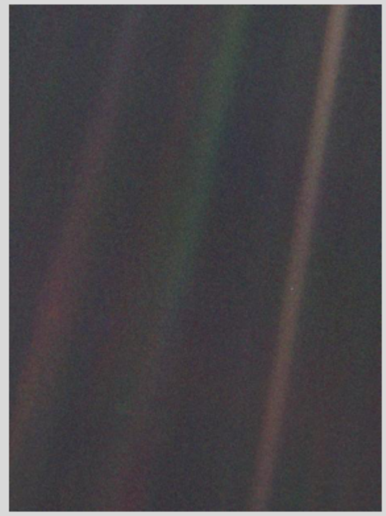
# Logistical notes

- Who has clicker #602? Please let me know ASAP, I don't know whose clicker that is!

# Today in science…

- Reflections and perspective: "Taking the telescopic view"
  https://www.brainpickings.org/2017/12/21/reflection/
  - "I don't think it is possible to contribute to the present moment in any meaningful way while being wholly engulfed by it. It is only by stepping out of it, by taking a telescopic perspective, that we can then dip back in and do the work which our time asks of us." –Maria Popova



https://www.brainpickings.org/2017/12/21/reflection/

## Bonus today in science…

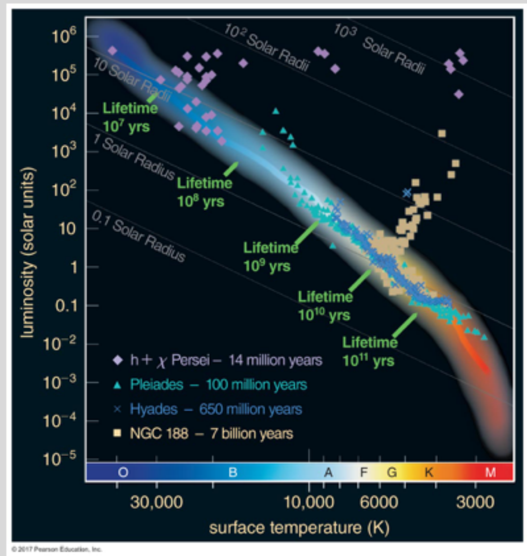
- Jagged, 50-foot blades of ice on a moon of Jupiter?
- Europa thought to have sublimation-formed extreme features near its equator
- Icy surface over salty ocean?
- Europa Clipper mission will investigate (2020)

https://www.theatlantic.com/science/archive/2018/10/europa-jupiter-ice-extraterrestrial-life/572527

Photo is of features called “penitentes” high in Chilean Andes

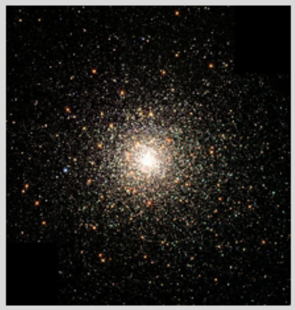
# Recap of last class

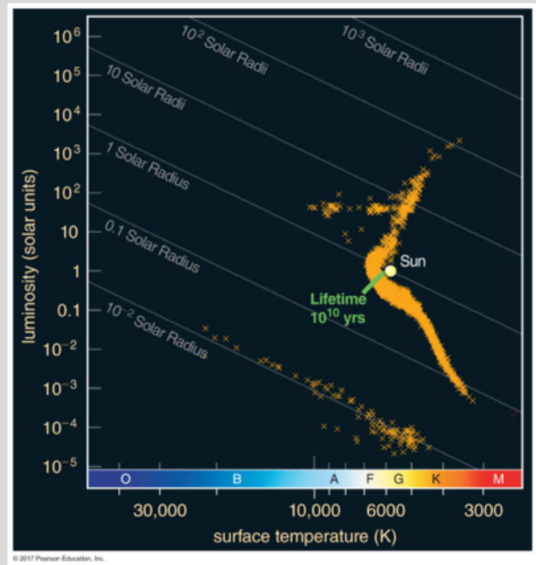
- Color, temperature, the power of the H-R diagram, and stellar mass



# Star clusters – age

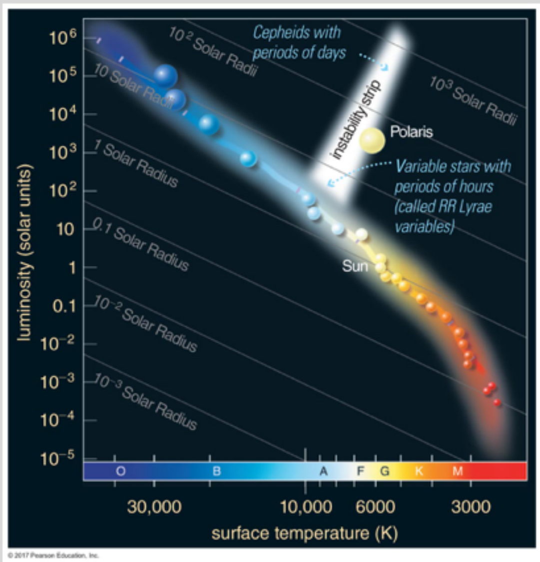
- How do we know how old a cluster of stars is?
  - Where they are on the H-R diagram
  - For young clusters, elements in the stars themselves (Lithium)



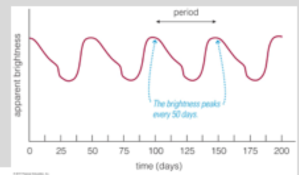


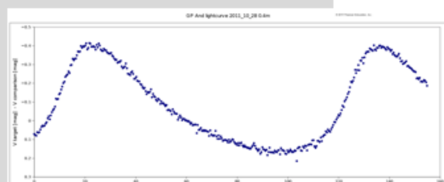

Compare the pictures here of the open and globular clusters… what pops out at you right away?

# The instability strip




- Variation in magnitude due to star's radius changing
  - $L = 4\pi r^2 \sigma T^4$
  - How much does the star's radius change?



## Luminosity and radius

- $L = 4\pi r^2 \sigma T^4$
  - For solar mass star on the giant branch, radius ~10Rsun, assuming solar surface temperature…

| Change in luminosity [%] | Change in radius [%] | Change in radius [Rsun] |
|---|---|---|
| 1 | 10 | 1.00 |
| 5 | 22 | 2.24 |
| 10 | 32 | 3.16 |
| 20 | 45 | 4.47 |
| 250 (1 mag) | 1.6 | 15.8 |
| 10000 (5 mag) | 1000 | 100. |

- Analytically, you can calculate this:
  - $L_1 = 4\pi r_1^2 \sigma T^4$
  - $L_2 = 4\pi r_2^2 \sigma T^4$
- Take the ratio of brightness after relative to before
  - $L_2 / L_1 = r_2^2 / r_1^2$
- Rearrange…
- If $L_2/L_1 = 0.1$, a 10% increase in luminosity,
- $0.1 * r_1^2 = r_2^2$
- or
- $r_2 = \text{sqrt}(0.1) * r_1$

Stars can become 100x brighter- 6th magnitude to 1st magnitude, for example

Each step in the magnitude scale is logarithmic, one step is an increase in brightness of about 100^(1/5) (which is about 2.5x)


The orion nebula cluster https://www.eso.org/public/images/eso1723a/

# Stellar nurseries

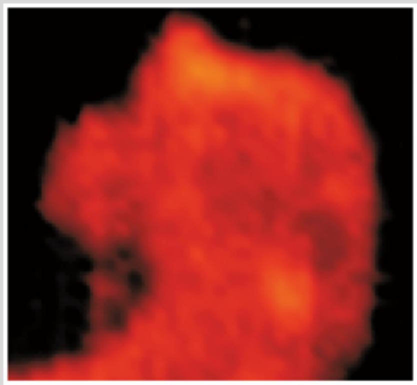
- We use imaging to put stars onto the H-R diagram
- The H-R diagram shows us stellar ages, the imaging shows the youngest stars are near dark clouds of gas and dust
  - …are they really dark?

a Visible-light image of the nebula. The dark (horsehead-shaped) region is a molecular cloud.

## Stellar nurseries

- We use imaging to put stars onto the H-R diagram
- The H-R diagram shows us stellar ages, the imaging shows the youngest stars are near dark clouds of gas and dust
  - …are they really dark?
  - not necessarily!

- Cold clouds, 10-30K
- aka 'molecular' because not enough energy to be ionized



**b** Radio-wave image of the nebula showing emission from carbon monoxide (CO) molecules.

**a** Visible-light image of the nebula. The dark (horsehead-shaped) region is a molecular cloud.

Depends on the wavelength you're observing. The material in the horsehead nebula is dense and cool compared to the background radiation- it absorbs visible light, but itself emits in radio wavelengths.

## Stars form in molecular clouds

- Slowly rotating
- Have magnetic fields
- Areas that are "over" dense attract nearby material
- Molecular clouds produce thousands or more stars
  - Remember last week: youngest = association or moving group
  - Open clusters: 1000s of stars, "middle aged"
  - Globular clusters: 100,000s-millions of stars, older, out of galactic plane


https://www.astro.ex.ac.uk/people/mbate/Cluster/cluster500RT.html

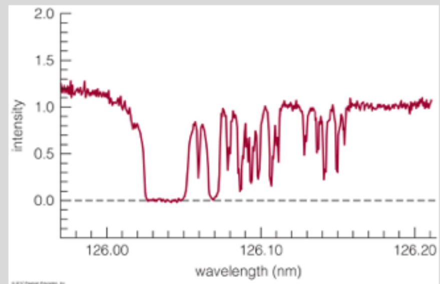
The calculation models the collapse and fragmentation of a 500 solar mass molecular cloud that is 0.8 pc in diameter (approximately 2.6 light-years). At the initial temperature of 10 K with a mean molecular weight of 2.38, this results in an thermal Jeans mass of 1 solar mass. The free-fall time of the cloud is 190,000 years and the simulation covers 285,000 years.

The cloud is given an initial supersonic `turbulent' velocity field in the same manner as Ostriker, Stone & Gammie (2001). We generate a divergence-free random Gaussian velocity field with a power spectrum P(k) \propto k$^{-4}$, where k is the wave-number. In three-dimensions, this results in a velocity dispersion that varies with distance, lambda, as sigma(lambda) \propto lambda$^{1/2}$ in agreement with the observed Larson scaling relations for molecular clouds (Larson 1981). This power spectrum is slighly steeper than the Kolmogorov spectrum, P(k)\propto k$^{11/3}$. Rather, it matches the amplitude scaling of Burgers supersonic turbulence associated with an ensemble of shocks (but differs from Burgers turbulence in that the initial phases are uncorrelated).

The calculation was performed using a parallel three-dimensional smoothed particle hydrodynamics (SPH) code with 35 million particles on the University of Exeter Supercomputer. It took approximately 6,000,000 core-hours running on up to 256 compute cores (16 compute nodes). The SPH code was parallelised using both MPI and OpenMP by M. Bate. The code uses sink particles (Bate, Bonnell & Price 1995) to model condensed objects (i.e. the stars and brown dwarfs). Sink particles are point masses that accrete bound gas that comes within a specified radius of them. This accretion radius is to set 0.5 AU. Binary systems are followed to separations as small as 0.01 AU - closer systems are assumed to merge (but no mergers occur in the calculation here).

# The interstellar medium

- The space between stars is called the interstellar medium (ISM)
  - It's a near perfect vacuum by Earthlings' standards, but no- not entirely empty
    - How do we know? It gets in the way of stars!
  - The ISM contains both gas and dust
- The ISM impacts observations of lone stars
- The ISM+molecular cloud along the line of sight between us and a forming star make them very hard to observe!



# Interstellar reddening

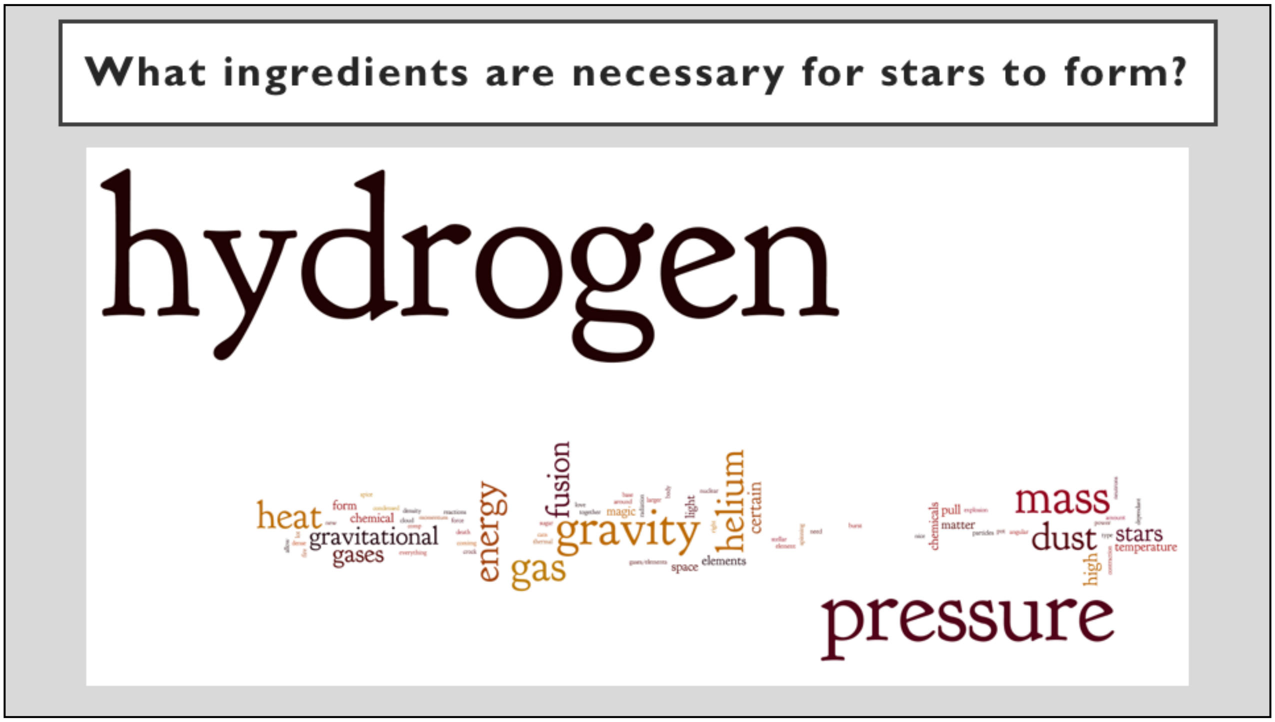
- Dust grains affect the way light travels through a molecular cloud
  - Absorb or scatter the light
    - Makes regions appear almost black relative to background light
  - Processes are wavelength dependent:
    - Bluer light is more readily scattered or absorbed, so objects appear more red than they actually are → called reddening
  - Reddening is a pain, but can be useful: if we know what the actual light source is, we can use reddening to figure out how much dust and gas are along our line of sight

# Multi-wavelength imaging

- Longer wavelengths pass through gas and dust more easily than shorter wavelengths

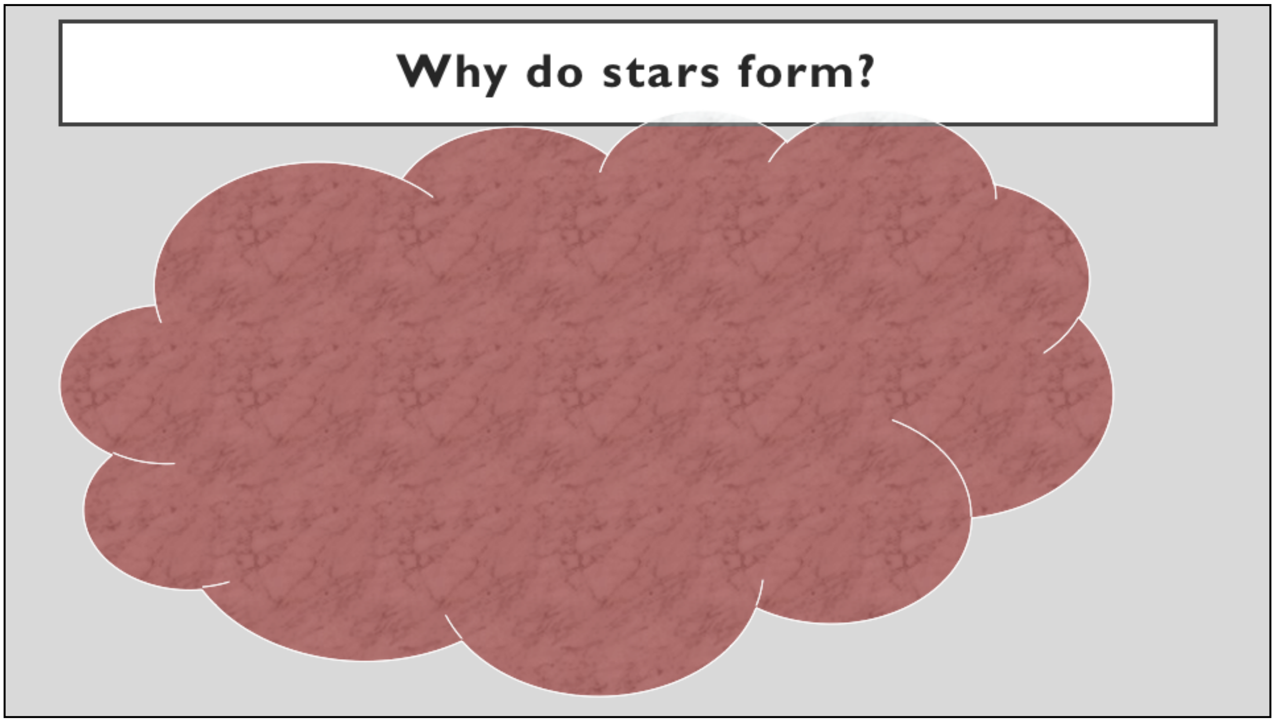


Visible light vs infrared light

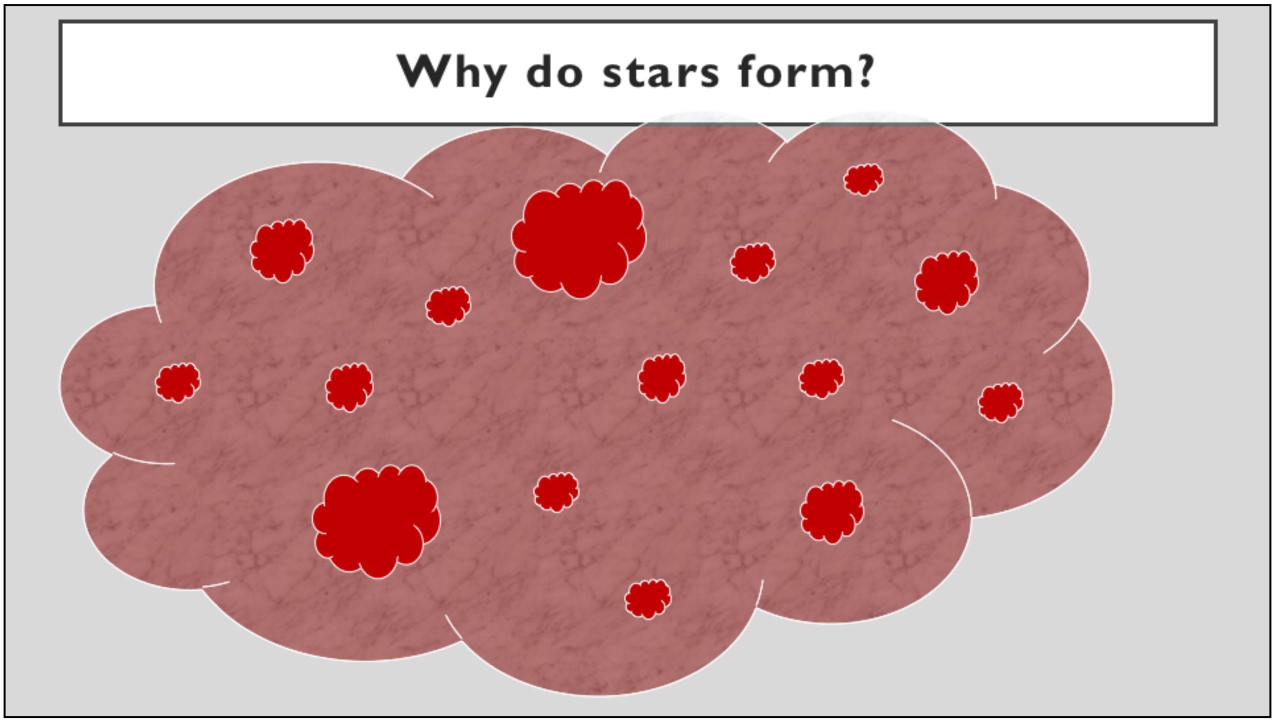

What ingredients are necessary for stars to form?
hydrogen
heat
form
chemical
gravitational
gases
energy
fusion
gravity
gas
magic
light
helium
certain
space
elements
chemicals
pull
matter
mass
dust
stars
temperature
high
pressure

# Why do stars form?

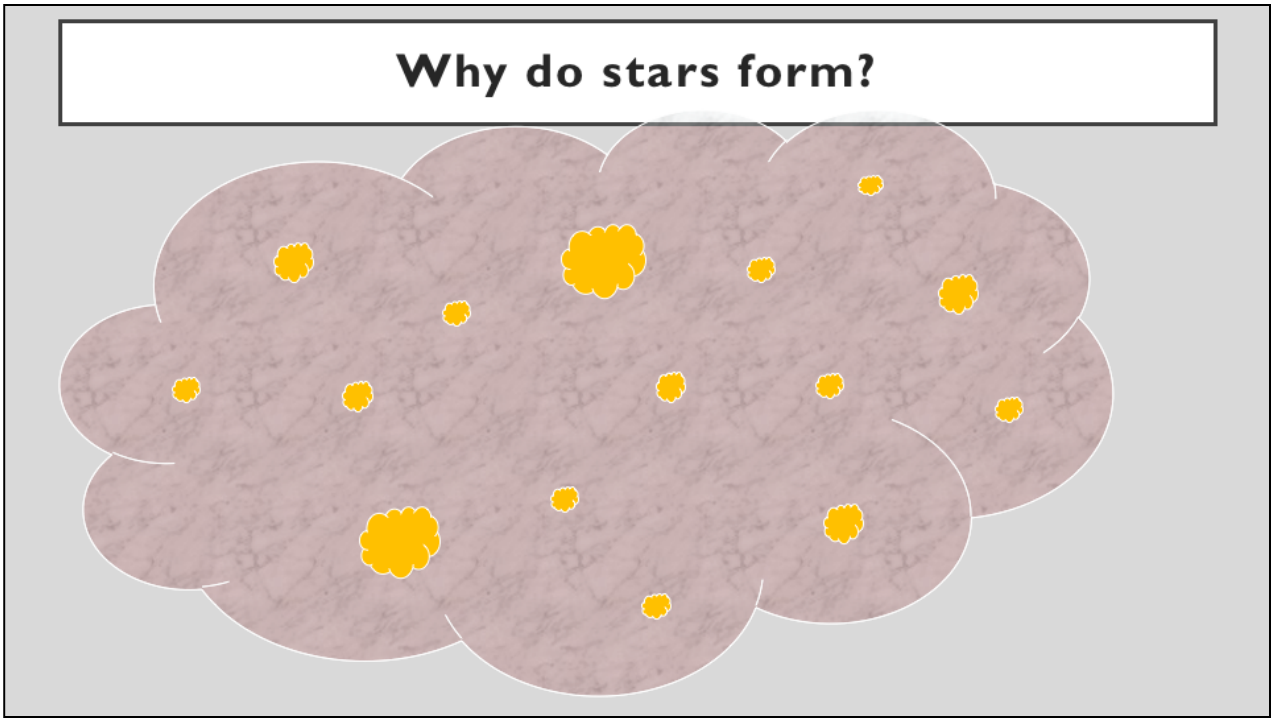
- Gas and dust of a certain temperature have a pressure due to the kinetic energy of the atoms/molecules/grains
  - Pressure depends on the temperature and density of the cloud
  - This is called *thermal pressure*
- In low density clouds, thermal pressure is enough to prevent collapse: not enough mass for strong $F_g$
- If density is high and temperature low, thermal pressure isn't enough; collapse will begin
  - The more massive a molecular cloud is to begin with, the more likely you'll get regions of sufficiently high density for $F_g$ to be strong!




Start with a cloud of molecular gas and dust



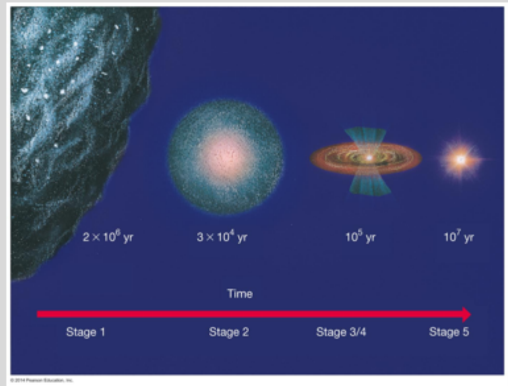

Regions just a little bit more dense than the surrounding cloud will start to attract nearby gas and dust



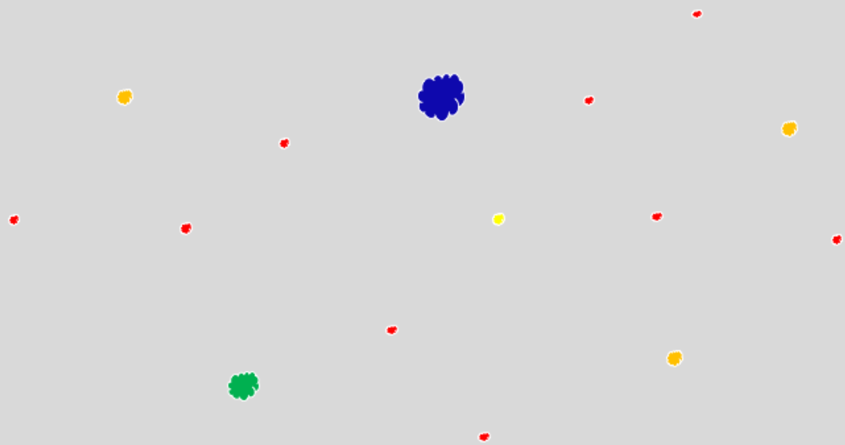

The collapsing cores will heat up; some of this energy the cores hang on to, some of it gets radiated away. The cloud starts to dissipate because the protostars are accreting mass from the cloud- some stars are easier to see at this point in the process, depending on how hot they are and how much is still around them.

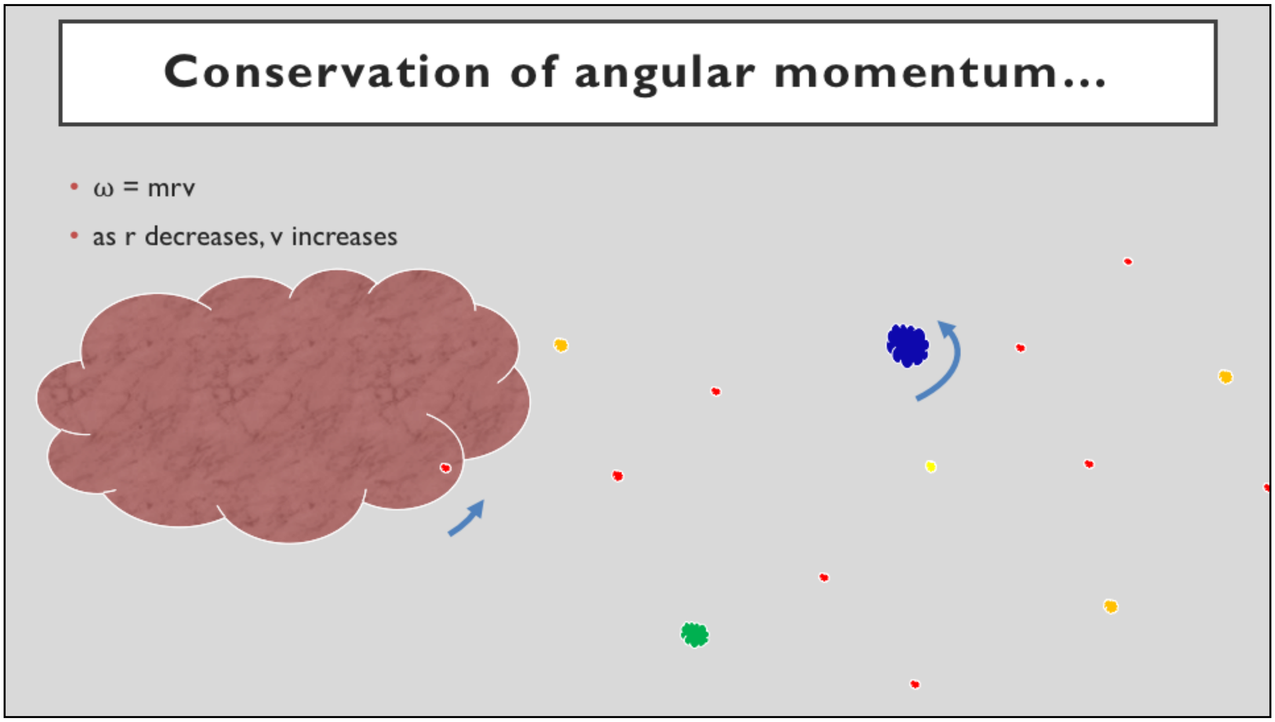
# Conservation of energy…

- As gravitational potential energy is converted to thermal energy, molecular clouds will heat up and radiate away the energy
  - What would happen if they didn't radiate the energy away?
    - Thermal pressure would increase, stopping collapse
- Radiation in infrared, radio, keeps cloud cool, gravity keeps working
  - …until density high enough, harder for photons to escape! Photons reabsorbed shortly after being emitted, thermal energy increases



# Why do stars form?




Conservation of angular momentum…
ω = mrv
as r decreases, v increases

## Star formation: wrinkles and mysteries

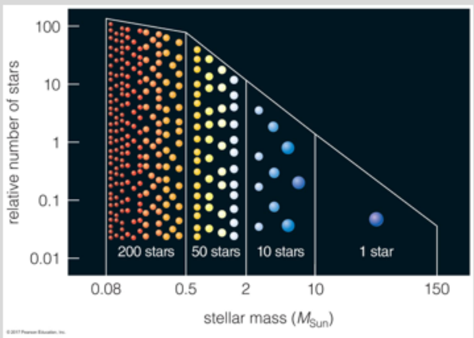
- We see stars forming in molecular clouds that are ~1000s of times more massive than the Sun
- Molecular clouds show lots of motion: turbulence, like wake of a boat in water
  - Need a lot more mass to overcome turbulence than thermal pressure
- We also see that molecular clouds have magnetic fields: light from behind them travels through and is polarized
  - What is the role of the magnetic field in star formation?
  - Remember magnetic fields interact with charged particles.. In a cold cloud, not a lot of these, but enough to interact with field, and for them to interact with neutral particles
  - Enough to possibly slow or halt gravitational collapse

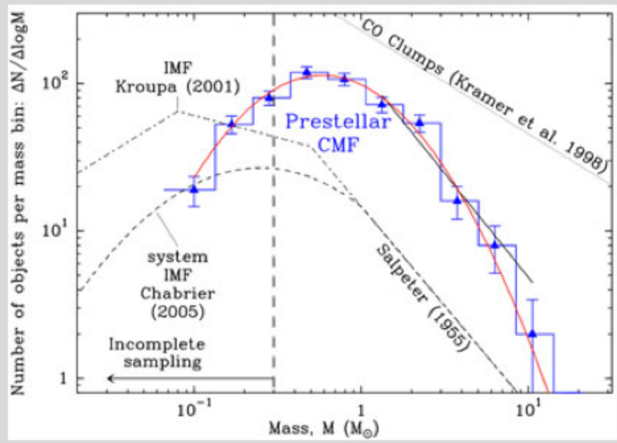
Turbulence is chaotic, the opposite of laminar flow, which is when liquids flow in neat, parallel layers


https://www.spacetelescope.org/images/heic1007e/

# Count the stars…

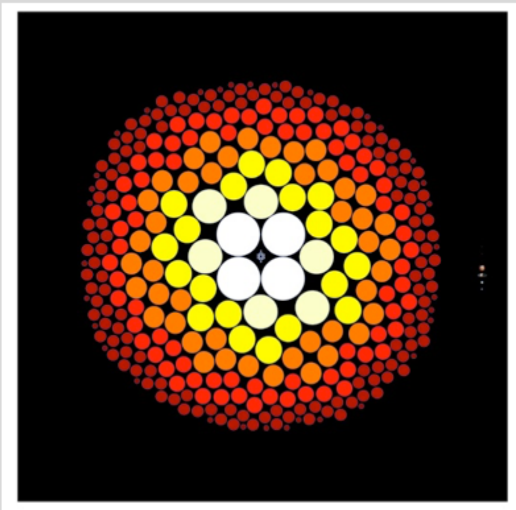
- It's difficult to survey molecular clouds (so much extinction!) But when we do, we observe mostly low-mass stars being formed
  - This is called the Initial Mass Function (IMF)
- Models produce the same results




https://ned.ipac.caltech.edu/level5/Sept13/Silk/Silk2.html

## Count the stars…



- This is an image of all the stars within 10 parsecs of the Sun
  - Vast majority of the stars in the Universe are low-mass stars
- Graphic by Todd Henry for RECONS (REsearch Consortium On Nearby Stars) project http://www.recons.org

## The first stars

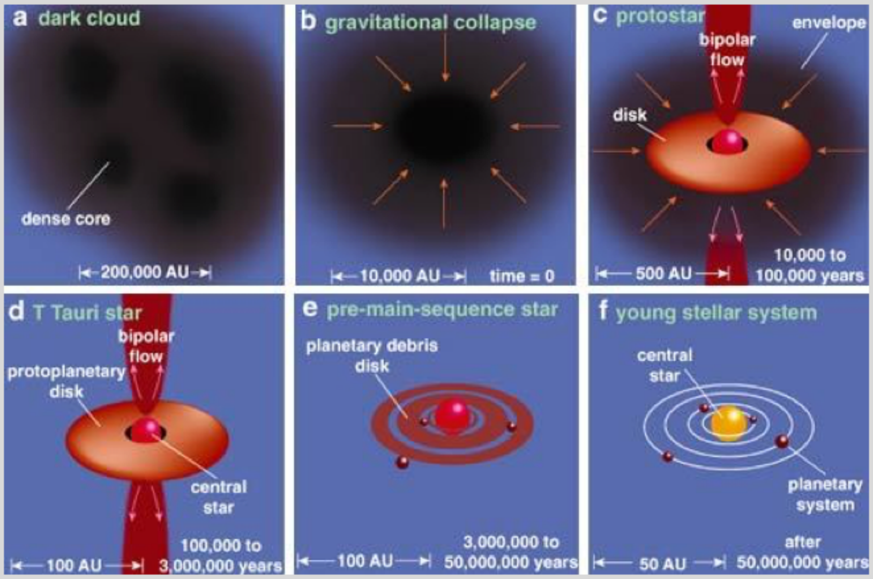
- The Sun consists of ~70% H, 28% He, and 2% everything else heavier than that (“metals”)
- The oldest stars we see in the Milky Way are in globular clusters
  - They contain the least metals of all the star clusters: < 0.1%
  - We conclude they were born before much enrichment occurred due to stars’ lives and deaths
- We see farther and farther galaxies have lower and lower heavy metal content
- The big bang only produced Hydrogen and Helium, so how did the first stars form from that?

You’ll note these slides are conspicuously void of images… why would we not have any images of the first stars?

# The first stars

- Heavy elements and molecules help molecular clouds cool
  - Absorb energy, electrons excited to higher energy states, energy released as radiation (photons)
  - If absent, core can't cool, thermal pressure halts collapse
  - This limits the mass that a protostellar cloud can form: skews toward high-mass stars only
  - They lived brief lives and then went supernova, their heavier elements enriching the next generation of stars

## Stages of star birth

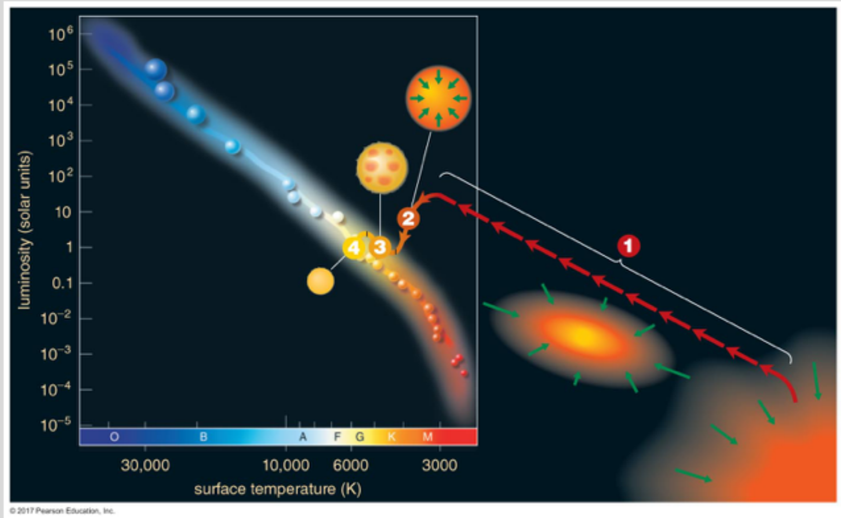



Material in the disk rotates around the star obeying Kepler's laws- this is often called Keplerian rotation

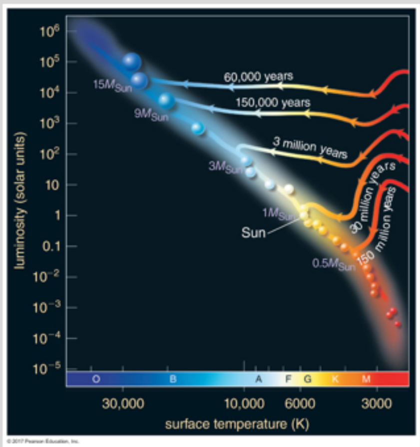
Friction can perturb gas, dust, planetesimals in the disk, taking energy from their orbits, and causing them to fall in and accrete onto the central star

# Stages of star birth

- Formation of protostar
- Convective contraction
- Radiative contraction
- Self-sustaining fusion



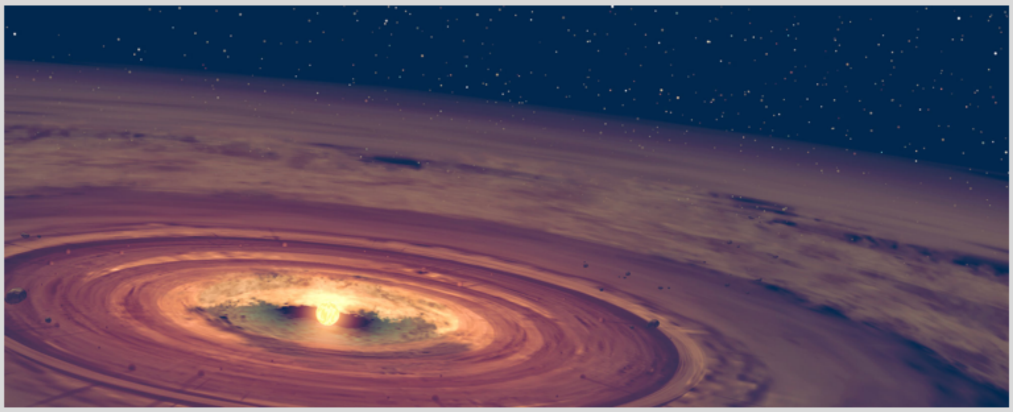
# Time scales for stellar birth




- Highest mass stars live the shortest lives
- Lowest mass stars live the longest

# When does a star become a star?

- When it hits a certain temperature?
- When it crosses a specific mass threshold?
- When it has a disk and can form planets?



https://news.virginia.edu/content/uva-astronomers-find-oasis-brown-dwarf-desert

## When does a star become a star?

- When it hits a certain temperature?
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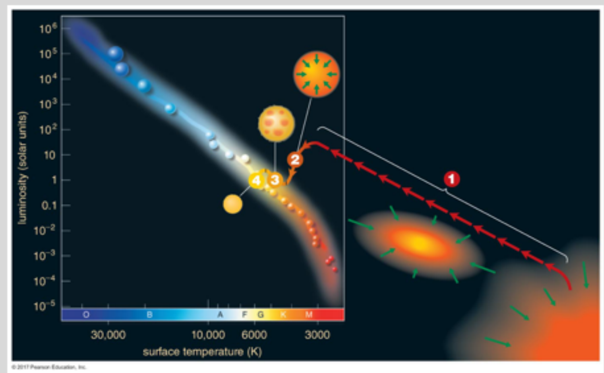
- **When it joins the main sequence**: outward pressure from H fusion balances inward force of gravity
- Before the main sequence, it is a pre-main sequence star or a protostar.

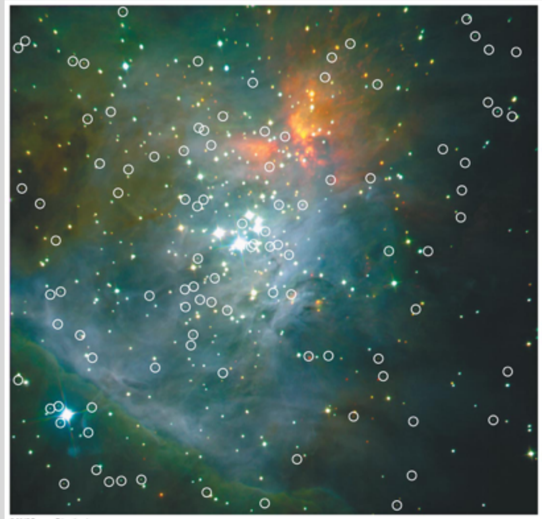


# When is a star a star?

- …and not, say, a planet?
- How small can a star be?
  - At low enough mass, dense core never becomes hot enough for fusion to be sustained
  - Collapse continues until *degeneracy pressure* halts it from going any further

# Brown dwarfs

- Thermal energy from formation gradually radiated away
  - Easier to see when hottest- young brown dwarfs in star forming regions
- This happens for < 0.08 Msun: called a sub-stellar object, or Brown Dwarf
- Brown dwarfs live in fuzzy region between stars, planets
  - Jupiter is 0.001 Msun; it is not a brown dwarf



## How massive can stars get?

- Remember as temperature goes up, so does rate of fusion
- At some point, fusion producing so much radiation pressure, it can overcome gravity and either blow a star apart, or not allow it to form at all
- Theoretical models show stars over 100 $M_\odot$ would blow apart
- Observations indicate stars ~120 $M_\odot$ may exist
  - Hard to measure masses—need a binary
  - Hard to measure short-lived, highest-mass stars: very rare!
  - How could it be >120 $M_\odot$? Two less massive stars could have merged? Unknown!

https://www.spacetelescope.org/images/opo1235b/