# Today in science…

- Happy $60^{th}$ birthday, NASA!
  - Bill to form passed Congress in July of 1958, Eisenhower signed into law a few weeks later
  - A distinctly civilian, not military, organization for the peaceful exploration and application of space science
  - Earth observing, heliophysics, astrophysics, and missions
  - ISS and launch/crew vehicles
  - $20.7 billion annual budget
  - 17,336 employees (plus many, many more support staff/contractors)


# Today in science…

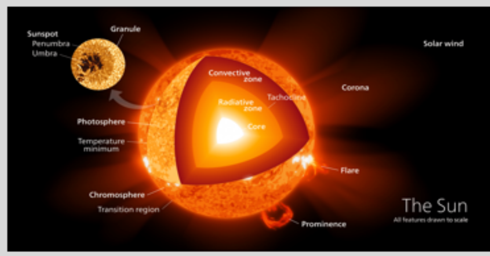

https://www.nasa.gov/image-feature/goddard/potw627-active-regions-galore.html

# Recap: the Sun's structure, energy source

## The Sun, from inside to outside

- Core
- Radiative zone
- Tachocline
- Convection zone
- Photosphere
- Chromosphere
- Transition region
- Corona
- Solar wind

- Where fusion happens
- Photons 'randomly walk' here
- Thin boundary between zones
- Energy is transported by convection here
- 
- UV
- change
- 
- n



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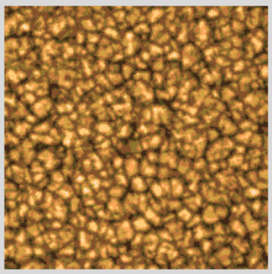
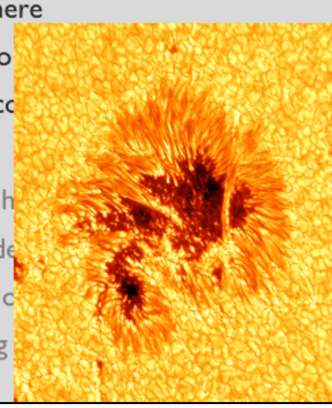


- Where fusion happens
- Photons 'randomly walk' here
- Thin boundary between zo
- Energy is transported by co
- Visible 'surface' of the Sun
- Atmosphere starts to get h
- Where temperature and de
- ~$10^6$K upper atmosphere c
- Stream of particles flowing



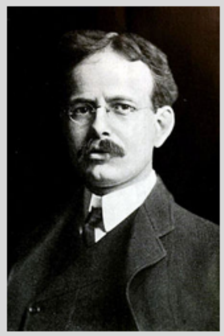
Recall: iron filings, that sort of filamentary structure- that's what you're seeing in the edges of the sunspot, magnetic field– George Hale observed this resemblance in 1908!

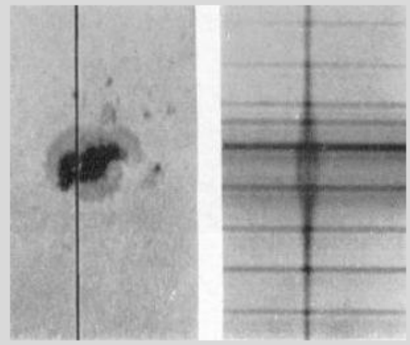
## Aside: sunspots and magnetic fields

- George Hale was the first to discover magnetic fields in sunspots in 1908
- Remember atomic energy levels? Atoms do funny things under the influence… of a magnetic field
- This was another huge moment in science history: the discovery of magnetic fields existing beyond Earth!
- Aside to an aside: George Hale

was a very interesting guy

(in a good way)





https://www2.hao.ucar.edu/Education/FamousSolarPhysicists/magnetic-nature-sunspots

http://adsabs.harvard.edu/full/1999ApJ...525C..60H

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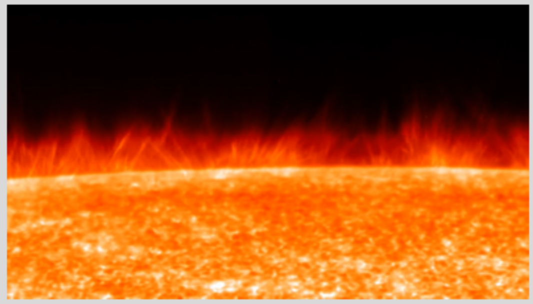
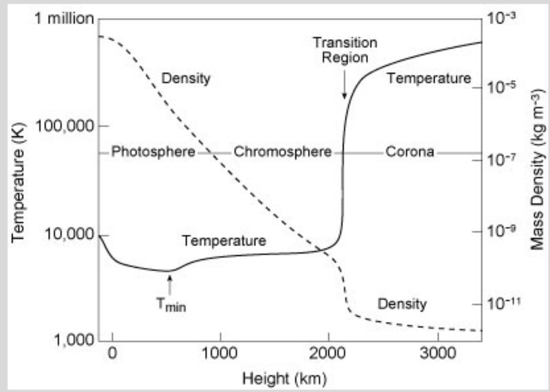


- Atmosphere starts to get hotter, radiates UV
- Where temperature and density abruptly change
- ~$10^6$K upper atmosphere of the Sun
- Stream of particles flowing away from Sun

# Recap: the Sun's structure, energy source

## The Sun, from inside to outside

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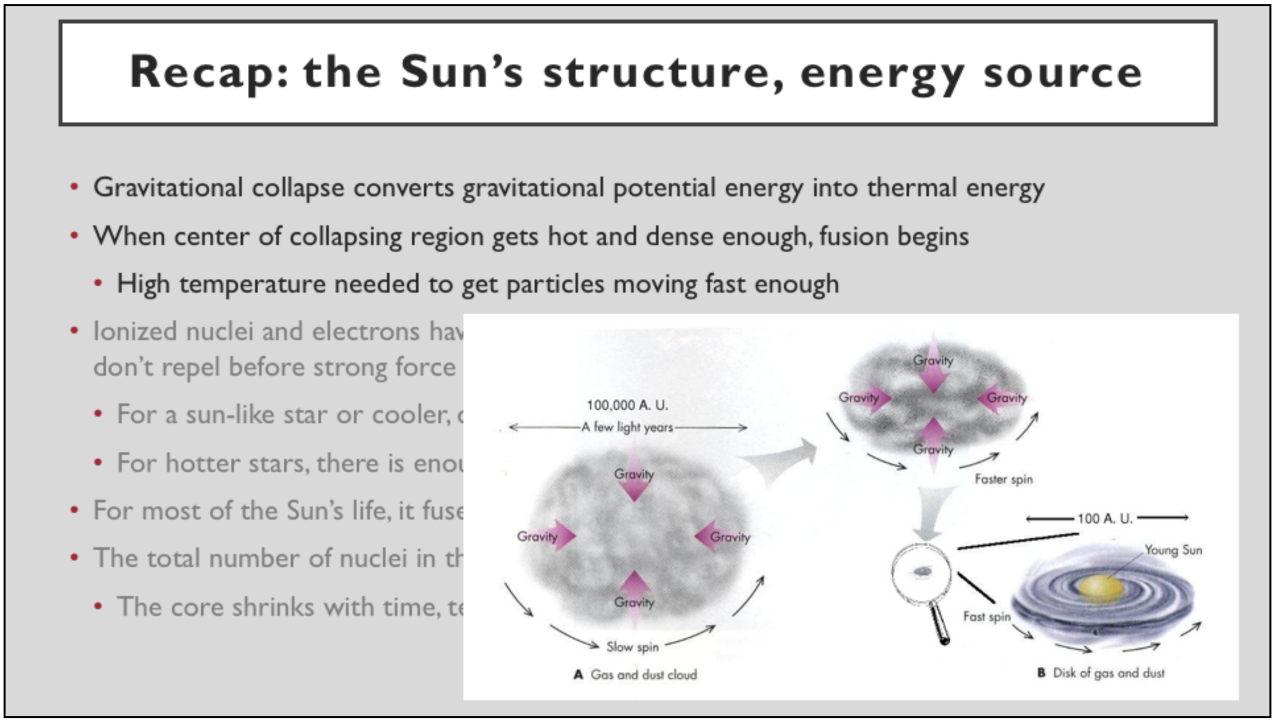


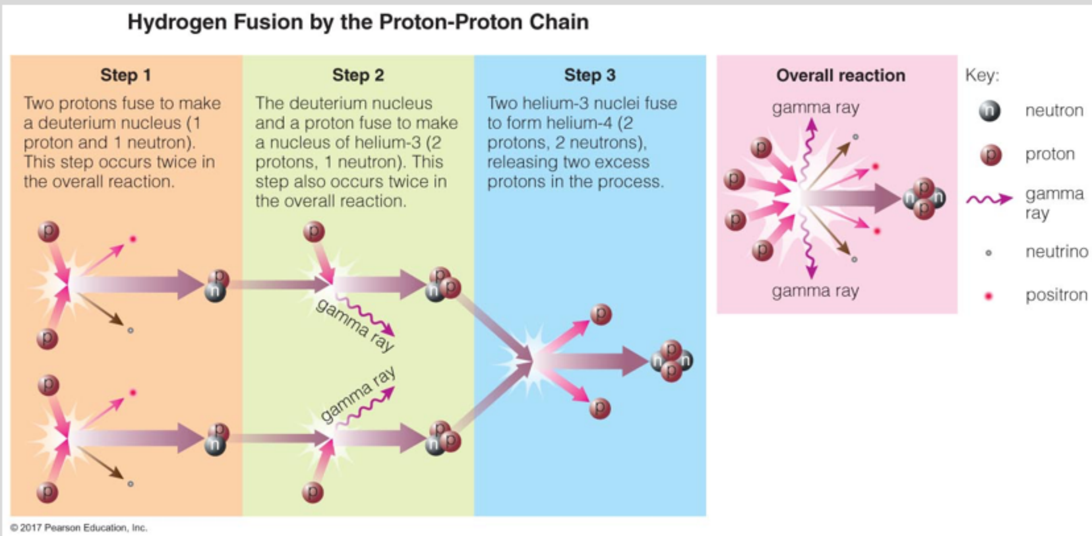

should I get into quantum tunneling or no?

## Recap: the Sun's structure, energy source

- Gravitational collapse converts gravitational potential energy into thermal energy
- When center of collapsing region gets hot and dense enough, fusion begins
  - High temperature needed to get particles moving fast enough
- Ionized nuclei and electrons have so much kinetic energy, moving fast enough like charges don't repel before strong force binds them together
  - For a sun-like star or cooler, quantum tunneling is necessary
  - For hotter stars, there is enough energy
- For most of the Sun's life, it fuses H into He in the proton-proton chain
- The total number of nuclei in the Sun's core decreases with time
  - The core shrinks with time, temperature goes up, fusion rate increases

Special guest today: Dr. Belmont, nuclear physicist!

## Fusion in the Sun

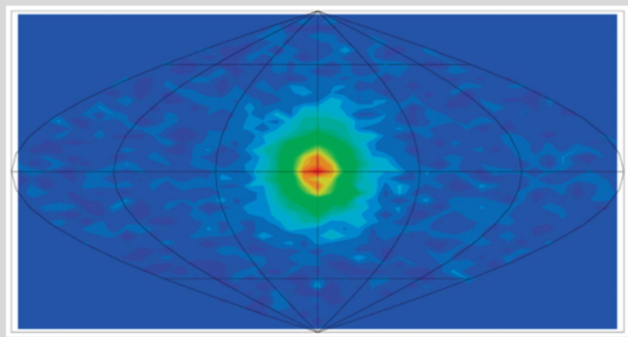



Fusion depends on temperature and density

Aside on fission…

# Recap: the Sun's structure, energy source

- Neutrinos
  - Yes, they have mass
  - Yes, they just keep going out into the universe! (Until they run into something they interact with)
  - Proof fusion is the source of energy for Sun



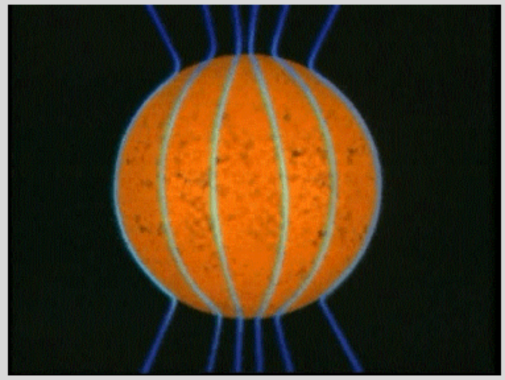
# Quantifying the Sun’s energy output

Recall: energy balance in Sun means energy produced at core = energy output at solar surface

- We measure energy in Joules
- Power is the rate that energy is used; Watts
  - 1 Watt = 1 Joule/s
- The Sun’s total power output, which we call *luminosity*, is $3.8 \times 10^{26}$ Watts
  - Compare to a 100 Watt light bulb, that uses 100 Joules of energy per second it’s on!

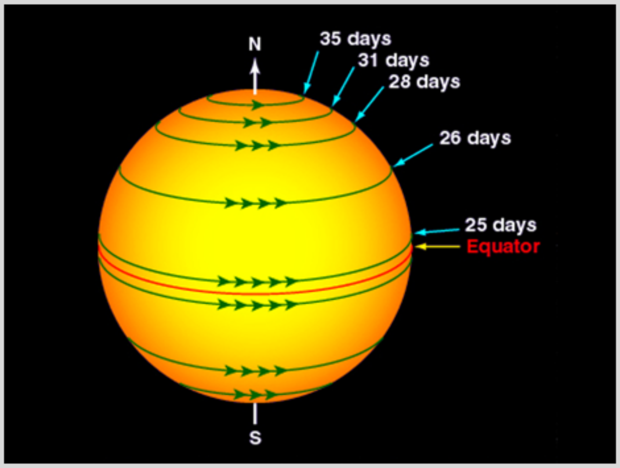
# Solar activity

- Charged plasma and magnetic fields interact
  - Depends on plasma properties (density) and magnetic field properties (strength)
- Magnetic fields stop plasma from moving
  - Sunspots
  - Magnetic loops
  - Solar streamers
- Or, plasma can move magnetic fields
  - Solar magnetic cycle
  - Energy transfer: kinetic energy of plasma→stored magnetic energy
- Sun's magnetic field generated by *dynamo*



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

# Solar rotation

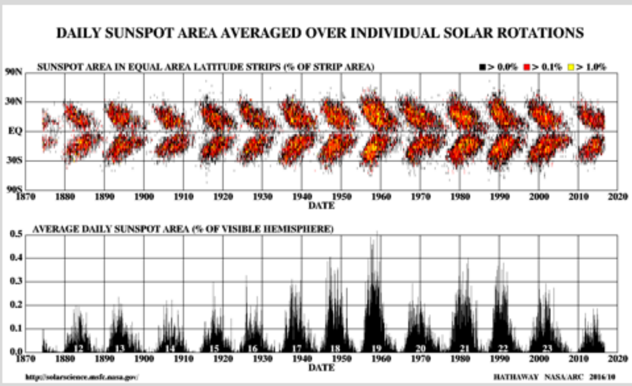


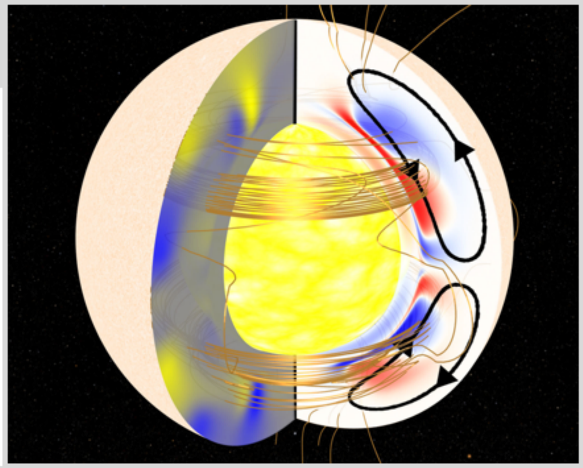

- Remember Earth's rotation? Called a rigid body
- As a plasma, different latitudes on the Sun can have different rotation rates! And they do!

https://www.nasa.gov/mission_pages/sunearth/science/solar-rotation.html

# Solar interior motions

- "Conveyor belt" → meridional flow

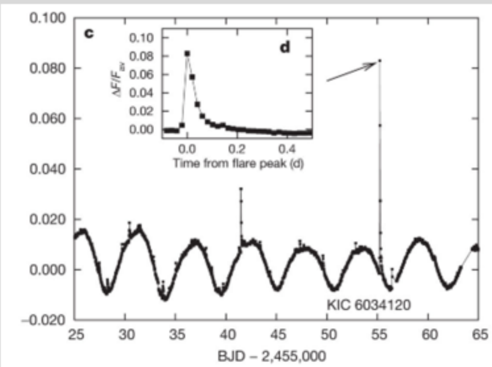


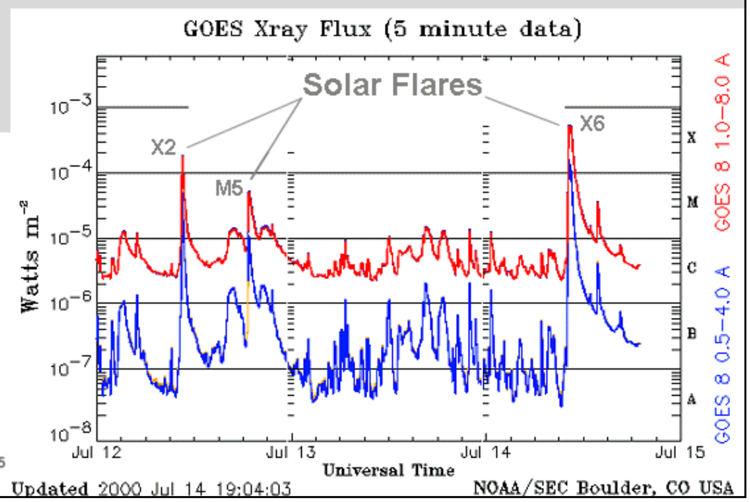



https://www.nasa.gov/mission_pages/sunearth/science/plasma-flow.html

## Solar activity: observations

- "Activity" refers to phenomena resulting from magnetism, release of magnetic energy
  - Sunspots
  - Flares
  - Mass ejections

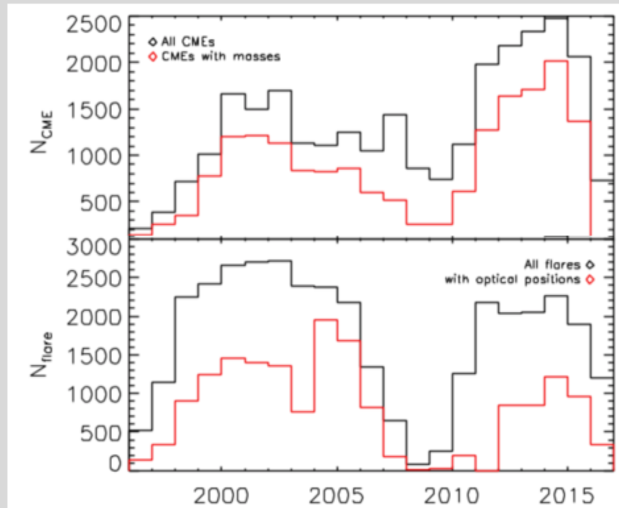


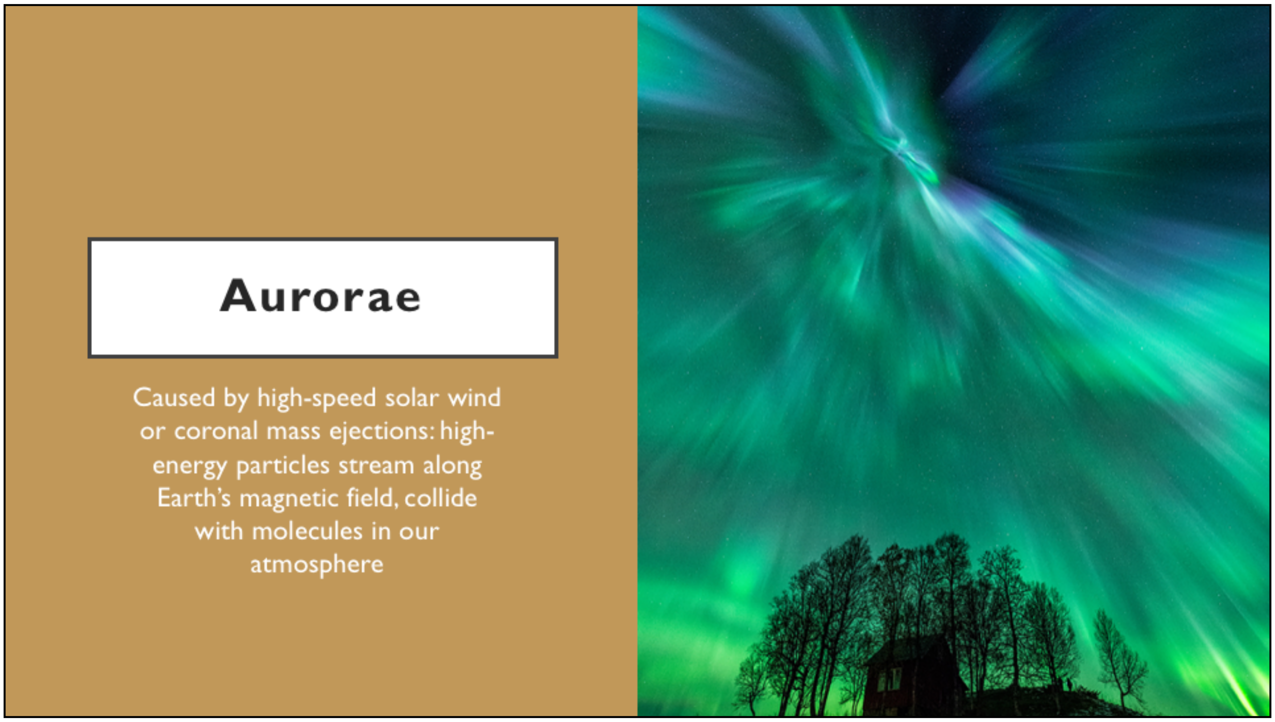

Figures from maehara et al 2013 and
http://spaceweather.com/glossary/flareclasses.html

## Solar activity: observations

- "Activity" refers to phenomena resulting from magnetism, release of magnetic energy
  - Sunspots
  - Flares
  - Mass ejections
- Activity follows Sun's 11-year magnetic cycle
  - Sunspot number
  - Flare, CME number
  - Overall solar irradiance
  - Solar wind speed




(plot made by Prof A)




Is this image false color?

What do you think the colors are from?

Why do you think aurorae are seen most at northern latitudes?

https://phys.org/news/2015-10-fast-solar-aurora.html


https://www.spacetelescope.org/images/heic1509c/

# Properties of stars

- Imagine that…
  - You're looking up at the sky from a field outside of Greensboro
  - You take out a pair of binoculars
  - You point a telescope at a random place in the galaxy.

- What will we see?

# Properties of stars

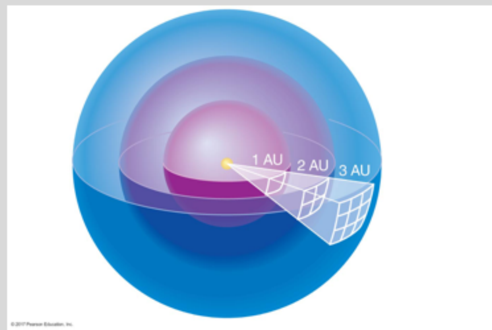
- Imagine that…
  - You're looking up at the sky from a field outside of Greensboro
  - You take out a pair of binoculars
  - You point a telescope at a random place in the galaxy.

- What will we see?
  - More and more stars the more magnified our view
  - Stars of different brightness
  - Stars of different colors
  - Maybe the milky way, or a nebula, or some galaxies

# Properties of stars

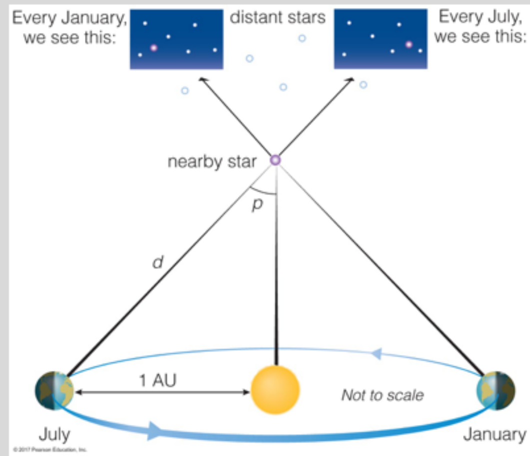
- How bright stars appear is called *apparent brightness*
  - Their actual brightness depends on how far away they are, how big they are, how hot they are!
  - A 100 W light bulb a foot away is much brighter than a 100 W bulb 100 feet away; light rays diverge
- How bright stars actually are is called *luminosity*
- Apparent brightness is related to luminosity:
  - $$\text{Apparent brightness} = \frac{\text{luminosity}}{4\pi \times \text{distance}^2}$$

Units= $\text{Watts/m}^2$

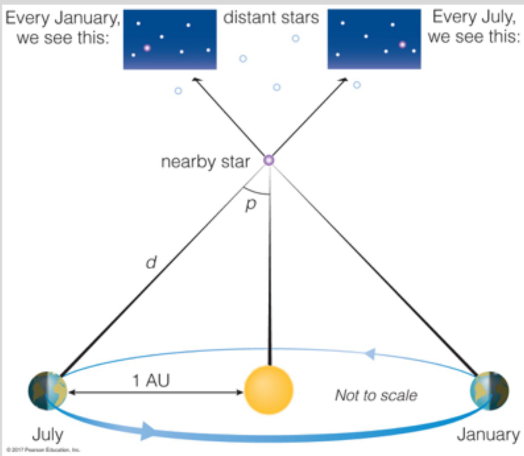


# Apparent brightness, parallax, and luminosity

- How can we measure a star's apparent brightness?
  - In parts of the electromagnetic spectrum
    - How do we know star's brightness across entire EM spectrum? Multiple measurements, or hypotheses about star's overall emission
  - With a detector that can measure watts/m$^2$
- If we know the distance to the star and its apparent brightness, we can calculate its luminosity!
  - How do we get its distance? Parallax!



# Parallax




- Use trigonometry to calculate distances to stars based on angle they subtend in the sky over the course of a year of observations
- New distance definition: the **parsec**, pc
  - Portmanteau of *parallax* and *arcsecond*
  - The distance to an object with a parallax angle of 1 arcsecond
    - Reminder: the arcsecond
    - 360 degrees on the sky
    - 1 degree = 60 minutes of arc (‘)
    - 1 arcminute = 60 seconds of arc (“)
  - d (in pc) = 1 / p (in arcsec)

Portmanteau literally means to carry a coat, it’s the word for a suitcase that opens on a hinge into two equal parts. In english usage, it refers to a combination of two words- like breakfast and lunch (brunch), golden retrievers and poodles (goldendoodles), frappucino (frappe and cappucino), etc … I think ginormous is one of my favorite portmanteaus

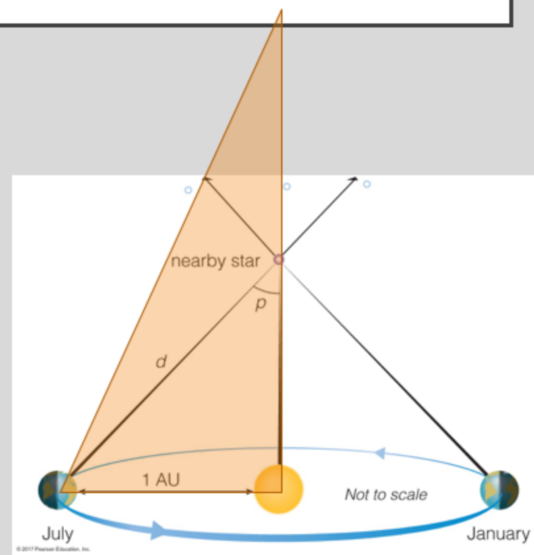
https://en.wikipedia.org/wiki/List_of_portmanteaus

# Parallax

- d (in pc) = 1 / p (in arcsec)
- Example: a star with a parallax angle of 0.5 arcsec
  - d = 1 / (0.5”) = 2pc
- Example: a star with a parallax angle of 0.1”
  - d = 1 / (0.1”) = 10pc

- Parsecs take prefixes like other SI units:
  - 1000pc = 1kpc
  - 1,000,000pc = 1Mpc

- 1pc = 3.26ly



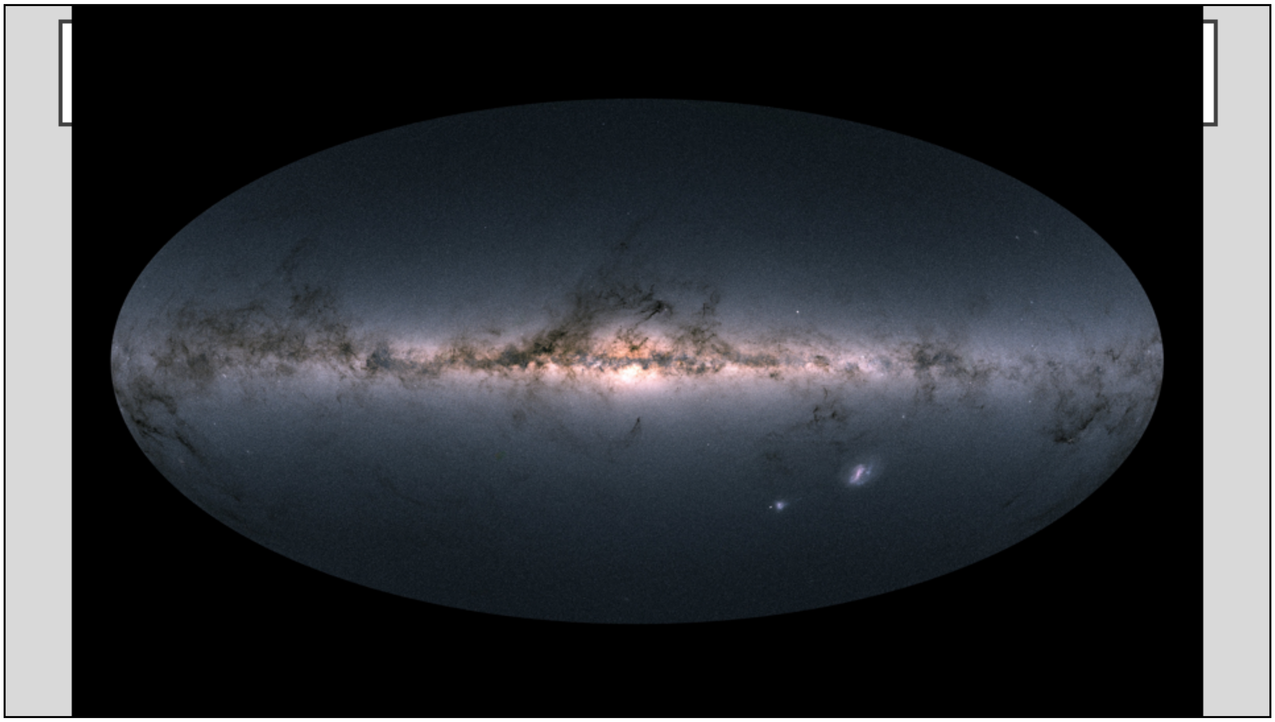

Notice as the parallax angle gets smaller, the distance gets bigger… does this make sense?

The book works with light years because it’s more intuitive; I tend to not know distances to things in light years because I’m working with stars at ~hundreds of pc; the factor of 3.26 is a little awkward

# Parallax

- Difficult for early astronomers to measure- recall Galileo attempting to overthrow geocentrism
- Still difficult, but currently the best way to measure distances to stars: no assumptions about stellar properties needed
- Limited to…

How do you think parallax is limited? How far can we measure?



GAIA mission

https://phys.org/news/2018-04-gaia-richest-star-galaxyand.html

Pause here. All these points of light are stars. They’re in a disk, because like the solar system formation.. Something spinning will flatten out, remember the pizza dough solar system analogy.

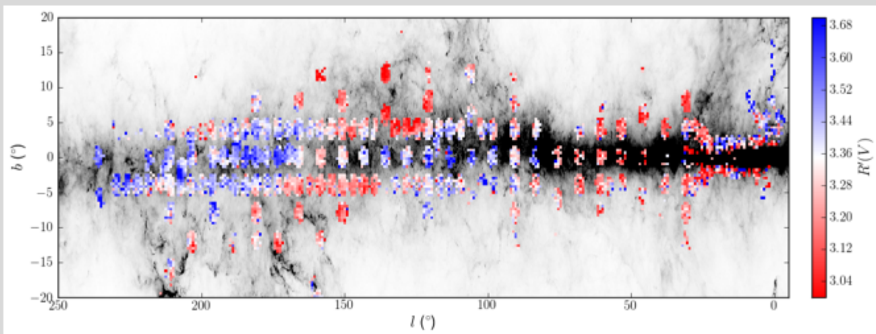
# Parallax

- Difficult for early astronomers to measure- recall Galileo attempting to overthrow geocentrism
- Still difficult, but currently the best way to measure distances to stars: no assumptions about stellar properties needed
- Limited to…
  - Nearest stars!
- GAIA surveying >1.7 billion stars
  - Positions
  - Apparent motions across sky (*proper motions*)
  - Only 10% are good parallax candidates

How do you think parallax is limited? How far can we measure?

# Apparent brightness, apparently

- When does and doesn't light's inverse square law work?
  - If light follows uninterrupted path, not absorbed or scattered on its way to us
    - Does this actually ever happen? (not really, no.)

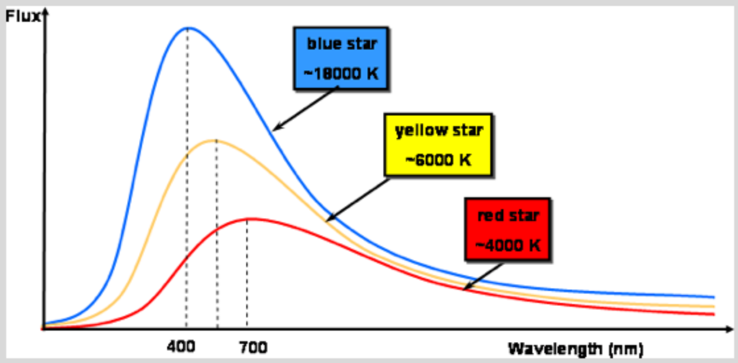



http://e.schlaf.ly/rvthreed/

This plot is showing dust in the galactic plane, and the color-coded part is how the dust changes apparent brightnesses of stars in the V, or visual (green) wavelength band

# Stellar luminosities

- Luminosity refers to intrinsic brightness, as if you were right by the star- no distance, no dust, nothing in the way
- Total (or, bolometric) luminosity: light added up over all wavelengths
- Stars' luminosity range:
  - The Sun = 1 $L_\odot$
  - Betelgeuse = 120,000 $L_\odot$
  - Proxima Centauri = 0.0006 $L_\odot$



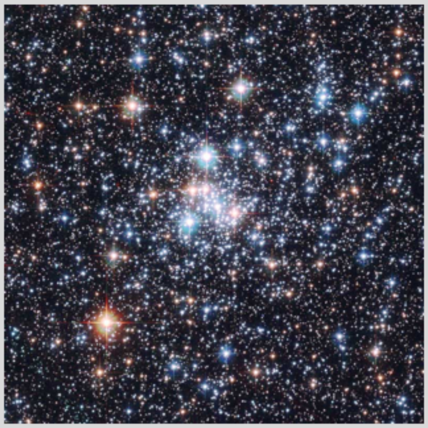

Recall thermal emission curves.. All of these are plotted scaled- the same little element of surface area emits more if it's hotter. Now, imagine you have more surface area.. You get more overall emission with more surface area. So Betelgeuse is cooler than the sun but way, way bigger, so it has a higher luminosity. Proxima centauri is cooler than the sun and smaller, so it has a much, much lower luminosity

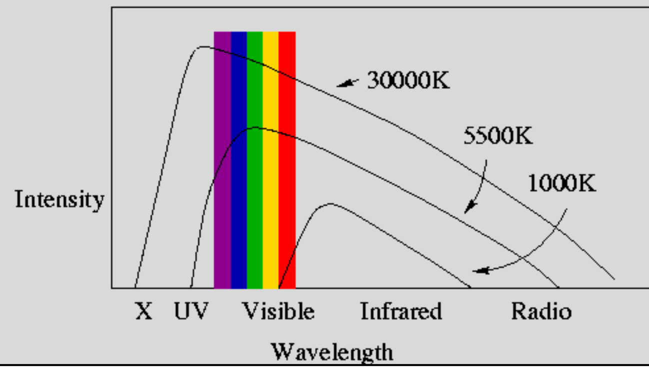
# Stellar magnitudes

- Apparent brightnesses often expressed as *magnitudes*
  - All initially defined by eye
  - Hipparchus defined brightest stars he could see as "first magnitude"
  - Fainter stars had higher numbers: second magnitude, third, etc
  - When brighter stars observed, went to 0, and then negative
  - Sirius is the brightest star in our sky: its apparent magnitude is -1.46
    - In the Visual, or V, wavelength range!
  - Every 5 magnitudes ~100x difference in brightness
- Later calibrated to an absolute scale: how bright would the star be if it were at 10 pc?

# Stellar temperature

- We see the stellar surface, and can only directly measure its temperature
  - Recall from thermal radiation: peak wavelength depends on the temperature of the object





## Spectral types

- Can roughly tell a star's temperature based on two different colors of light. Can more precisely tell from its spectrum!
- Before we knew about quantum mechanics, we measured and classified stellar spectra
- And by "we," I mean…

https://www.space.com/34707-annie-jump-cannon-biography.html

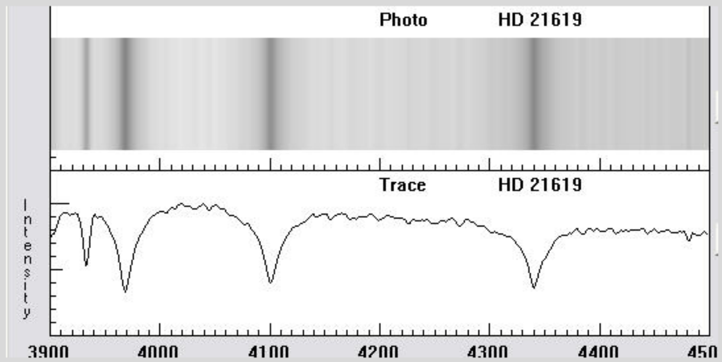
## The ”computers”

Often women’s college graduates who were not allowed to obtain degrees or jobs in science fields.. Hired because they could be paid less. Hiring women at all in the first place was a cynical precedent set by an exasperated man in power

https://www.sciencenews.org/article/astronomys-unsung-heroines-celebrated-glass-universe

## Spectral types

- How would you go about sorting something when you don't know what it is?
  - Size
  - Shape
  - Color
  - …
- The "computers" sorted on all these things. Were lines present? Yes, no. Are they weak, or strong?



## Spectral types

- "Pickering had turned to women out of exasperation with a male assistant. Declaring that even his maid could do a better job, he hired Williammina P. Fleming, a twenty-four year old Scottish immigrant, to assist him." –The Perfect Machine: Building the Palomar Telescope, Ronald Florence (p. 13-14)
- Paid half the rate a man would earn, Williammina/Wilhelmina Fleming was a BOSS. She discovered and catalogued over 10,000 stars, nebulae, and the existence of white dwarf stars.
- worked to define a spectral order
  - Gave spectra letters based on strength of Hydrogen lines
- She also oversaw the work of Annie Jump Cannon and Henrietta Swan Leavitt

https://www.atlasobscura.com/articles/how-female-computers-mapped-the-universe-and-brought-america-to-the-moon

## Spectral types

- Annie Jump Cannon
  - Defined spectral sequence as we know it today
  - Sorted sequence in order of descending stellar surface temperature
  - Divided into sub-classes: A0, A1, A2, etc: higher number → lower surface temperature
  - Classified over 400,000 spectra over her career
  - Why don't we know her name? (Spoiler: who paid for the catalog? Henry Draper/his estate)
  - The sequence was visually clear, but it wasn't known **why** stars were in this order until Cecilia Payne-Gaposchkin realized stellar composition was mostly H, He, and surface temperature determined properties of stellar spectra
- Henrietta Swan Leavitt discovered Cepheid variables: regularly pulsating stars, periods related to luminosity

https://www.atlasobscura.com/articles/how-female-computers-mapped-the-universe-and-brought-america-to-the-moon

## Stellar masses

- How might we measure stellar masses?

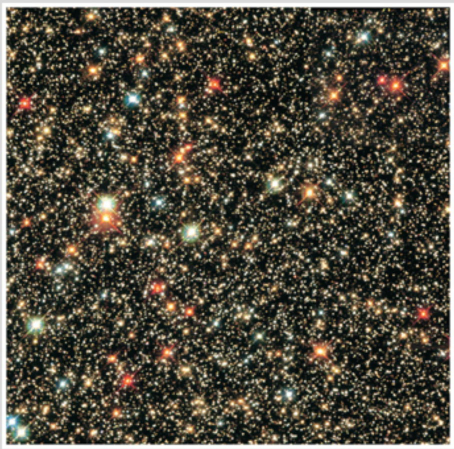
Can’t put a star on a scale… what do we know about right now that could allow us to measure a star’s mass?

## Stellar masses

- How might we measure stellar masses?
  - $F_g$! Gravitational interactions!
    - With what?
    - Binary stars! Almost half of all stars are in binaries.
      - Visual
      - Spectroscopic
      - Eclipsing

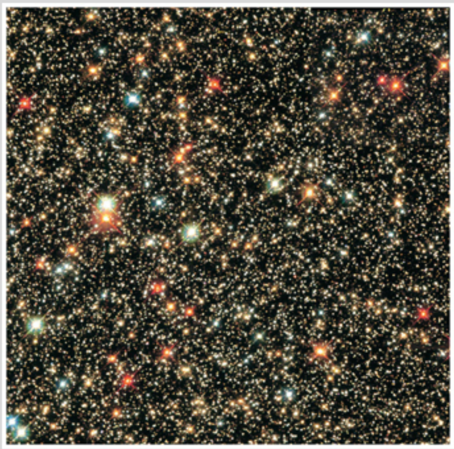
Can't put a star on a scale…

# Patterns in stars



- What do you notice about this picture?

## Patterns in stars



- What do you notice about this picture?
  - Stars are in a cluster: assume they're all at about the same distance
  - Biggest, brightest ones are red or blue-white
  - Rest are different sizes, some blue, most yellow-white-ish, some small red dots
  - There's some kind of relationship between stars' color and luminosity

More about this.. Next time.