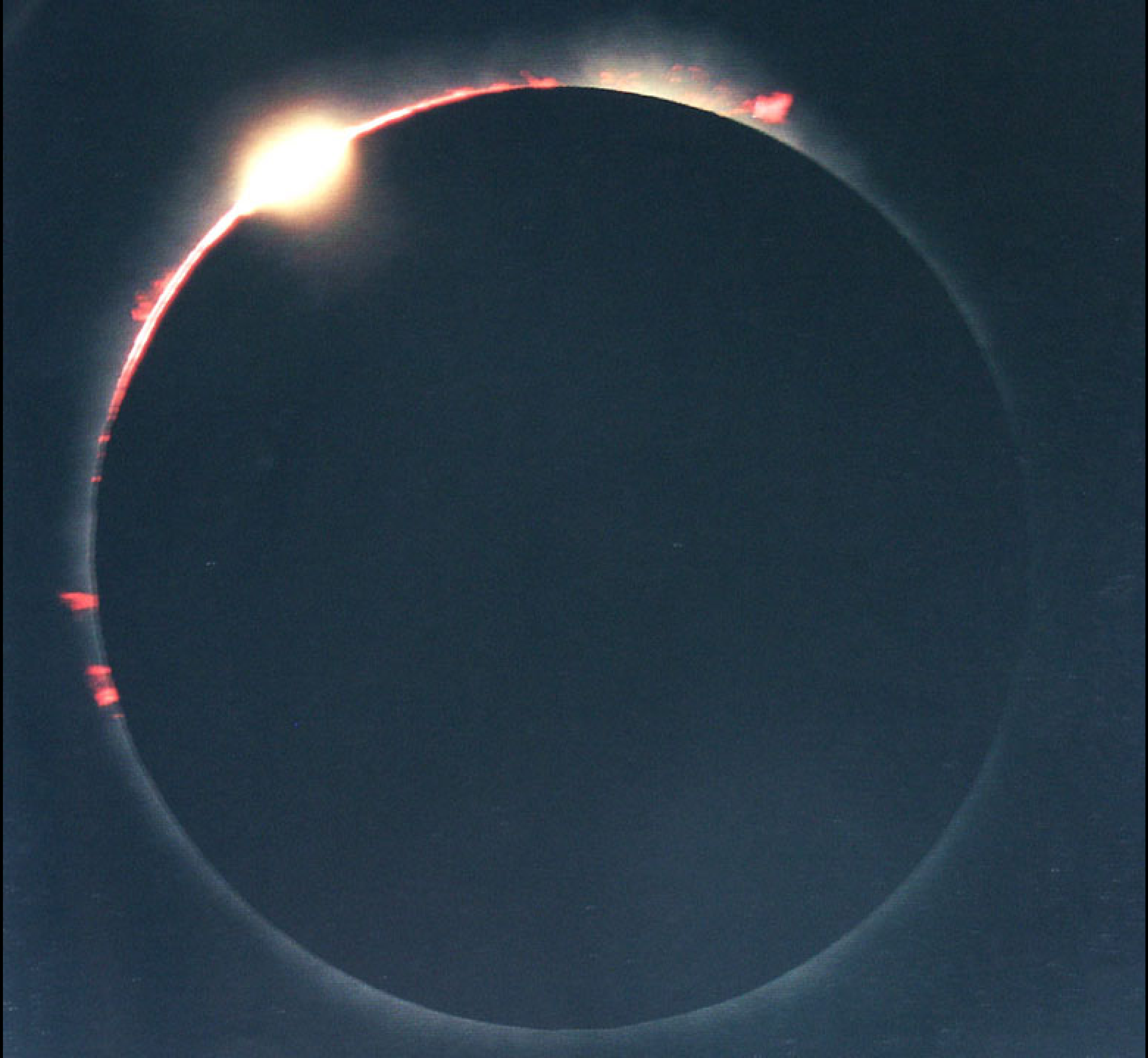
The Sun isn't the only star showing magnetic fields and star spots

- Magnetic field activity on the sun is relatively mild compared to many stars, even stars of similar mass and surface temperature. On average, the sun has less variance than most of our similar stellar brothers
- 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!
- And it was discovered right here at Cabrillo Observatory!


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

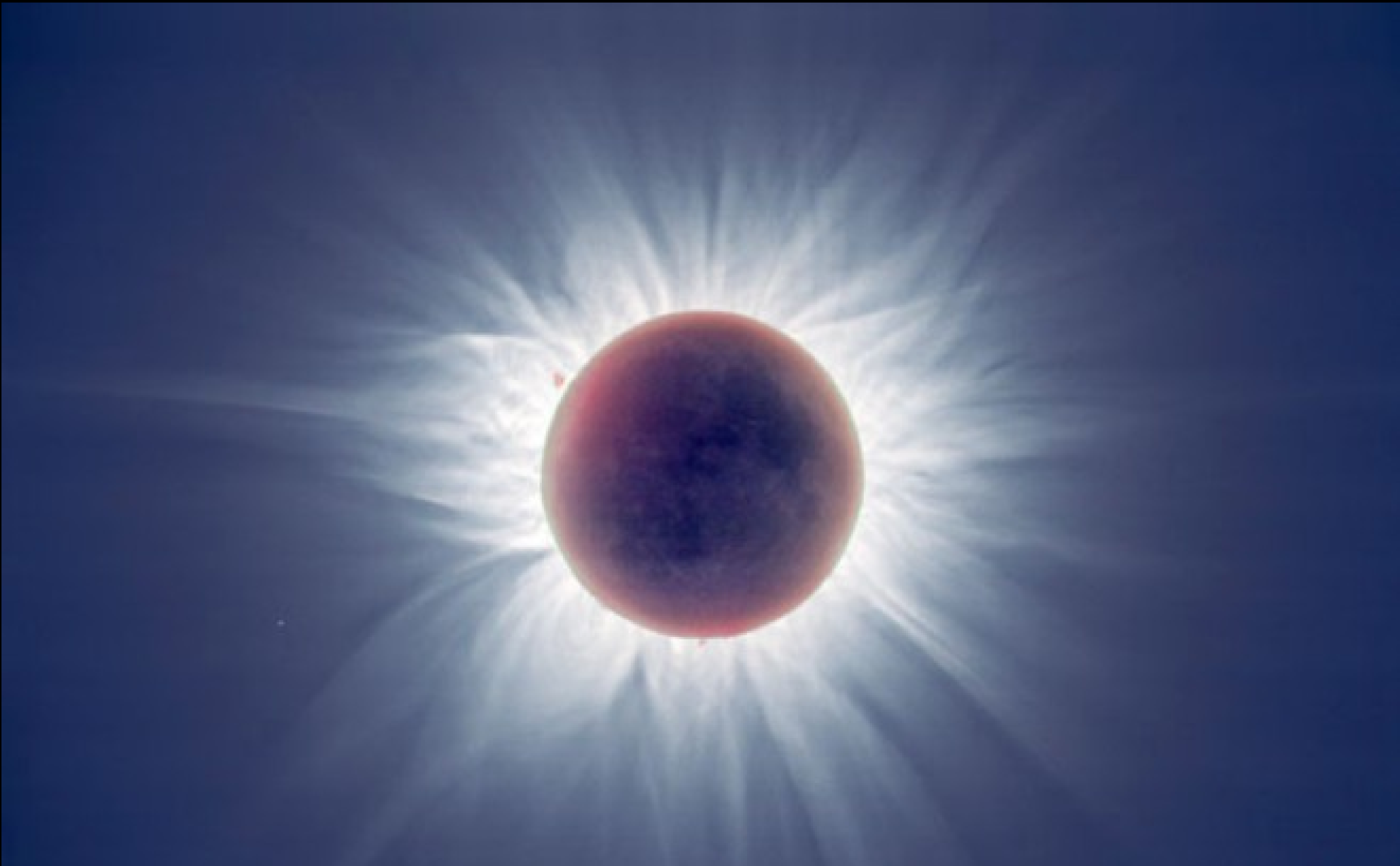
The chromosphere, 10,000K and deep red due to H-alpha emission

Just before totality, at the 1999 Eclipse. The moon has covered the brilliant photosphere at the top rim (not yet along the sides), revealing the faint, red Chromosphere

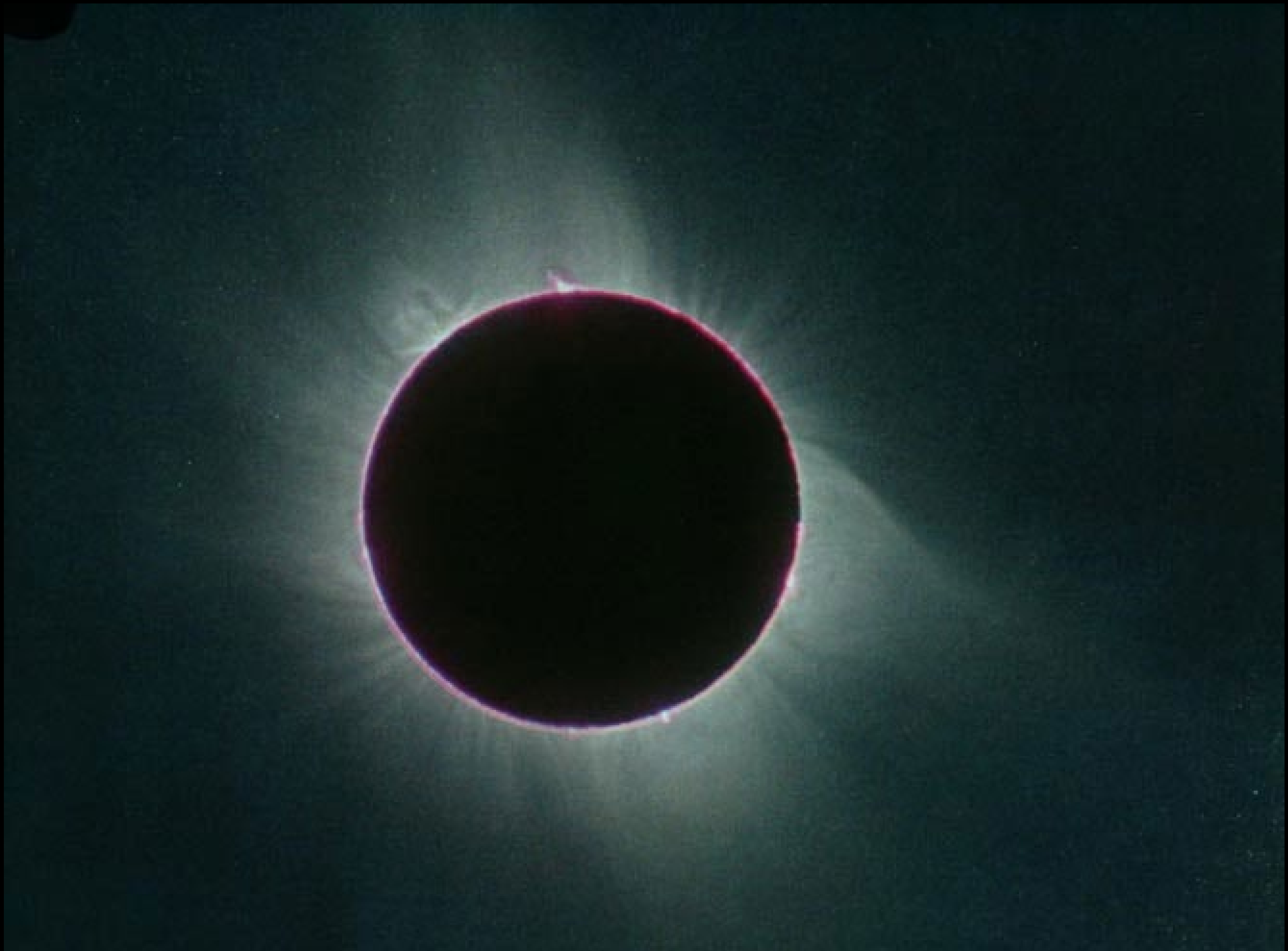


The corona is ~ 1-2 million K – white because the free electrons and ions simply scatter the ordinary visible light from behind the moon.

At Solar Max, the magnetic field lines are chaotic due to the many areas of sunspots



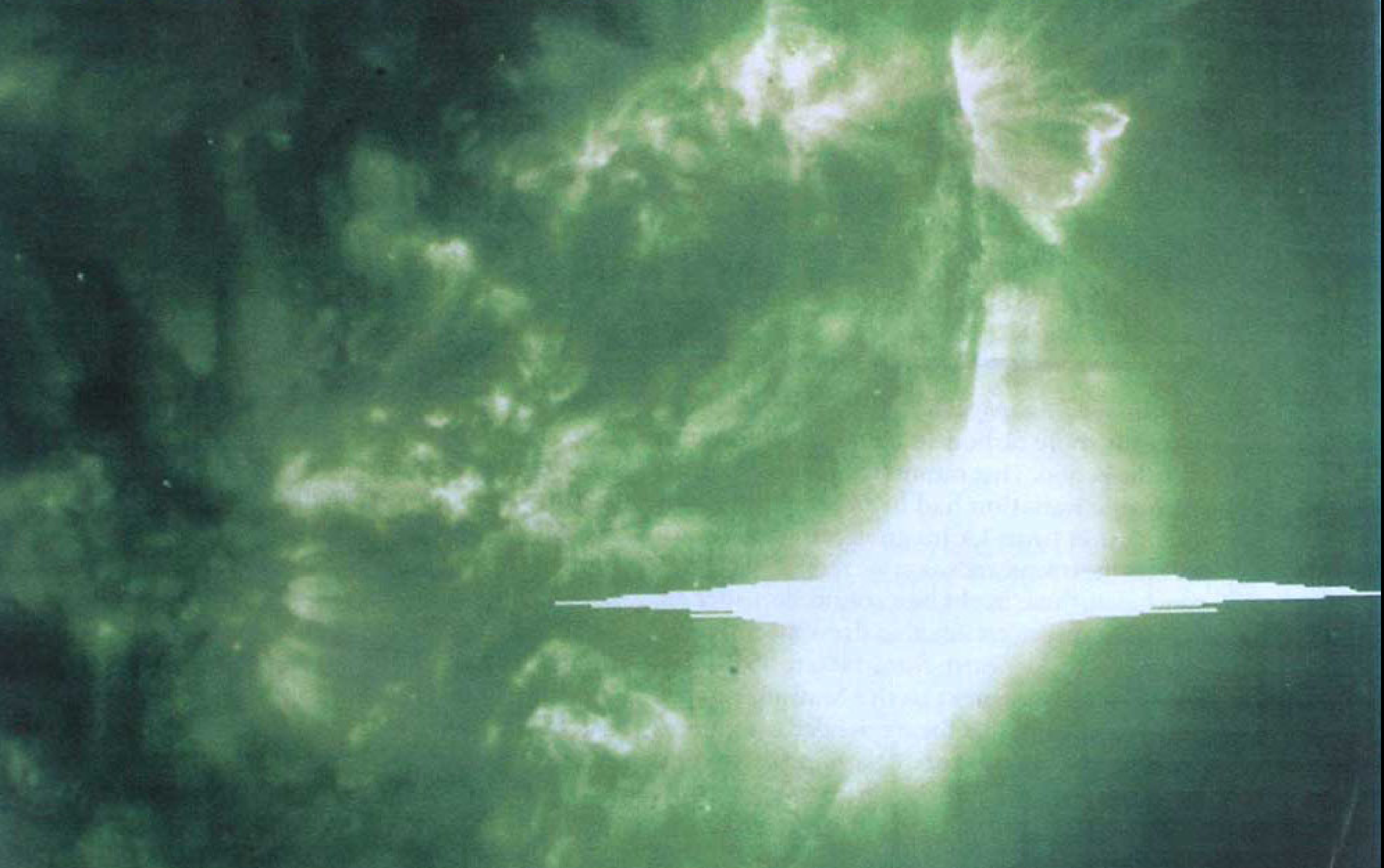
At Solar Minimum, magnetic field lines more like a regular dipole,

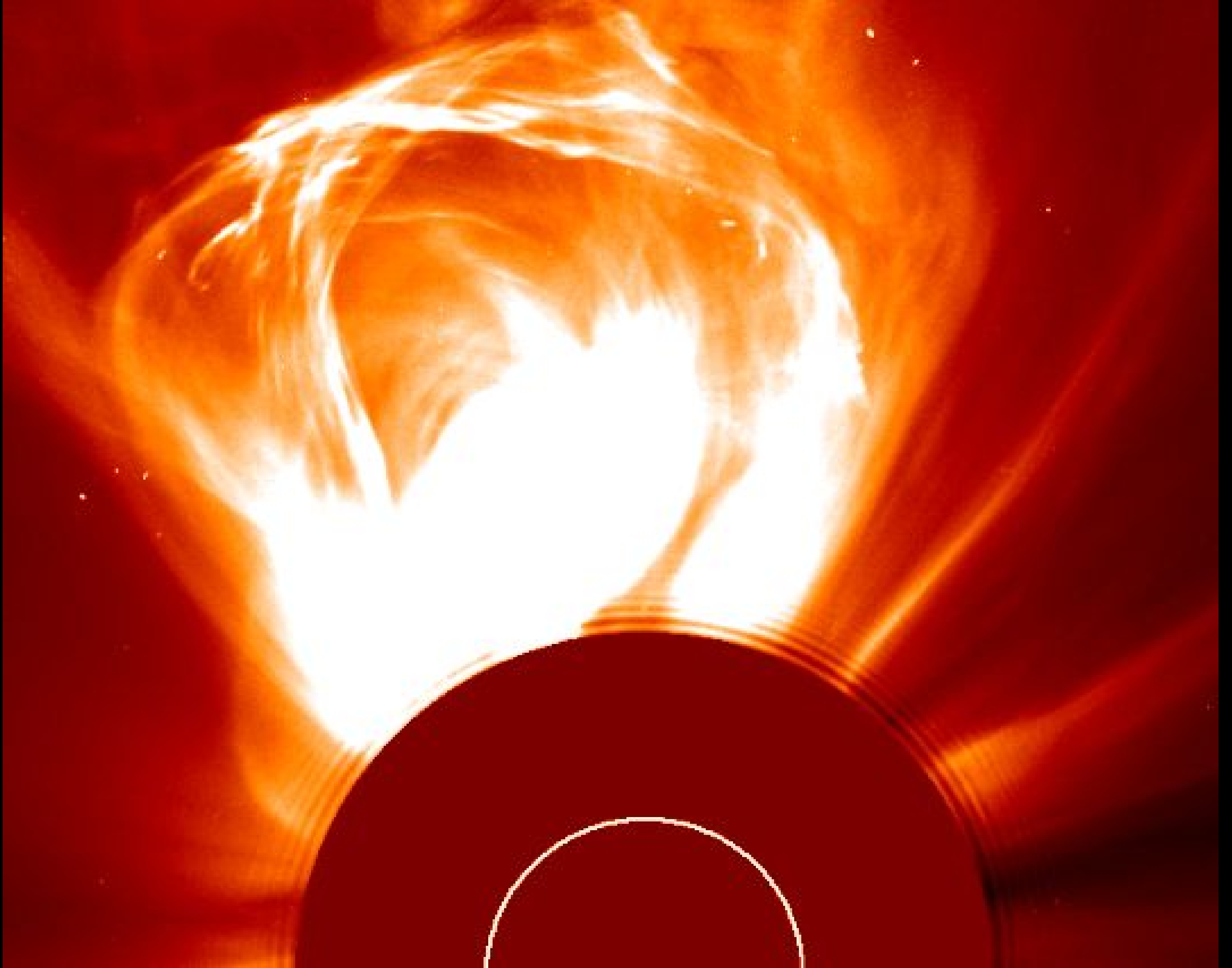


11/2: Nearly rotated away from Earth, the spots keep firing flares and CMEs.

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

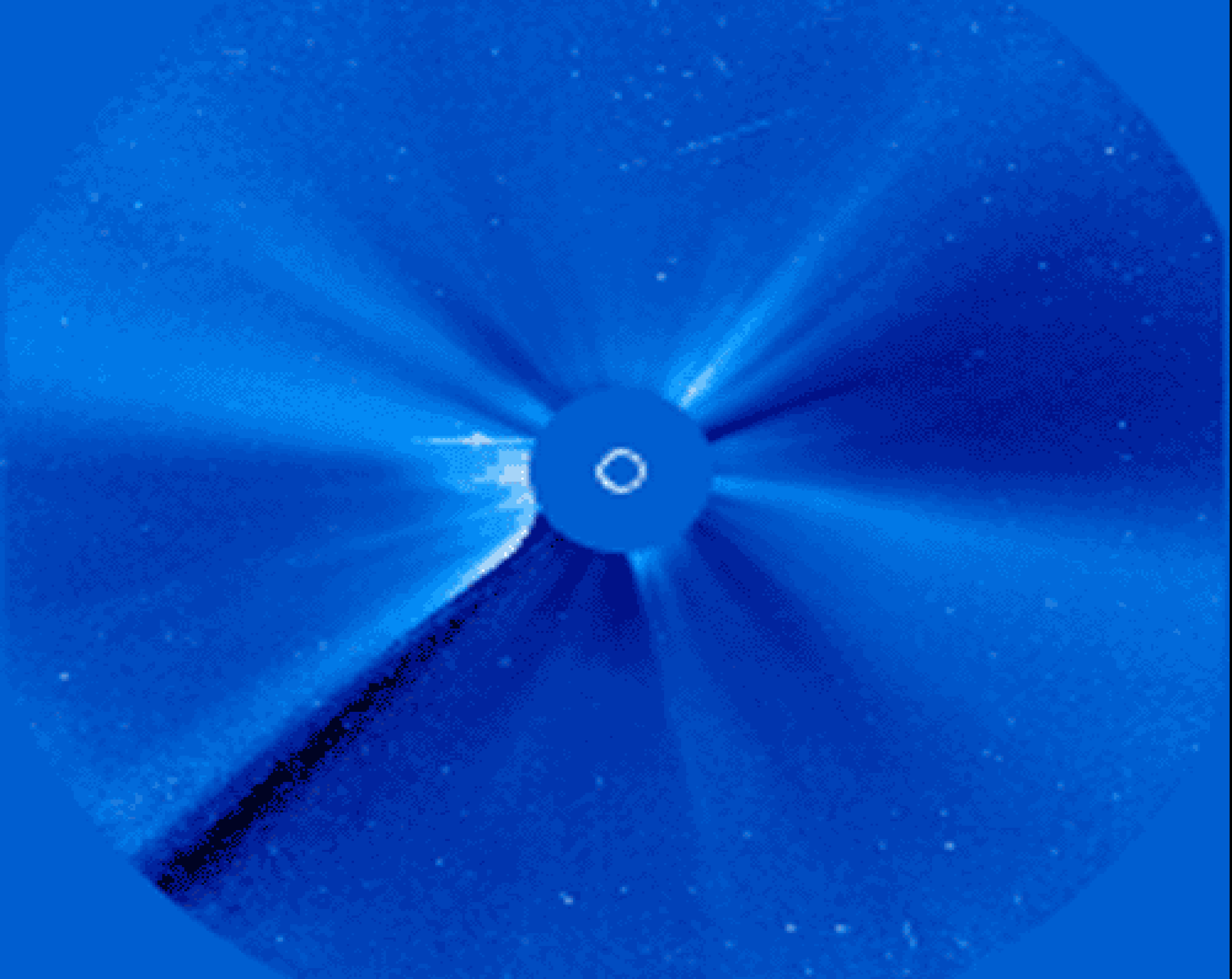
A fast-moving CME follows, but at an angle that only glances Earth.

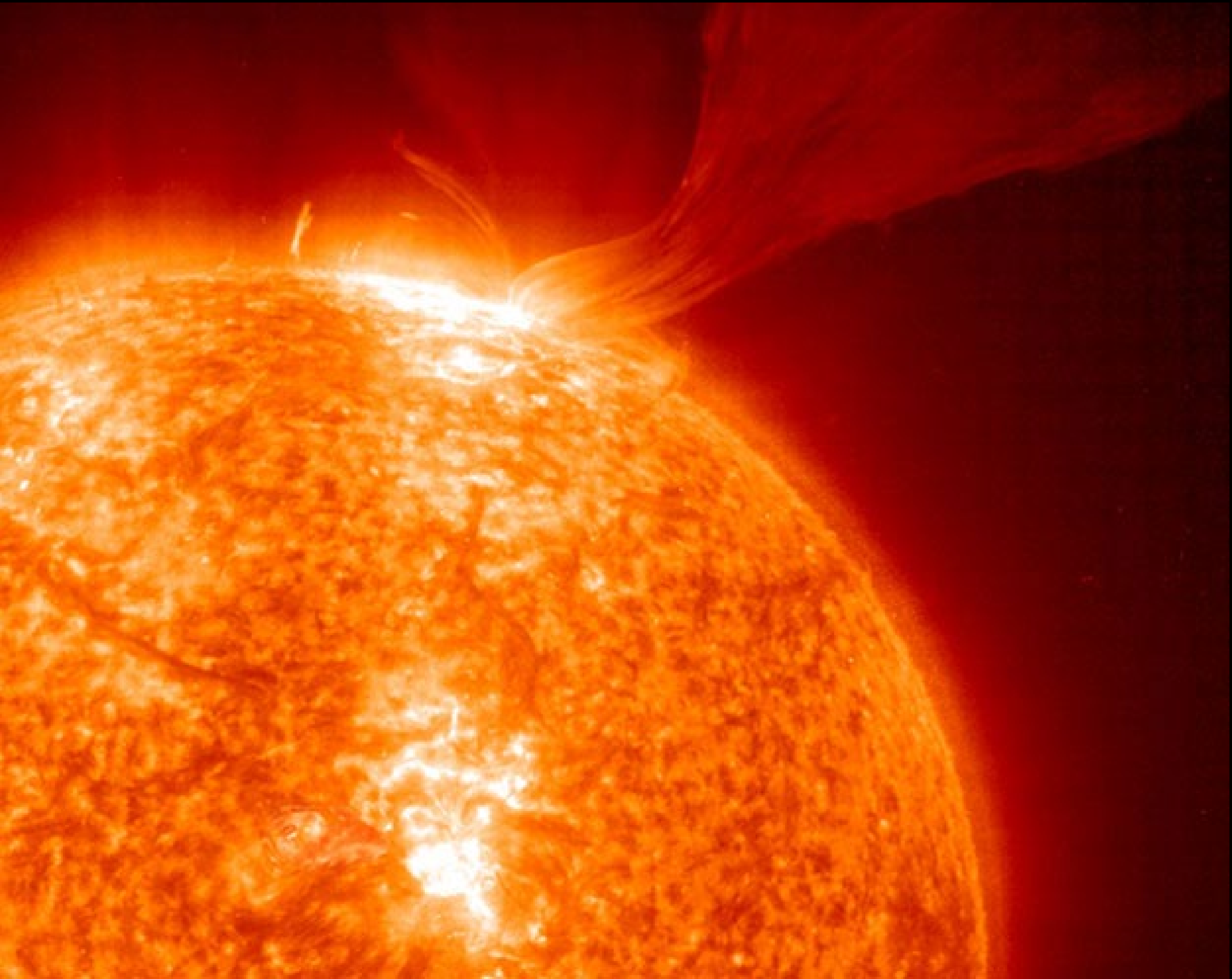


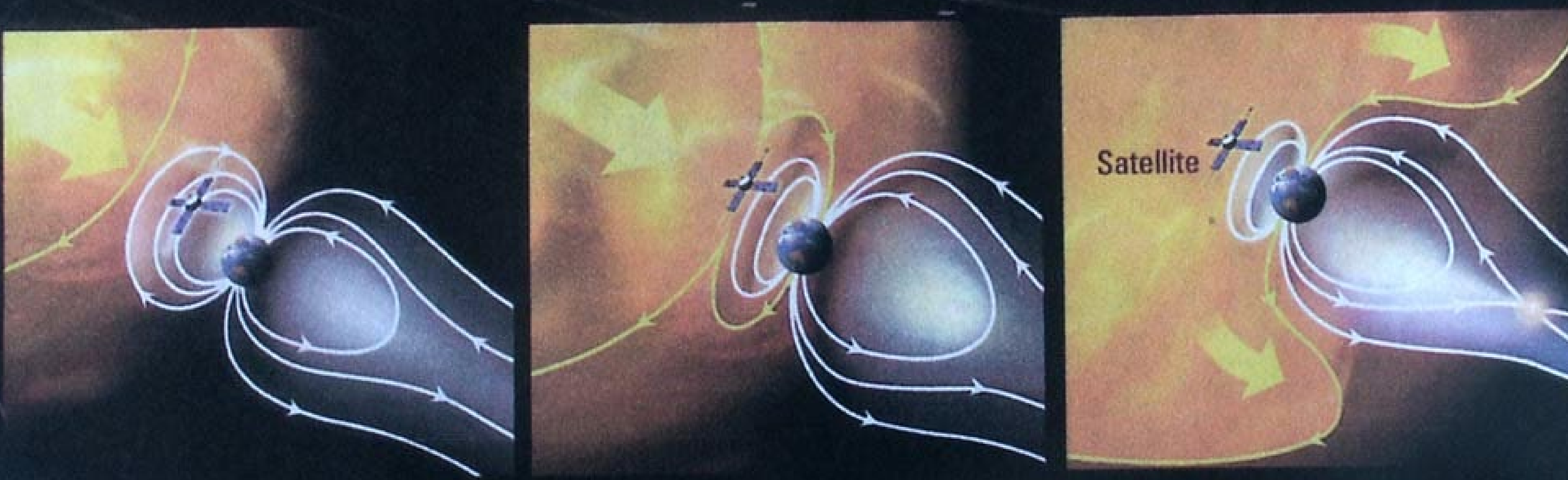


Video Images of Solar Activity

- Convection on photosphere (0:34)
- Solar Flares (Goddard) (2:53)
- --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



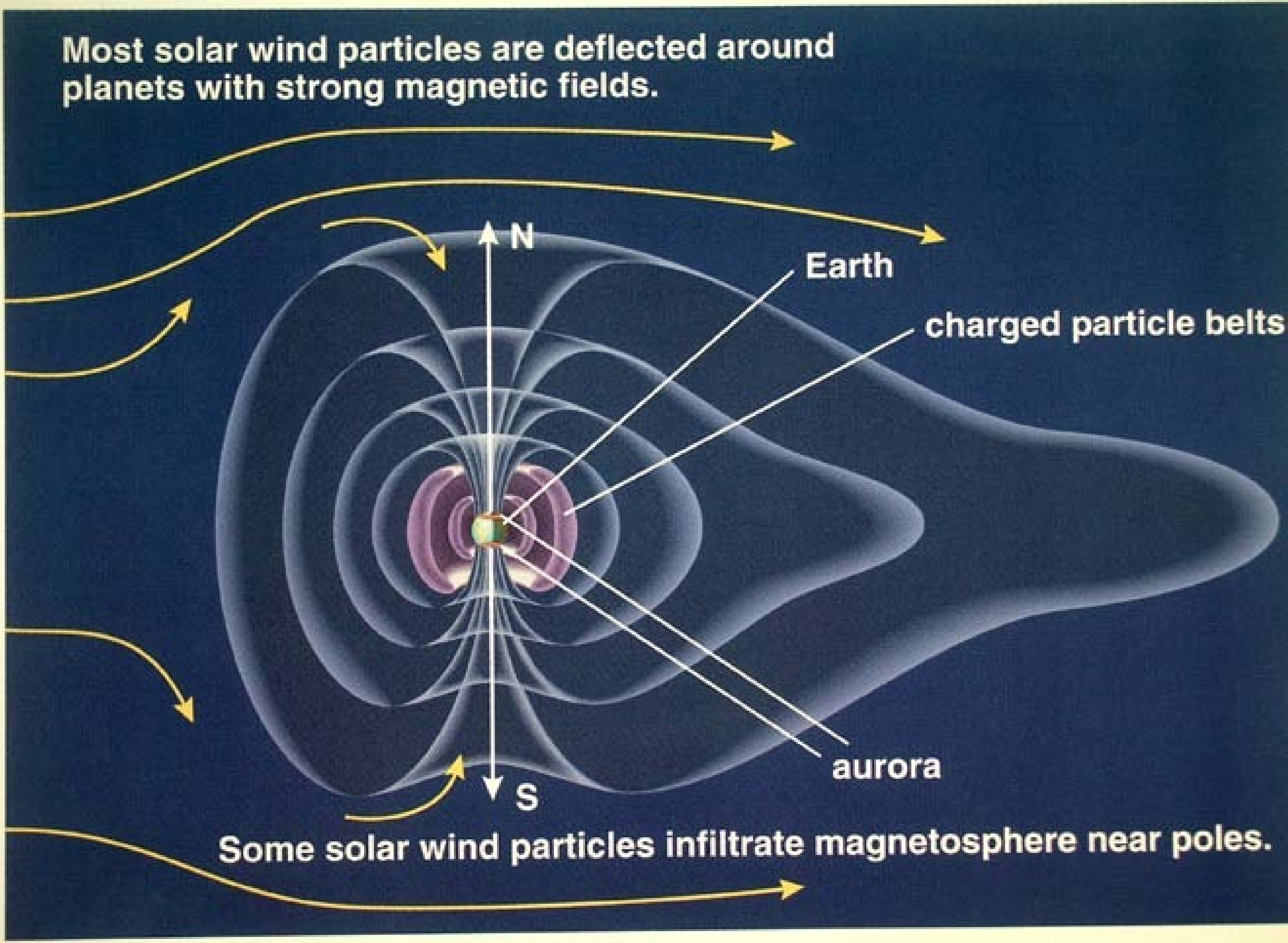


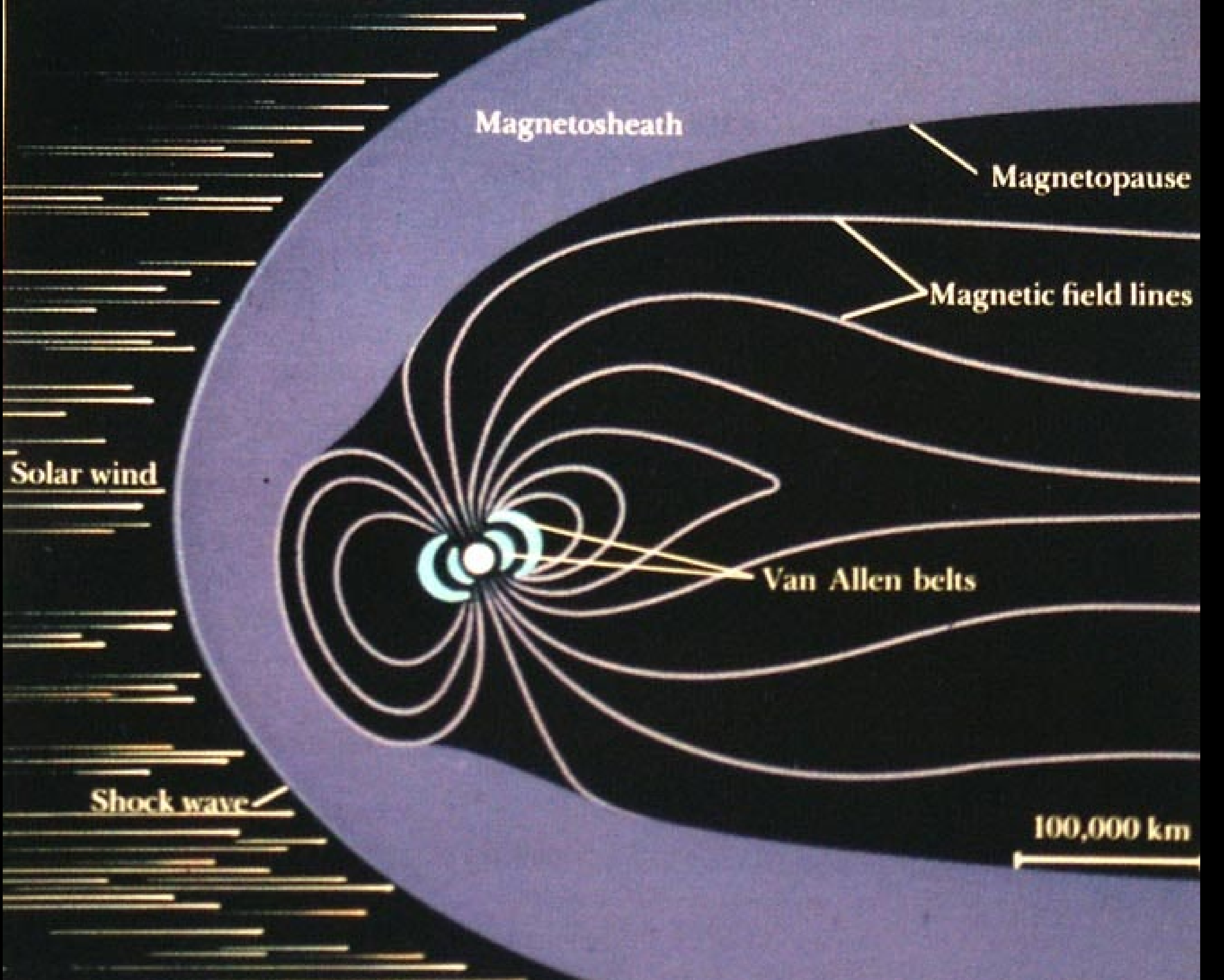


Earth Takes a Hit

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 – Capture particles of the Solar Wind

- (no, not the hokey StarTrek episode…)
- 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 a ***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!

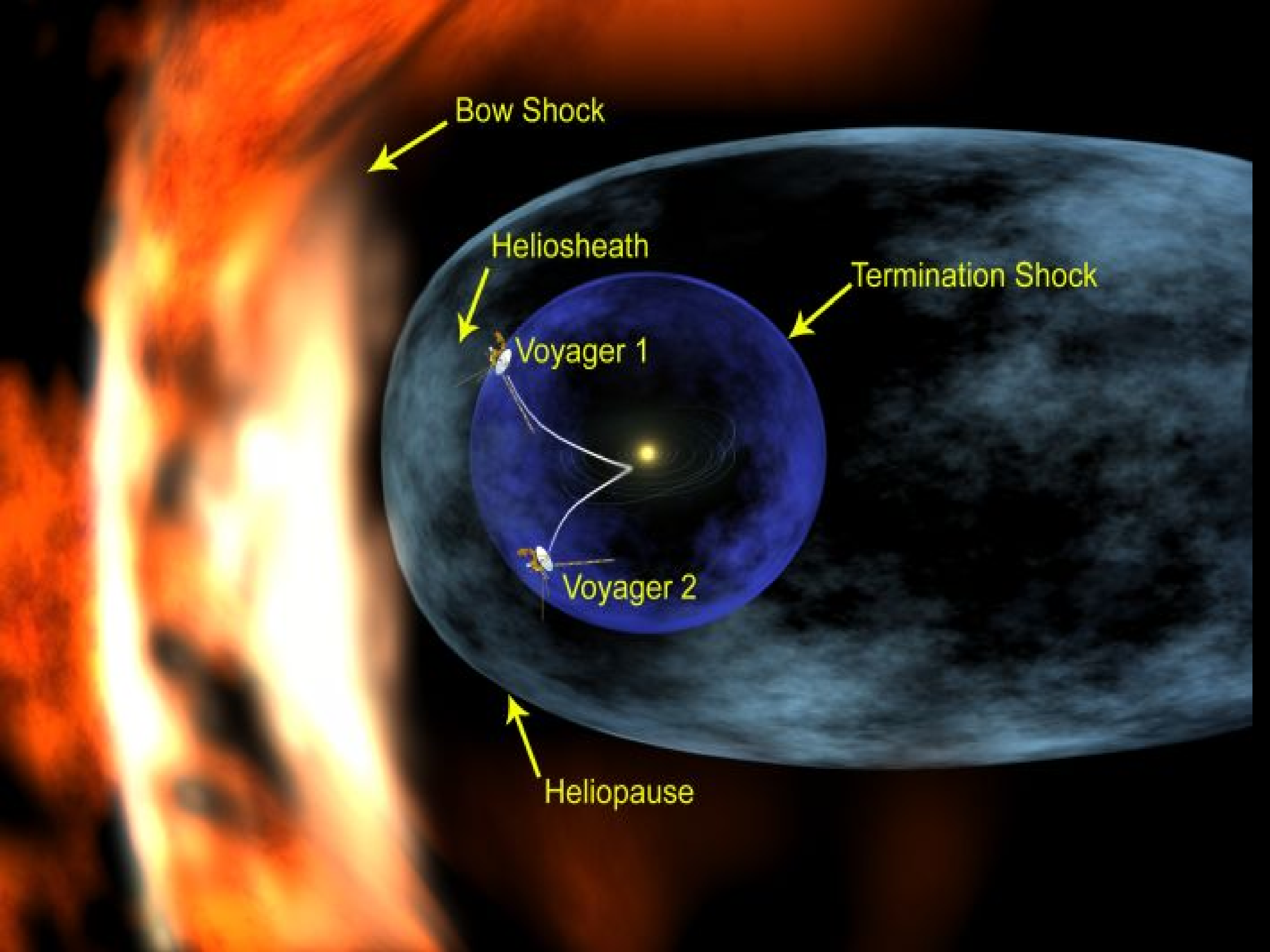
Videos of Solar Wind / Earth Magnetic Field interactions

- Discovery Channel **video clip**. Start at 3:45, to the end
- The Aurorae are the Earth's atmosphere being ionized by these high-speed solar wind particles, and recombination sends the electrons down through the levels
- Green, due to twice ionized oxygen
- Red, and purple, due to ionized nitrogen
- Enjoy, on the following slides…


© Phil Hoffman

Aurora from ISS

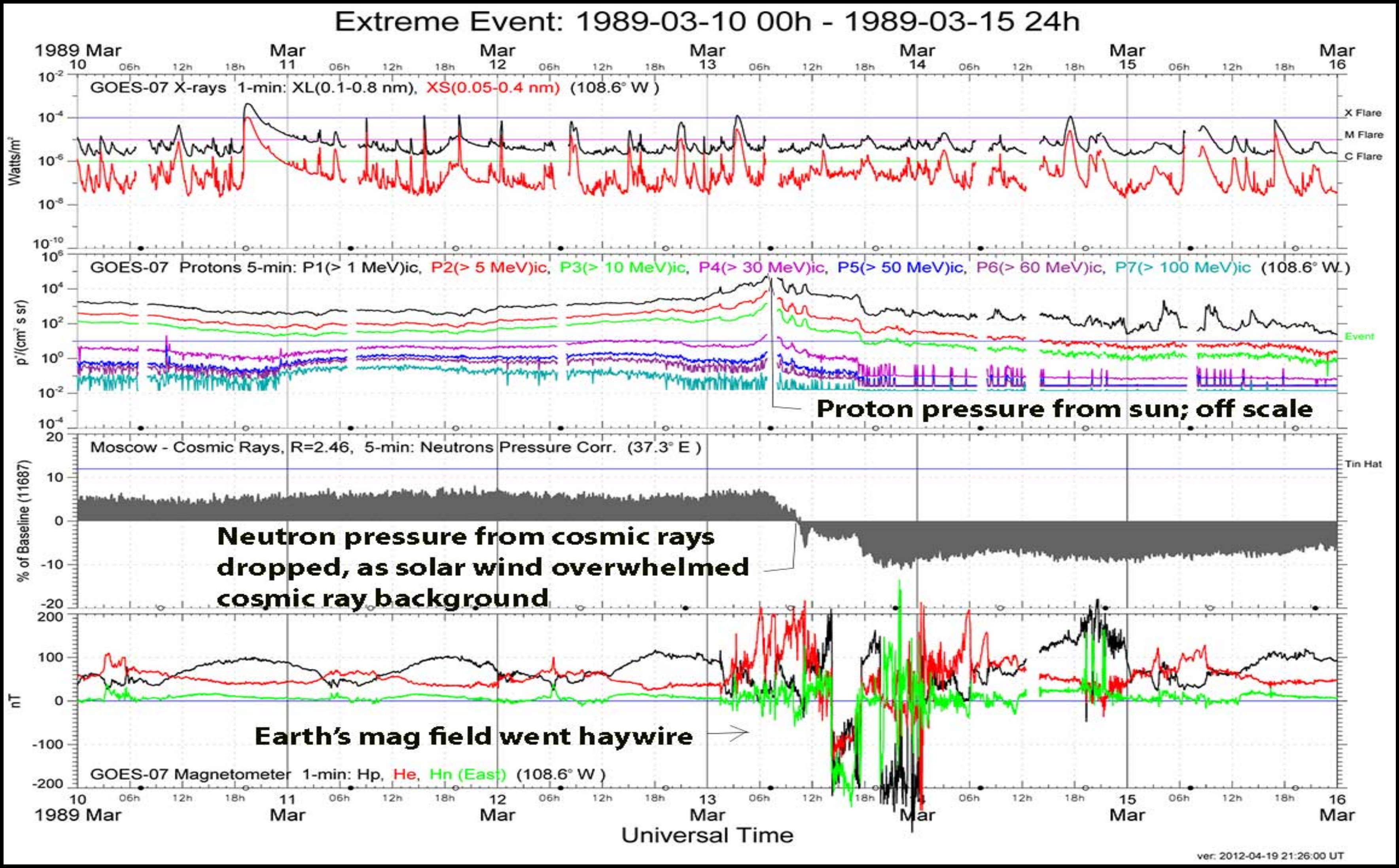
Comet NEAT's kinked tail from solar storm boundary crossing


Bow Shock
Heliosheath
Termination Shock
Voyager 1
Voyager 2
Heliopause

3. Solar Flares produce intense ejections of high speed protons, electrons, and helium nuclei to space.

- If directed at Earth, and the Earth's magnetic field is oriented so that it channels the blast wave more directly to Earth, we can have a Geo-Magnetic Storm.
- These cause such a large voltage difference between the atmosphere and ground, that it can short out expensive electrical equipment, and even entire electrical grids

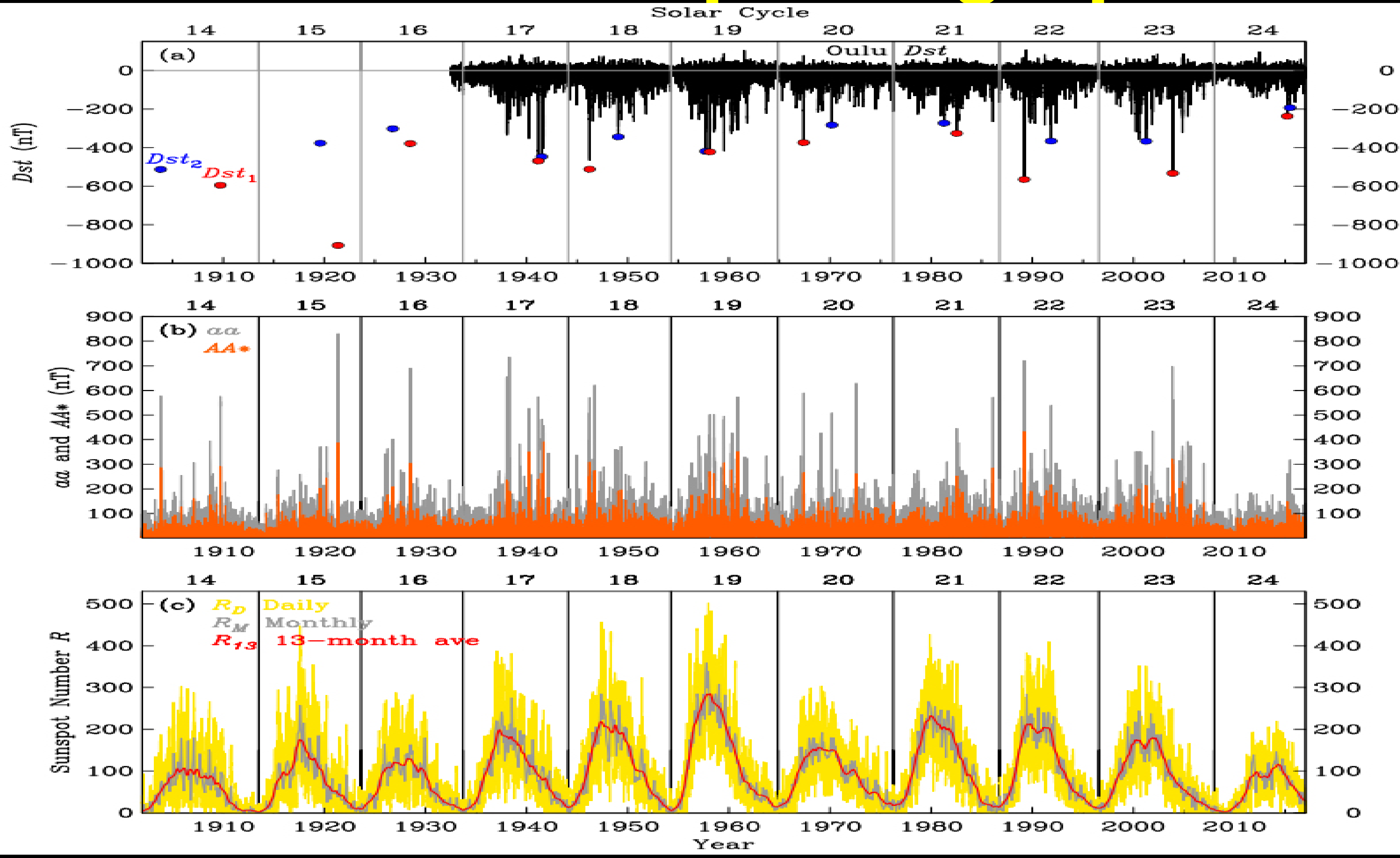
Ottowa, Canada's hydro electric grid was knocked out for a time by the March 1989 GeoStorm, and northern lights seen all the way to Texas



Unfortunately, a new study by Love (2021)

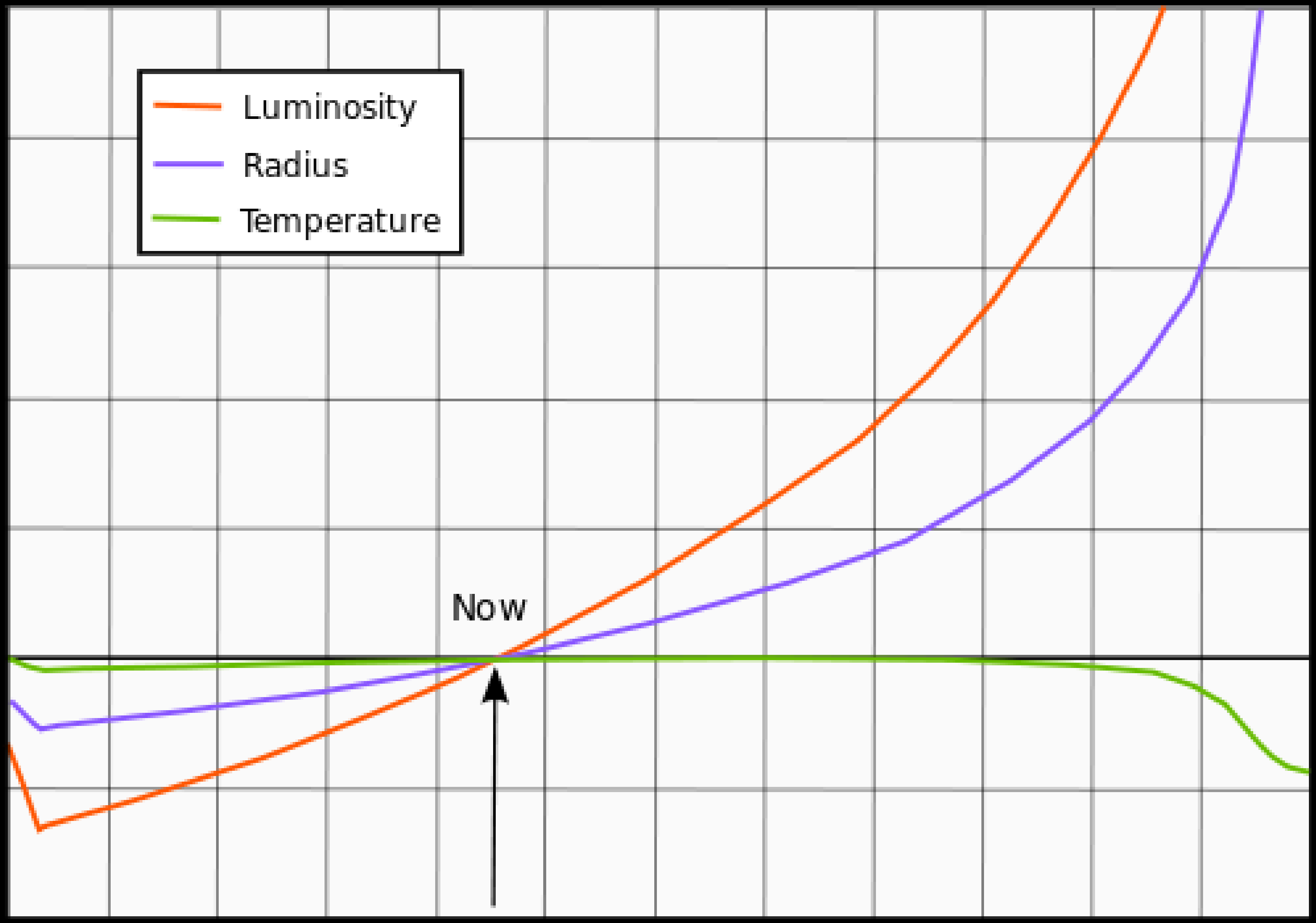
- …Finds that the frequency of intense solar storms has been underestimated by more than a factor of 2.
- We have been lucky in recent decades, since the intensity of the sun's luminosity and frequency of sunspot-related solar flares has also been low.
- See next slide. Note too how clearly the data right up to 2020 show decreasing solar cycle intensity and solar luminosity.

From Love (2021). Geo-Storm indicators top two graphs



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 brighter 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.
- This increase will continue and even accelerate.
- But we have a couple hundred million years before it gets significantly hotter for this reason.
- But longer term…


Luminosity
Radius
Temperature
Now

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!

Ch 14 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
- Sun: balance of nuclear powered pressure and inward gravity. Altering either will alter the size, structure of the sun
- Sunspots; high magnetic fields trap gas on photosphere surface, where it cools and therefore darkens.
- 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
- Neutrinos emitted during most nuclear reactions, travel unimpeded out from the core, so neutrino detectors give us direct info on the sun's nuclear core