Astr 2310 Tues. March 31, 2016
This week's Topics

- **Chapter 7: The Sun, a Model Star**
  - Structure of the Sun
    - Physical Properties
  - Photosphere
    - Opacity
    - Spectral Line Formation
    - Temperature Profile
  - The Chromosphere
    - Properties and Features
  - The Corona
    - Properties
  - Solar Activity
    - Sunspot Cycle
    - Zeeman Splitting and Magnetic Fields
    - Differential Rotation
    - Solar Wind

Basic Properties of the Sun

- First we need to know the distance of the Sun, i.e., the AU
  - Huge effort required to measure the AU
  - Measure parallax of Mars (not precise enough)
  - Timing of transits of Venus (precise but very rare)
    - Reason Captain Cook sailed to Tahiti
    - People died trying to measure the AU!

- Luminosity:

  We integrate the Sun's spectral energy distribution (S_λ) over all wavelengths to give the bolometric flux at the Earth:

  F_{bol} = INT $\{S_\lambda\ d\lambda\}$ = 1370 W/m^2 (Solar constant)

  This radiation is spread over a sphere with a radius equal to that of the Earth's distance. Thus:

  $L_{bol} = F_{bol}\ 4\pi r^2 = (1370)(12.57)(1.496 \times 10^{11})^2$

  $= 3.853 \times 10^{26}$ W

Chapter 7 Homework

Chapter 7: # 7.2, 7.3, 7.4, 7.6, 7.8

Due Tues. April 12.

Basic Properties of the Sun

- Angular size + distance

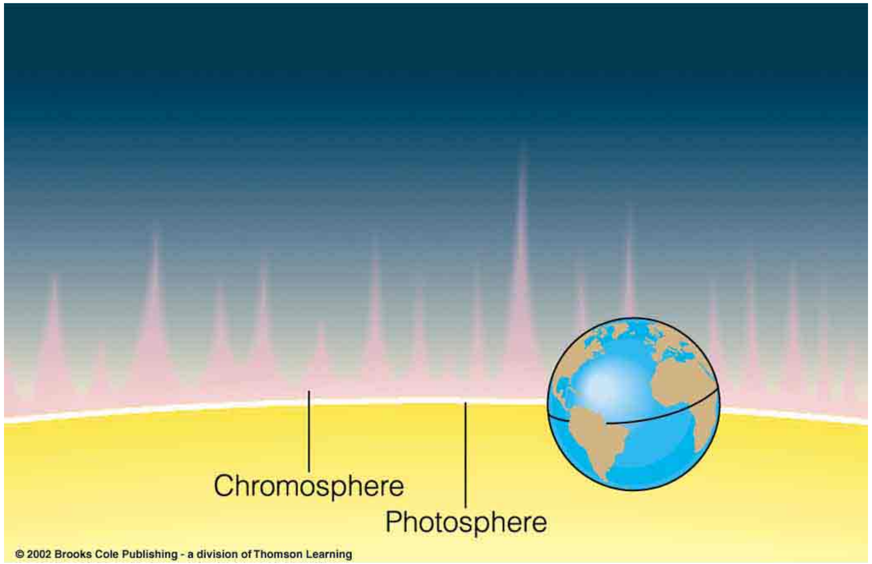
  (s = rθ)

  Radius: $R_{sun} = 6.96 \times 10^5$ km

- Newton's form of Kepler's Law

  $M_{sun} = 4\pi^2 a^3/GP^2$

Mass: $M_{sun} = 1.99 \times 10^{30}$ kg



$$\text{DENSITY} = \rho = \frac{\text{Mass}}{\text{Volume}} = \frac{M}{\frac{4}{3}\pi R^3}$$

Average density of Sun: $\rho = 1.41$ gm/cm^3

Will be higher in center and (much) lower on outside

Basic Properties of the Sun

Surface Temperature:

Recall that we computed the Solar Luminosity from the bolometric flux:

$$L = F_{\text{at Earth}} \times 4 \pi R^2_{\text{1 AU}}$$

We now can compute the temperature since the Sun's luminosity = luminosity/unit area and multiply by Sun's surface area:

$$L = \sigma T^4_{\text{surface}} \times 4 \pi R^2_{\text{sun}}$$

Solving for the temperature:

$$T = (L/ 4 \pi \sigma R^2_{\text{sun}}) = [(3.853 \times 10^{26})/(12.57)(5.67 \times 10^{-8})(6.94 \times 10^{8})^2]^{1/4}$$

Known as the Effective Temperature: 5788 K

– Not all that hot by laboratory standards

Physical State of material in Sun

- At these T's, ρ's, hydrogen will be a gas
  - At high enough T, as pressure (P) increases and ρ increases, you never really get a "liquid", just a very dense gas.

- H ionization?
  - On outside, H mostly neutral (a small fraction is ionized)
    - remember H ionized and Balmer lines gone only above 10,000 K
  - Over most of interior, H completely ionized
    - separate electrons (e^-) and protons (p^+)
    - Ionized gas called a "plasma"

- No discrete "surface" – just increasing ρ, T, P, and "opacity"

How we determine T, ρ, P vs depth?

- **From theory:**
  - Pressure (P) and density (ρ) must increase with depth
    - Weight of overlying gas compresses lower material -- "Hydrostatic equilibrium"
  - Temperature (T) must increase with depth
    - Energy is flowing out of the sun – and it flows from hot to cold -- so hot inside
  - Numerical modeling of details let us calculate T(r), ρ(r), P(r)

- **From observations of "oscillations" or "solar seismology"**
  - The sun oscillates like a bell (or the air in an organ pipe)
  - The frequency depends upon sound speed, which depends upon T(r), ρ(r), P (r)
  - Observations from "Global Oscillation Network Group (GONG) telescopes.

- **From interpreting the spectrum using Kirchoff's laws**
  - The Sun looks like continuous emission: Solid or hot dense gas
  - Absorption lines in the spectrum: Cooler gas between us and the dense gas

How we determine T, ρ, P vs depth? - I

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How we determine T, ρ, P vs depth? - II

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- From using Kirchoff's laws
  - The Sun looks like continuous emission: Solid or hot dense gas
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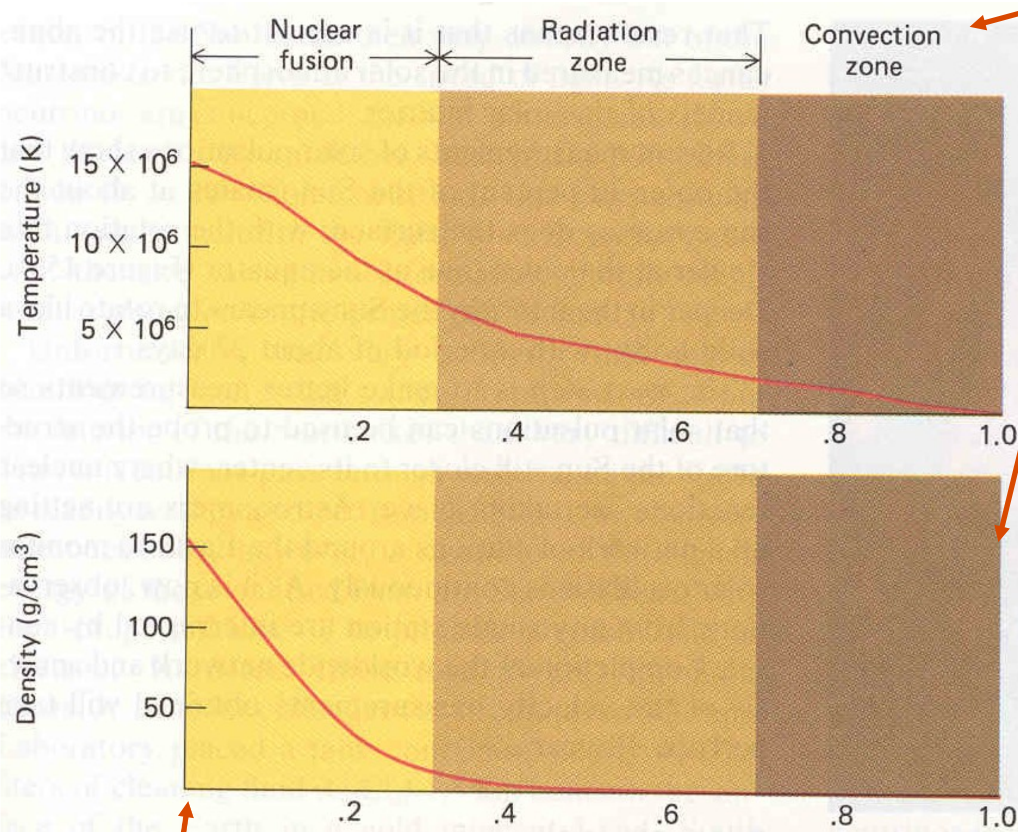
The "Surface" of the Sun

- No discrete "surface" – just increase ρ, T, P, and "opacity"
  - "Surface" or photosphere defined by depth from which visible photons can escape.

- Opacity depends on wavelength, so apparent "surface" will be at different depths for different wavelengths
  - High opacity in absorption lines because these photons easily absorbed/emitted
    - Won't see very far in at these wavelengths.
  - Low opacity in between absorption lines
    - Can see in deeper at these wavelengths.
  - Eventually ρ so high gas opaque at all wavelengths (just as in solid)
  - "surface" high = cool = dark in lines; deep = hot = bright between lines

T,ρ dependence upon depth inside the sun



From Realm of the Universe by Abell et al.

Will explain these "zones" later

Photosphere: ~400 km thick region here.

Full radius ~700,000 km

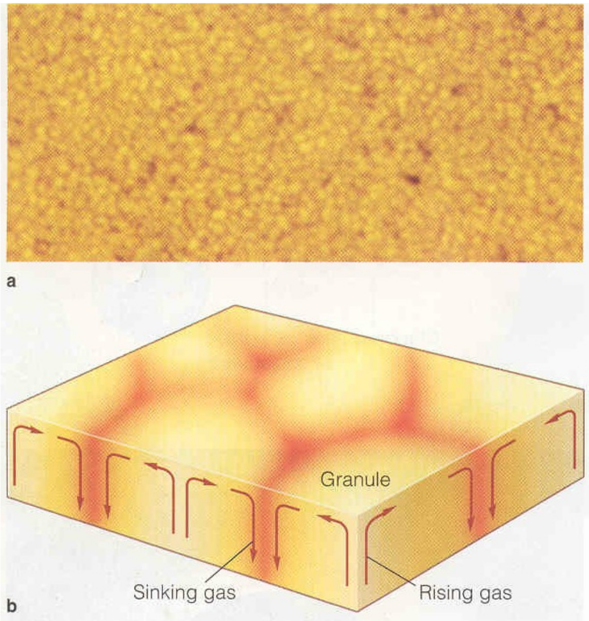
Light from deeper absorbed before it escapes.

Atmosphere above this too thin to emit (or absorb) much light.

Center

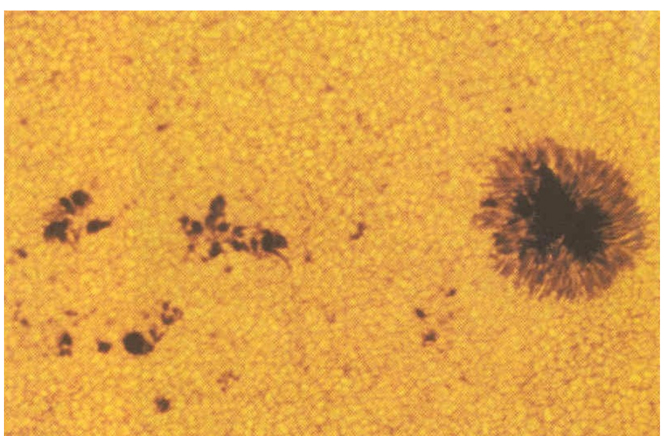
Outside

Detailed structure of the outer photosphere

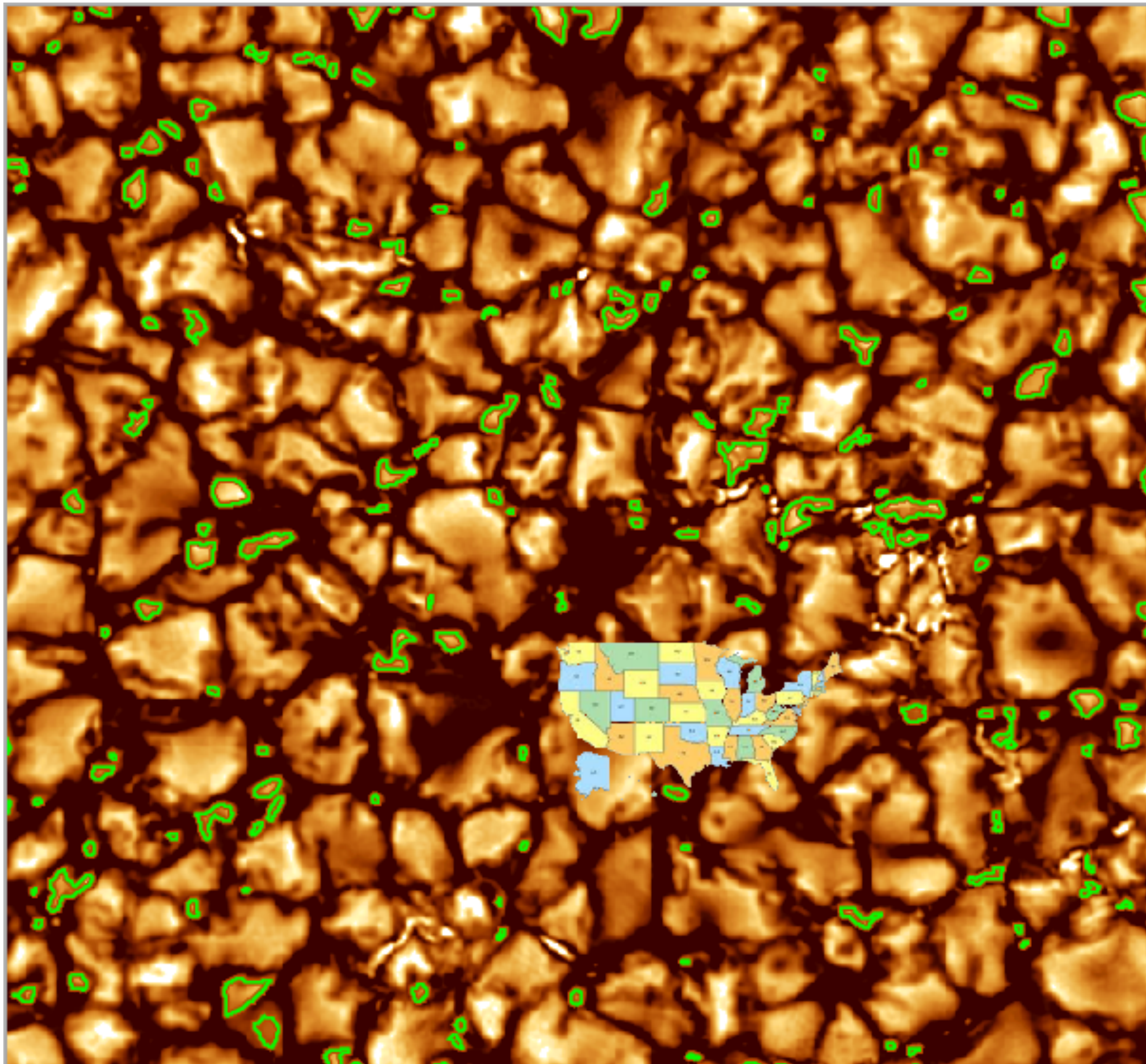


- **CONVECTION:**
  - Granulation and Supergranulation
  - Heat carried by actual motion of gas
  - Different than radiative transport
    - energy carried by photons
    - dominates deeper in sun

- **SUNSPOTS**
  - Darker (and cooler) regions of sun
  - Strong magnetic fields limit convection
  - Come and go in 11 (really 22) year cycle
  - Magnetic energy releases cause "flares"
  - Material ejected causes aurora



From our text: Horizons, by Seeds

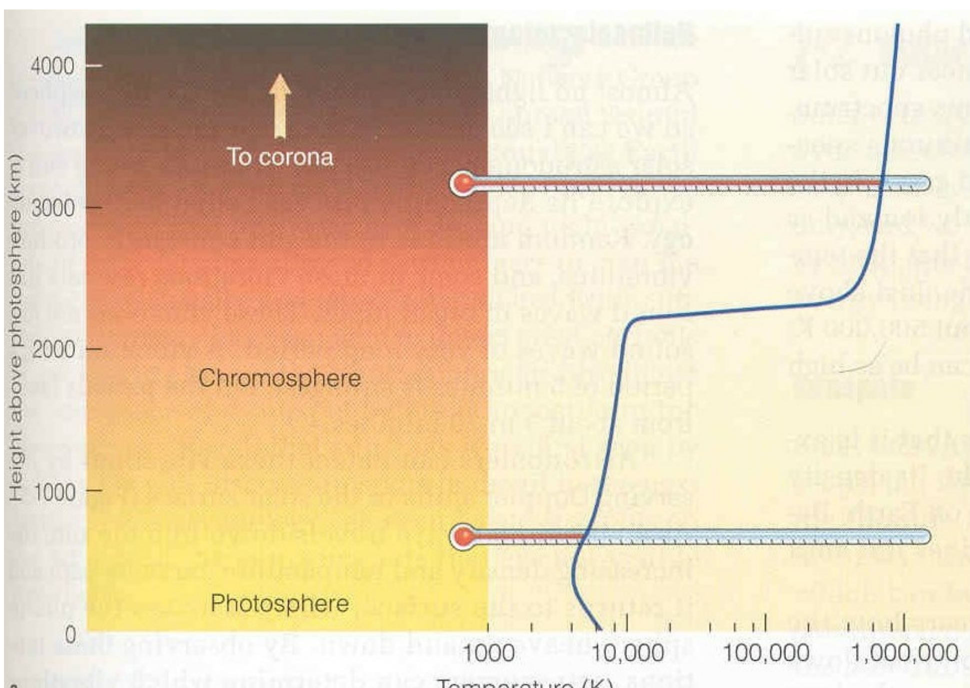


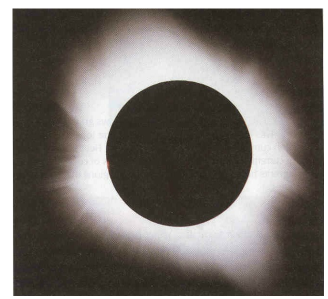
Outer Atmosphere: Chromosphere

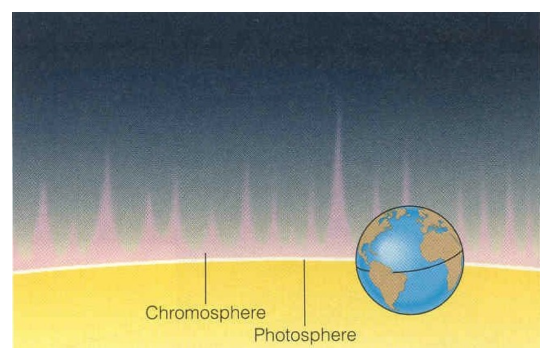
- Visible during solar eclipse
  - **Spectrum shows emission lines**
- Emits emission lines
  - Can be seen anytime by tuning narrow filter to these emission lines
  - Recall that the brightness of a given emission line depends on temperature and density
  - We can examine the chromospheric structure by imaging the Sun in several of these lines.
    - **Resulting temperature profile reveals sharp transition region**
- Promenences: flame-like projections
  - **Some show loop-like morphology associated with pairs of sunspots**
  - "Supergranulation" pattern
  - Filament: Prominence seen projected upon Sun
  - Spicules: small flame-like features

Complicated T dependence at the very edge

- We see emission lines at some wavelengths:
  - Implies very THIN HOT overlying gas at top of atmosphere
  - Gas is so thin it has trouble radiating heat away
  - Sound waves or magnetic fields heat thin gas
    - Chromosphere (“colored region” glows at a few wavelengths)
    - Corona (“crown” seen during solar eclipses)
    - Solar Wind (escaping wind of tenuous gas)

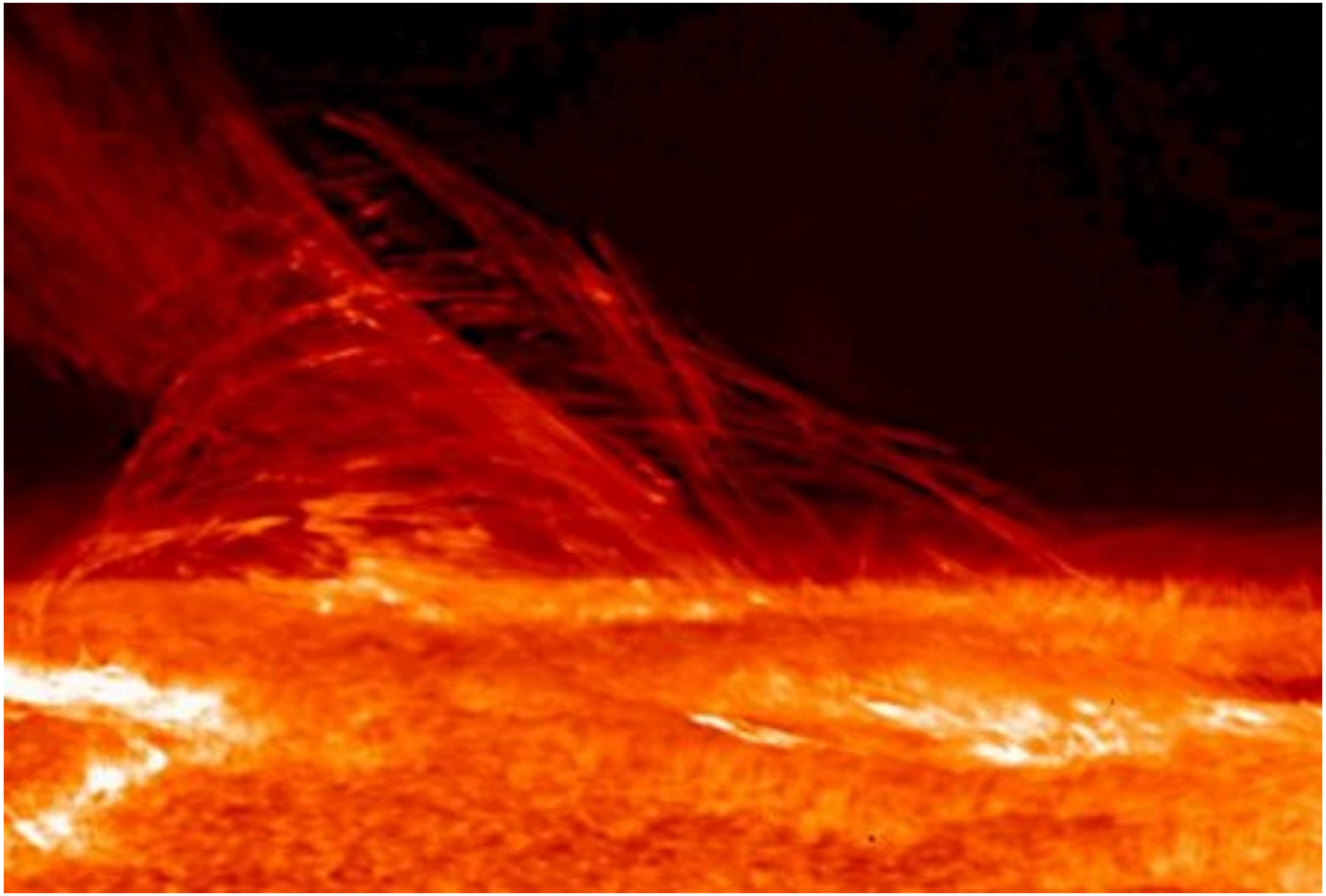


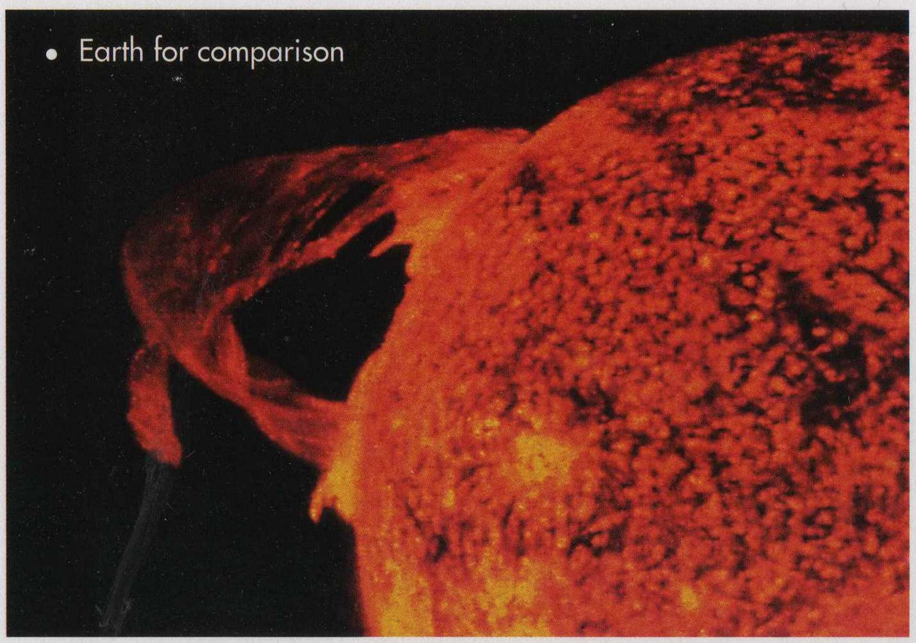


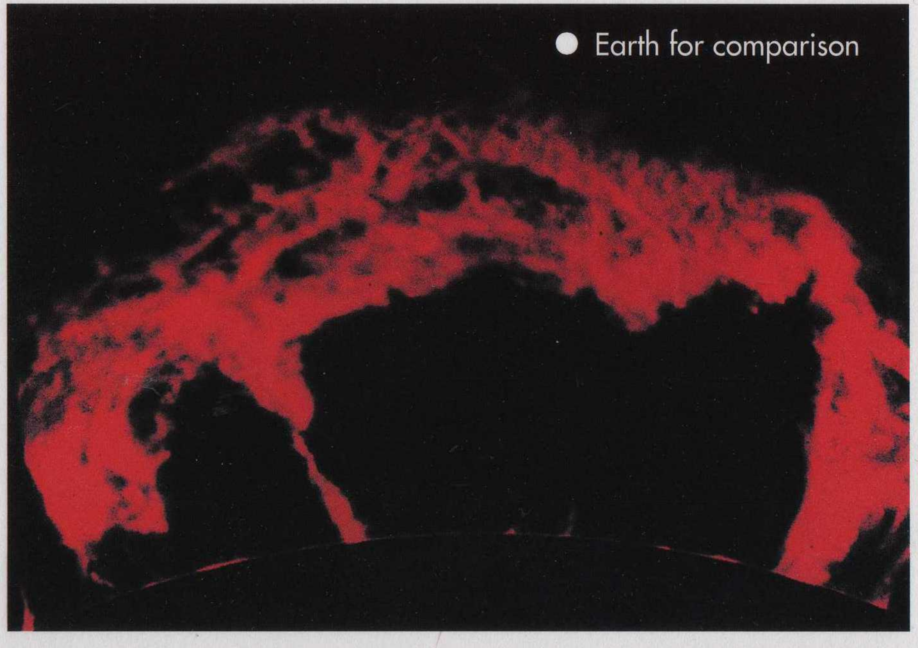


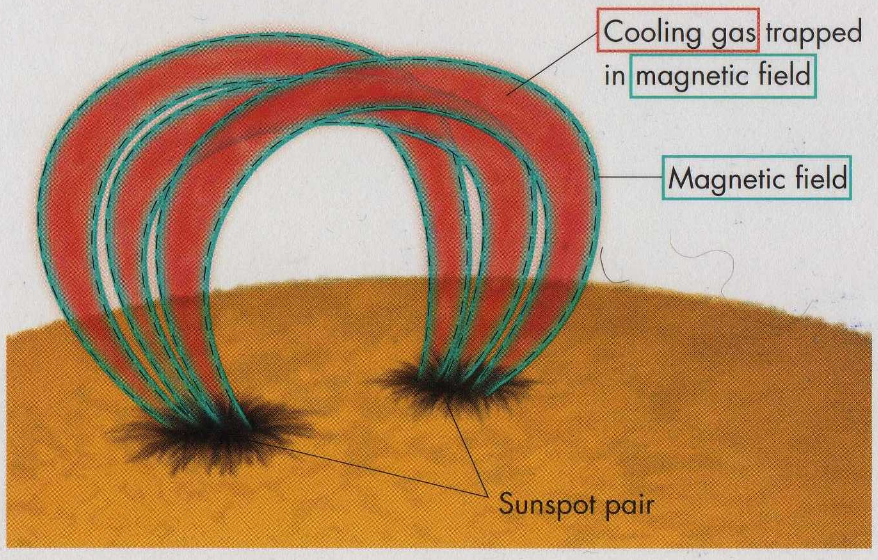
From our text: Horizons, by Seeds

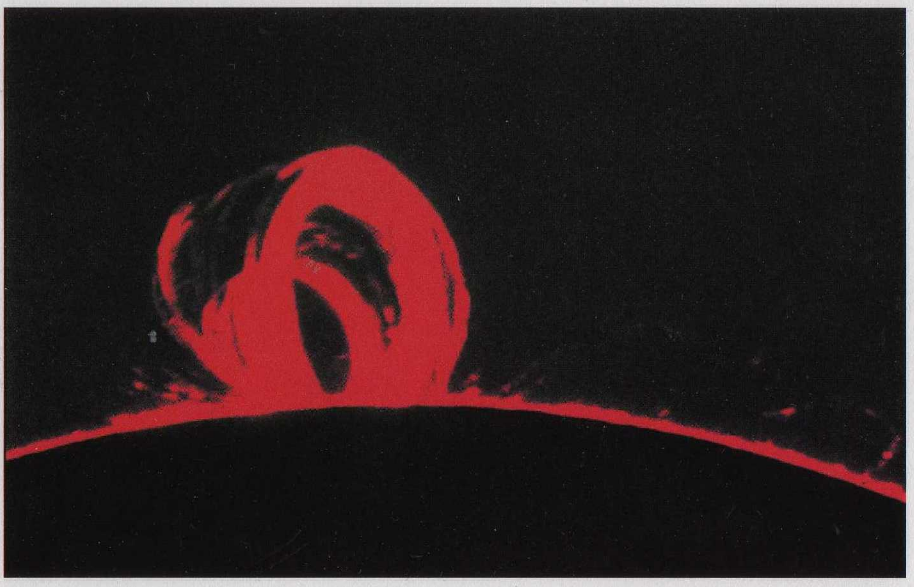
- Promenences and Spicules
- Bright Flares around active regions

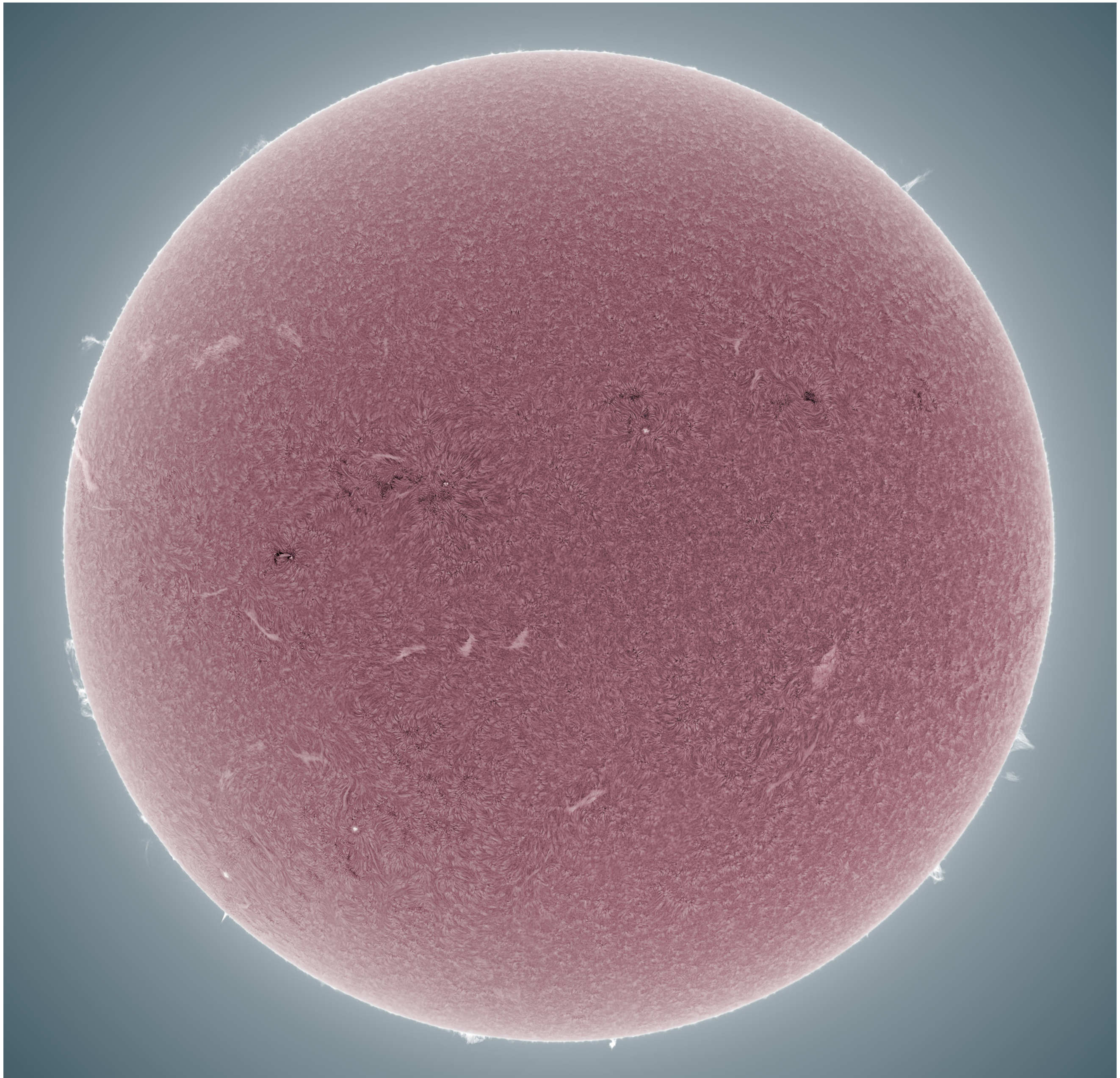


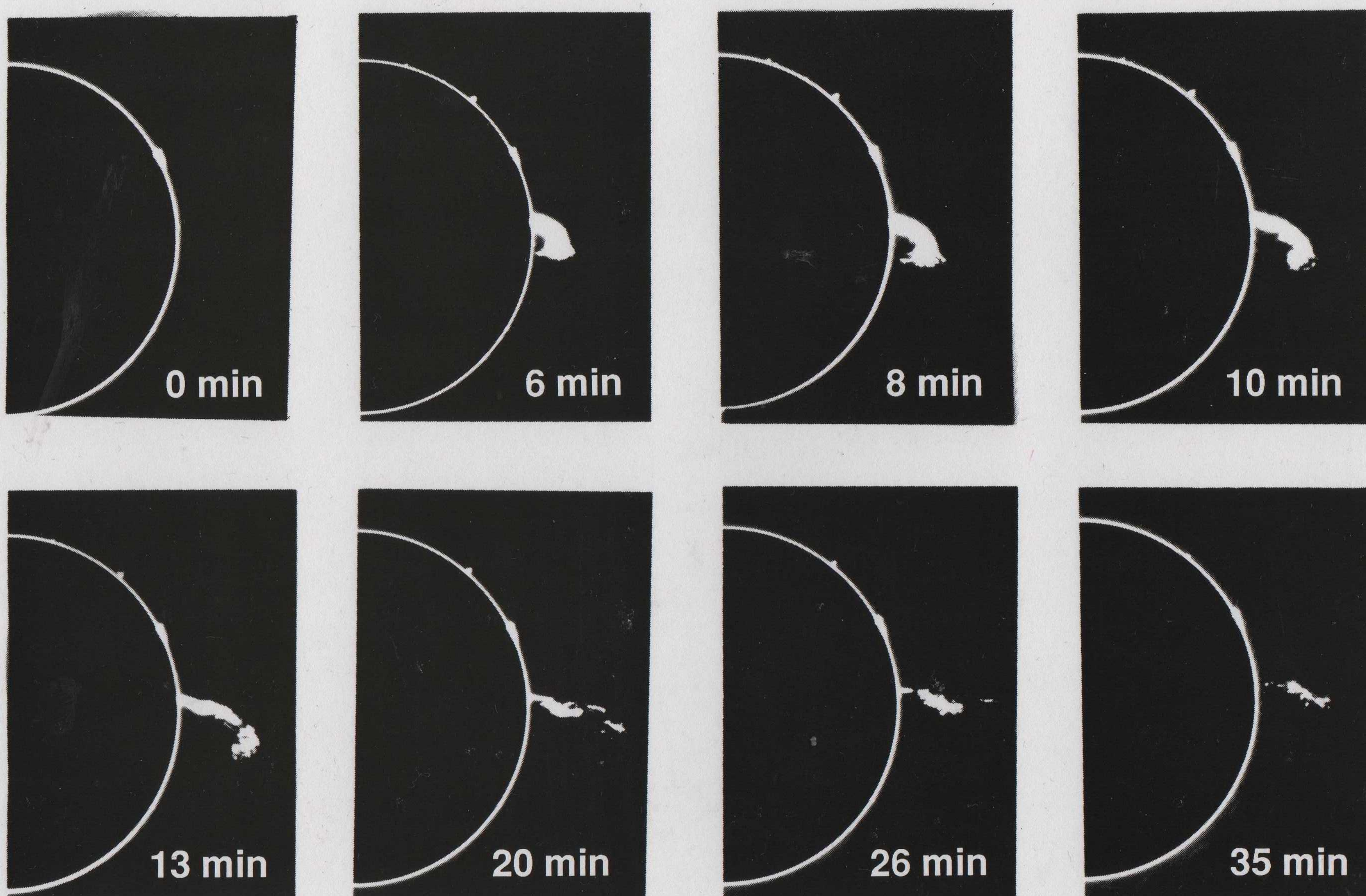

Earth for comparison


Earth for comparison


Cooling gas trapped
in magnetic field
Magnetic field
Sunspot pair






0 min
6 min
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20 min
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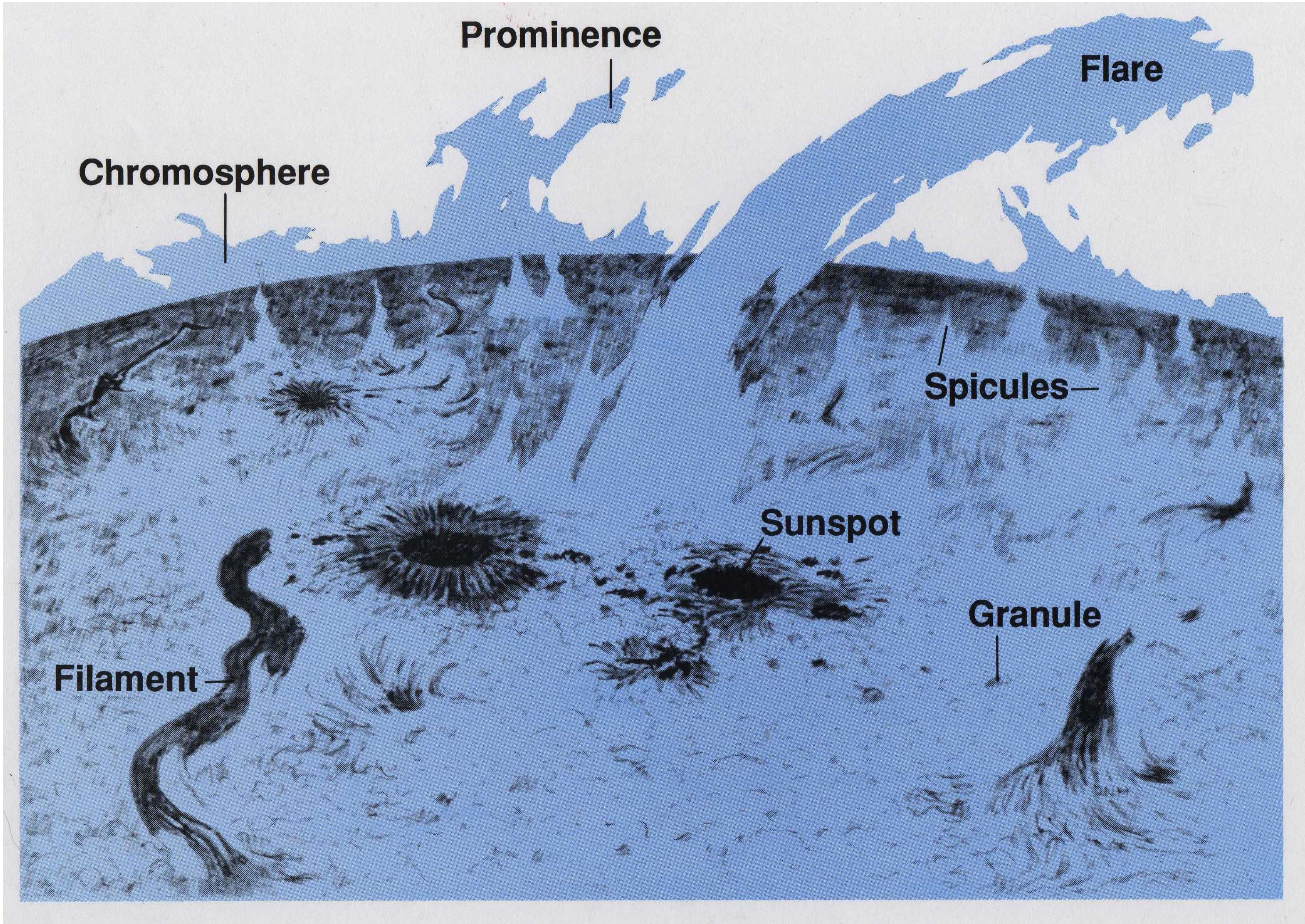
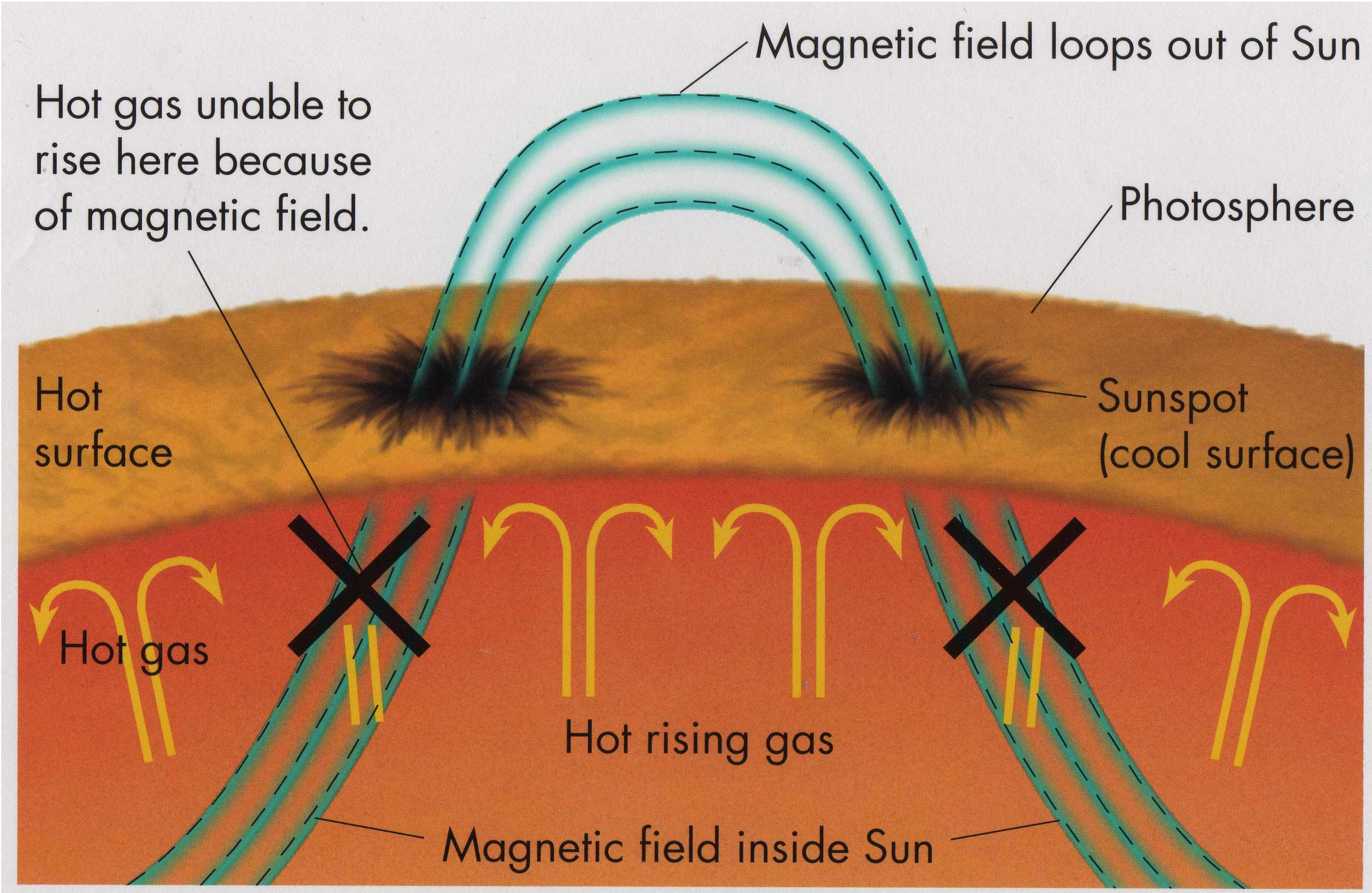

Prominence
Flare
Chromosphere
Spicules
Sunspot
Granule
Filament


Magnetic field loops out of Sun
Hot gas unable to rise here because of magnetic field.
Photosphere
Hot surface
Sunspot (cool surface)
Hot gas
Hot rising gas
Magnetic field inside Sun

Diffuse Atmosphere: Corona

- **Visible during solar eclipse**
  - Coronal structure varies from eclipse to eclipse
  - Subtle brush-like features at poles suggest magnetic field
  - Can be seen anytime with specialized instruments that carefully block the light from the photosphere
    - **Particularly effective in space where atmospheric scattering is nonexistent**
- **Spectrum also shows emission lines but VERY highly ionized**
  - Fe XIV line requires T = 2 x 10^6 K
  - Sun's corona should emit x-rays
- **X-ray Corona**
  - **Can be monitored anytime using x-ray telescopes in space**
  - Complex features associated with sunspots and flares

Coronal structure varies from eclipse to eclipes

Spectrum of corona reveals two components:

Highly ionized atoms

polarized solar spectrum

Ions indicate T = 2 x 10^6 K

Polarized solar spectrum results from scattering of photospheric light by free electrons

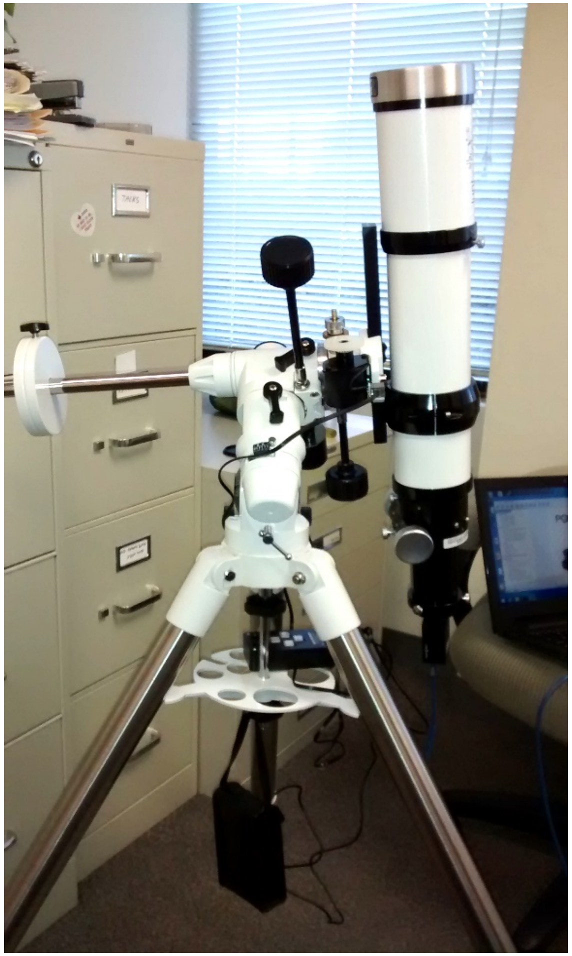
Note the brush-like structure suggestive of a large-scale magnetic field

CATE Eclipse Experiment

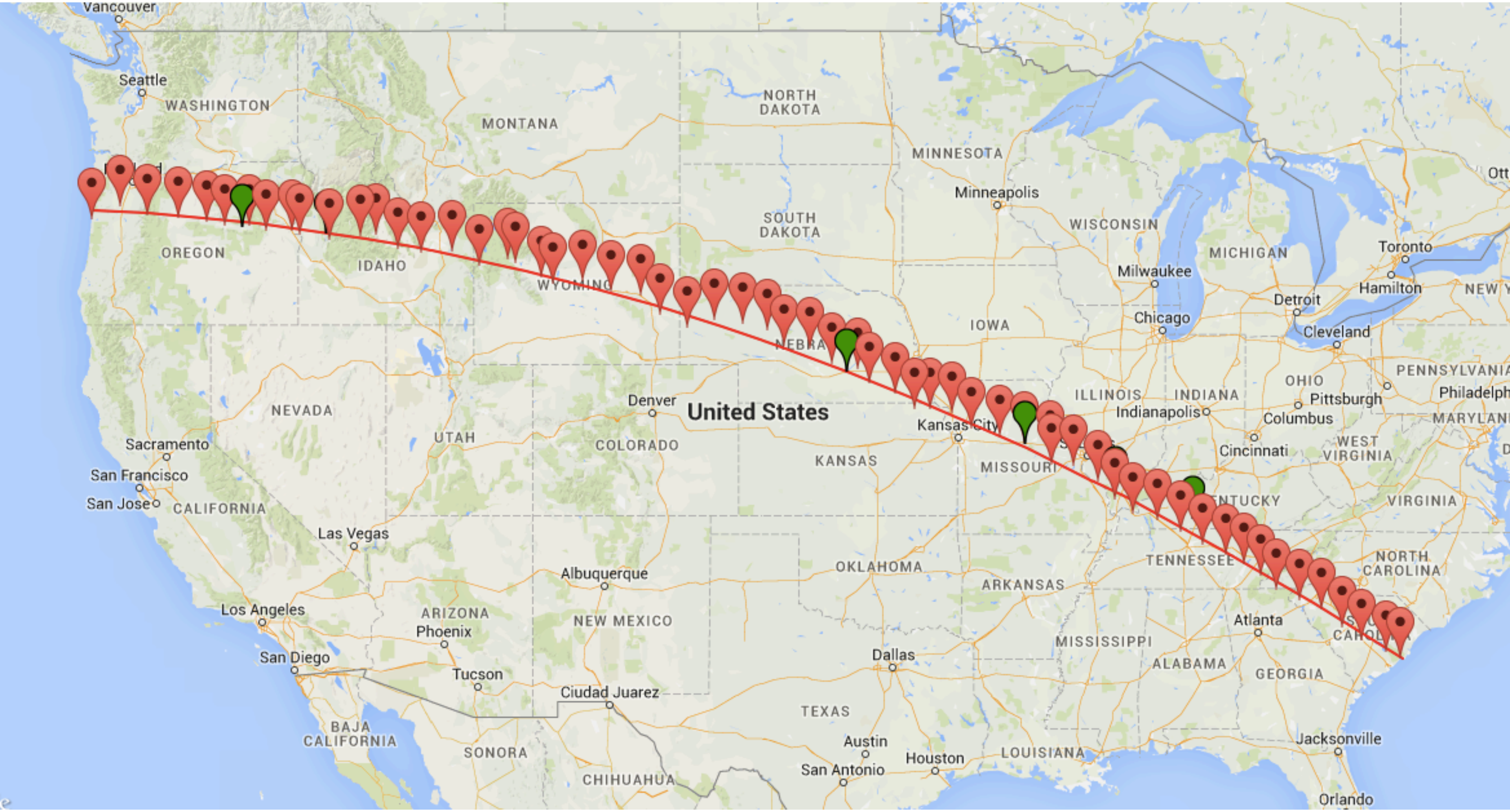
- **Image Coronal Evolution at 2017 Eclipse**

CATE Eclipse Experiment

- **An 80-mm Refractor**
  - **Corporate Sponsorship**
- **Equatorial Mount & Drive**
- **Point Grey High-res. CMOS Camera**
- **Solar Filter for Partial Phases**
- **Laptop & Cell Phones**
  - **GPS Time-tags**
  - **Phone Upload of Video to Cloud**



Eclipse Path & CATE Stations



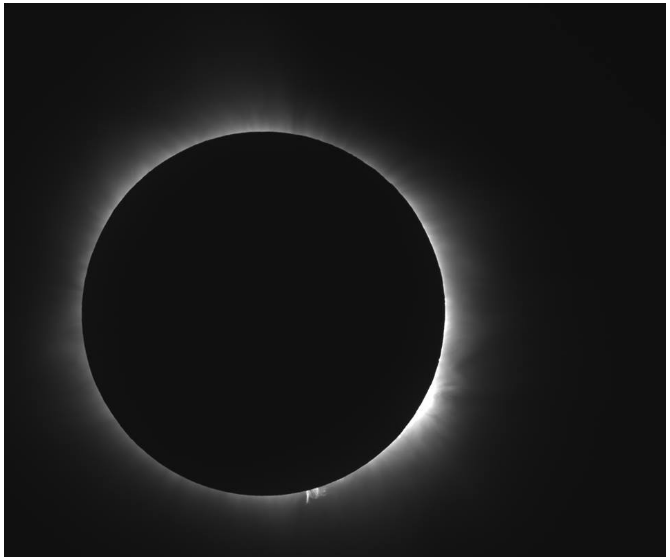
Indonesian Testing 2016

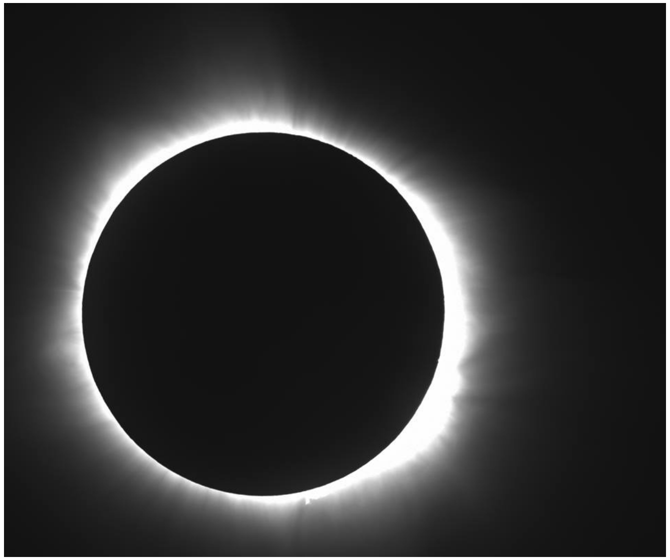
- **Five Prototypes Planned for Deployment for 2016 Indonesia Eclipse**

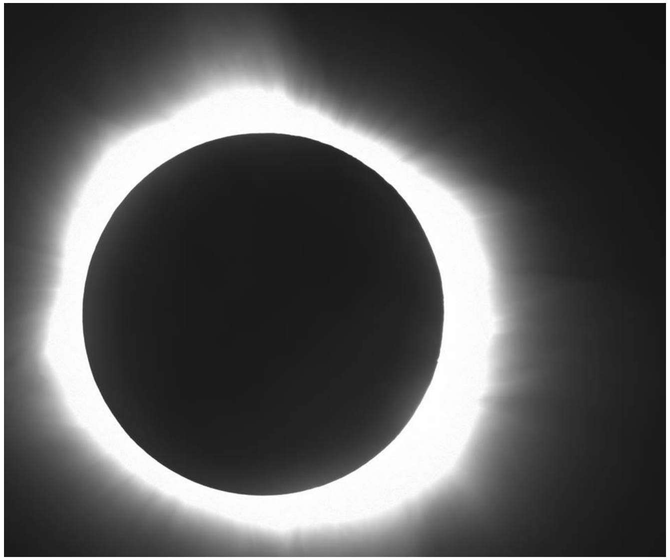
- **Hardware Testing**
  - **Telescopes & Video Cameras**
  - **Calibrations**
  - **Matlab Scripting**
- **Faculty/Student Coordinator Training**
  - **Telescope Assembly**
- **Data Analysis Techniques**
  - **Calibrations**
  - **Data Alignment**
  - **Spatial Filtering**

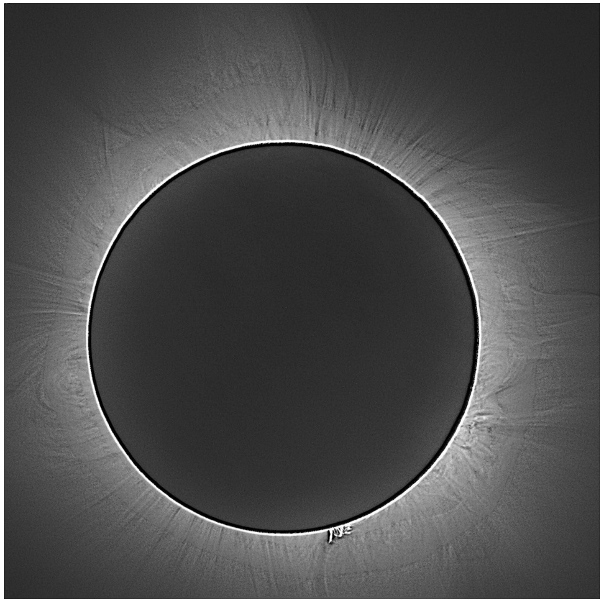
Crescent Sun Just after Totality

CATE SIU Team's Data

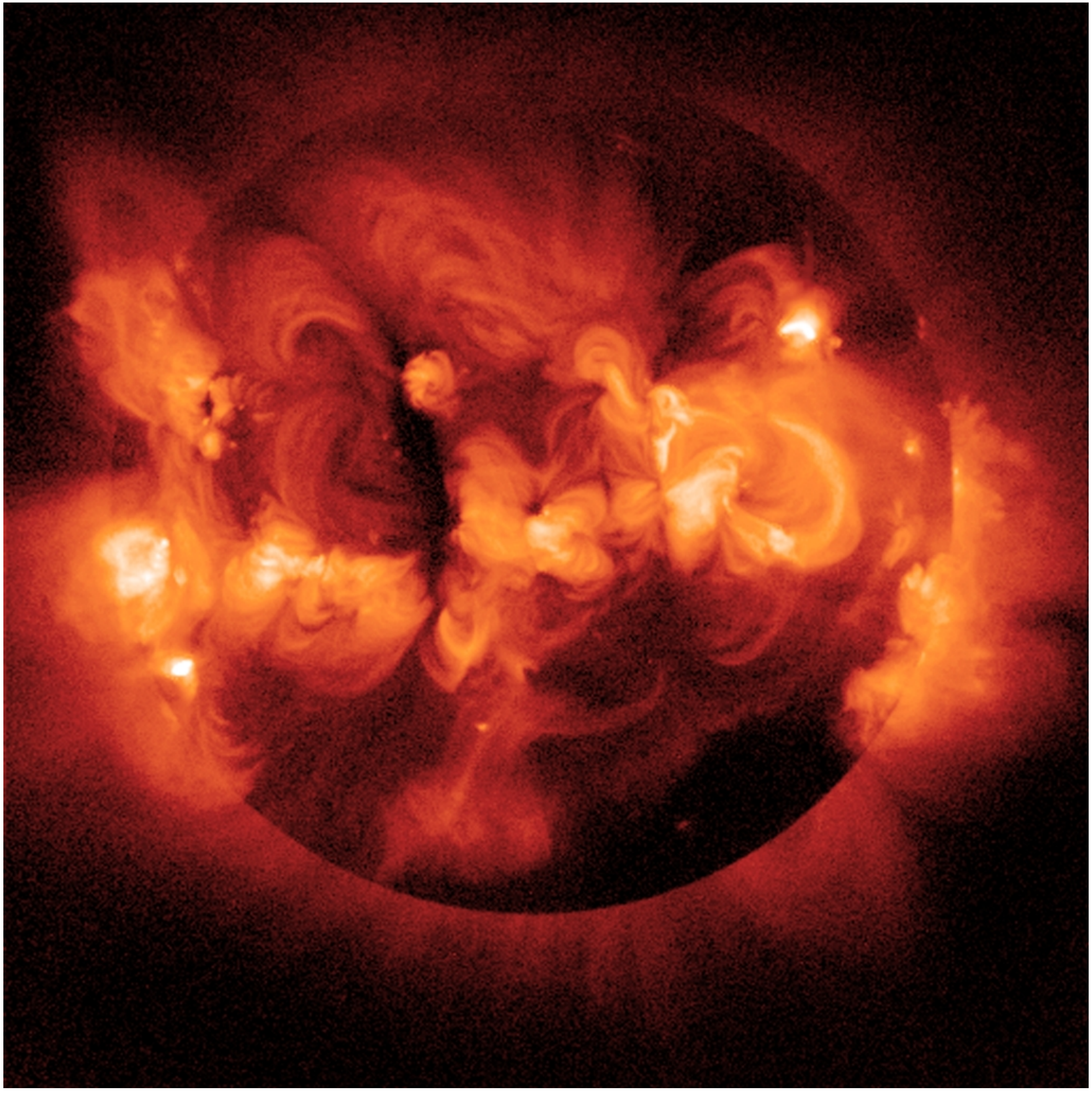






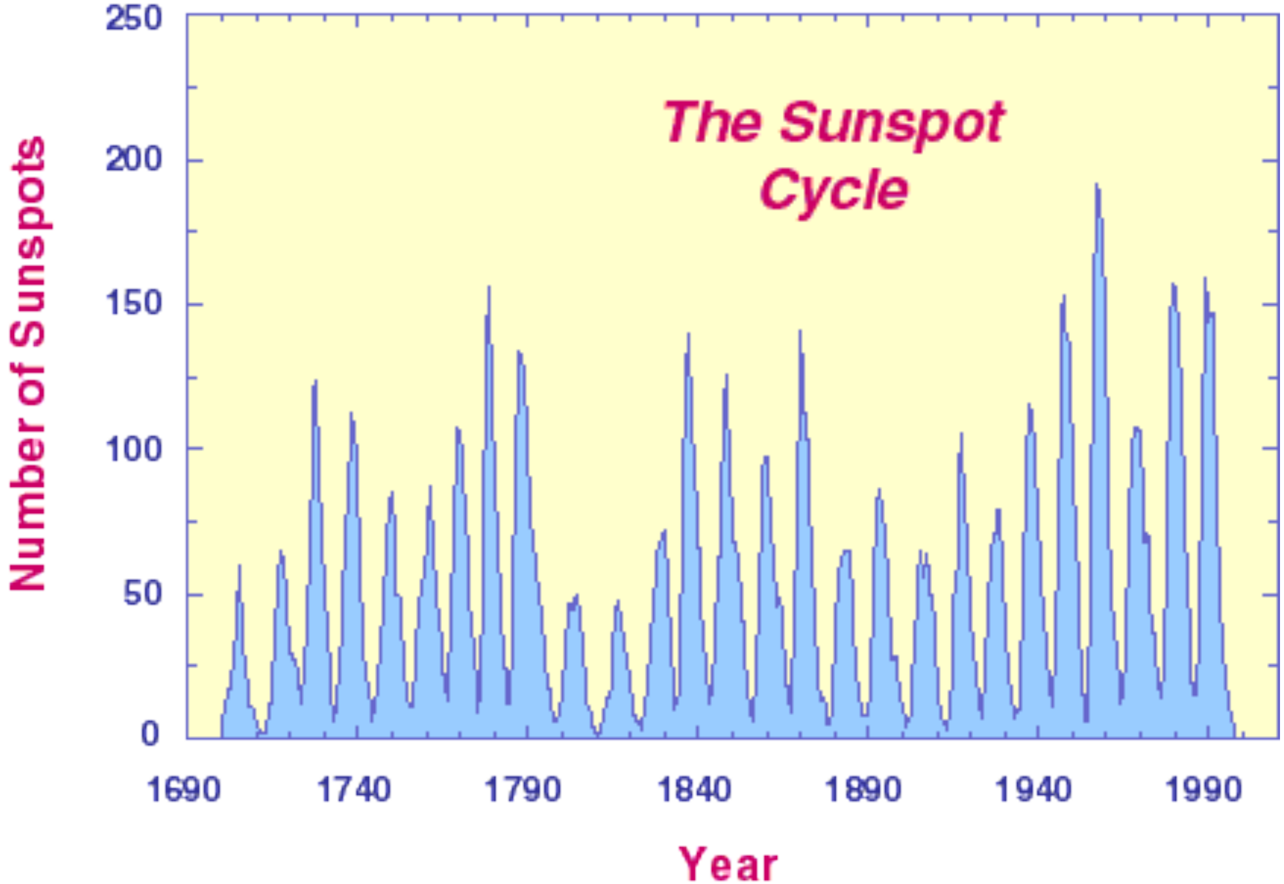


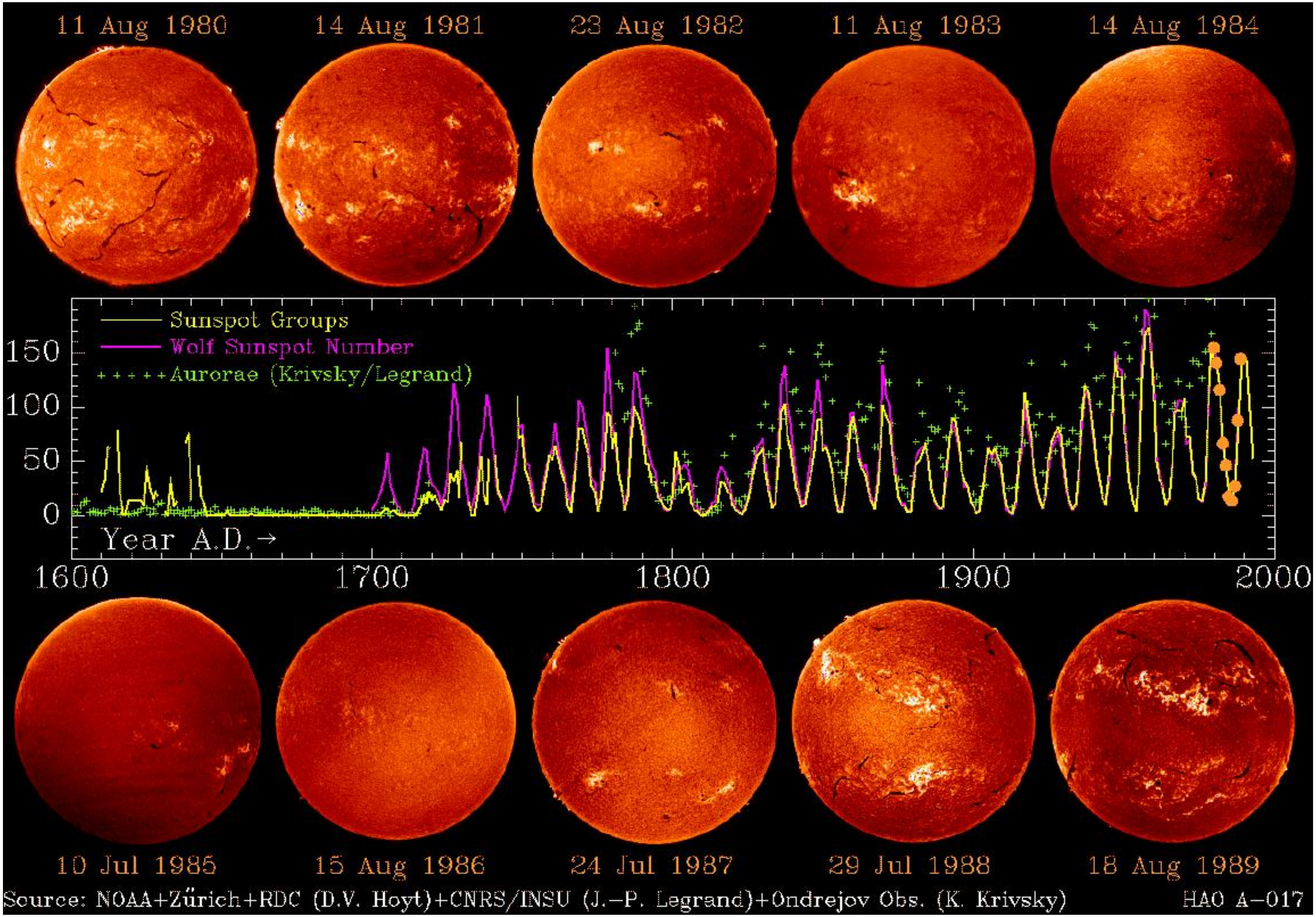
Nice Color Image (What to Expect)



Solar Activity

- Sunspot numbers regularly increase and fall with an 11 year cycle
- High resolution spectroscopy of sunspots reveals “Zeeman splitting”
  - Zeeman splitting results from strong magnetic fields





11 Aug 1980
14 Aug 1981
23 Aug 1982
11 Aug 1983
14 Aug 1984
Sunspot Groups
Wolf Sunspot Number
Aurorae (Krivsky/Legrand)
150
100
50
0
Year A.D.→
1600
1700
1800
1900
2000
10 Jul 1985
15 Aug 1986
24 Jul 1987
29 Jul 1988
18 Aug 1989
Source: NOAA+Zürich+RDC (D.V. Hoyt)+CNRS/INSU (J.-P. Legrand)+Ondrejov Obs. (K. Krivsky)
HAO A-017

Solar Wind

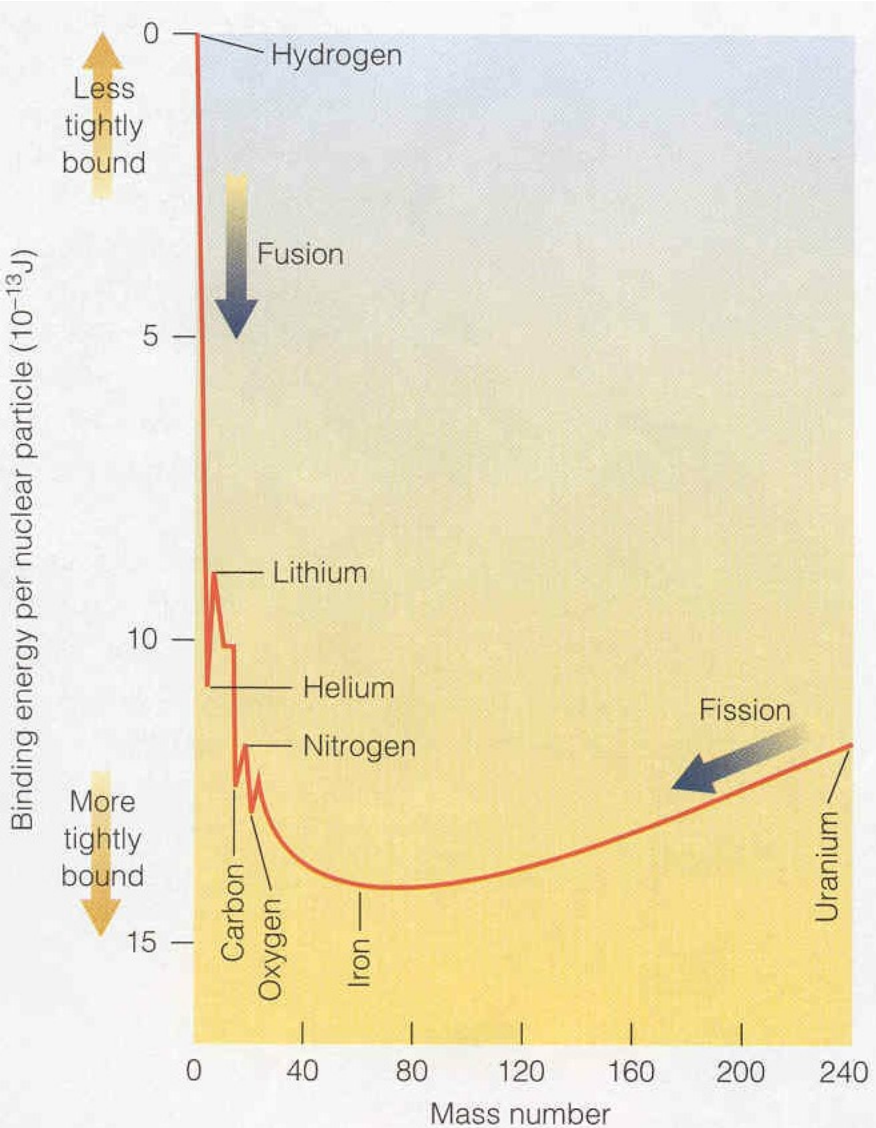
- **Coronal Mass Ejections**
  - Ejection of mass from the Sun
  - Hot ionized gas (plasma) expands
  - Result is the "solar wind"
- **The Solar Wind**
  - Charged particles (ions) that fill the solar system as the gas expands
  - Earth protected by magnetosphere
  - Origin of Aurora
  - May influence Earth's weather

Nuclear forces and nuclear energy

- What holds protons in the nuclei of atoms?
  - Coulomb (electric) repulsion should make protons fly apart
    - They are packed so close together – must have very strong force to hold them
  - Nuclear "Strong force" attracts nucleons (protons, neutrons)

- Why doesn't strong force collapse all atoms into a giant nucleus?
  - Nuclear Strong force is very short range
    - falls off quickly after a few proton radii
  - Coulomb force is long range
    - falling off only as $1/r^2$
- At large distances only coulomb force is important ⇒ repulsion
- Nuclear Strong Force important only close together
  - Requires very high speed (high temperature) collision for fusion

The Curve of Binding Energy



From our text: Horizons, by Seeds

- If you keep adding protons to a nucleus?
  - Coulomb repulsion continues to increase
    - new proton feels repulsion from all other protons
  - Strong force attraction reaches limit
    - new proton can't feel attraction from protons on far side of a big nucleus

- Gain energy only up to point where Coulomb repulsion outweighs strong force attraction.
- Most "stable" nucleus is ^{56}Fe (26 protons, 30 neutrons, 56 total)

- Release energy by fusion of light nuclei to make heaver ones– up to ^{56}Fe
- Release energy by fission of heavy nuclei to make lighter ones – down to ^{56}Fe

The Role of the Nuclear "Weak Force"

- Why can't we keep adding neutrons rather than protons?
  - They feel strong force attraction – with no Coulomb repulsion.
  - You should be able to get lots of energy by adding neutrons.

- Nuclear Weak Force can (slowly) convert protons to neutrons and back.
  - The reactions involve an electron or "positron" to keep charges balanced.
  - The reactions produce an almost massless particle called a neutrino.

  - $p^+ + e^- \Leftrightarrow n + \nu$

    p^+ is proton
    e^- is electron
    n is neutron
    ν is neutrino

  - $p^+ \Leftrightarrow n + e^+ + \nu$

    e^+ is positron = antiparticle of electron

    If this second reaction happens then the positron annihilates the next electron it encounters, thereby producing the equivalent of the first reaction.

- The weak force likes to keep ~equal protons and neutrons in a nucleus.
- The proton repulsion tips the balance towards slightly more neutrons in big nuclei.

The four fundamental forces

- **Gravity** — Dominates on astronomical scales
- **Electromagnetic** — Holds atoms together: Chemistry
- **Strong force** — Holds nuclei together: Nuclear energy
- **Weak force** — $n \Leftrightarrow p^+, e^-$ Radioactive decay

  (will also play critical role in solar fusion)

Fusion in the sun I.

- Have lots of hydrogen (p^+ and e^-) – what can we make from it?

- If ^{2}He (2 protons, 0 neutrons) were stable, fusion would be "easy"
  - Run two protons into each other at fast enough to overcome Coulomb repulsion
  - Once they get close enough strong force takes over, and holds them as nucleus.

Fusion in the sun II.

- "Unfortunately" ^{2}He isn't stable
  - To get stable He need to add one or two neutrons to:
    - Increase Strong Force, without increasing Coulomb force
  - Not really "unfortunate" – If ^{2}He were stable:
    - Sun would burn energy way too fast – and would have gone out by now

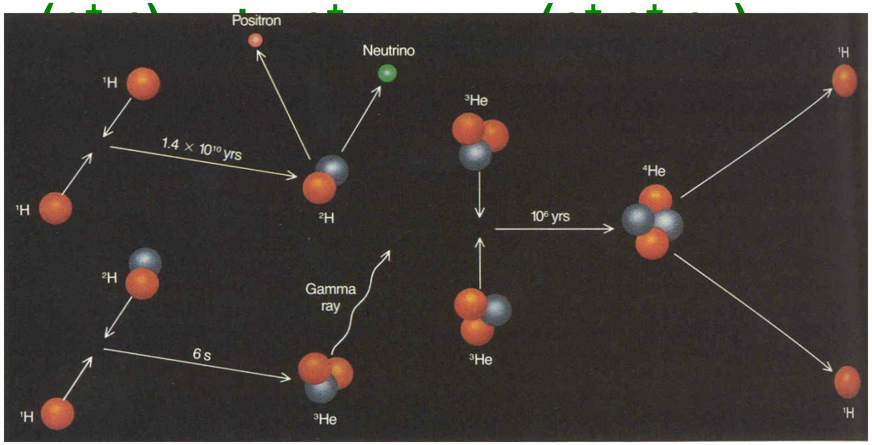
- Weak force converts proton to neutron–fusion will be slow
  - In solar fusion no excess neutrons lying around
  - Hydrogen bombs use deuterium: $^{2}H = (p^{+}\ n)$ or tritium: $^{3}H = (p^{+}\ n\ n)$ to provide it

The Proton-Proton chain

- The first step is slow because it relies on two rare events happening simultaneously
  - Two protons collide with enough energy to overcome the Coulomb barrier
  - While they are close the weak force turns one proton into a neutron
    - The resulting combination of a proton and a neutron IS a stable nucleus
  - $^{1}H + {}^{1}H \rightarrow {}^{2}H + e^{+} + \nu$ $p^{+} + p^{+} \rightarrow (p^{+}\, n) + e^{+} + \nu$

- The next two steps go quickly because they rely only on the strong force
  - $^{2}H + {}^{1}H \rightarrow {}^{3}H$
  - $^{3}H + {}^{3}H \rightarrow {}^{4}He + {}^{1}H + {}^{1}H$
    n n) + p^{+} + p^{+}

- The net effect is $4\ {}^{1}H \rightarrow {}^{4}He$



From Realm of the Universe, by Abell et al.

Energy Released?

- Could work it out "classically" by strength of forces
  - Classical mechanics doesn't work at this scale – Need quantum mechanics
  - Strength of nuclear forces not originally known

- Use $E=mc^2$ to do accounting

  - Mass is a measure of the energy stored in a system
  - Loss of mass from a system means release of energy from that system

- Compare mass of four ^1H to mass of one ^4He
  - 6.693×10^{-27} kg - 6.645×10^{-27} kg = 0.048×10^{-27} kg mass lost in reaction
  - $E = mc^2 = 0.048 \times 10^{-27}$ kg $\times (3 \times 10^8$ m/s$)^2 = 0.43 \times 10^{-11}$ kg m^2/s^2 = 0.43×10^{-11} J

    (note == a Joule is just shorthand for kg m^2/s^2)

  - So 4.3×10^{-12} J of energy released from each reaction
    - This is huge compared to chemical energy: 2.2×10^{-18} J to ionize hydrogen

How long will Sun's fuel last?

- **Luminosity of sun: 3.8×10^{26} J/s**
- **H burned rate:** $4 \text{ H atoms / He created} \times \dfrac{3.8 \times 10^{26} \text{ J/s}}{4.3 \times 10^{-12} \text{ J / He created}} = 3.5 \times 10^{38} \text{ H atoms / s}$
- **H atoms available:** $\approx \dfrac{M_{\text{Sun}}}{m_{\text{H}}} = \dfrac{2.0 \times 10^{30} \text{ kg}}{1.67 \times 10^{-27} \text{ kg/ H atom}} = 1.2 \times 10^{57} \text{ H atoms}$
- **Lifetime:**

$$\frac{1.2\times10^{57} \text{ H atoms}}{3.5\times10^{38} \text{ H atoms / s}} = 3.4\times10^{18} \text{ s} = \frac{3.4\times10^{18} \text{ s}}{3.14\times10^{7} \text{ s/yr}} = 1.1\times10^{11} \text{ yr} = 110 \text{ billion years}$$

- **In reality not all the atoms we start with are H, and only those near the center are available for fusion. The structure of the sun will change when about 10% of the above total have been used, so after about 10 billion years.**

Testing the solar fusion model

- Does lifetime of sun make sense?
  - Oldest rocks on earth ~4 billion years old
  - Oldest rocks in meteorites ~4.5 billion years old
- Other stars with higher/lower luminosity
  - Causes for different luminosity
  - Lifetimes of those stars
- Look for neutrinos from fusion
  - Complicated story – due to neutrino properties
  - Example of how astronomy presents "extreme" conditions

Neutrinos

- Generated by "weak" force during $p^+ \rightarrow n + e^+ + \nu$
- "Massless" particles which interact poorly with matter
  - In that first respect, similar to photons
  - Can pass through sun without being absorbed
  - Same property makes them very hard to detect

- Davis experiment at Homestake Mine in Black Hills
  - 100,000 gallon tank of C_2Cl_4 dry cleaning fluid
  - in Cl nuclei $n + \nu \rightarrow p^+ + e^-$ so Cl (Z=17) becomes Ar (Z=18)
  - Physically separate out the Ar, then wait for it to radioactively decay
  - Saw only 1/3 the neutrinos predicted

Missing Neutrino Problem

- **Lack of solar neutrinos confirmed by Kamiokande II detector in Japan. (Using different detection method)**

- **Possible explanation in terms of Neutrino physics**
  - **3 different types of Neutrinos:**
    - **electron, muon, and tau neutrinos**
    - **Sun generates and Cl detectors see only electron neutrinos**
    - **Can electron neutrinos can change to another type on way here?**
  - **These "neutrino oscillations" are possible if neutrino has non-zero mass**

  - **Kamiokande II evidence of muon neutrinos becoming electron ones**

- **Read "Window on Science 7-2" on "scientific faith"**

- **Neutrino mass may have implications for "cosmology"**
- **Neutrinos also used to study supernova 1987A**

Chapter 7 Homework

Chapter 7: # 7.2, 7.3, 7.4, 7.6, 7.8

Due Tues. April 12