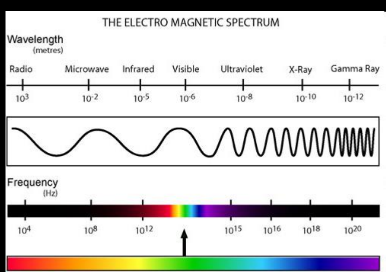
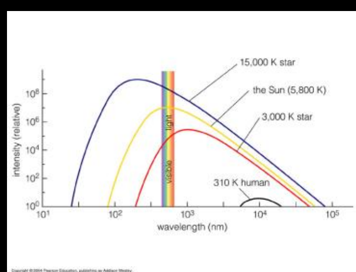
Upcoming Astronomy-themed Talks and Events

Thursday, 10/24, 3:45-5:00p Astronomy Colloquium – Phys-Astr A102 – Sally Oey (Michigan) – “Suppressed Superwinds: A New Paradigm for Extreme Massive-Star Feedback”.

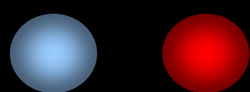
Quick Recap:

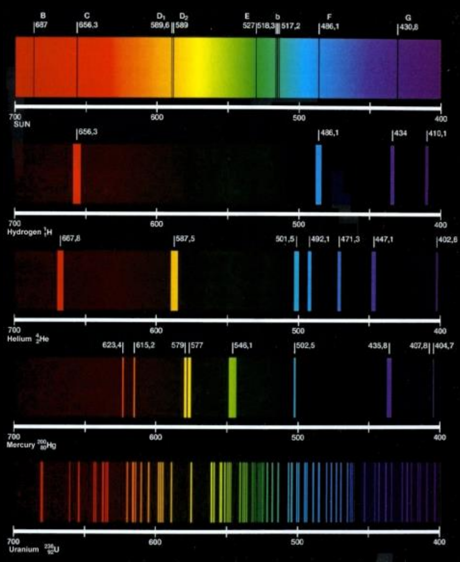


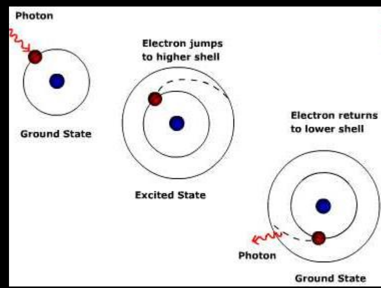


The basics of light.

The relationship between light and heat.

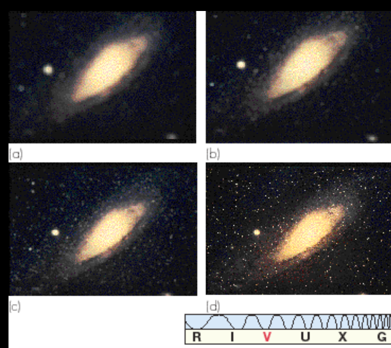






The interaction of atoms with light (or other forms of energy) to produce emission spectra.

We also talked about telescopes, and the advantages to be gained by making them very large:



1. More light-collecting area, which lets us see fainter objects.

2. Greater angular resolution, which lets us see objects in greater detail.

It’s not always clear skies at Mauna Kea’s Keck Observatory!

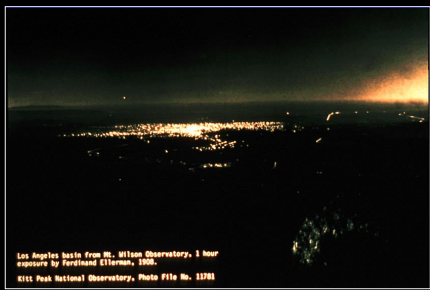
But we had just begun (with a very sad tale!) to discuss the practical issues of collecting light coming to the Earth from above its atmosphere. That atmosphere is notorious for torturing astronomers in ways that just begin with mountain snowstorms!

The sky above a house in Ontario, Canada – before and after the placement of a poorly designed streetlight.

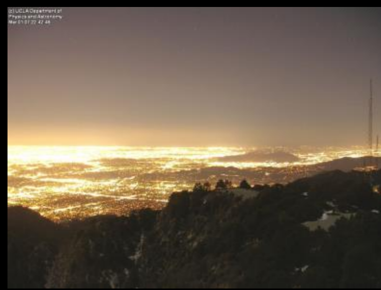
The atmosphere also ***reflects*** light from the surface – typically man-made lights – making the night sky brighter.

This effect is called ***light pollution***, and it can dramatically reduce what you can see at night!

The changing view from the Mt. WilsonObservatory, CA, just outside Los Angeles:



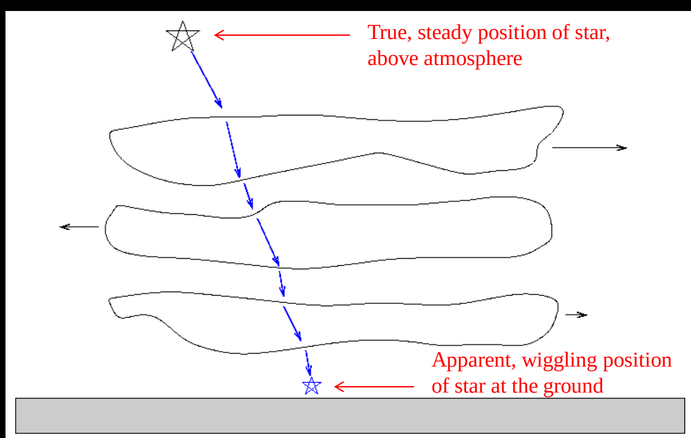
A 1-hour exposure in 1908



< 1-second exposure in 2007!

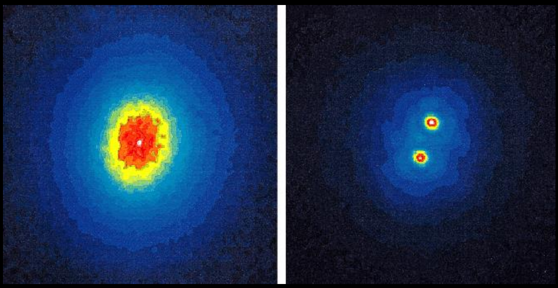
Light pollution is one of the major reasons that astronomers seek to place their largest telescopes in remote locations – unfortunately, the front lines of this battle are constantly shifting!

But there's more: turbulence in the atmosphere also ***distorts*** light, making stars appear to "twinkle" in color. This apparent jiggling of the stars also causes their ***angular resolution*** to be degraded.



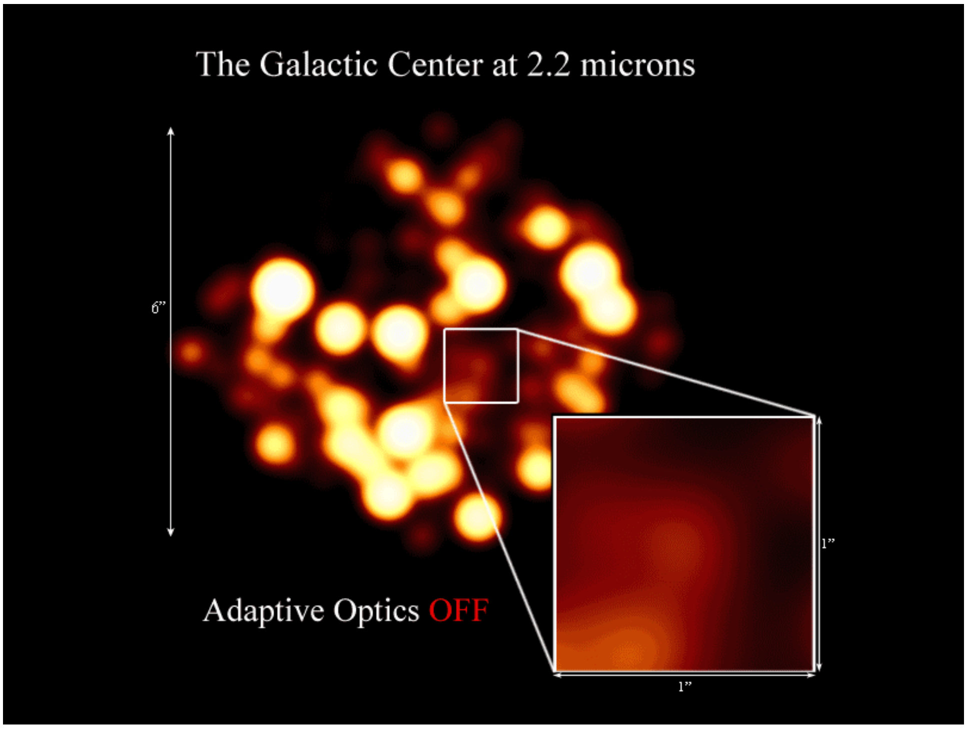
Moving atmospheric cells with different temperatures and pressure affect the light that passes through them. The result is a "blurry" or "smeared" image.

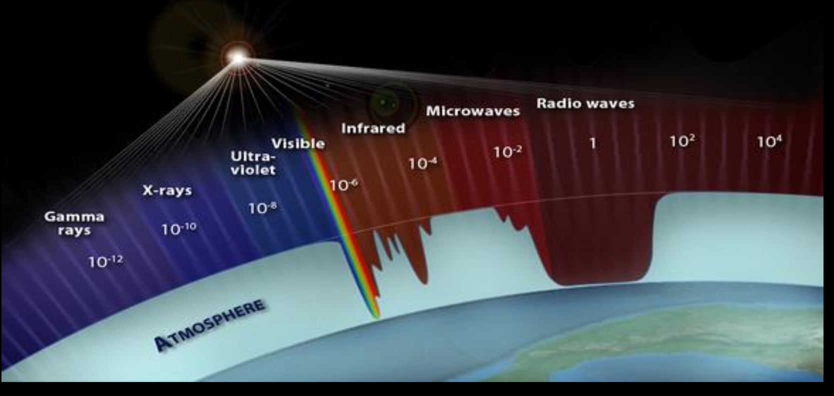
Thanks to new technologies (there we go again!), it is has recently become possible to “de-twinkle” stars using ***Adaptive Optics***. This is done by monitoring the distortions of light from a known, standard source (often a laser shot up into the air), and then moving the telescope’s mirrors millions of times per second in a way that precisely counters the atmospheric distortions.



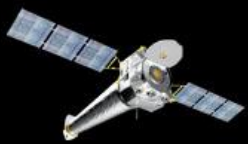
adaptive mirror off   adaptive mirror on

The light waves can then be restored to their original state, improving the angular resolution. These two stars are separated by 0.38 arcseconds; without this technique, we’d see only one star!





But the most severe problem caused by the atmosphere is ***absorption*** of light. Earth’s atmosphere absorbs most types of light – which is a good thing, or we would be dead! Only visible, radio, and some IR and UV light make it to the ground.



Chandra X-ray Observatory

Hubble Space Telescope

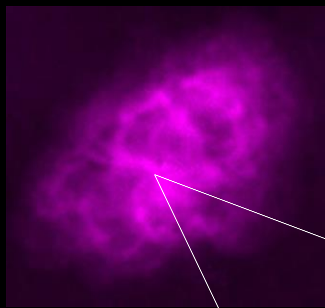
Seeing these forms of light is ***the key reason*** we put telescopes in space (it's certainly **<u>not</u>** because it moves our instruments any closer to the stars!) – although these telescopes are also happily free from weather and light pollution, and the distortive effects from the Earth's turbulent atmosphere.

X-ray

Visible

Infrared

Those non-visible wavelengths of light are critically important, giving us information about what's physically happening in areas of different pressures, temperatures, and chemical composition!



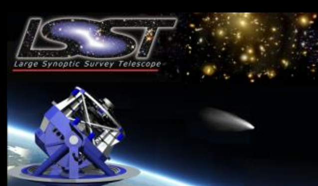
An X-Ray image of the
Violent Center of the Crab Nebula

These images
could not be taken
without the use of
space-based telescopes!

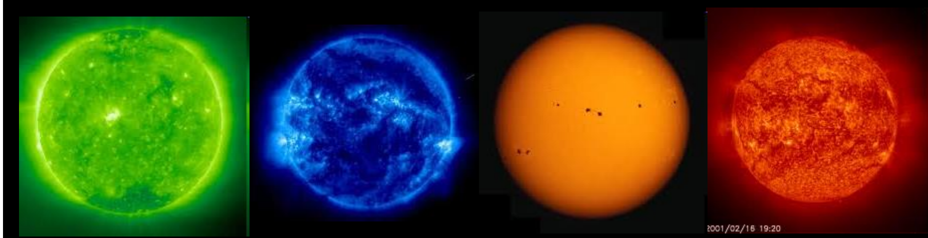
However, space-based telescopes have much, **much** higher costs than their terrestrial cousins. The 2-meter wide Hubble Space Telescope, for example, cost over 2 billion dollars to make operational, while the 9-meter Hobby-Ebberly Telescope cost less than 200 million dollars – a factor of 10 cheaper, and a lot easier to maintain or upgrade too! Riding on a bomb not required!

The 6.5m James Webb Space Telescope, scheduled for launch in 2021, will revolutionize our view of the infrared universe, capturing data completely unavailable from the ground – but it will have cost over 9 billion dollars! Far more than the 1-2 billion dollars it would cost to build a 100m telescope on the ground!

Nevertheless, costly though they may be, thanks to the growth of space-based observatories – as well as continuing advances in ground-based telescope and computing technology – we here in the 21st century have the ability to measure almost every form of light coming from outer space in staggering detail.



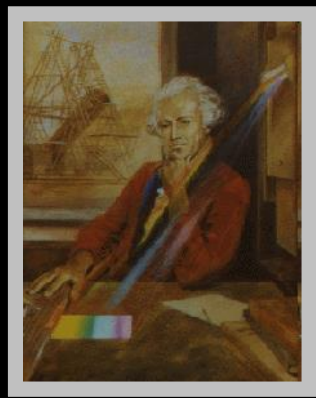
What can all of this light tell us about the Sun – and by extension, the other stars?



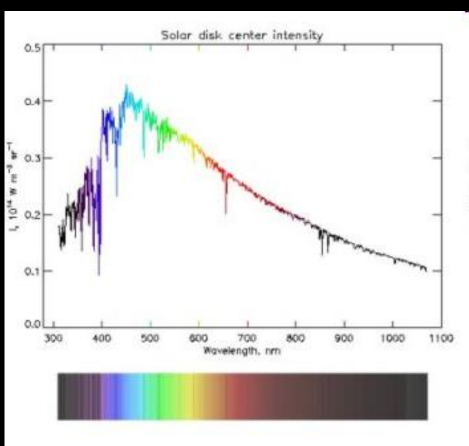
We'll start our exploration of that by taking on a very old question, only answered less than a hundred years ago – how does the Sun produce its energy?

From the point of a view of a modern scientist, you might think this would be a question that humanity would have explored in depth a long, long time ago. It is THE SUN, after all – giver of life and light and all that sort of thing.

But even a *basic* understanding of the inner workings of the Sun eluded astronomers and physicists for centuries. In 1795, for example, William Herschel – arguably the greatest astronomer of his time, discoverer of Uranus, and the person who first found that there *were* "nonvisible" forms of light – proposed that the Sun was actually *cool* in its interior, and might support life on its surface.

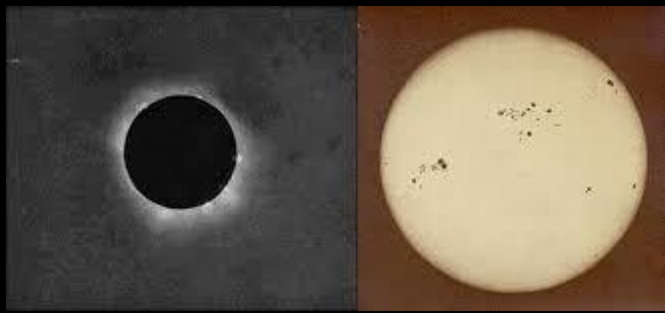


William Herschel, 1738 – 1822; musician turned astronomer!



However, by the turn of the 20th century, the science of spectroscopy – the careful study of the emission and absorption lines we discussed last time – had begun to reveal secrets about the composition and structure of the Sun.

Basic Stats of the Sun – all known by ~ 1900.



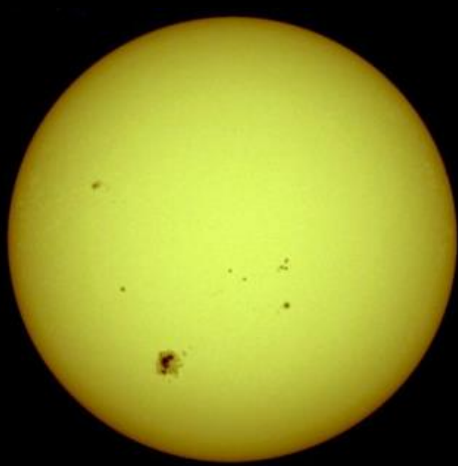
Radius: 6.96×10^5 km
(Earth ~ 6.37×10^3 km)

Density: 1.41 g/cm^3
(water = 1 g/cm^3)
(rock ~ 4 g/cm^3)

Distance: 1.48×10^8 km
= 1 A.U.

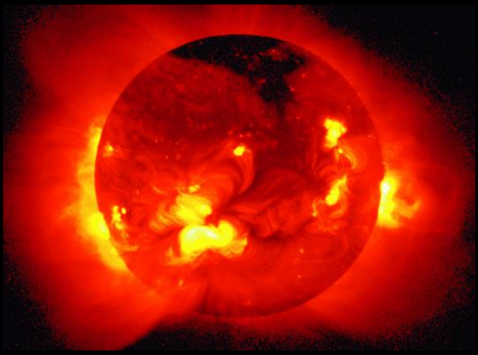
Mass: 1.99×10^{30} kg
(Earth ~ 6×10^{24} kg)
(Jupiter ~ 2×10^{27} kg)

Luminosity: 3.8×10^{26} watts ~ 1 billion "Megatons"/sec!



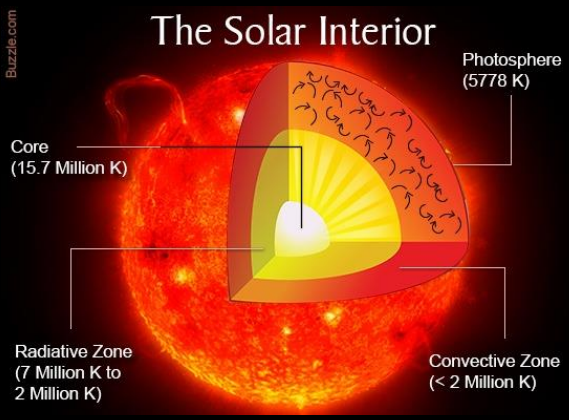
We quickly learned that most of the light and the spectral features we see come from the photosphere, a ~ 400 km thick 'atmosphere' that surrounds the opaque interior of the Sun. Its temperature is about 5,800 K, and gives the Sun its characteristic color.

We could also see the Corona – a region of very hot, ionized gas that surrounds the Sun. Its temperature is ~ 2 x 10^6 K and so it emits mostly X-rays – but it's so tenuous that it's only easily seen in ordinary visible light during a total solar eclipse.



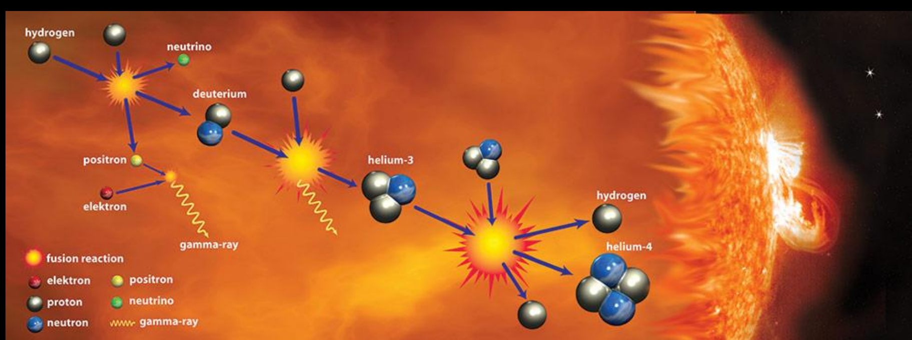
X-ray image (YOHKOH telescope)

Visible image



And though we could not observe the interior directly, from our basic understanding of gravity and the physics of gases, we knew that the core of the Sun must be even more dense and hot than the surface – an estimated 15.7 million degrees K.

As late as the 1920s, however, the ***reason*** for those high temperatures – the underlying source of the Sun's enormous (and stable!) energy output – remained a complete mystery to us. What could keep the Sun – and by extension, other stars – so bright and so hot for so long?



As a quick aside – I know you know the answer to that question, because you read Chapter 16, where they tell you that the Sun generates energy by fusing hydrogen into helium. The authors do that because it's a natural part of a chapter that describes the Sun in great detail – but the true story behind this is a bit more complicated.

Because in truth, answering that question first required us to consider the ***other*** stars, and to place the Sun amongst them – to understand our star as not just ***our Sun***, but as one of the many billions of stars in our Galaxy.

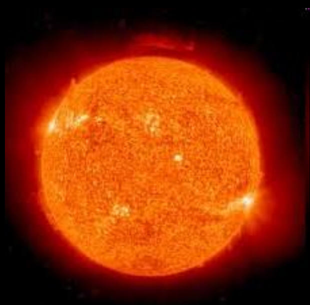
So… How do we study those more distant stars?

Well… it's tricky. Almost all other stars are so far away that they appear as unresolved points of light even in telescopes – but with the tools we've described in class so far we can reliably measure:

- how bright stars appear to be as seen from Earth
- how much and in what directions they are moving
- their color (or more precisely, their *Spectral Energy Distribution* – how much UV vs. Visible vs. Radio, etc.)
- which absorption/emission lines are present in their spectra

We must use these observations, along with our models of basic physics, to estimate more 'interesting' physical quantities:

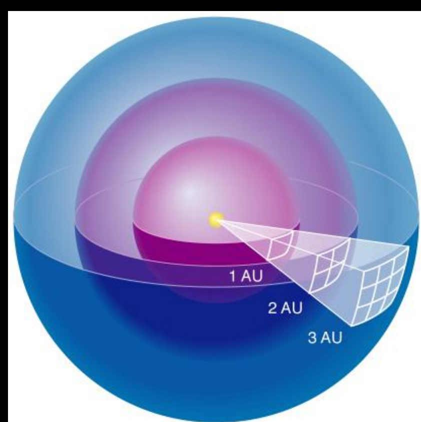
Luminosity, Distance, Mass, Radius, Temperature, Age



Luminosity – the total amount of power radiated by a star into space, as measured at the star's surface.

Apparent brightness refers to the amount of a star's light which reaches us *per unit area* here on Earth.

The relationship between the two terms is purely geometrical – since the total radiation from any star is diluted over a greater and greater surface area at large distances away from it, the apparent brightness measured at that distance drops off as an ***inverse-square law***.



App Bright $= L / 4\pi d^2$

Undergraduate students at the UW's Manastash Ridge Observatory – staying up late and looking at the stars!

Now from a practical point of view, measuring apparent brightness is easy these days – all we do is take a digital image of an astronomical object (such as a star), and count how many photons per second we receive on our detector.

So… if we could then find a way to measure (or reliably estimate!) *either* the luminosity *or* the distance to an object, we could use basic geometry to calculate the other value!

$$\text{App Bright} = L / 4\pi d^2$$

Measure the luminosity – get the distance!
Measure the distance – get the luminosity!

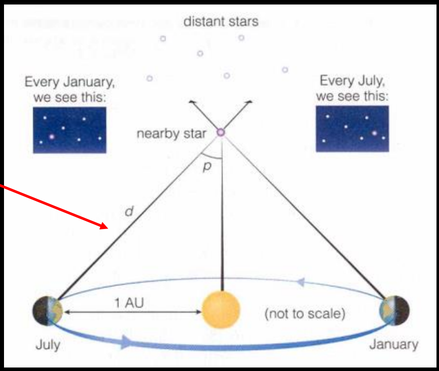
One way to measure the distances to stars is to use 'parallax', the apparent wobble of a star due to the Earth orbiting the Sun.

This is a right triangle, so the math is relatively easy:

$\sin p = 1\ AU / d$

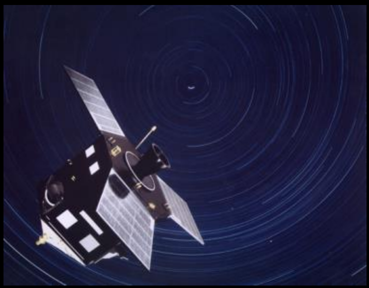
if $p \ll 1$; $\sin p \approx p$

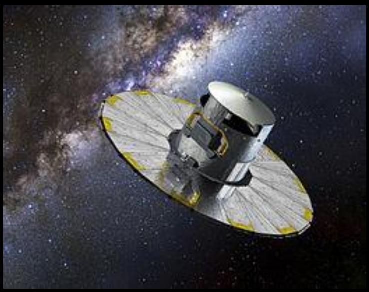
$d = 1\ AU / p$



(if 'p' is measured in 'arcseconds', then 'd' is given in units called "parsecs"; 1 parsec = 1 PARallax arcSECond ~ 3.26 light years)

Unfortunately, measuring those angles is very difficult since they are so small – and the farther away a star is, the smaller its parallax motion is. To date, we've only been able to measure the distances to about a million or so stars this way (***Hipparcos***, above right), and all of them are within a few hundred light years from us. A recently launched satellite mission, ***Gaia*** (below, right), will extend this to the nearest billion stars by 2020!

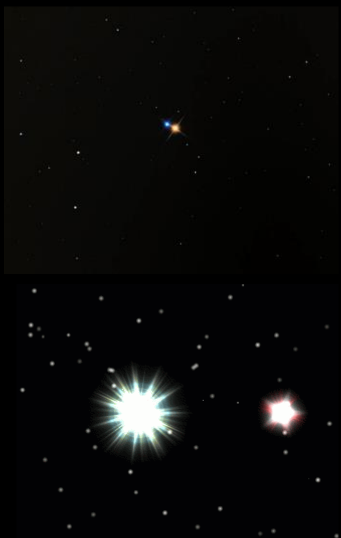




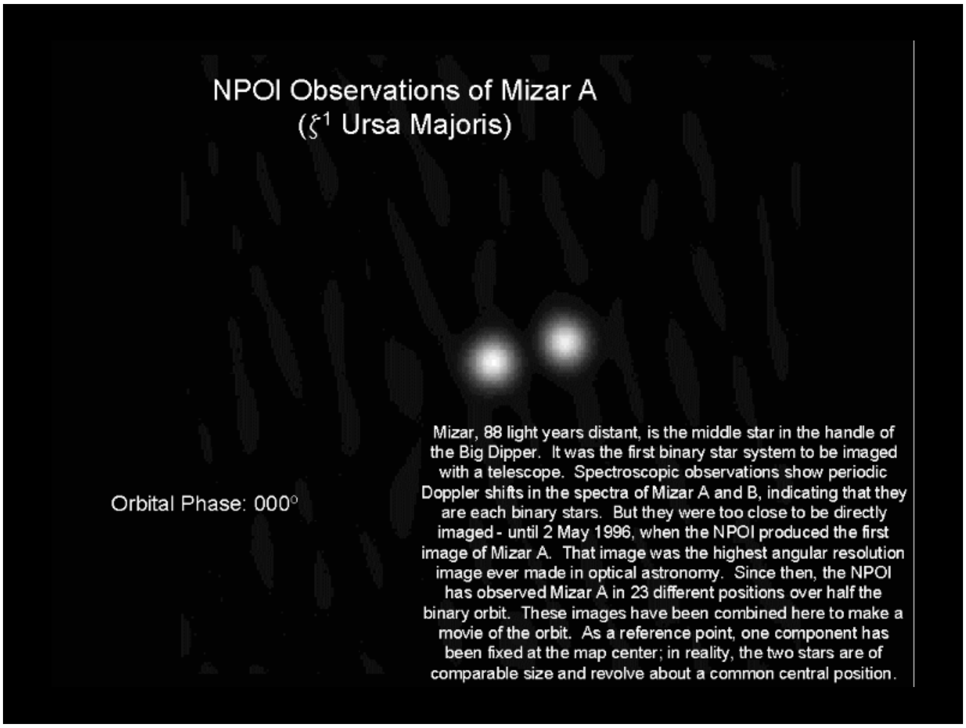
But so far we've focused on using distance to get luminosity. Is there a way to measure an object's ***luminosity*** directly, and then use that information to get the object's distance?

It is possible, and astronomers actually do this a lot – but it requires that you know a great deal about how that object is generating energy. We'll see many such ***standard candles*** in the coming weeks.

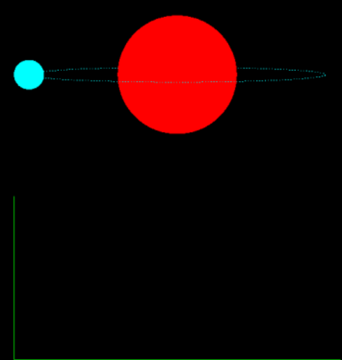
The ***mass*** of a star can also be measured from here on Earth, but only by directly observing the effect that gravity from another object has on the star. This is most easily done for stars which orbit one another in a "binary" (or more generally, "multiple") star system. If you know their distances and can measure their orbital periods, it's easy to use Newtonian physics to work out how massive they each must be.



Top, Albireo, a possible binary system;
Bottom, artist impression of a binary orbit.



Binary systems can also reveal the ***radius*** of a star – but only for stars in systems that actually *eclipse* each other. By carefully timing the details of the eclipse, such as how long it takes for one star to fully move in front of the other, and how long it takes to fully cross – the sizes of both are revealed.

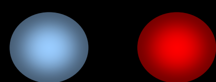


Animation of an eclipsing binary system.

$$L = 4\pi R^2 \sigma T^4$$

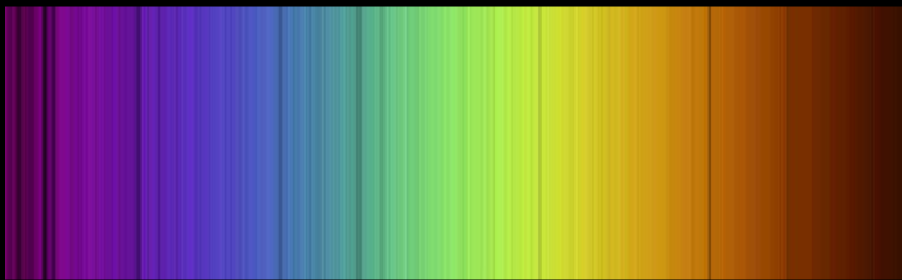
More commonly, though, we estimate a star's radius by assuming that its luminosity is based on its temperature alone, and using fairly simple and well-tested laws of thermal radiation. But this does mean that you need to know the temperature first, and know it well – any uncertainties are magnified heavily by that T^4 term!

How could you precisely measure the temperature of a star?

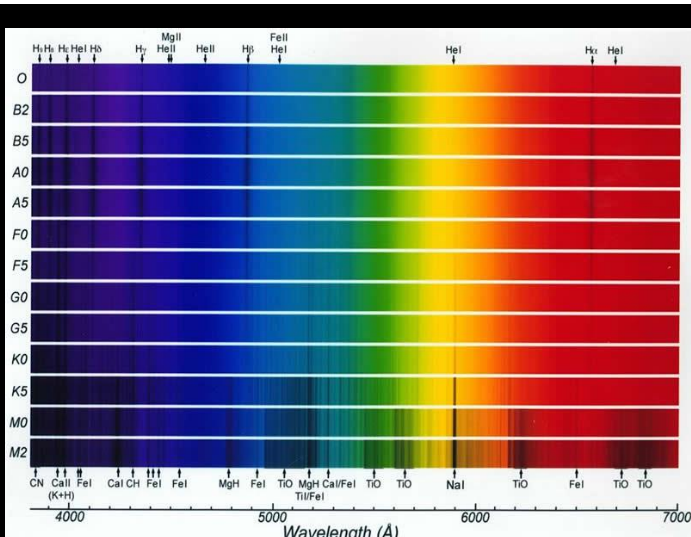


Color is one way – recall our discussion on thermal radiation! Bluer means hotter!

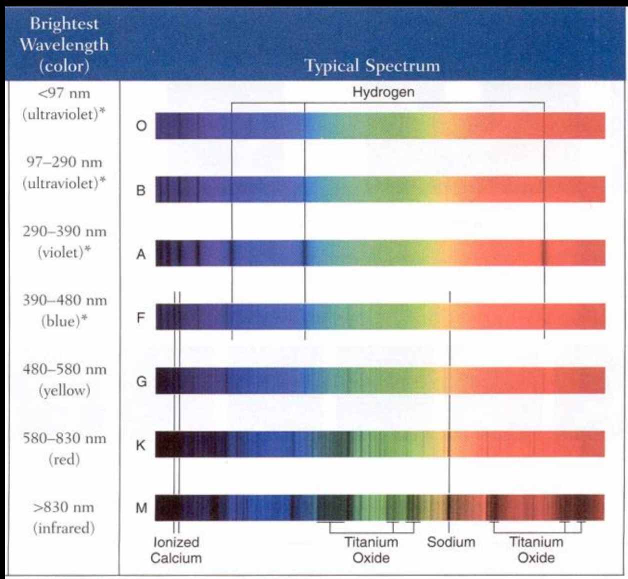
However, a much better temperature scale can be found through examining the details of stellar spectra!



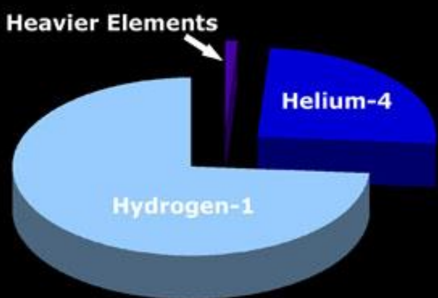
These lines tell us far more than just what chemicals are found in the atmospheres of stars!



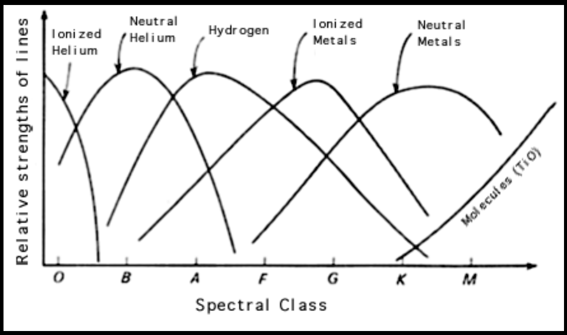
A comparison of spectra from many different stars (first done around the turn of the 20^{th} century) reveals many differences and many common patterns of absorption features.



These different "types" of spectra come from different "types" of stars – but what is the underlying difference? Because they have more spectral lines, do M-class stars have more elements?



No – it turns out that "spectral type" is <u>not</u> determined by a star's chemical composition – by mass, ***all*** stars contain roughly 75% H, 23% He, and only 1-2% of all the heavier elements combined. This dominance of H and He in stars, and the uniformity of the H-to-He mass ratio – first uncovered in 1925 by Cecilia Payne-Gaposchkin – is one of the great historical mysteries of astronomy, and one we'll return to in weeks 9 and 10!



Graphic showing the relative presence of different types of absorption lines in different types of stars.

Payne-Gaposchkin showed that the ***temperature*** of a star's atmosphere dictates the types of ***ions*** or ***molecules*** that can exist there, and the energy states of the electrons and atoms in those ions and molecules. This sets how the ions and molecules can possibly interact with light, and determines the number and the relative depth of the absorption lines in a star's spectrum.

So ***Spectral Type*** tells you ***Temperature.***

O B A F G K M (L,T)

50,000 K ← 3,000 K

Temperature

Patterns of absorption lines can reveal the temperatures of the stars to a precision of better than 50 degrees K – a factor of 10 better than what can be done by looking at "colors" alone.

Putting It All Together – the Hertzsprung-Russell Diagram

This plot, first developed in 1910, turns out to be very useful for understanding stars. It shows two major physical properties:

Temperature (x) and **Luminosity** (y)
-- or to put it another way --
Spectral Type (x) and "**Absolute Brightness**" (y)

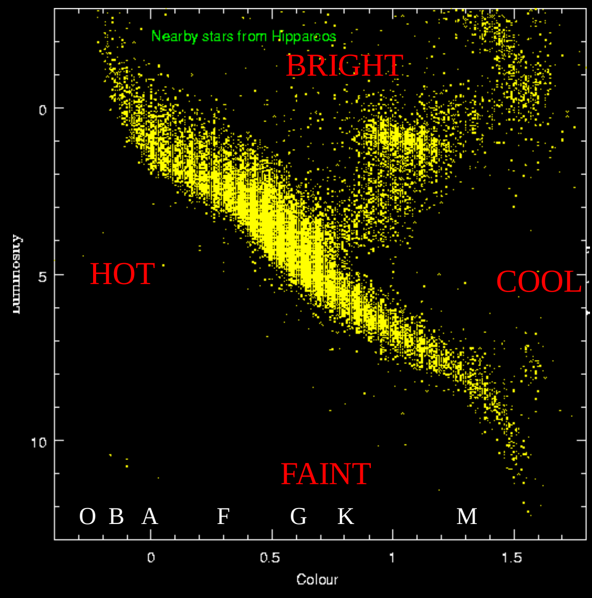
bright

M_V

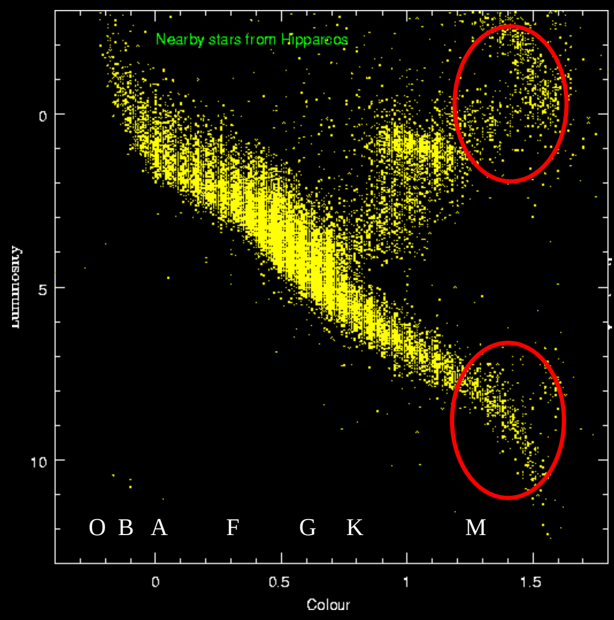
faint

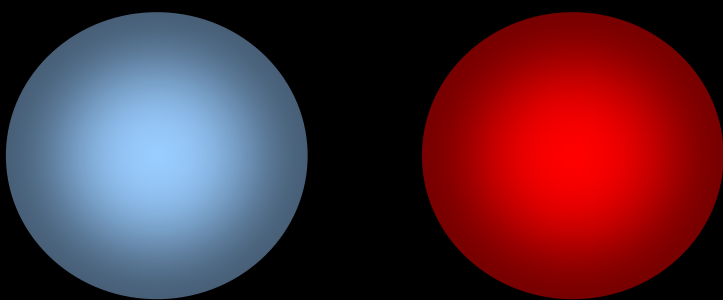
hot   Spectral type   cool

H-R Diagrams – and the many patterns of stars seen in it – reveal a great deal about how stars work.



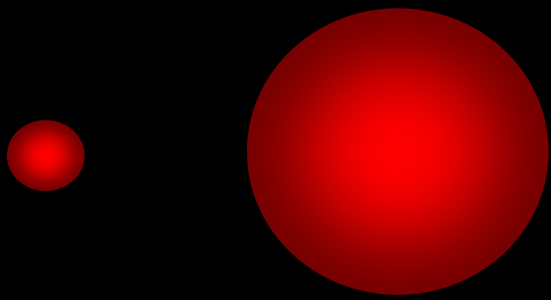
For example – notice that many stars have the same temperature, but vastly different luminosities. What's up with that?



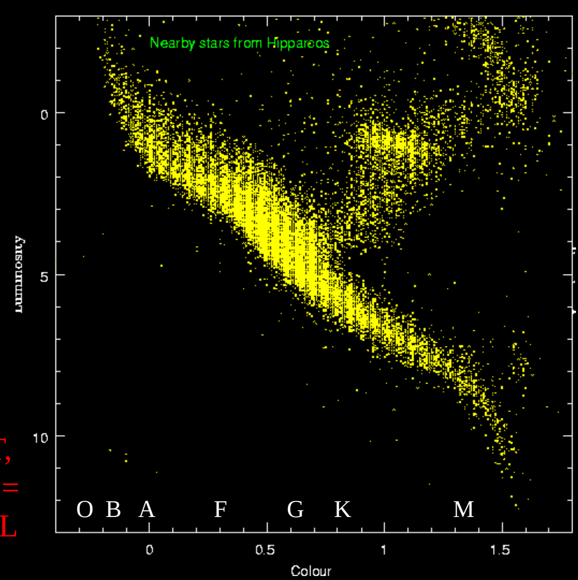


The luminosity of a star depends primarily on its surface **temperature** – at a fixed size, hotter is brighter.

But a star's luminosity also depends on its surface **area** (and therefore its **radius**) – at a fixed temperature, a bigger star is brighter than a smaller star.

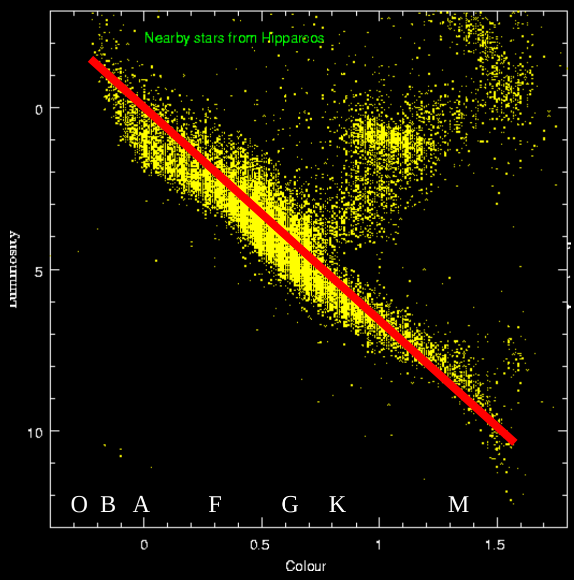


So if the temperature of two stars is the same, but they have different luminosities, then those stars must have different sizes.

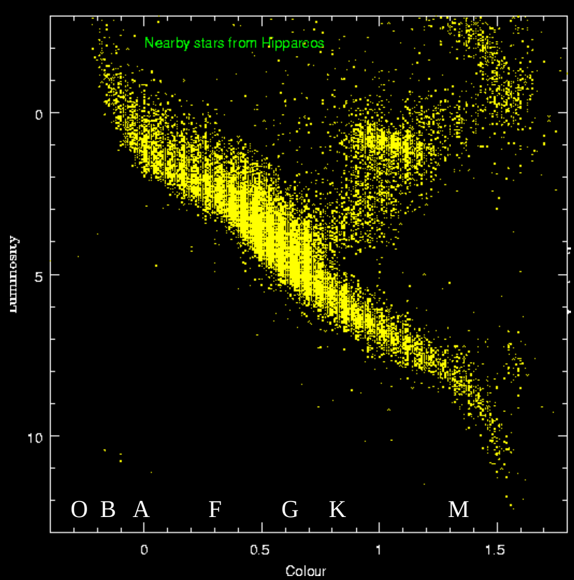


Low T, High L = BIG

High T, Low L = SMALL

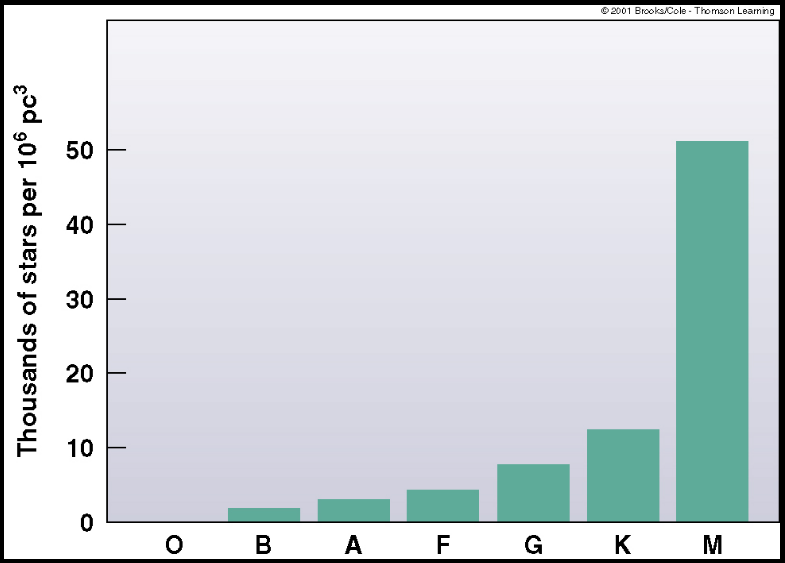


But the most striking pattern in an H-R diagram is the stripe down the center – the "main sequence" (MS). Over 90% of all stars lie on the MS, which suggests that ***most*** stars spend ***most*** of their lives generating their luminosity in a similar, temperature dependent manner.

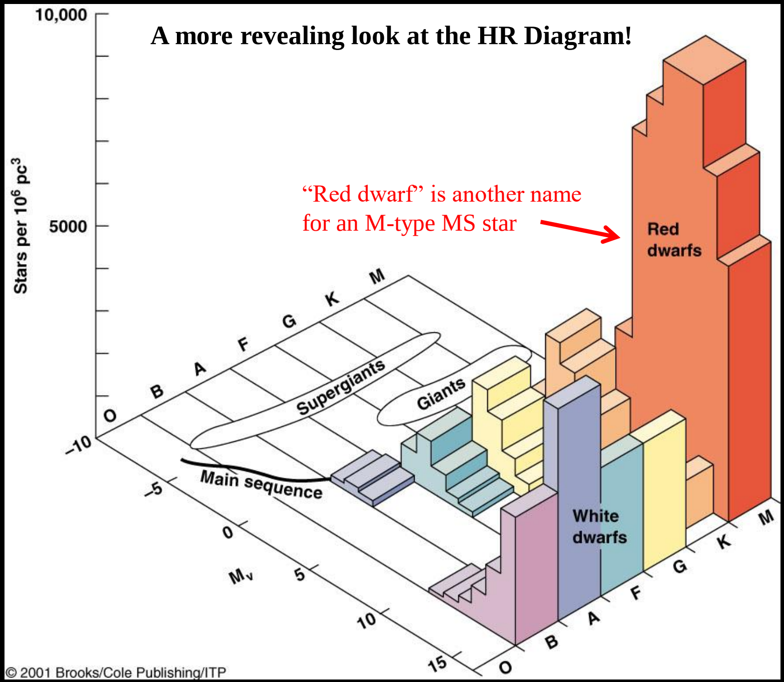


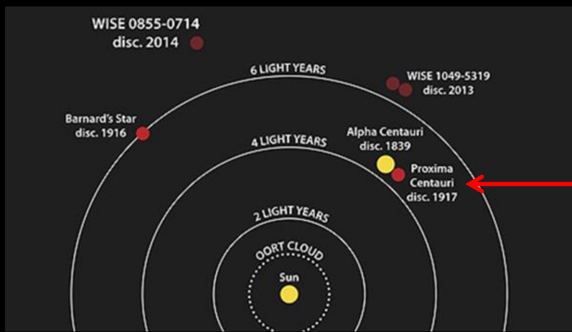
Though there's another key point about ***most stars*** to be made here before we press on, because an H-R diagram like this one disguises another key characteristic of the stellar content of our galaxy…

From this figure, what is the most common type of MS star?



Proper counting reveals that over half of all stars are type M!





As a quick aside – remember this map of the nearby universe?

That closest star – Proxima Centauri – is a spectral type M, main sequence star, and you ***can't*** see it with your naked eye!

Such dim red stars represent the overwhelming majority of stars in our galaxy, yet even the ***nearest*** is completely invisible to you!

Think about that – even on the darkest night, the stars we 'see' represent only the most luminous tip of an absurdly deeper and dimmer iceberg of stars!

What is going on? Why are there so many M dwarfs? Does the star formation process strongly favor the production of such stars? Or is there some other process at work, ‘removing’ hotter and more luminous stars from the populations we observe?

That’s where we’ll pick up next time, as we try to uncover how stars like the Sun change with time (age!) by carefully studying natural laboratories of stellar evolution – ***open and globular clusters***.