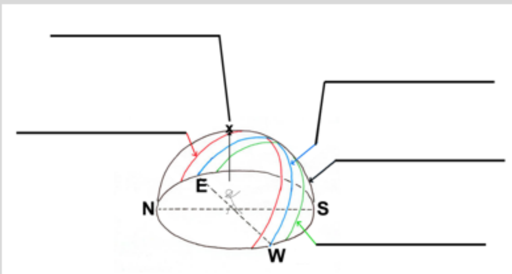
Logistical notes

- About the exam!
  - I finished grading the multiple choice, true/false, fill in the blank, and labeling
  - I'm sorry for this figure and associated blanks- it was not clear at all what I was going for, and that's my bad



- General stats:
  - 16 multiple choice (1pt each)
  - 1 column matching (2pts)
  - 4 true/false (1pt each)
  - 4 fill in the blank (1pt each)
  - 3 labeling/drawing (2pts each)
  - 4 short answer (3pts each)

Logistical notes

- Once I'm done grading, I will return the tests to you. Let me know what you would like to do-you can either:
  - Opt for a general curve: I'll weight the section you did best on the most toward your grade, or
  - Re-do the questions you missed, explaining enough to show me you understand the new answer you're changing to, for up to ¾ credit back per question.
    - Open book, open note, work with others
    - Get test back 10/2, return to me after Fall break, no later than class on 10/11
    - No doing the bonus questions in the re-do; if you didn't try them the day of the test, they're off the table
    - No curve if you opt for redo option

16 + 2 + 4 + 4 + 6 + 12

1 pt options: 16 + 4 + 4 = 24

2 pt options: 2 + 6 = 8

3 pt options: 12

Total possible: 44

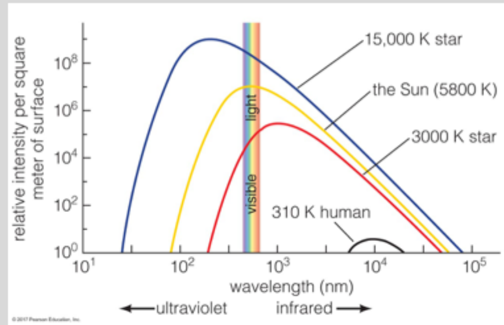
1 pointers 24/ 44 or 55% of final grade

2 pointers 8/44 or 18% of final grade

3 pointers 12/44 or 27% of final grade

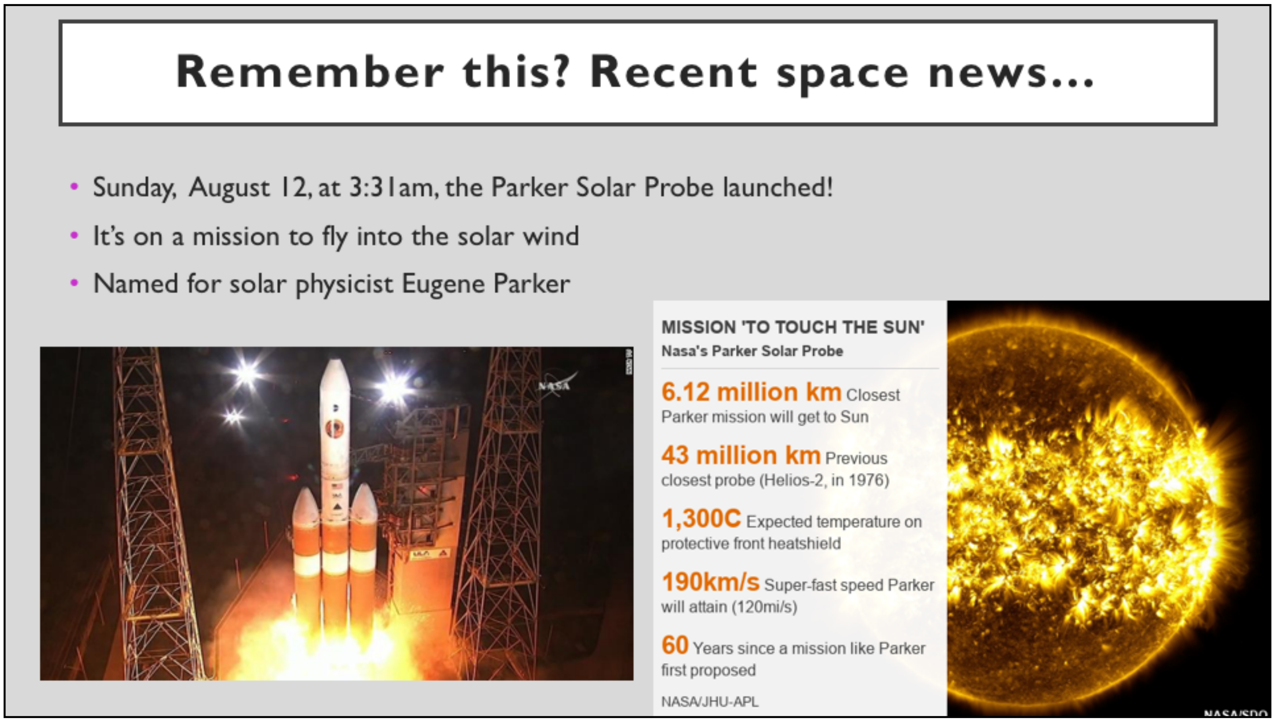
So say you got

A couple last things about Chapter 5…



- Homework is due tonight, 11:59pm
- Two concepts I didn't cover that are on the homework:
  - Stefan-Boltzmann law (math insight 5.2, p155)
    - Power per square meter of surface, $P/A = \sigma T^4$
  - Mass-energy relationship (chapter 4, p122)
    - $E=mc^2$
    - Book describes mass itself as a form of potential energy
    - Einstein found $E=mc^2$ while making framework for special relativity
    - Experimentally, we've seen that indeed—light can be converted into mass, and mass into energy
    - In stars, we use this to understand why they shine

http://www.emc2-explained.info/Emc2/Einstein_Equation-MP3.mp3



Throwback to the very first day of this class

I'll try to start every lecture with a recent space news story

http://parkersolarprobe.jhuapl.edu

https://www.cnn.com/2018/08/10/us/parker-solar-probe-launch-nasa/index.html

https://www.bbc.com/news/science-environment-45058911

3.8 million miles, or 8.8 solar radii (that's really, really close, y'all)

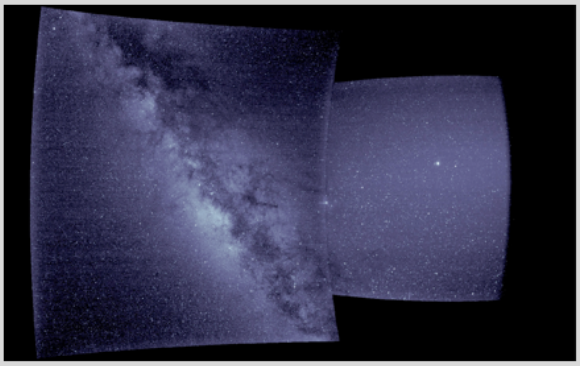
2400 F

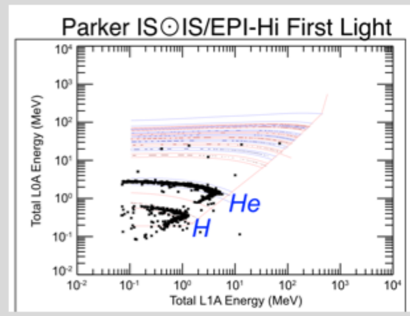
432,000 mph

Bonus: why is it so hard to crash stuff into the sun?
https://www.popularmechanics.com/space/rockets/a21896/why-we-cant-just-launch-waste-into-the-sun/

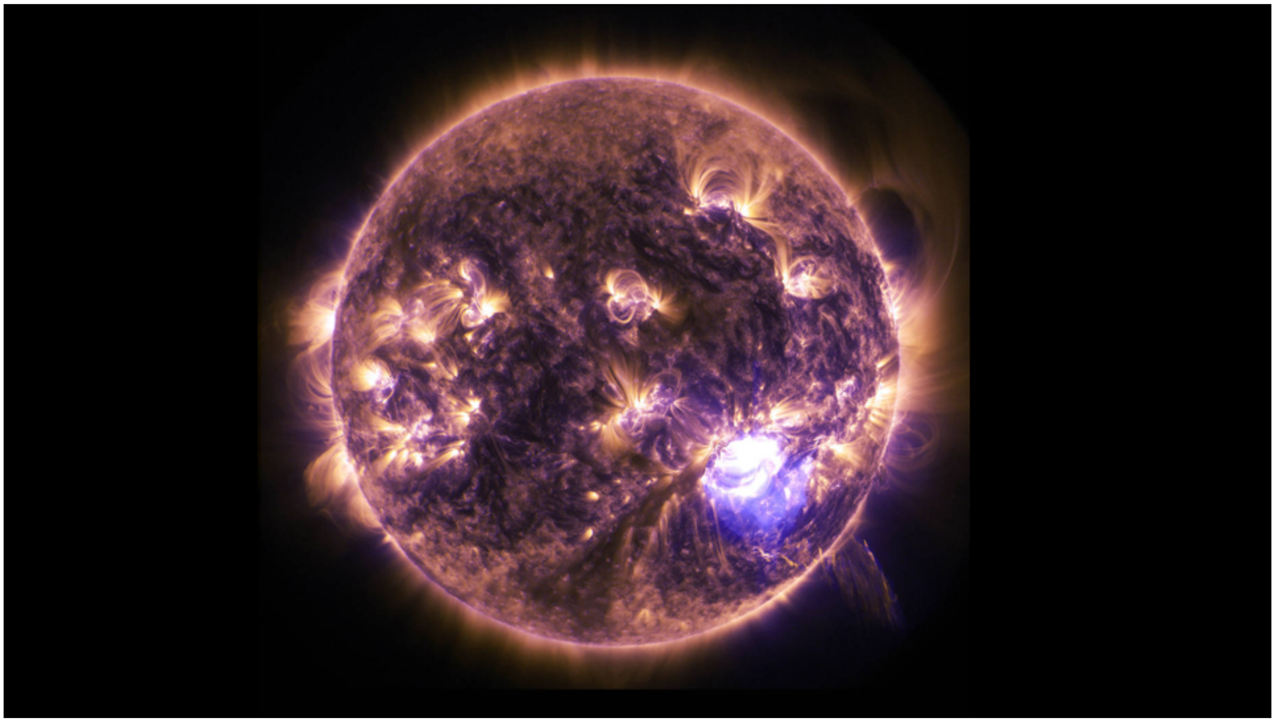
Parker Solar Probe

- Has started testing cameras and sensors!
- First close approach to the Sun will be November 2018





https://www.nasa.gov/content/holiday-lights-on-the-sun-imagery-of-a-solar-flare



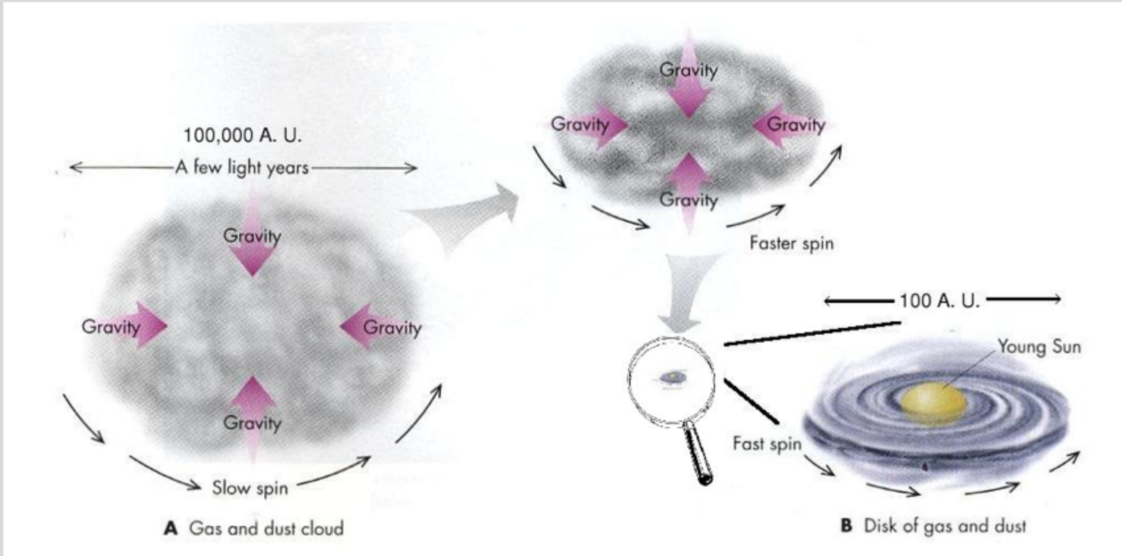
https://www.nasa.gov/content/holiday-lights-on-the-sun-imagery-of-a-solar-flare

Why does the Sun shine?

- Ancient view: a hot, glowing rock of the size of Massachusetts
- Early 19th century: cooling or chemical reactions
  - Enough energy for a few thousand years (coal burning: 24 MJ/kg)
- Late 19th century: gravitational contraction
  - Enough energy for ~25 million years
  - But … geology: Earth known to be >25 million years
- 20th century: nuclear fusion ($E=mc^2$)
  - Can shine for ~10 billion years

https://www.ancient-origins.net/ancient-places-africa/art-amarna-akhenaten-and-his-life-under-sun-002587

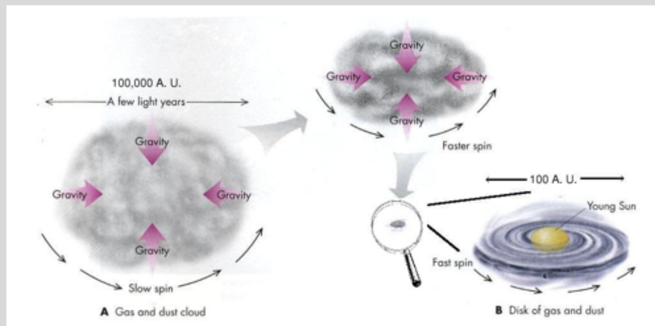
How does fusion start?



Remember this figure that I love so much?

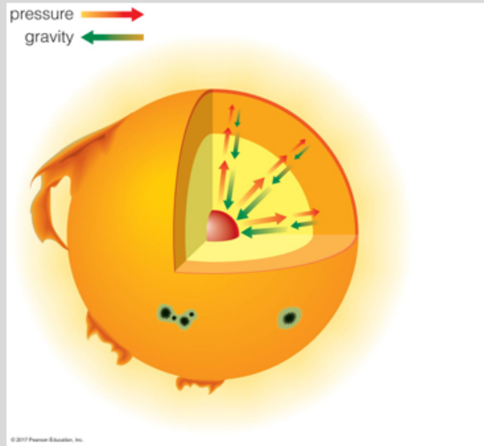
Role of Gravitational Contraction

- Contraction was important in the past and will be in the future
- It has made the Sun's interior hot and dense enough to sustain nuclear fusion
- Fusion brought the Sun into gravitational equilibrium
- When nuclear fuel is exhausted, internal pressure will drop, and contraction will begin again



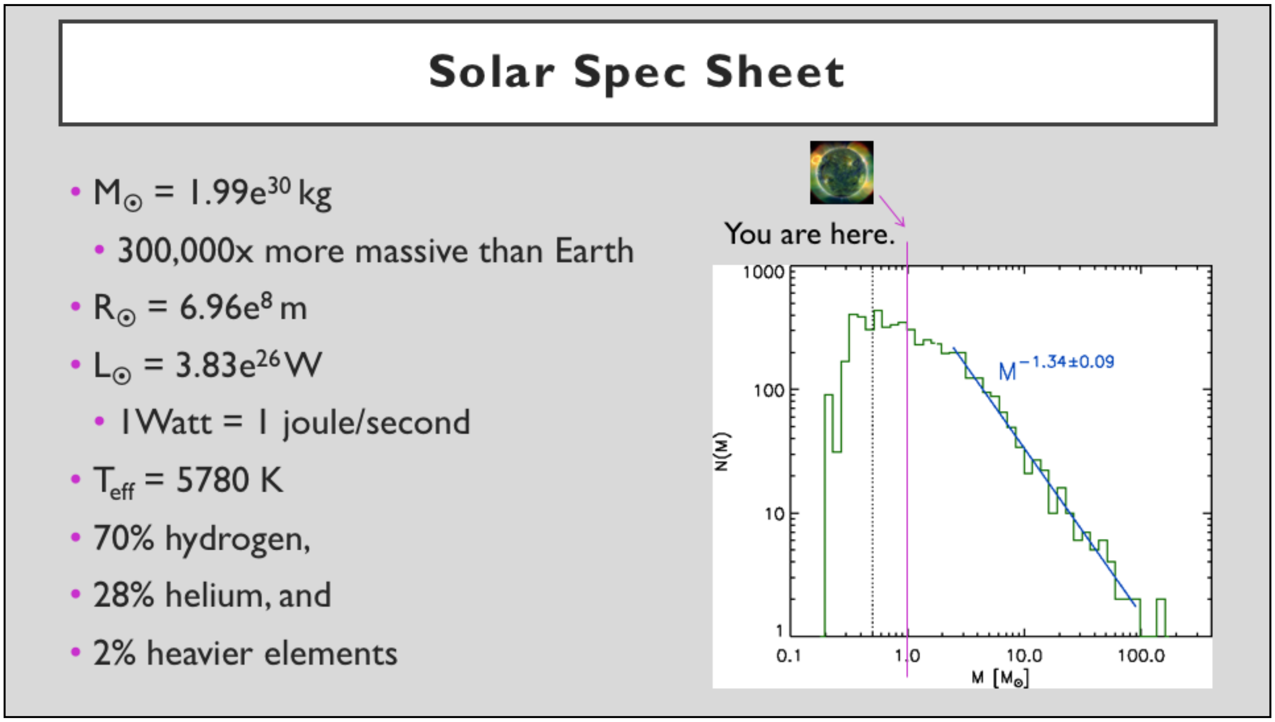
Current state of the Sun: equilibrium

- The Sun's size is stable, maintained by a balance between the force of gravity and gas pressure.
- This balance is called hydrostatic or gravitational equilibrium.
- As you go deeper into the Sun, there is more mass up above, so pressure and temperature increase toward the core of the Sun



Energy balance

- The Sun is fusing to produce energy, but it's also shining, which loses energy
- Since we observe the Sun in equilibrium, there must be balance between energy created and energy lost
  - If more were radiated than generated, fusion wouldn't be able to keep contraction from starting again
- Fusion rate is highly temperature dependent; the two parameters are proportional to each other. What would happen if we could independently adjust the core temperature?
  - Increase in core temperature would increase fusion rate. Energy generated would increase outward pressure; the core would expand and cool until balance reached with inward force of gravity
  - Decrease in core temperature would decrease fusion rate, gravitational pressure would cause the Sun to shrink until equilibrium reached



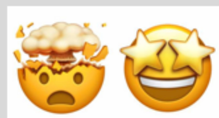
Sir Isaac Newton was the first to estimate the mass of the Sun by using the parallax to derive a mass ratio of the Sun to the Earth. The Sun = 332946 Earth masses.

Where does the Sun fit, property-wise, into the grand scheme of things? Turns out, it's pretty average.

http://www.astro.rug.nl/~etolstoy/ACTUEELONDERZOEK/JAAR2005/rob/salpeter%20imf.bmp

Hidden figure: Cecilia Payne Gaposhkin

- Lived May 10, 1900-December 7, 1979
- Born in England, went to Cambridge for college but didn't get a degree: Cambridge would not confer earned degrees to women until 1948
- Inspired to study astronomy by a lecture by Arthur Eddington
  - Eddington made eclipse observations to confirm Einstein's general theory of relativity
  - Payne said, "The result was a complete transformation of my world picture. My world had been so shaken that I experienced something very like a nervous breakdown."

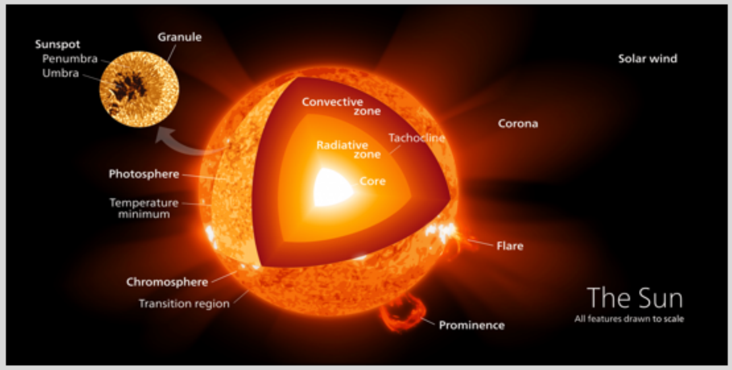


Cecilia Payne Gaposhkin

- Denied rightly earned degree, Payne went to the US to work with Harlow Shapley who convinced her to write a PhD thesis at Radcliffe College (womens college later absorbed by Harvard)
- "Stellar Atmospheres, A Contribution to the Observational Study of High Termperature in the Reversing Layers of Stars"
  - Her thesis often called "the most brilliant Ph.D. thesis ever written in astronomy"
  - Related the spectral classes of stars to their actual temperatures
  - Related the strengths of absorption lines to temperatures rather than abundances of elements
  - Realized that while Sun and Earth are comparable in metal content, Sun has waaayyy more H, He
  - Payne suggested H as most abundant element in the Universe. A prominent astronomer at the time, Henry Norris Russell, said that can't be the case, she changed her thesis but was later found to be right. Russell ended up also realizing she was right, and often gets credit for the discovery.

The Sun's interior structure

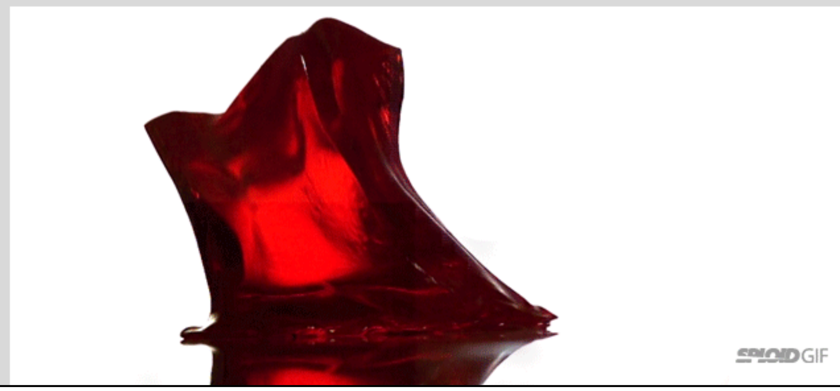
- The core is in the center, where fusion occurs
- In the radiative zone, photons make their way out from the core
- The convection zone is similar to the Earth's mantle: plasma is heated from below and it rises, expands, cools, and falls back down



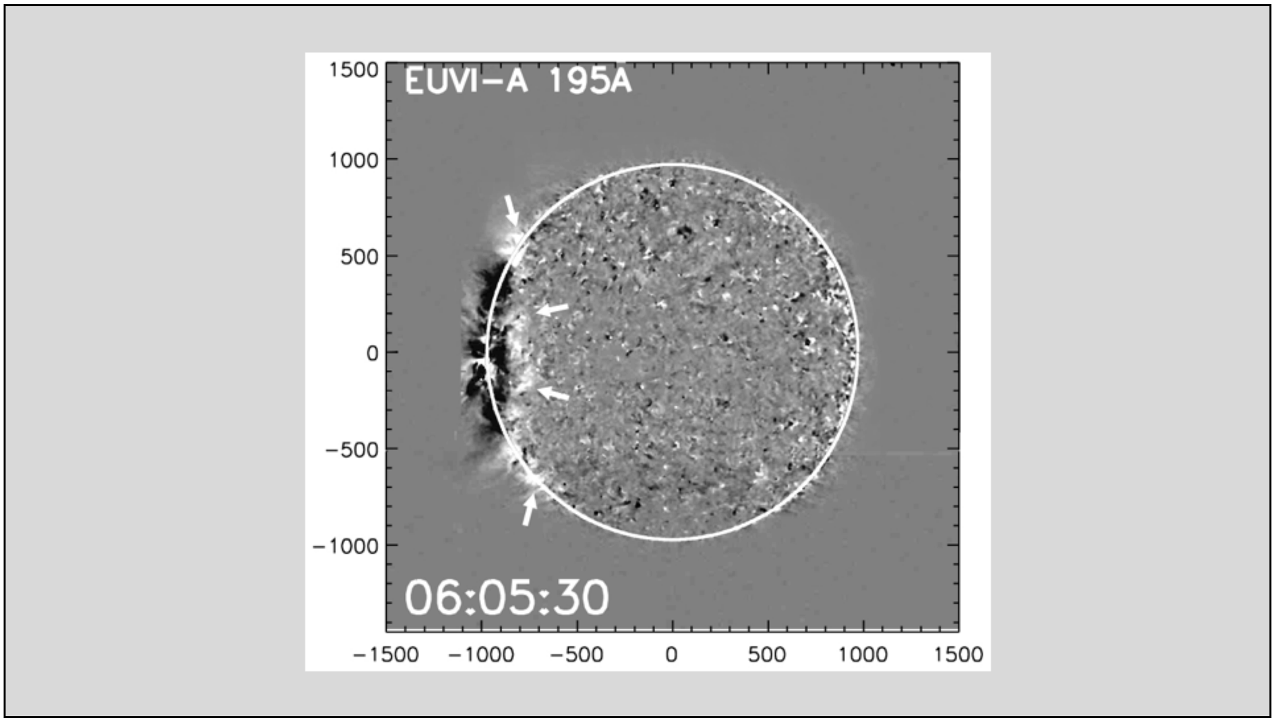
https://phys.org/news/2015-12-sun-energy.html

How do we know what’s inside the Sun?

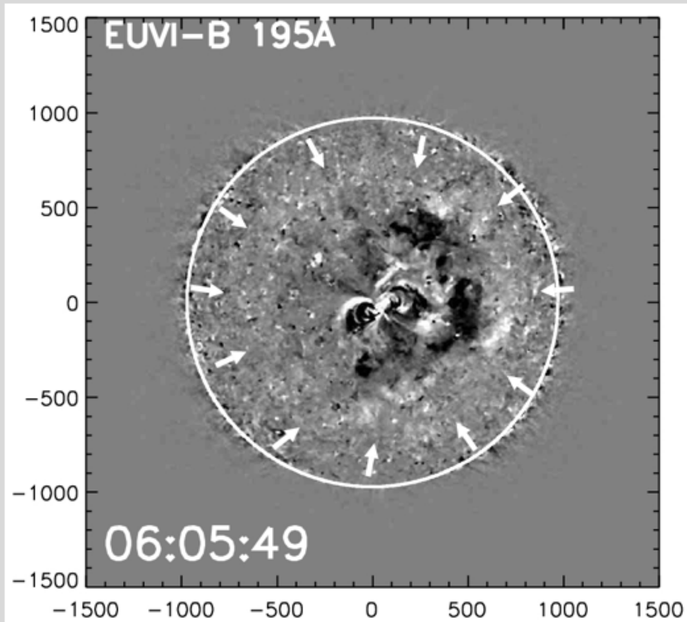
- Observations of “Sunquakes”
  - Helioseismology: seismology of the Sun
- Sun quakes are vibrations of the solar surface due to sound waves (waves of pressure).



Imagine you have a blob of jello. If you poke at it and it wiggles, depending on how fast the wiggle travels, you can guess at how much denser the jello is than water, or air, or some material you know the density of

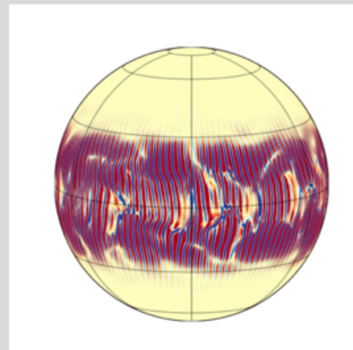


Why is the stellar wind so much stronger? A current theory is that material impacting the stellar surface is creating waves which drive material up into open field lines to be carried away!


EUVI-B 195Å
06:05:49
1500
1000
500
0
−500
−1000
−1500
−1500 −1000 −500 0 500 1000 1500

How do we know what's inside the Sun?

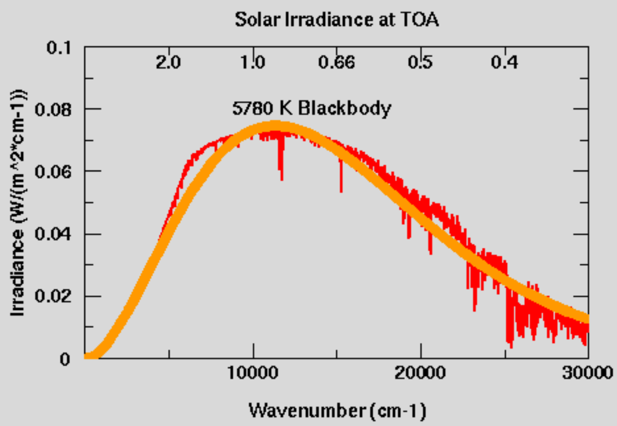
- Observations of "Sunquakes"
  - Helioseismology: seismology of the Sun
- Sun quakes are vibrations of the solar surface due to sound waves (waves of pressure).
- They can be observed by measuring Doppler shifts of light from portions of the surface.
  - Rising portions appear blueshifted, while
  - Falling portions appear redshifted.



Here's an actual simulation I calculated of convection (the rising and falling motions due to heating and cooling) in a star as it's rotating. The color coding is by doppler shift

The solar surface and beyond

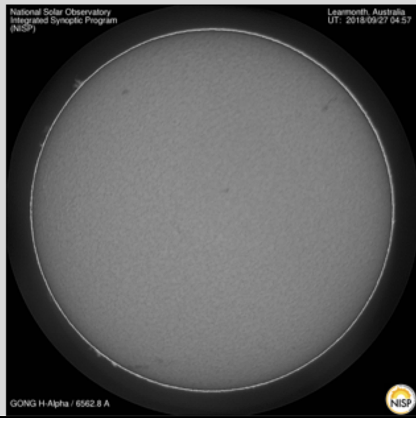
- The photosphere is the visible surface of the Sun, 5800K

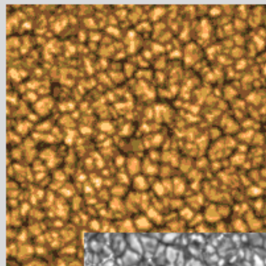


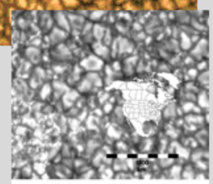
http://ircamera.as.arizona.edu/NatSci102/NatSci/lectures/sun.htm

The solar surface and beyond

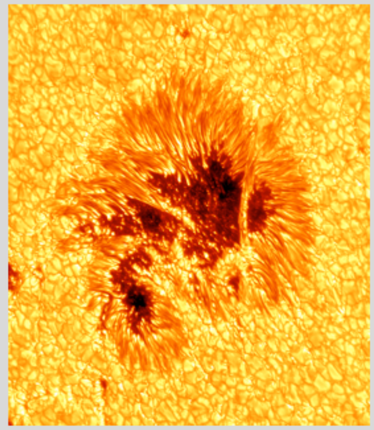
- The photosphere is the visible surface of the Sun
  - Sunspots are often seen on the photosphere; they are colder than their surroundings and appear dark







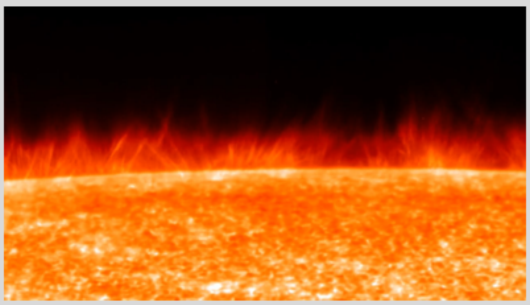
Photospheric granulation, G. Scharmer
Swedish Vacuum Solar Telescope
10 July 1997

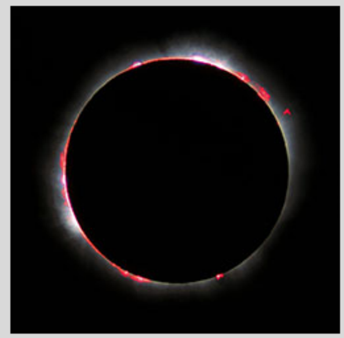


http://halpha.nso.edu

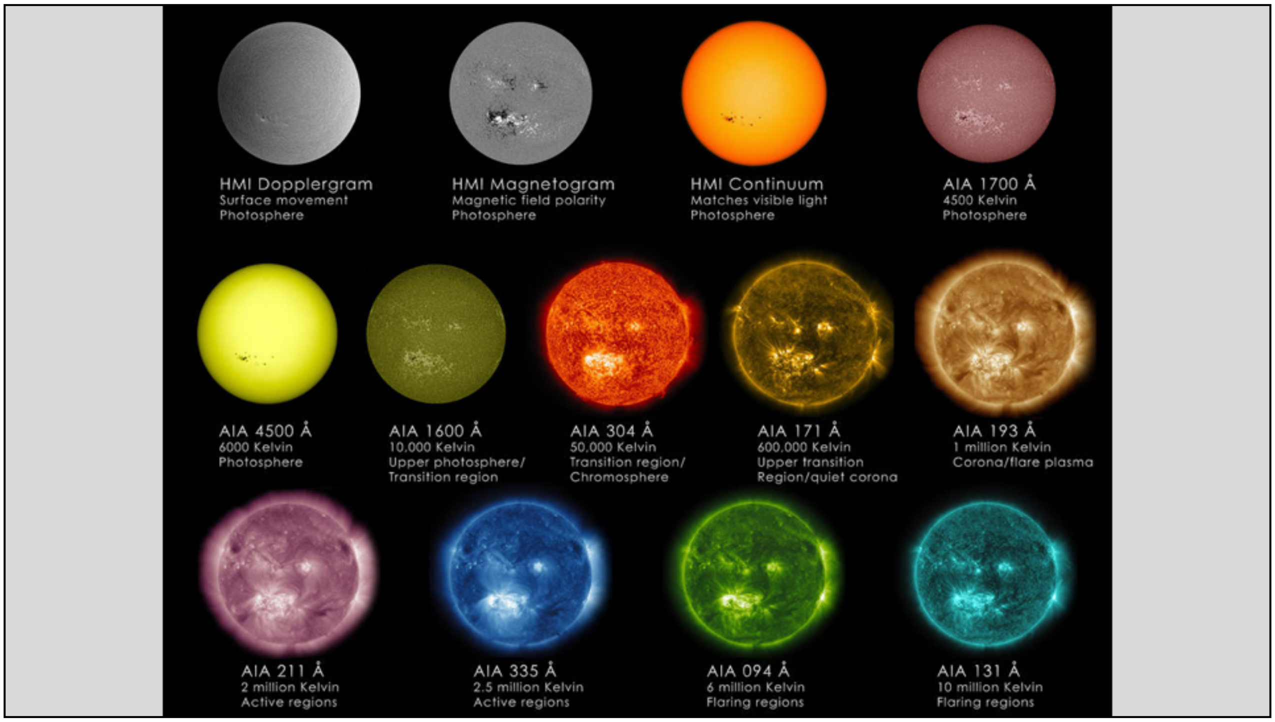
The solar surface and beyond

- The photosphere is the visible surface of the Sun
  - Sunspots are often seen on the photosphere; they are colder than their surroundings and appear dark
- The chromosphere is the next layer up in the solar atmosphere. As temperatures rise, higher energy light is emitted (very blue visible light, near-ultraviolet)





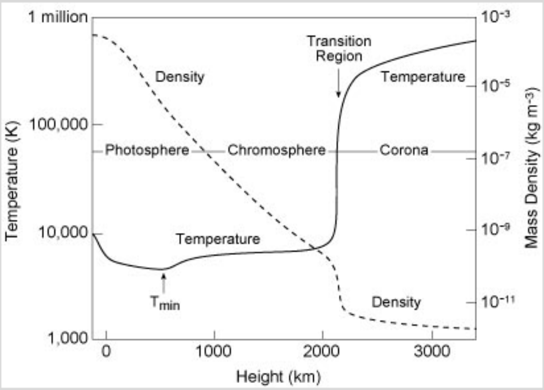
https://eclipse2017.nasa.gov/chromosphere

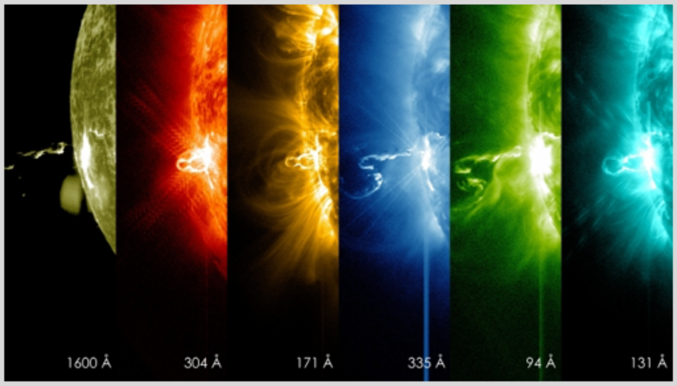


https://www.nasa.gov/content/goddard/how-sdo-sees-the-sun

The solar surface and beyond

- Next region moving up is the transition region, where the Sun's UV radiation is produced (T~10,000 K+).
  - Dramatic shift in temperature and density over a very short distance





https://ase.tufts.edu/cosmos/view_picture.asp?id=174

http://ramosvarela.blogspot.com/2014/02/satelite-detecta-erupcao-no-sol.html

The solar surface and beyond

- Next region moving up is the transition region, where the Sun's UV radiation is produced (T~10,000 K+).
  - Dramatic shift in temperature and density over a very short distance
- The solar corona is the uppermost layer of the atmosphere, which extends up to a few million kilometers and has a temperature of ~1 million K

The solar surface and beyond

- Next regio oduced (T~10,000
  - Dramati
- The solar few million kilometers

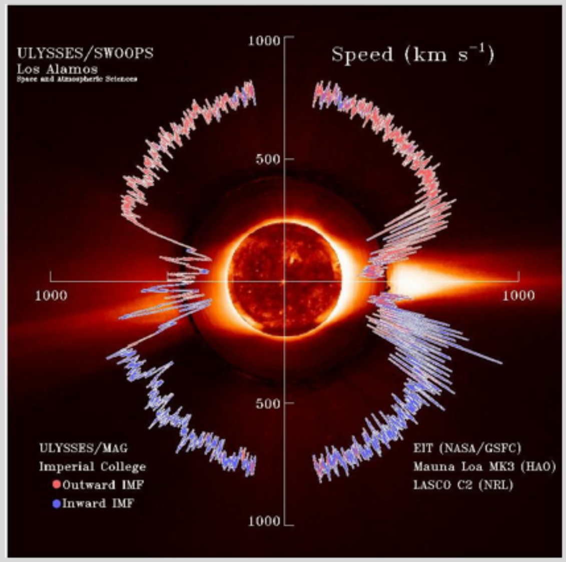
http://www.astropix.com/eclipse/2017_Total_Solar_Eclipse_HDR_Corona.html

The solar surface and beyond

- Next region moving up is the transition region, where the Sun's UV radiation is produced (T~10,000 K+).
  - Dramatic shift in temperature and density over a very short distance
- The solar corona is the uppermost layer of the atmosphere, which extends up to a few million kilometers and has a temperature of ~1 million K
- The solar wind extends away from the Sun from there; it is a stream of photons, ions, and subatomic particles into the solar system

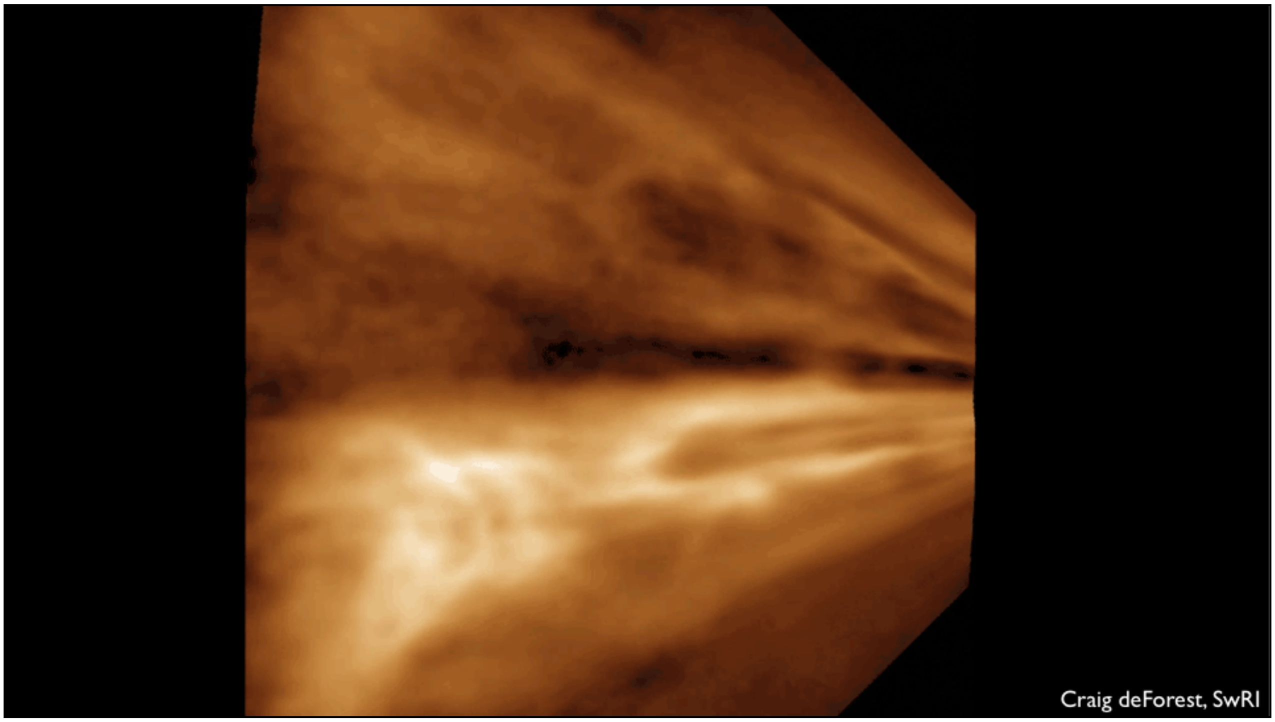
Solar Wind

- The solar wind is not uniform.
- It is faster in coronal holes, and slower over streamers.
- Streamers are often associated with prominences, which lie at the streamers' base.
- Episodic matter outbursts, called coronal mass ejections, produce bubbles of plasma which joins slower solar wind particles and accelerate some of them to dangerously high energies.



https://solarscience.msfc.nasa.gov/SolarWind.shtml

There are also spacecraft that hang out by Earth and measure ions in the solar wind

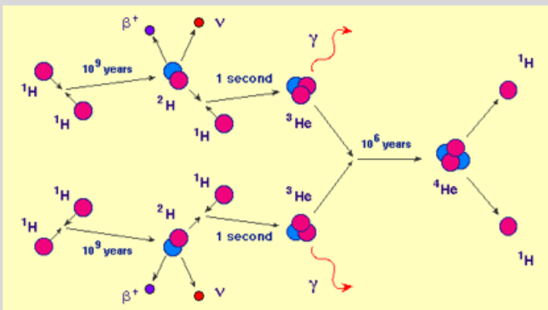


https://www.nasa.gov/feature/goddard/2016/images-from-sun-s-edge-reveal-origins-of-solar-wind

https://www.nasa.gov/sites/default/files/thumbnails/image/data2.gif

Hydrogen Fusion in the Sun

Nuclear fusion is the process of combining nuclei to make a nucleus with a greater number of protons and neutrons



The main nuclear reaction going on inside the Sun is fusion of hydrogen into helium or the proton-proton chain.

1. Two protons fuse to make a deuterium nucleus (1 p+, 1 n0). This happens twice
2. The deuterium nucleus and a proton fuse to make a nucleus of helium-3 (2 p+, 1 n0). This also happens twice
3. Two helium-3 nuclei fuse to form helium-4 (2 p+, 2 n0), releasing the two leftover protons

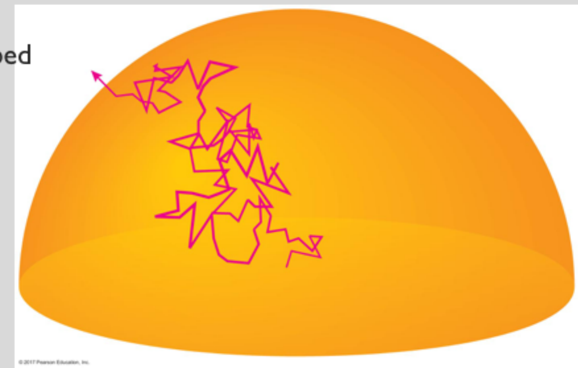
Here I use p+ for proton, n0 for neutron. Sometimes e- for electron

Solar neutrinos

- Neutrinos are subatomic particles, by-products of the solar proton-proton cycle
  - They barely interact with anything
  - Counts of neutrinos coming from the Sun are crucial to test our knowledge about solar physics

Ok, so what happens after fusion?

- Photons "random walk" their way on out of the core
  - Traveling at c, but…
  - High density means lots of electrons to smack into
  - Process takes hundreds of thousands of years
- Once photons reach higher layers, can be absorbed
  - Convection begins

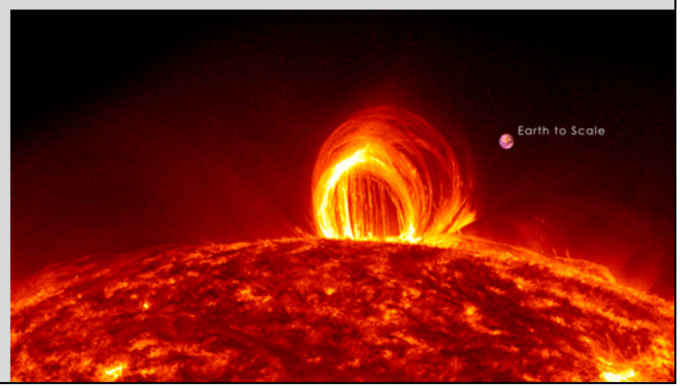


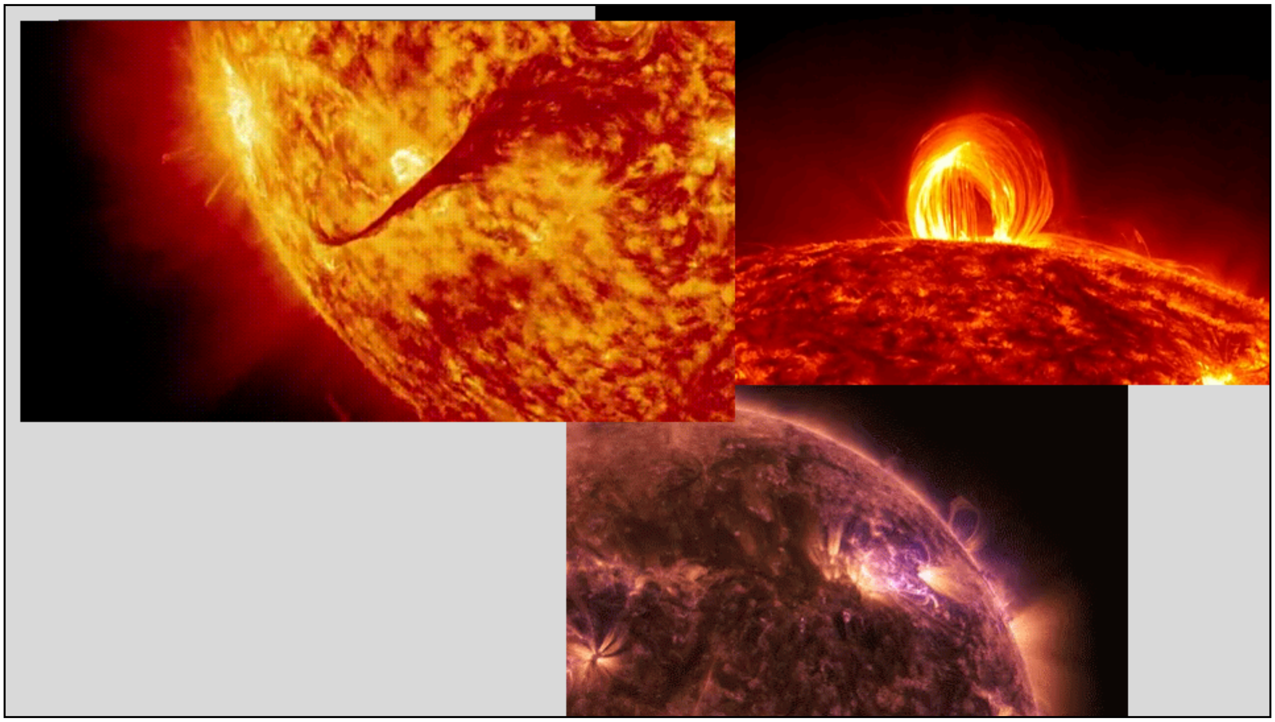
Sunspots and solar activity

- Magnetic phenomena
  - Sunspots:
    - T~4,000 K, cooler than the 5,800 K surrounding plasma
    - Usually appear in pairs connected by a loop of magnetic field lines
  - Solar prominences
  - Flares
    - Sudden release of magnetic energy: particles, light
  - Coronal mass ejections
    - Also a sudden release of magnetic energy: drives eruption of portion of solar atmosphere

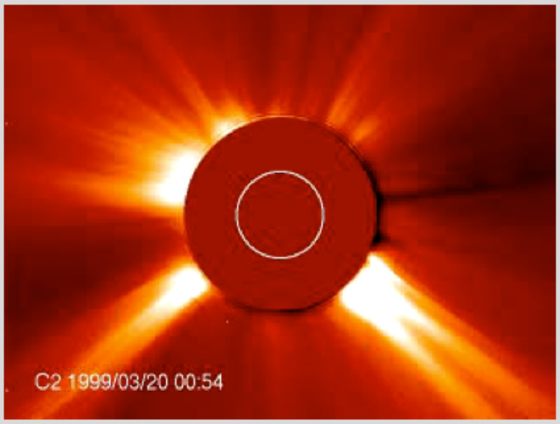
Magnetic phenomena on the Sun

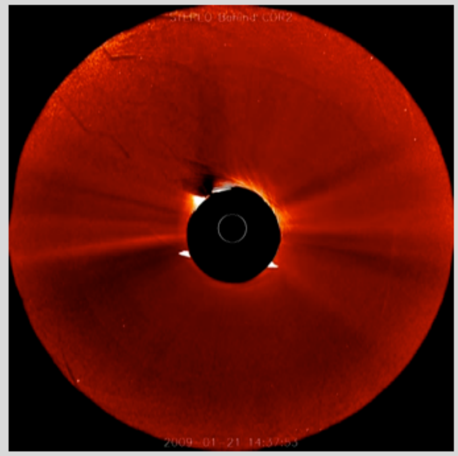
- To keep in mind:
  - A plasma is an ionized gas; very hot, lots of free electrons wandering around
  - Moving electrons generate electric and magnetic fields
  - Magnetic fields and charged particles interact
  - Magnetic fields can receive and store energy: kinetic energy from moving plasma can be stored as magnetic energy to be released later!



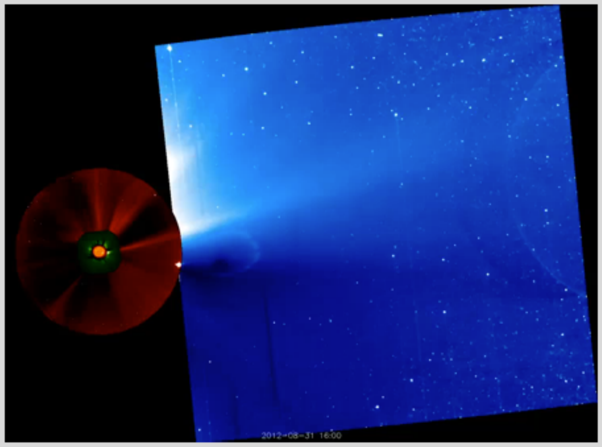


Magnetic phenomena on the Sun



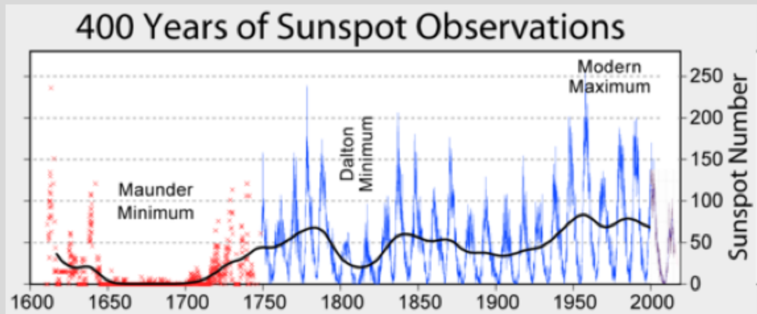


Magnetic phenomena on the Sun



The Sunspot Cycle

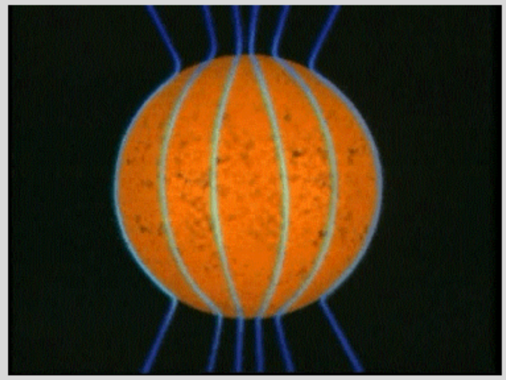
- Observations of the Sun since the beginning of the telescopic era revealed that the number of sunspots gradually rises and declines.
- An average period is 11 years (from 7 to 15 years).
- The magnetic fields in sunspots reverse their direction when a cycle is over.
- No sunspots were observed in 1645-1715 (Maunder minimum), when a Little Ice Age took place in Europe and America.



https://en.wikipedia.org/wiki/Maunder_Minimum

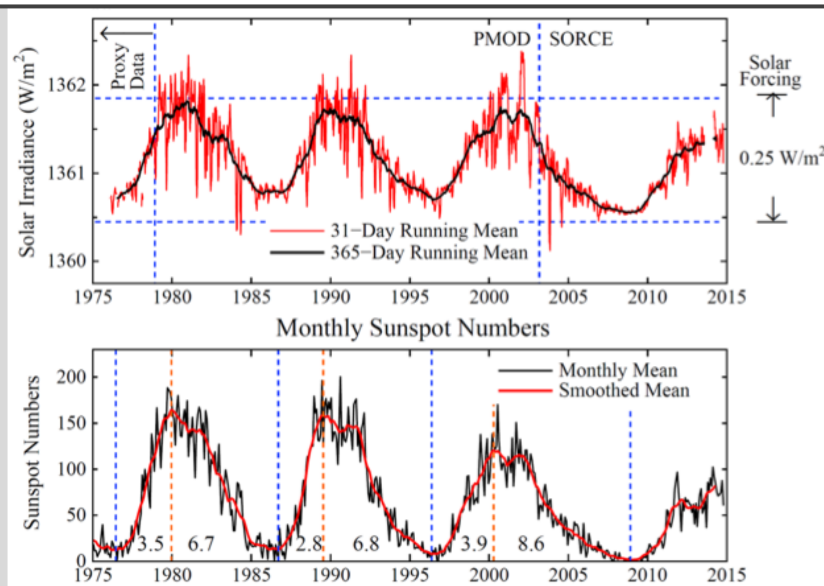
Causes of the sunspot cycle

- Convection amplifies weak magnetic field generated in the solar interior
- Differential rotation stretches and shapes these fields
- Interior flows push spots to equator (“butterfly diagram”)

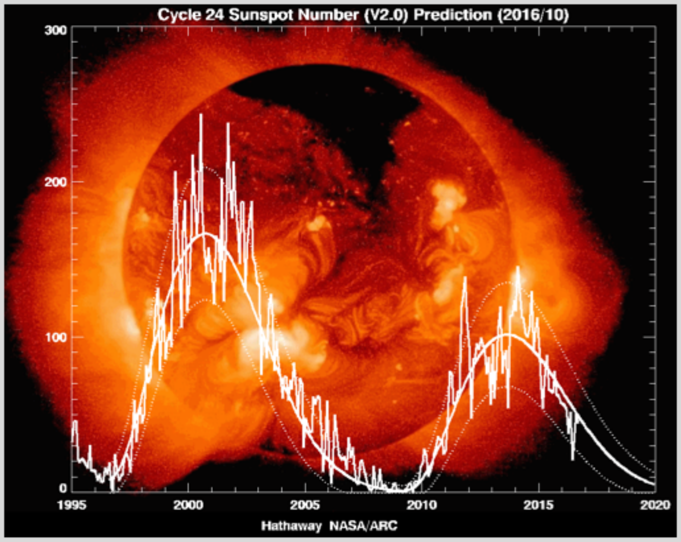


http://ircamera.as.arizona.edu/NatSci102/NatSci/lectures/sun.htm

Total solar energy at Earth and sunspot cycle



Prediction of the Sunspot Cycle



Solar Activity and the Earth

- The solar wind creates aurorae
- Particles created in solar flares produce electrical storms, which disturb radio communications, disrupt electrical power delivery, etc.
- Increase in solar X-rays near activity cycle maxima heats the Earth's upper atmosphere and increases its density, affecting low-flying satellites.