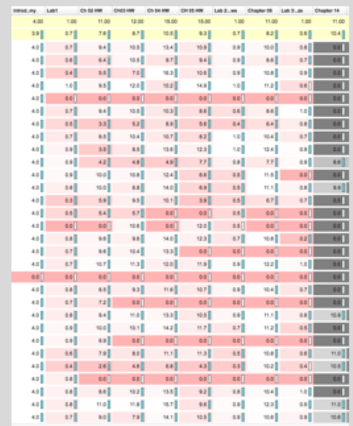
# Logistical notes

- Vaccines …?
- Homeworks
  - Chapter 14 due ~~today~~ Monday!
  - Average completion time: 13mins
  - Talk to me if you've fallen behind on homework. Email, office hours; just talk to me. I'm receptive: I want you to be on track and getting things done, not overwhelmed by the volume of work, especially if it's already piled up a bit.
  - It's better to attempt the homework and get something wrong than to let days (and -10% per day) slip by
- Exam corrections due to me/in my mailbox by Friday at 5pm!

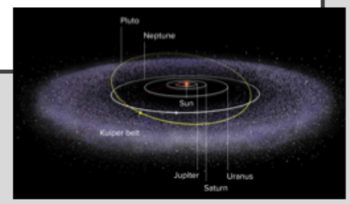


## Math/significant figures

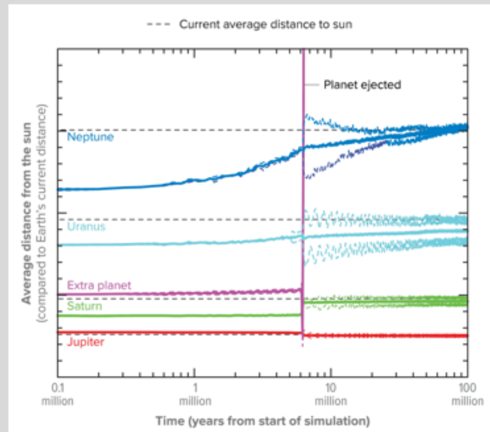
- Chapter 14 homework asks questions about…
  - how long the Sun could burn
    - You're given how much energy it has per unit mass
    - You know how much it radiates (Luminosity: Watts (aka J/s))
  - how much mass the Sun loses due to fusion
    - You're told to assume its luminosity is constant
    - You're told the lifetime is 10 billion years
    - You know its luminosity
    - Use $E=mc^2$, rearranged, to calculate mass
- Significant figures:
  - Any non-zero integer is significant (1, 2, 3, …)
  - Any digit expressing the limit in precision that you can measure is significant
    - Examples:
      - 2.0 – 2 sigfig
      - 0.02 – 1 sigfig
      - 2000 – 1 sigfig
      - 2000. – 4 sigfig
      - $2\times10^6$ – 1 sigfig
      - 2.0300 – 5 sigfig
      - 0.00203 – 3 sigfig

Let me know if you already attempted this problem and had issues- I can adjust points up if you re-work it

# Today in science…




- Planet X?
- “Orbital Forensics Hint at Sun’s Long-Lost Planet”
  - Early orbital simulations ended with Uranus and Neptune being ejected
    - ‘the problem is Jupiter, it’s a massive bully with far-reaching $F_g$’
  - Scientists created millions of randomized early solar systems, let their orbits evolve
  - Only 1% of the time would planets settle into orbits as we know them today
  - Scientist David Nesvorný tried adding “martyr planets” to be main recipient of orbital energy from Jupiter and ejected




https://www.scientificamerican.com/article/orbital-forensics-hint-at-suns-long-lost-planet

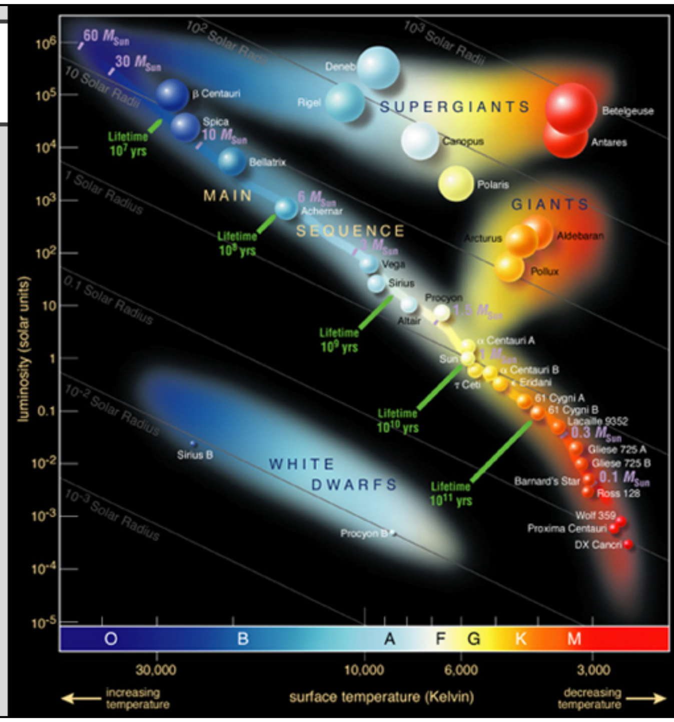
Simulate your own outer planets!

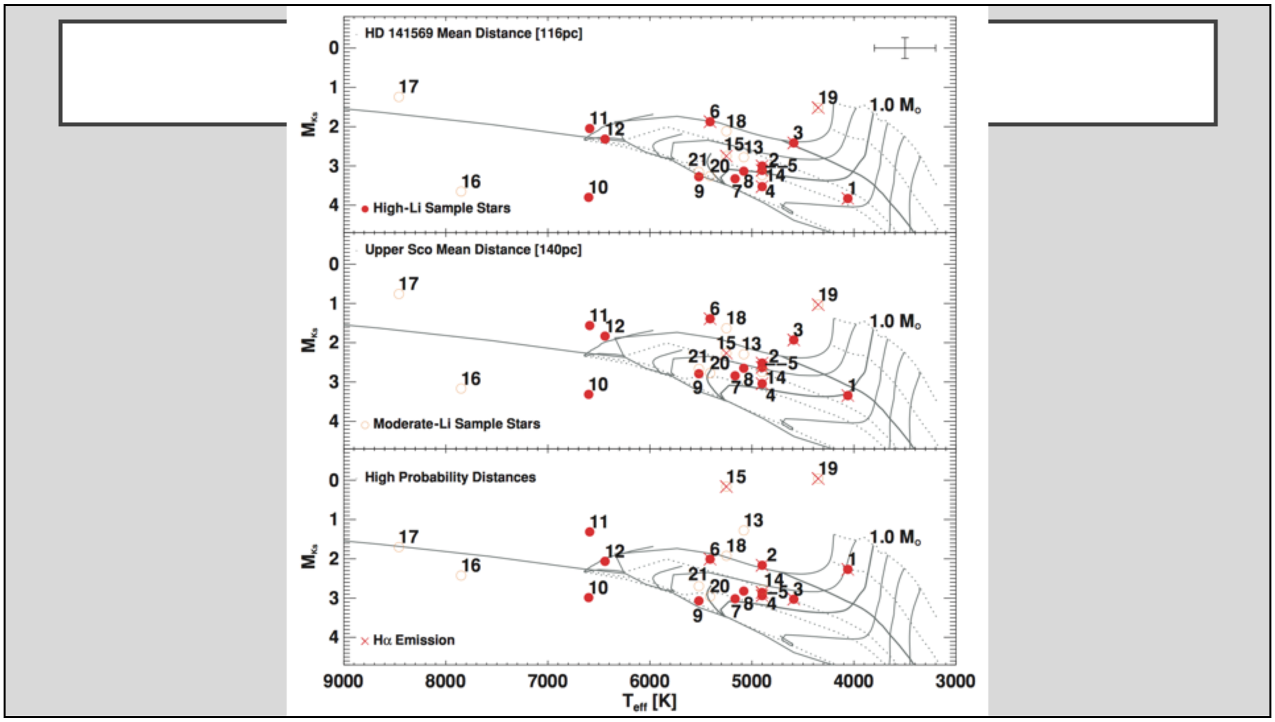
http://lasp.colorado.edu/education/outerplanets/orbit_simulator/


Melotte 15

# The H-R diagram

- Rosenberg, Hertzsprung and Russell were working on this around the same time.. 1910, 1911, 1913
  - Plotting spectral lines indicative of temperature against stars' apparent magnitudes, absolute magnitudes, and eventually, luminosities
  - Shows a relationship between fundamental stellar properties: temperature and brightness
  - Note to Alicia: don't forget to do H-R Diagram demo here.


SUPERGIANTS
GIANTS
MAIN
SEQUENCE
WHITE
DWARFS
Deneb
Rigel
Canopus
Polaris
Betelgeuse
Antares
Arcturus
Aldebaran
Pollux
β Centauri
Spica
Bellatrix
Achernar
Vega
Sirius
Altair
Procyon
α Centauri A
Sun
α Centauri B
τ Ceti
Eridani
61 Cygni A
61 Cygni B
Lacaille 9352
Gliese 725 A
Gliese 725 B
Barnard's Star
Ross 128
Wolf 359
Proxima Centauri
DX Cancri
Sirius B
Procyon B
60 $M_{Sun}$
30 $M_{Sun}$
10 $M_{Sun}$
6 $M_{Sun}$
1 $M_{Sun}$
0.3 $M_{Sun}$
0.1 $M_{Sun}$
Lifetime $10^7$ yrs
Lifetime $10^8$ yrs
Lifetime $10^9$ yrs
Lifetime $10^{10}$ yrs
Lifetime $10^{11}$ yrs
$10^2$ Solar Radii
$10^3$ Solar Radii
10 Solar Radii
1 Solar Radius
0.1 Solar Radius
$10^{-2}$ Solar Radius
$10^{-3}$ Solar Radius
luminosity (solar units)
$10^6$
$10^5$
$10^4$
$10^3$
$10^2$
10
1
0.1
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
O B A F G K M
30,000
10,000
6,000
3,000
increasing temperature
surface temperature (Kelvin)
decreasing temperature

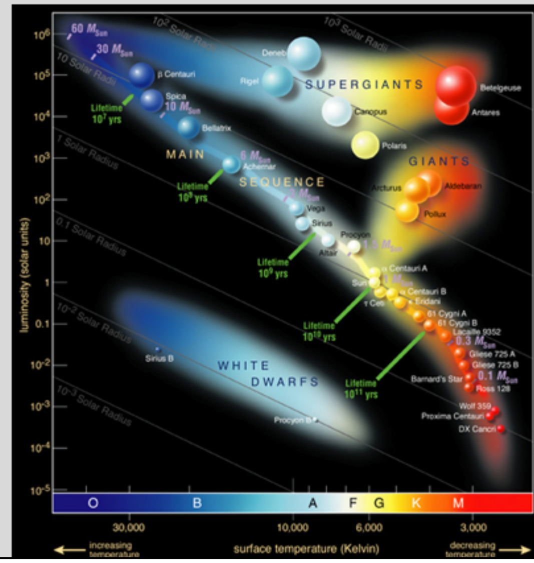



This is a figure from my first paper where I made a H-R diagram for a group of stars I didn't know the distance to.

# What is the H-R diagram really telling us?

- Almost everything, tbh.
- Once brightness is corrected for distance, intermediary effects, H-R diagram can tell us:
  - Stellar temperature
  - Stellar radius
  - Stellar mass
  - Stellar age

- Is this easy to measure/model? No! But ideally, yes- you can get all of this information out of the H-R diagram



## What is the most fundamental stellar property?

- What determines everything about a star?
  - How long it lives (fuses at its core)?
  - How hot its surface gets?
  - Its radius and brightness?

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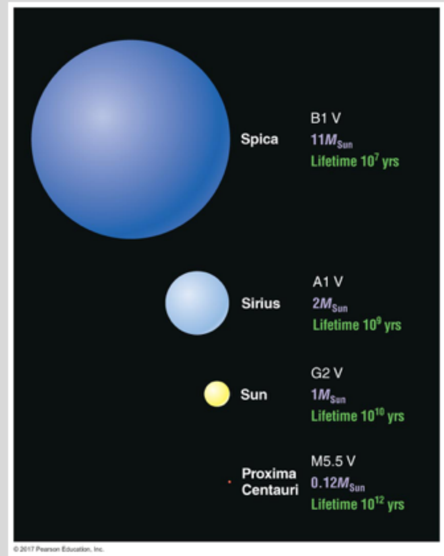
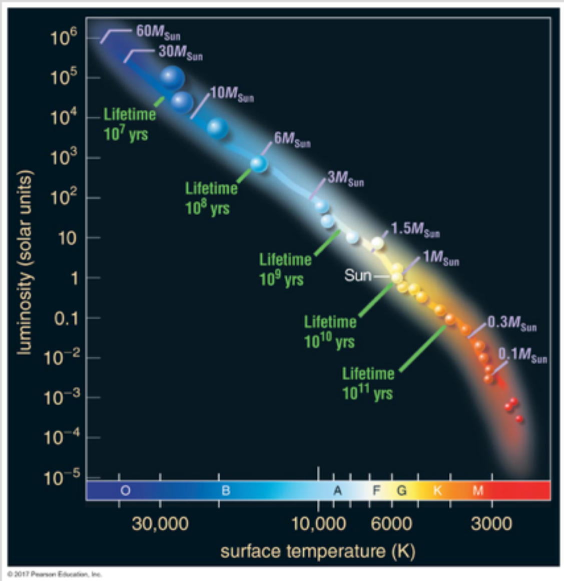
  - How hot its surface gets?
  - Its radius and brightness?

- Its mass!



# The main sequence






- Stars on the main sequence are burning H in their cores
- Stars of different masses have both varying amounts of H to burn, and different rates of burning
  - This leads to different lifetimes
    - Very massive stars are rare!
  - The most massive stars have the shortest lives

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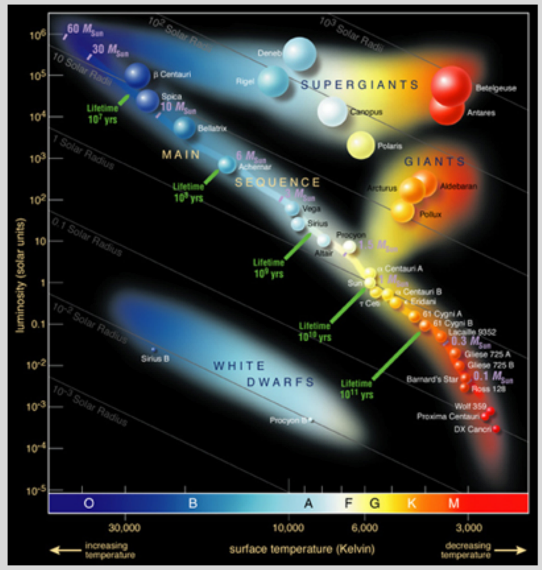
    - Very massive stars are rare!
  - The most massive stars have the shortest lives
  - And yet..They play a very important role in stellar evolution and the chemical enrichment of the universe

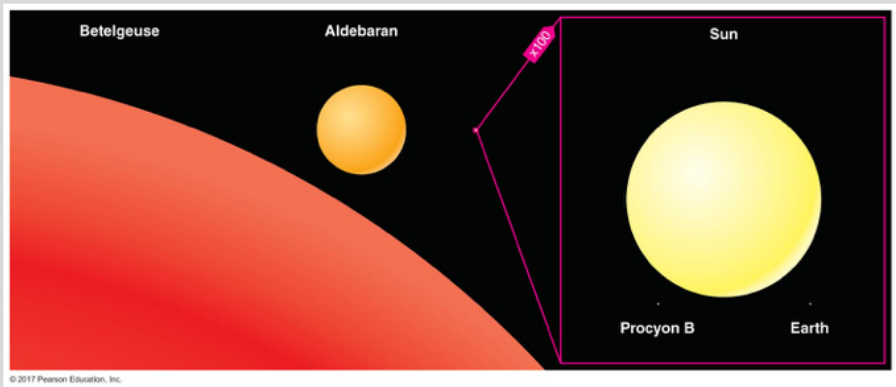
# After the main sequence…

- Giants and Supergiants
  - Cooler and more luminous than the Sun (larger radii)
  - Nearing end of their lives: H fusion has ended, trying to fend off $F_g$
  - Will talk about more in chapter 17…

- White dwarfs
  - What's left after a Giant or Supergiant poofs off its outer atmosphere
  - About Earth-sized, but ~Solar mass
  - No energy source, so they just cool into eternity

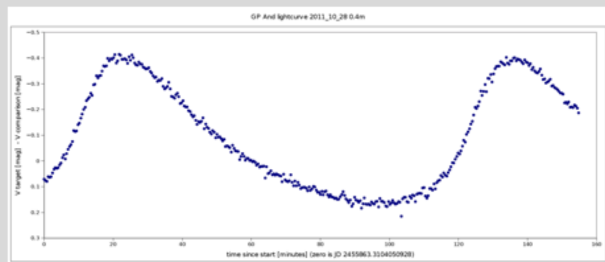


## Size scales: Supergiants, Giants, the Sun, red dwarfs, the Earth



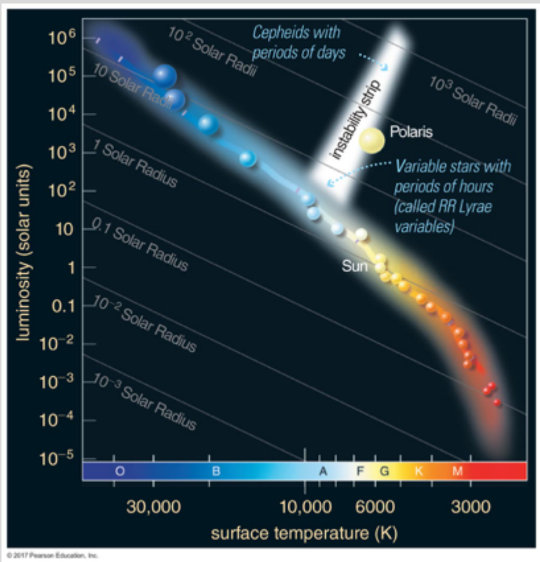
# After the main sequence…

- What happens when stars run out of H?
  - Gravitational equilibrium lost: can have pulsations, variability
  - Recall: fusion reactions decrease the numbers of light elements in the core of a star
  - Proton-proton chain no longer functions
  - Heavier elements start to fuse
  - Reactions begin in outer layers of star: instabilities develop



https://www.sheffield.ac.uk/physics/teaching/astronomy/hicks_telescope/hicks_observatory_pics

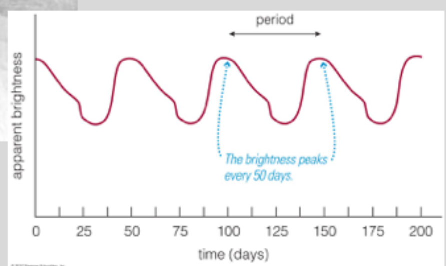
# After the main sequence…




- Variable stars: their luminosity, as the name implies, varies with time!
- Categories of pulsating variable stars, depending on period of luminosity changes:
  - Delta Scuti (minutes-hours)
  - RR Lyrae (hours)
  - Cepheids (days-weeks)
- What are other forms of variability we've talked about?
  - Eclipsing binaries
  - Spotted stars

# Cepheid Variables

- Discovered by Henrietta Swan Leavitt




- What's the big deal with these stars?
  - They are really bright
  - Like, seriously really bright--we can see them in other galaxies, they're that bright
  - Weirdly, their pulsation periods are related to their luminosity
    - Remember: Luminosity is the star's inherent brightness—distance independent!
    - We'll learn more in Chapter 20…

# Star clusters

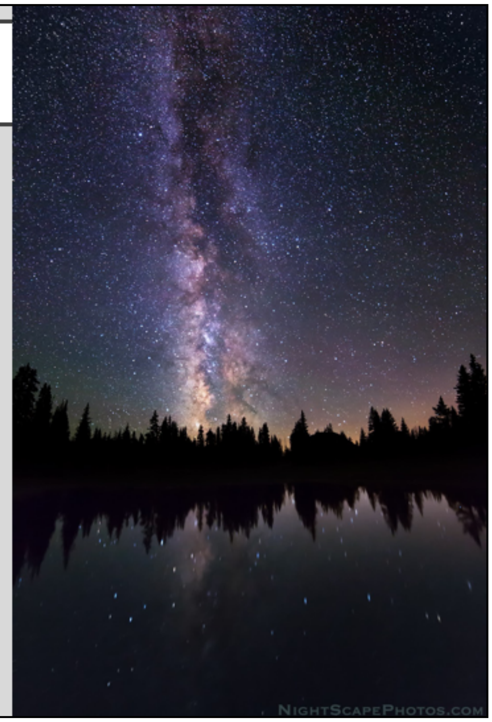
- Remember how sun-like stars born from cloud of gas and dust?
- More than one star can be born in one of these clouds, depending on its size and mass distribution!
- Entire star-forming regions are observed
- Clusters of stars of various ages:
  - Associations and moving groups (very young)
  - Open clusters (main sequence-ish and older)
  - Globular clusters (very old)

## Clusters in the Milky Way

- We think the Milky Way is shaped kind of like a UFO…
  - The flat part is called the *disk*
  - The middle part is called the *bulge*
  - The parts away from the plane of the galaxy are called the *halo*
- Different parts of the galaxy are thought to be different ages, possibly due to how the Milky Way formed
- Stars in the Milky Way form and evolve in clumpy structures (the Milky Way's spiral arms)
- Stars in clusters are gravitationally bound to the center of mass of the cluster: orbits can be complex, depending on how dense the cluster is!

# Open clusters

- Open Clusters are
  - younger, always found in the galactic disk
  - less densely packed (~few 1000 stars)
  - typically about 30 ly across
  - example: the Pleiades (aka Subaru...)




http://intothenightphoto.blogspot.com/2014/07/finding-milky-way-with-sky-guide.html

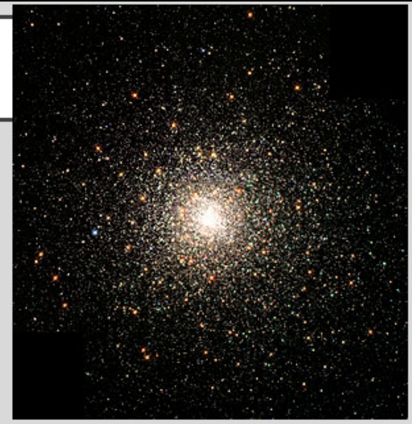
# Open clusters

- Open Clusters are
  - younger, always found in the galactic disk
  - less densely packed (~few 1000 stars)
  - typically about 30 ly across
  - example: the Pleiades (aka Subaru..., aka the Seven Sisters)
    - Several 1000 stars, we can see about 6 of them
    - Looks like a wee tiny dipper
    - About 100 Myr (million years) old


Subaru also means 'unite' in addition to referring to the constellation known as pleiades

# Globular clusters

- Globular Clusters are
  - older, found in the galactic halo
  - can have >1,000,000 stars!!!
  - typically 60-150ly across
  - planets in this cluster would likely have lovely nights
    - densely packed=lots more very, very nearby stars
    - Milky Way would possibly take up bigger segment of night sky

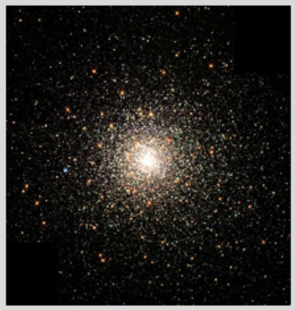


https://en.wikipedia.org/wiki/Globular_cluster – M80 (top)

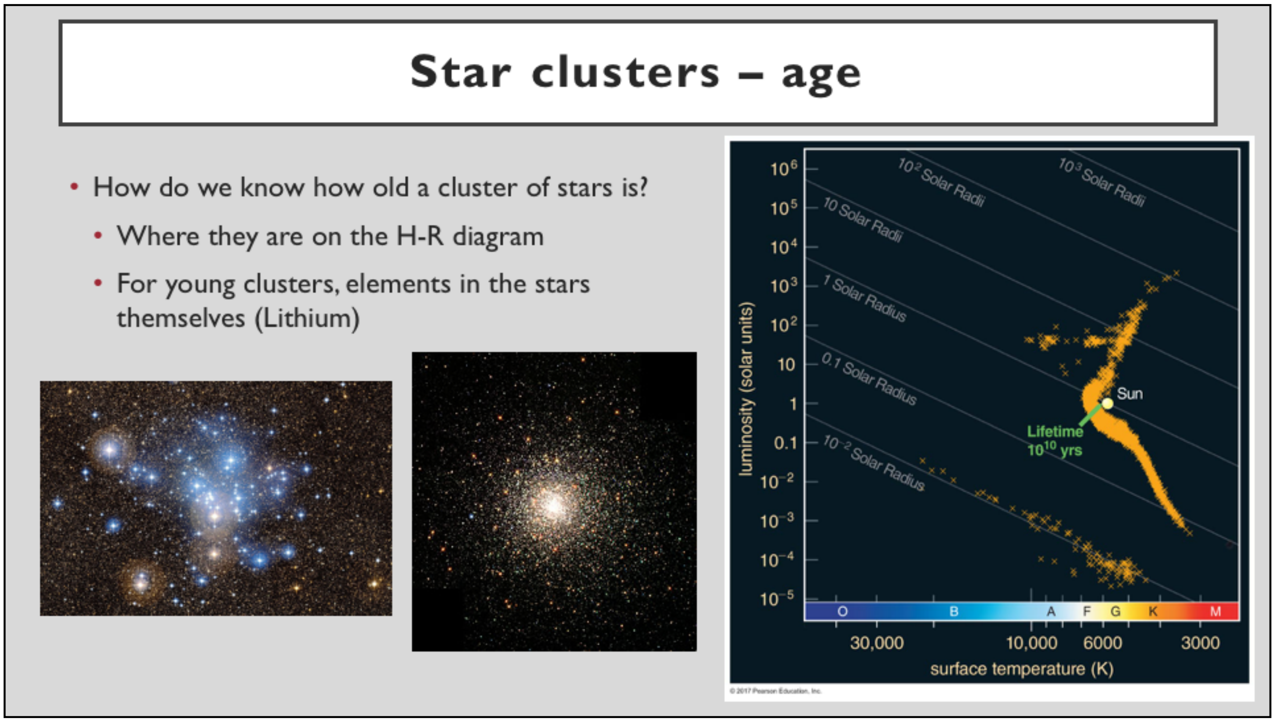
http://www.apod.nl/ap100527_nl.html -- M13 (bottom)

# Star clusters

- How do we know how old a cluster of stars is?



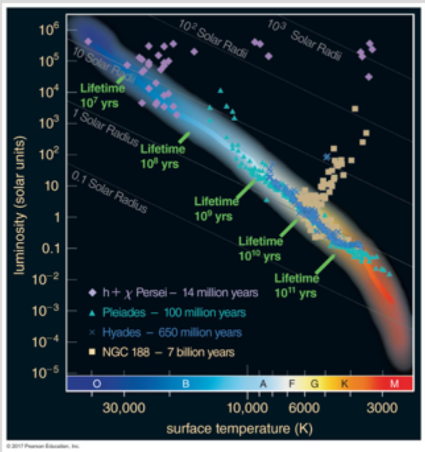
Compare the pictures here of the open and globular clusters… what pops out at you right away?



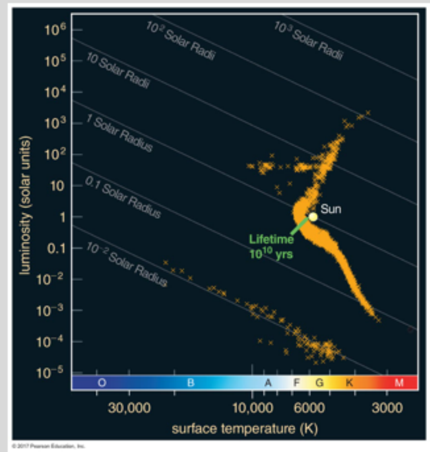

Compare the pictures here of the open and globular clusters… what pops out at you right away?

# Star clusters – age

## Open Clusters




## Globular Cluster ~$10^{10}$yrs




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

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## Stellar nurseries

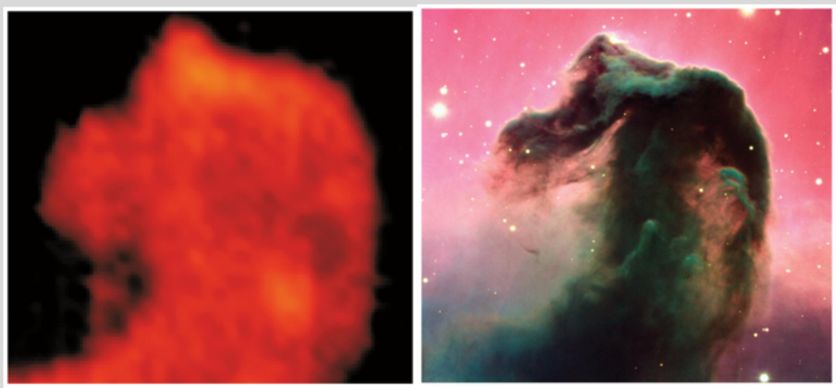
- We use imaging to put stars onto the H-R diagram
- The H-R diagram shows us stellar ages, the imaging shows the youngest stars are near dark clouds of gas and dust
    - …are they really dark?

**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



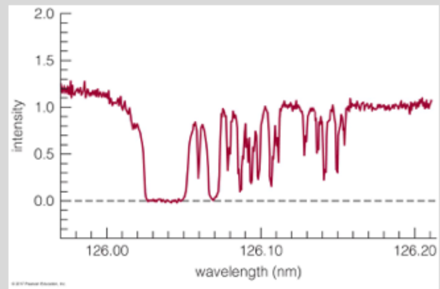
**b** Radio-wave image of the nebula showing emission from carbon monoxide (CO) molecules.

**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.

## 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

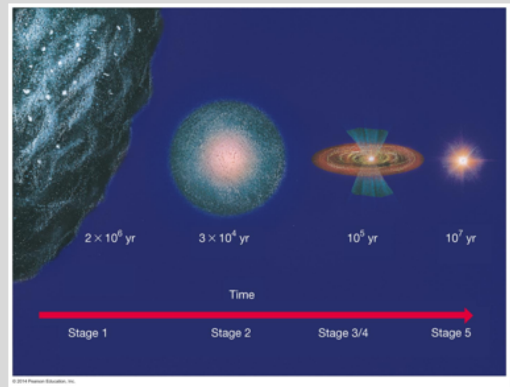

Visible light vs infrared light

# 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

## 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



# Star formation: wrinkles and mysteries

- We see stars forming only 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


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).

**What topics do you have questions on after today's class?**

Clicker free response question, anonymized polling

- What from today might have been unclear?
- What would you like me to review next class?
- Is there some question on your mind I haven't answered yet?