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Other stars?

How do they compare to the sun?

We've already made some observations: we've noticed that stars have different colors which means they have different temperatures (as determined from Wiens law)

how do they compare in size? Output power?

These questions are difficult to answer without knowing how far away the stars are. For example, a given source of light could look faint to us because it is intrinsically low power, or it could be that it's very far away, or some combination.

When we here on earth measure a star's brightness (the flux we receive from the star) we call that its apparent brightness (or more formally, apparent magnitude, symbol m). About 2000 years ago, Greek astronomers classified stars they saw by brightness and divide them into 5 or six steps from brightest (1^{st} magnitude, say) to faintest (5^{th} magnitude). Because the response of your eye is not linear to light, each magnitude step corresponds to a factor of about 2.5 in brightness.

We know from our discussion of light that the flux we receive = Power/(4PiR^2).

So if we measure the flux from star and can determine our (the distance we are from the star), we can figure out the power (remember that the total power output is also called the luminosity of the star).

So for a 2^{nd} magnitude star we'd measure 2.5 times smaller flux than a for a 1^{st} magnitude star.

For a 3^{rd} it would be 2.5 times smaller flux than a 2^{nd} or 2.5x2.5 = 6.25 times smaller flux than a 1^{st} magnitude star.

We've extended the apparent magnitude scale in modern times to go to the fainter stars you can't see by eye and to brighter things (planets, moon, sun). Oddly enough, because of the historical origins, things like Venus, Jupiter, the sun and moon have negative apparent magnitudes: m=-1 is brighter than m=0, etc.

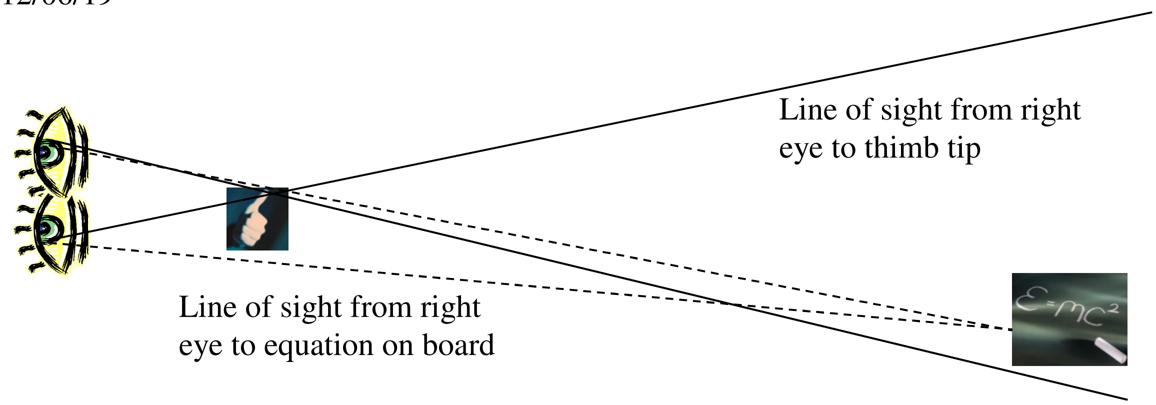
If we know how far a star is, we can make absolute, rather than relative, statements about how bright a star is. Rather than give the luminosity in Watts of radiated power, we introduce and absolute magnitude scale. If all the stars were the same distance from us, then what we see (the apparent magnitude) would be directly related to its Luminosity (b/c we removed the distance dependence). So, for stars whose distance we know (methods below) we imagine moving a star to a known distance (3.26 light years) and using the same flux scale as for apparent magnitude, call its brightness at this distance its absolute magnitude, symbol M. So two stars with the same absolute magnitude really are the same luminosity (since M corresponds to stars at same distance).

So now the question becomes how can we tell how far away a star is? It turns out they are much too distant to send radar waves two and expect reflected pulse of enough power to detect (besides, if they are good black bodies like the sun, they will just absorb it).

The best scheme we have for nearby stars is called parallax.

How does your visual system tell how far away from you something is?

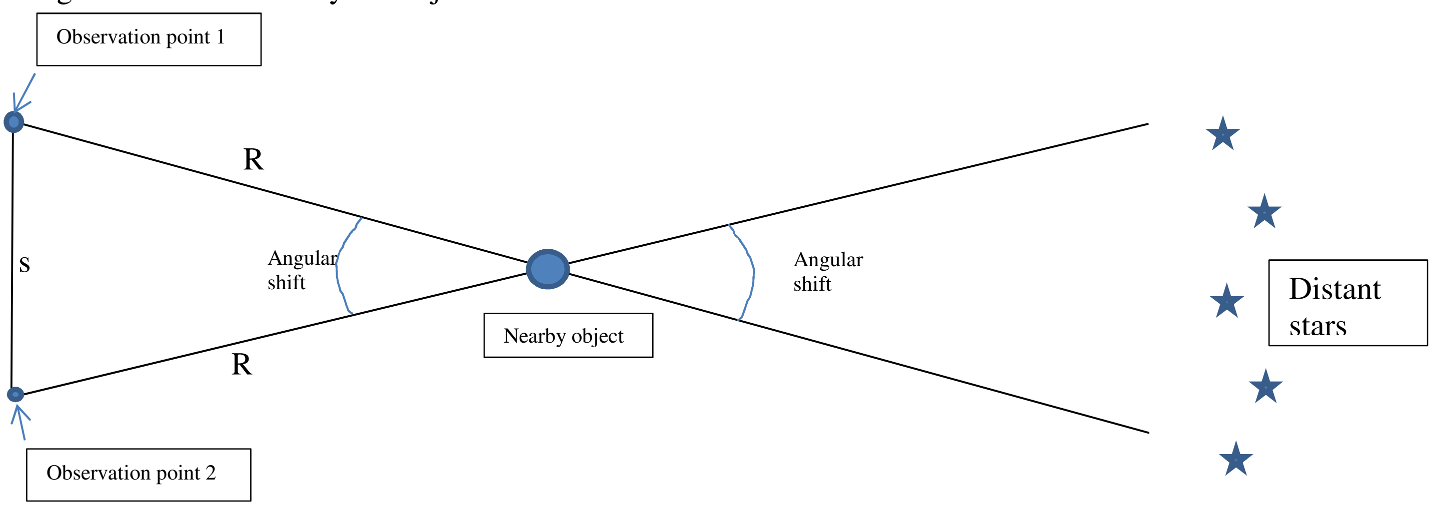
Parallax is simply the relative shift in our field of view of distant objects:



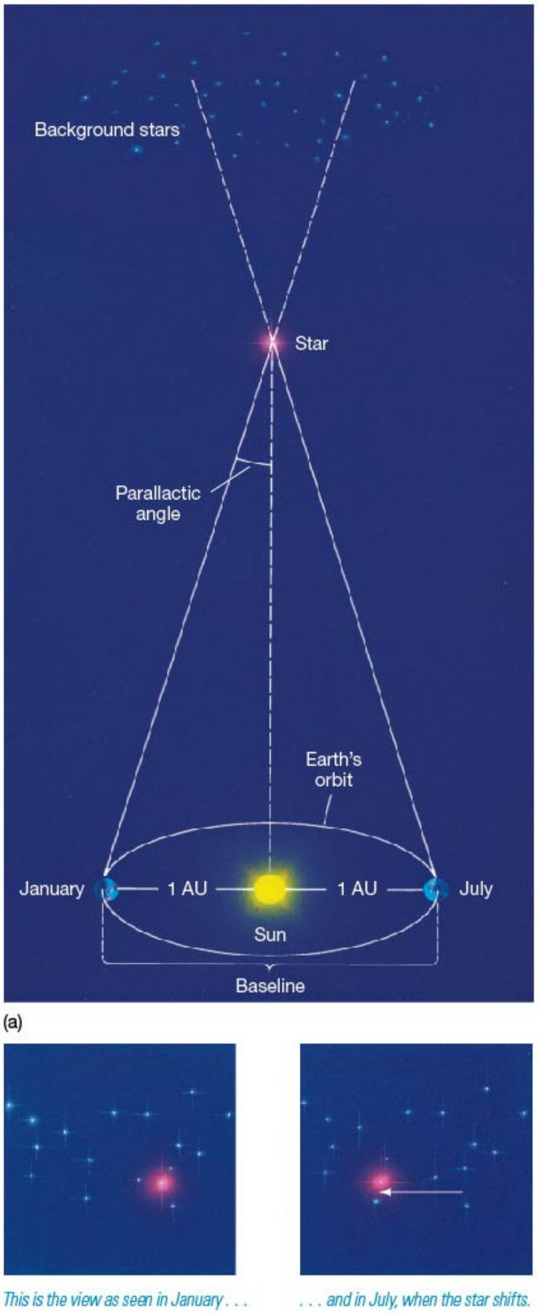
If we know the separation between the two observations (distance between the eyes in this case) and measure the angle in the change position of the nearby object to the very distant objects, we can use our usual small angle relationship:

$$\frac{\theta}{360°} = \frac{s}{2\pi R}$$

To figure out how far away the object is.



The longest baseline ("s") we've had for astronomical purposes throughout most of history is size of Earth's orbit. We make observations 6 months apart so that "s"



For a parallactic angle (see fig left) of 1 arc second, the distance is called 1 parsec (short for parallax arc-second, abbreviated pc) and is about 3.26 light years or just over 200,000 AU. The nearest stars to our sun are a little over 1 pc away.

So, now we can tell how far some stars are. Parallax is limited by how well we can measure the angular shifts. This is easier above earth's turbulent atmosphere and so we've put satellites up to do this. They can use parallax to determine distances out to many thousands of light years (GAIA mission).

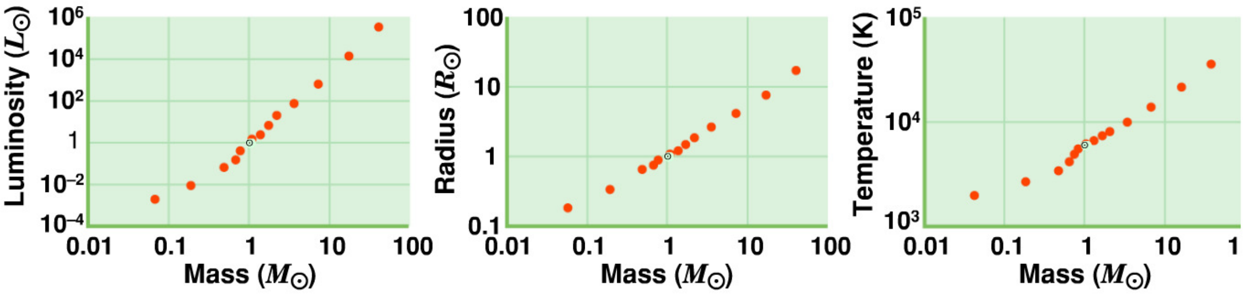
Knowing the distances to stars, we can determine their absolute magnitude (which is directly related to the luminosity or total power output).

Using a star's black body spectrum, we can use Wien's law to tell its temperature.

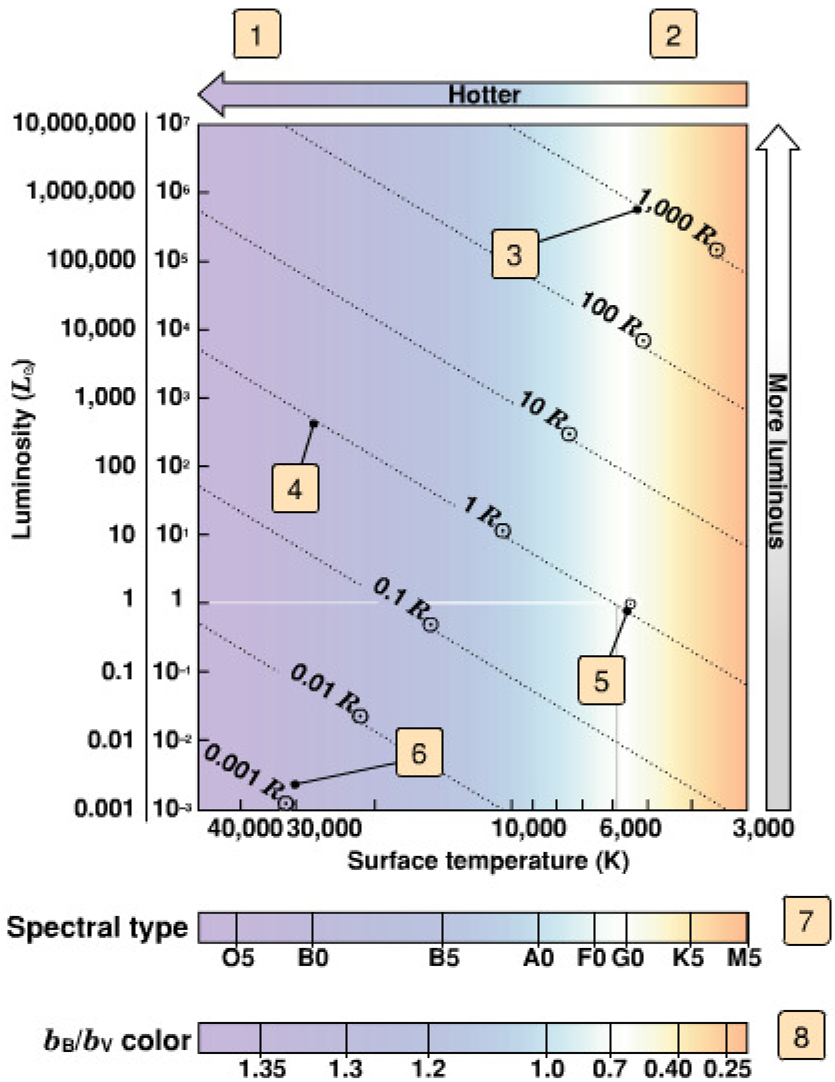
For a black body its temperature also tells us the flux emitted by the surface (power per area that is emitting). Recall then that the luminosity is the emitting area times the flux. Putting these two together means we can determine the area of the star or—since most stars are very close to spherical—we can determine the star's size (radius).

Lastly, if the star is orbiting another star (which we might tell from the Doppler shift as both stars orbit their center of mass) we can use Newton's form of Kepler's third law to get the mass of the system. Other aspects of the motion of the orbiting stars can tell us the ratio of the star masses so we can get the mass of each star.

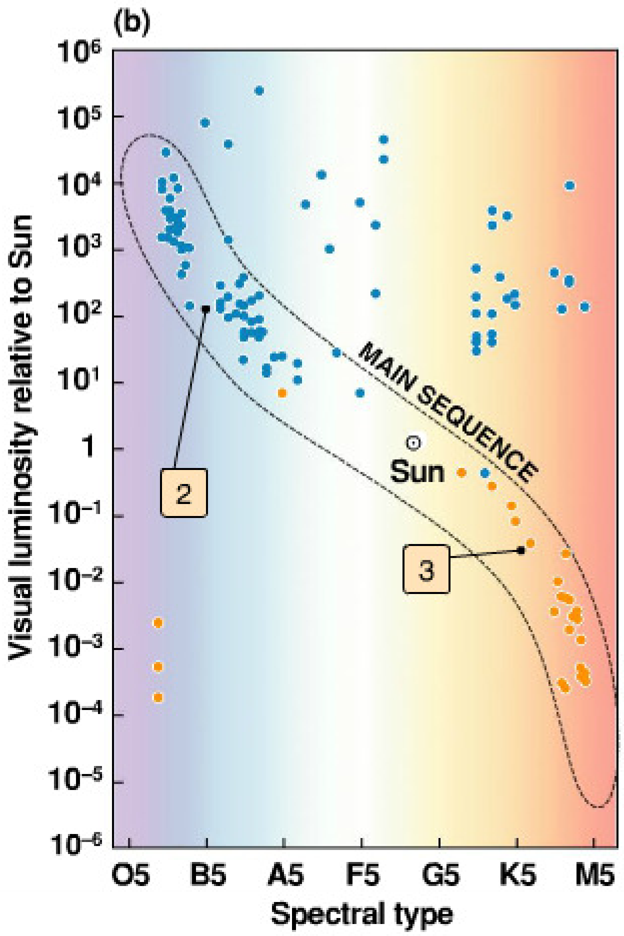
So, with masses, temperatures, sizes, luminosities for many stars we can look for patterns in the properties.



So the first thing we see are strong relationships among these variables! Another way to represent these relations is on a Herzsprung-Russell (H-R) diagram:

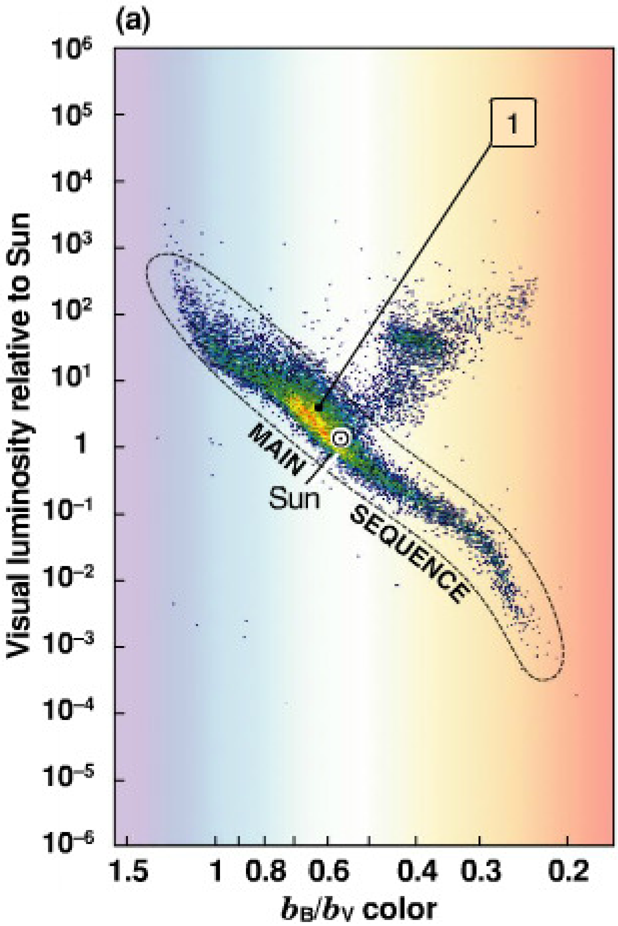


Before careful spectroscopy gave us temperature for lots of stars, other features were used to group stars into spectra types or classes (OBAFGKM) which are related to, but not linear to temperature. Plotting stars on such a diagram shows a remarkable pattern:
For the nearest stars (red dots) and the brightest stars (blue dots) almost all fall into one band:

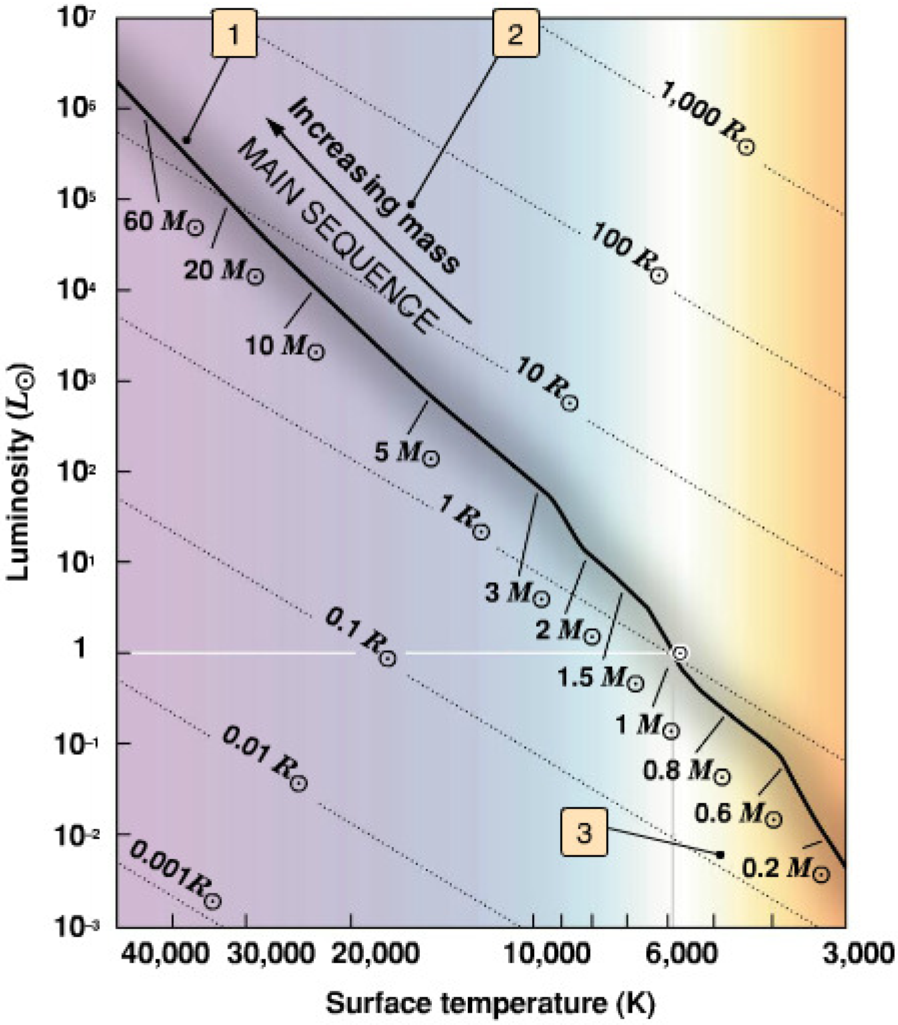


This band, where most stars we see lie, is called the Main Sequence. Since the nearest stars to the sun are not likely to be anything special in particular, they probably represent the majority of stars. As such, that means most stars are fainter and cooler than the sun!

If we extend the range of stars plotted we see this:



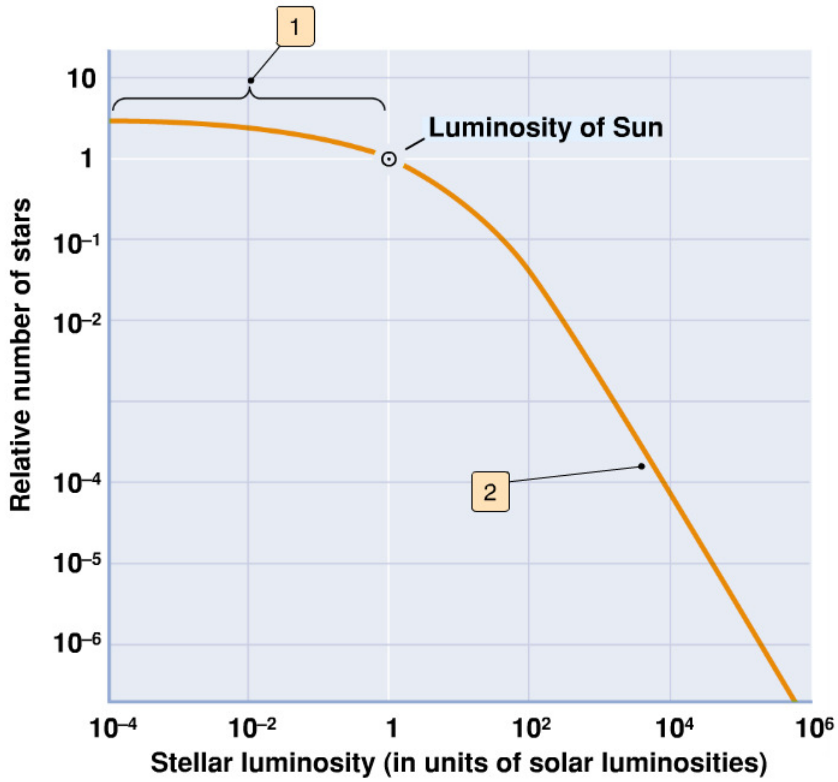
Which fills in the main sequence even more. The sample may be somewhat biased because it is easier to see and to measure brighter stars. Given what we said about sizes and masses we can see more detail as well:



Which reflects the mass/luminosity/temperature correlations we saw earlier:
Star masses in the main sequence run from large (60 Msun) in the upper left to small (0.2 Msun) in the lower right.
The angled lines represent the radii of stars: Small (0.001 Rsun) lower left, Giant (1000 Rsun) upper right.

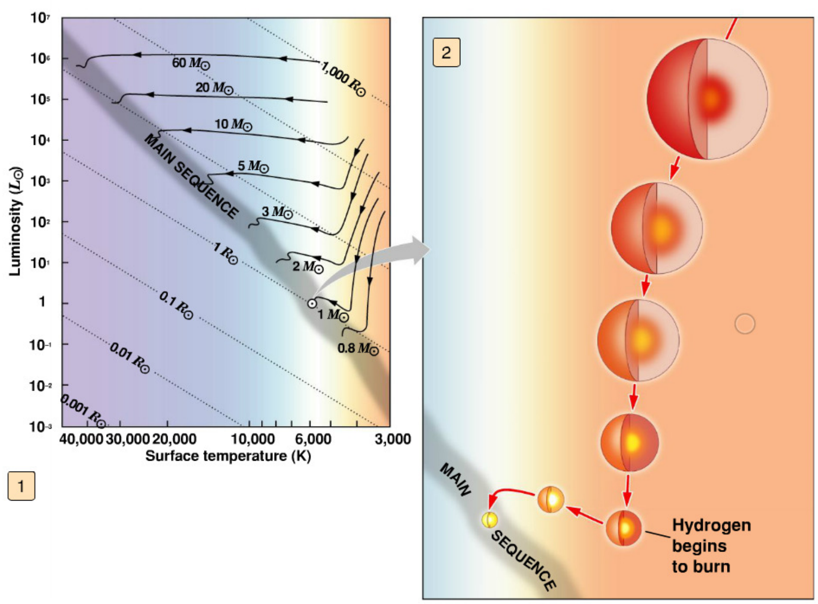
All together these patterns of properties say that while the range of values of these parameters may be quite large, not just any combinations are possible for a functioning star.

From our survey of properties we also find that our sun is relatively high on the luminosity distribution:



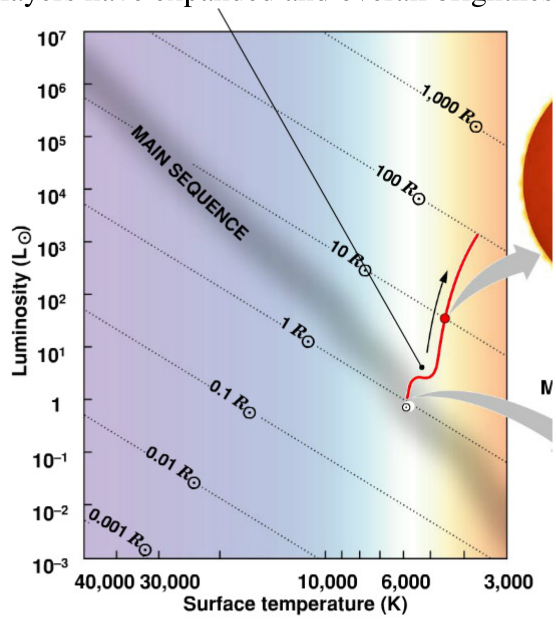
This says there are relatively more (by a lot) fainter stars than the sun than brighter stars.

From the time that a star begins to collapse from a solar nebula, we can track its progress on a HR diagram. Before fusion reactions take place, we have a large, fairly low temperature cloud that shrinks and heats up, eventually it gets hot and dense enough for fusion to start in its core and it settles in on the main sequence. The general path then is from upper right down and left onto the main sequence. Different mass stars have slightly different paths as shown below, along with a close-up of the Sun's approach to the main sequence.

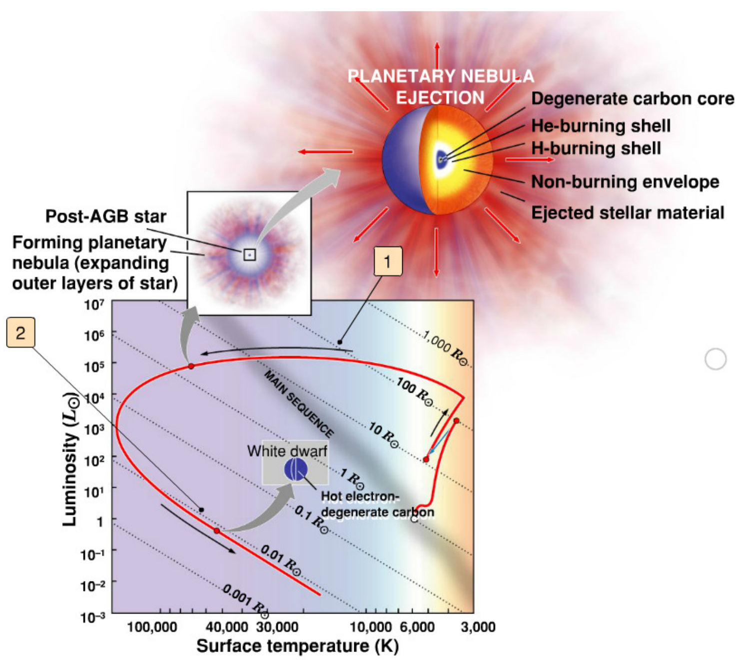


This then is a fundamental aspect of the HR diagram: stars are on the main sequence when they are getting their energy by fusing Hydrogen to Helium in their cores.

Once the star uses up all the Hydrogen in its core, it leaves the main sequence as is continues to fuse Hydrogen, but now in a shell around its Helium core—generally at a higher rate than before. At this stage the stars outer layers have expanded and overall brightness has increase making it a red giant:



Eventually, the Helium in the core build up enough pressure and temperature to start fusing into carbon (3 He -> 1 Carbon). Carbon builds up in the core and eventually we're fusing Helium in a shell around the core (and still fusing Hydrogen in a shell around that).
The bloated giant star has only a tenuous grasp on its very outer layers and can loose significant amounts of mass to its surroundings (this the source for what are called "planetary nebulas")
For star masses like the sun, that's all that happens. Temp and pressure never get up to values that allow any reactions with the Carbon. At this point, the Carbon core is hot (called a white dwarf) and most of the outer mass has been lost. With no further source of energy the white dwarf will slowly cool to obscurity (if it has no partner, anyway):



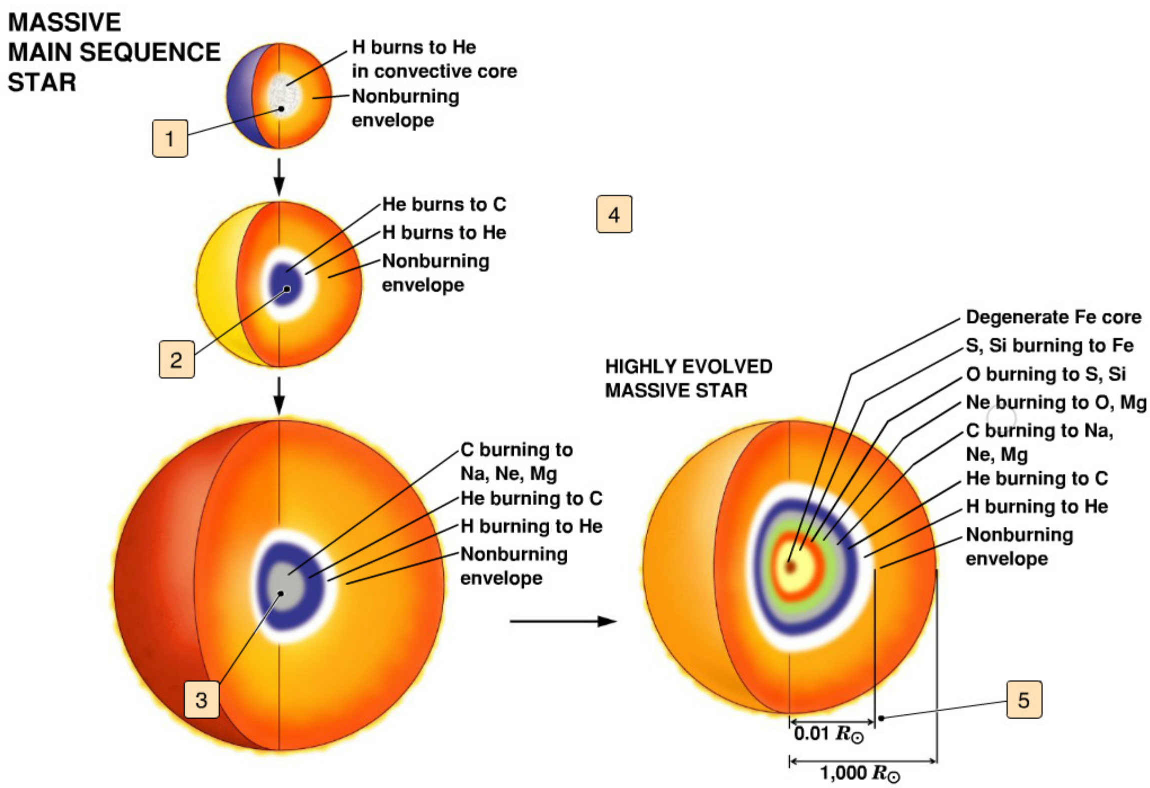
From the HR diagram you can see that main sequence stars luminosity grows much faster than its mass. This mean that high mass stars use up their fuel much faster and live shorter lives in spite of the larger mass: they go through it disproportionately faster. This is illustrated in the table below—see how the estimated lifetime (last column) is much shorter for higher mass (3^{rd} column).

TABLE 10.6 Key Properties of Some Well-Known Main-Sequence Stars

Star	Spectral Type/ Luminosity Class[1]	Mass (solar masses)	Central Temperature (10^6 K)	Luminosity (solar luminosities)	Estimated Lifetime (millions of years)
Spica B*	B2V	6.8	25	800	90
Vega	A0V	2.6	21	50	500
Sirius	A1V	2.1	20	22	1000
Alpha Centauri	G2V	1.1	17	1.6	7000
Sun	G2V	1.0	15	1.0	10,000
Proxima Centauri	M5V	0.1	0.6	0.00006	16,000,000

*The "star" Spica is, in fact, a binary system comprising a B1III giant primary (Spica A) and a B2V main-sequence secondary (Spica B).

For more massive stars (which are hotter and denser in the core), it is possible for the Carbon to undergo nuclear reactions and the process continues up until we get to Sulfur and Silicon fusing to Iron (Fe). After that there are no exothermic (energy releasing) reactions that can happen on Fe in a star. At that point a massive star may look like this:



When the Iron core builds up large enough, with no energy source to prop it up, it collapses—protons and electrons in the Fe combine to make neutrons, likely leaving a neutron star. This happens rapidly and the outer layers of the star eventually fall in on top of the neutron star, undergo a burst of fusion due to the heating/compression from the infalling matter. This rapid energy release blows the outer part of the star apart and creates (in the nuclear reactions) many other elements besides those in the above fusing shells). Neutron stars are essentially giant nulei: balls of neutrons at nuclear densities about as massive as our sun!

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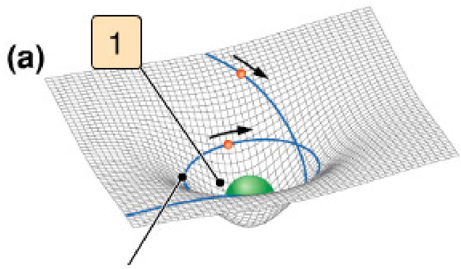
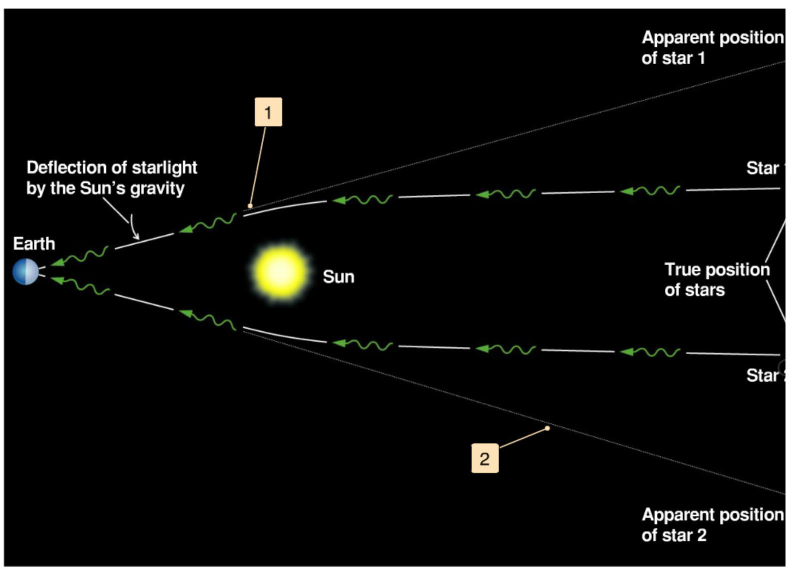
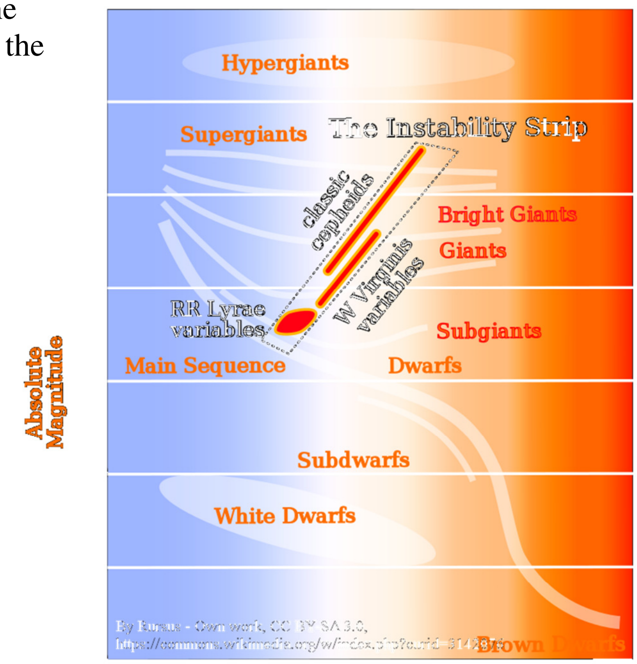
For even more massive stars (say, 25 Msun or so) there may be so much mass in the Fe core that the neutrons will be squashed together enough to form a black hole: an object with so much mass in such a small space that its escape speed is larger than the speed of light!

(Recall: $v_{escape} = \sqrt{\frac{2GM}{R}}$ to escape a mass M starting from a distance R from its center)

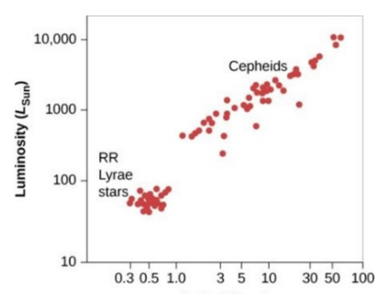


Black holes then don't emit visible light (or anything else really) and so we see them by their indirect effects: we see things orbiting them and can infer their mass and size, stuff falls into the and in the process heats up by compression and collisions and emits characteristic radiation that lets us identify the black hole. Additionally, the black hole itself is described not by Newton's gravity, but by a more complete theory developed by Einstein (the General Theory of Relativity). This theory describes how the dimensions of space (x,y,z say) and time are actually parts of a single structure called space time. Gravity is describe in this theory not a force but this way: Massive objects make spacetime bend, and bent spacetime causes objects to curve. An analogy often used it so imagine our 3D world as a 2D rubber sheet stretched out with nothing under it. If we put a cue ball on it, the cue ball will distort the sheet (stretch/bend/curve it). If you roll a marble past it, the marble will be deflected by the curvature caused by the cue ball. The black hole does this to the spacetime around it (all mass does this, but the extremeness of the black hole makes these effects dominant). In addition to other matter, light is also deflected by this warpage of spacetime:





Back to the distance ladder: When stars leave the main sequence, some of them (depending on mass) become variable stars: their light output varies over time (see instability strip in above HR diagram). Some types of variables are regular and have interesting properties. One type (Cepheid variables) has a period (time for cycle to repeat) that is directly related to its luminosity (figure at right). That means just by measuring the cycle time, we can know its luminosity, then with its apparent brightness, we can calculate its distance. This rung of the distance ladder is good out to several million light years because these stars are so intrinsically bright you can see and measure them well even at those distances.



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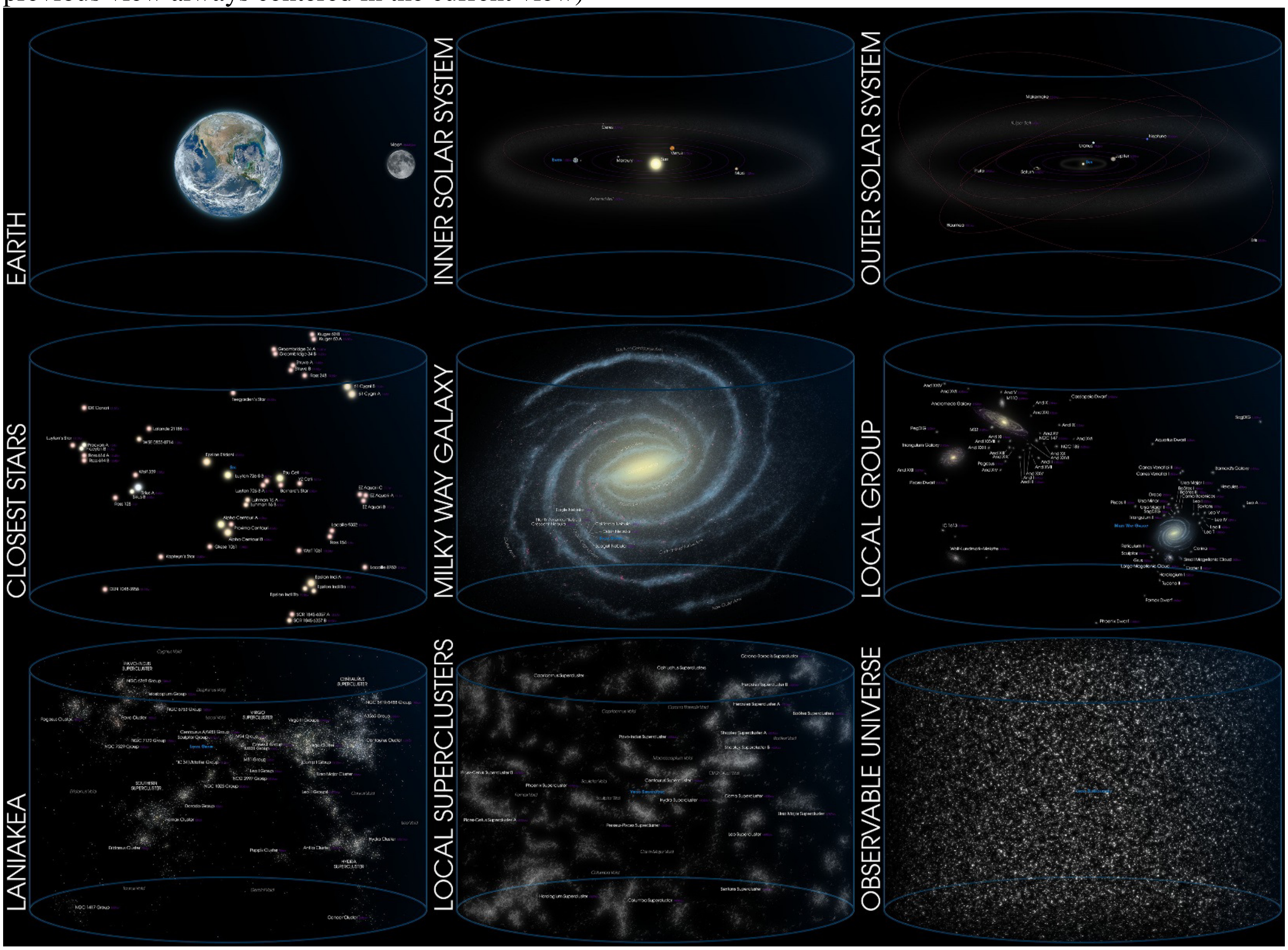
We mentioned white dwarf stars. They are all the leftovers of a particular process in stellar evolution and so are all about the same size. If a white dwarf is part of a binary system (orbiting with a partner star around common center of mass) it is possible for mass (Hydrogen) from the partner to fall onto the white dwarf. If enough builds up, it will be hot and dense enough to undergo fusion reactions. In this case it is an explosive reaction and since white dwarfs are all about the same, their explosions release the same amount of energy. If we see one go off, knowing how bright is absolutely and how bright we measure it to be can be used (inverse square law for light again) to figure its distance. These are so bright we can see them across the visible universe and they provide our most extensive rung on the distance ladder.

With the distance ladder "complete" we survey our universe and find (from upper left to lower right with previous view always centered in the current view)

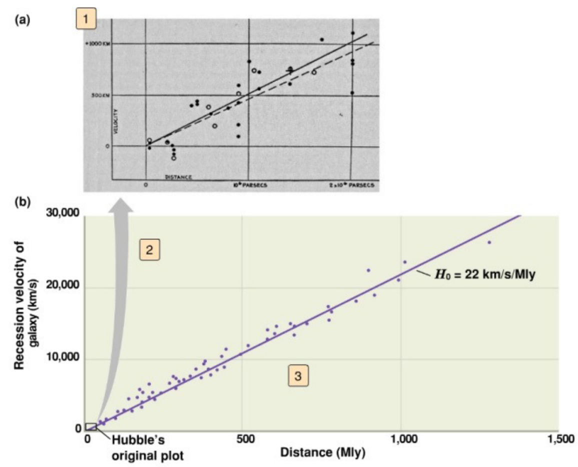


Earth/moon/Inner solar system outer solarsystem.
Nearby stars (within 10 light years or so)
We are part of a giant collection of stars (a galaxy) which we call the Milky Way (after its signature appearance in our skies (well, in skies that are darker than Springfield's). The Milky way is a fairly circular disk about 100,000 light years across and about 1,000 light years thick, with a roughly spherical bulge in the middle. There we are, about 2/3 of the way out from the center. The Milky Way is a fairly common type of galaxy called a spiral galaxy because of the spiral arms of new star formation. These are slightly higher density regions in a galaxy where new stars are forming. Since short lived stars are hot (blue and bright) areas of new star formation

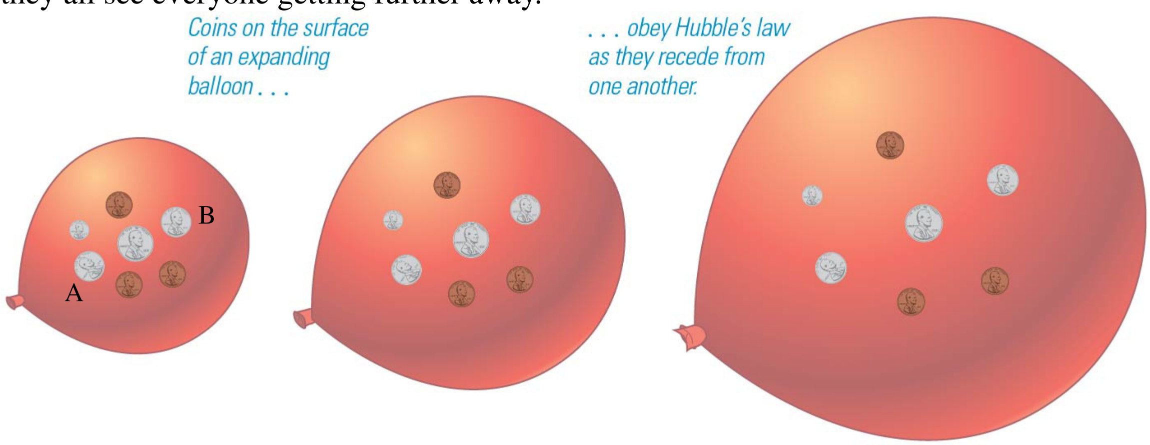
tend to stick out as bright and blue, in between are areas that have more older stars that are therefore redder since small cool stars live longer.
Our galaxy is part of a gravitationally bound (all orbiting each other) cluster of galaxies called the Local Group. Clusters form superclusters.
Finally, on the largest scales, the universe appears uniform: every patch is about like every other patch.

So, from the distance ladder we've learned about the layout or structure of the universe: what is where, etc.

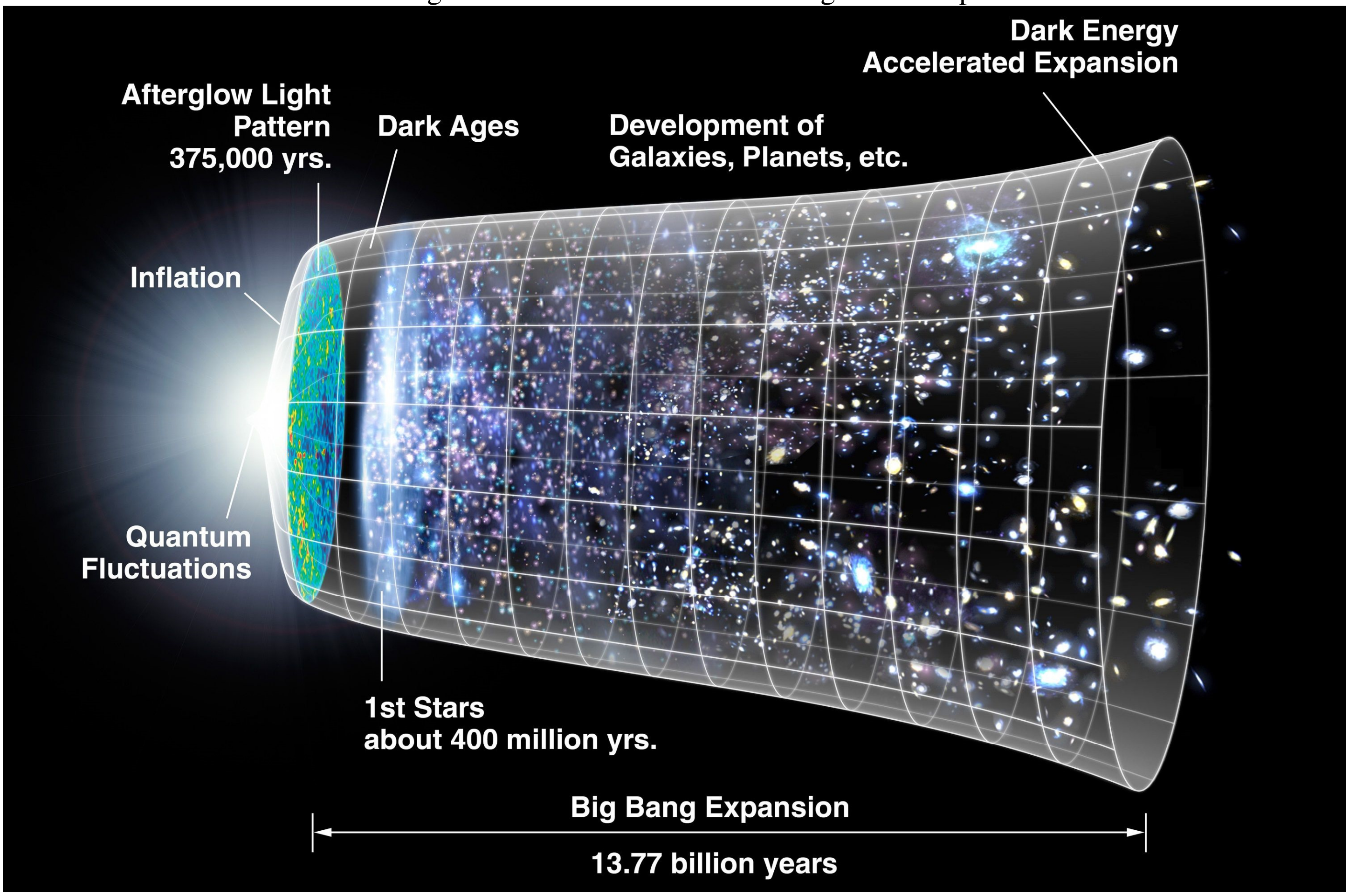
What else do we learn? Looking at spectra helped a lot to understand stars. Starting in the early 1900's Edwin Hubble looked at the spectra of distant galaxies and noticed that the spectra from them were red shifted. All of them! (Remember, redshifted means moving away). And the further away a galaxy was, the faster it was moving away. His original data an more recent continuation are at right. So it looked like we were sitting in the middle of everything and everyone was running away from us. Seems unlikely we were in the center of the Universe—we're not even in the center of our own galaxy! An analogy that helps get at what we think is really going on is shown in the figure below:



Think of galaxies in the 3D universe as coins stuck on a balloon. As the balloon is inflated, the distance from a coin to each of its neighbor increases. This is true for every coin—they all see everyone getting further away.



Also, if we look at coins A and B in the left part, by the time the balloon has inflated to the middle part, each has moved a certain distance (maybe 1 cm) from the center coin. But that means that the separation from A to B has grown by 2 cm. So coins further away are moving away faster—just like the galaxies Hubble saw. To be clear then, what we think is happening is that the 4Dimensions of space and time of General Relativity are expanding, carrying the galaxies in it further and further from each other on the longest distance scales (the expansion isn't enough to separate things that are tightly gravitationally bound—like the stars in our galaxy, but for distant/weakly bound things it is). Thinking about what this means for the past, think of the expansion as a movie and run it backwards-the universe in the past was less expanded (smaller, denser, more compressed and so hotter). Eventually it gets to a time where all the matter and energy in the universe is compressed together at unimaginably high density and temperature in essentially the size of a point. This is the start of what we know as our universe—the Big Bang as it is commonly called. An immensely hot dense ball of energy which expands rapidly, cools and eventually forms all the things in the universe. This is shown schematically in the figure below. Time increases toward the right and the vertical extent of the gridded shape is the size of the universe.



From looking at distant galaxies (remember, since light takes time to get to us, we see light from distant galaxies as they looked millions or billions of years ago, depending on how far they are and therefore how far the light has traveled) we see the expansion over time as shown. But we expected gravitational attraction between the masses of the universe would tend to slow the expansion down. Recent observations instead see to show the rate of expansion is speeding up! We don't know why. We call the unknown reason "dark energy" because of how the expansion is described by General Relativity. There's a lot of this stuff. To make the universe behave this way, about 2/3 of the mass/energy of the universe must be dark energy!

Relatedly, when we look at a galaxy, like the Andromeda Galaxy. We can use the Doppler effect to see how fast the stars in it are orbiting. In particular, we can look at the speed of stars at different distances from the center. We call this data a "rotation curve" for the galaxy. Based on the matter we see in the stars of the galaxy, we can use Newton's form of Kepler's orbital laws to predict what the orbital speeds should be for those different distances. The predictions and the data disagree. The data indicate much more mass is there than we can account for from the ordinary matter of stars and gas and dust! This mass is weird. It exerts gravitational forces, but is doesn't emit or absorb electromagnetic radiation that we can tell. From the rotation curves we can get the distribution of the stuff and it seems not clumpy on the scale of galaxies. Because we don't know what it is, we again cleverly name it “dark matter”. There’s a lot of it too. About 27% of the mass/energy of the universe seems to be dark matter. For those keeping score, that’s 95% dark stuff and 5% ordinary matter (protons, neutrons, electrons, EM radiation).

These dark energy and dark matter problems are two of the biggest in physics/astronomy at this time. Much effort is being put into trying to find out what they are. While we have developed an amazing understanding of the ordinary stuff of the universe compared to, say 100 years ago, it is somewhat mind boggling to find out that represents only 5% of everything that’s out there. Who knows what we’ll find next?