Stellar Astronomy

(The Too-Short Version)
When we go outside at night and see stars it is natural to suppose that they are all about the same distance away. Indeed, early people conjectured that they were all attached to a single sphere that rotated around the fixed Earth.

The alternative hypothesis, of course, is that the stars remain relatively fixed and the Earth rotates beneath them, but it took a long time for people to recognize this as an alternate possibility.

It also took a long time to realize that the stars are far from us, except for the sun. In fact, it took a long time to realize that the sun actually is a star, similar in all respects (except distance) to other stars.

It took even longer to realize that stars have a predictable history, and that the objects we see in far away in the night sky represent different parts of that history. Among the other historical aspects of the stars is the fact that they are all moving with respect to each other.

Some of the observations necessary to make and test the necessary hypotheses to reach these conclusions can be made with the eye alone. Some require a telescope, others require a spectrometer. We will see a little about how each instrument is useful.
We can use the notion of a fixed sphere of stars even while realizing that it isn’t literally true. Serious stargazers will refer to the position and apparent movement of a star in the sky (seen from a particular location at a particular time) in terms of how far above the eastern or western horizon it is (in degrees) and how far north or south of the zenith (in degrees), as if the sky were actually rotating around the Earth.

**Figure 29.3**
The celestial sphere is an imaginary sphere to which the stars are attached. We see no more than half of the celestial sphere at any given time. The point directly over your head at any time is called the **zenith**.
Constellations are groups of stars that mark particular regions of the sky. There are 88 regions, each defined by a constellation. In ancient times people learned to recognize them by comparing the patterns to things in their culture – gods and goddesses, mythical kings and queens, animals, and so on. Most of the constellations don’t really look much like what they are supposed to represent. If you take up stargazing I promise it will be easier to recognize them by where they are (with respect to other constellations) than by what they look like. Some of them don’t really look like anything at all.

This picture shows a schematic representation of some stars in the northern sky. In reality the stars are not equally bright and there are other stars among and around them, some of which are as bright as these.

So this is a version of what you would see in the sky, modified to accentuate certain stars and to ignore others altogether.

What do you see?
My first answer for what I see is, “a bunch of stars”.

If I force an image onto them then I see a galloping giraffe.

What they are sold as is on the next page.
They’re supposed to be a bear. A big one. An Ursa Major.

A distinct or useful grouping of stars that is either part of a constellation (like the Big Dipper, shown in the dotted circle) or that lies in more than one constellation (like the Summer Triangle) is called an “asterism”.

The constellation Ursa Major, the Great Bear. The seven stars in the tail and back of Ursa Major form the Big Dipper.
... and obviously some liberties have been taken in forcing the stars to look like what they are supposed to look like.

**FIGURE 29.1**
The constellation Ursa Major, the Great Bear. The seven stars in the tail and back of Ursa Major form the Big Dipper.
The Big Dipper asterism is useful for locating Polaris, the North Star. Polaris is an unimpressive star by itself and needs considerable help to be noticed.

Polaris sits (almost) directly above the north pole of the Earth and so stays fixed as we rotate beneath it. All the other stars seem to move except for one directly above the south pole. Presently there is only a very faint star, farther from the South Pole than Polaris is from the North Pole.

A long-exposure (many minutes) photograph toward either pole star (this one is toward Polaris) shows the apparent motion quite clearly. Notice that the tracks of each star’s apparent path get longer the farther from Polaris they are. The ones farther from the pole “move” farther in a 24 hour period.
Distances to Stars (1)
Not only are the stars not on a single celestial sphere they are removed from us by huge distances, and from each other by huge distances as well. This diagram shows the distances to the various bright stars in the Big Dipper.

A light-year (ly) is the distance light travels in a year – roughly $9.4607 \times 10^{12}$ km or about 6 trillion miles.

This begs the question of how we can determine the distance to an object that far away. Obviously an odometer won’t work.

**Figure 29.7**
The seven stars of the Big Dipper are at distances from Earth. Note their distances in light-years (ly).
In this example, if we view two stars six months apart (when we have traveled half-way around the sun) we see that their relative positions have changed. As objects out your car window seem to move at different rates, closer ones faster than more distant ones, some nearby stars do this as well. A few of the closer stars move enough with respect to very distant ones that we can tell they are closer to or farther from each other as we orbit the Sun. This apparent motion is called “parallax”, and, of course, it does not mean the stars are actually moving any more than the trees and such beside a road move as you zoom past.

Most stars are so far away that we cannot measure any difference in their spacing over time.
This slide shows the basic idea of parallax. These two pictures were taken one right after the other from two points about 1.6 m (5 feet) apart.

The point here is to reinforce the idea of parallax, not explain how the distance is derived from it. Unless we know how far one of the objects is we cannot get an exact distance. What we can do is determine the relative positions – which object is closer and which farther, how far apart they are in the direction we’re looking, and so on. See if you can spot how it works.
The apparent change in position of an object allows us to set up a triangle solution to get its distance. If we determine the amount that we have to rotate the telescope to see the object on two observations six months apart we can find angle A (half the angle we turned the telescope). It is easy to determine angle B from this (B = 90° - A).

If \( X \) is the distance to a star and \( \tan B = \frac{93 \text{ million miles}}{X} \) it is easy to determine the angles A and B and then solve for X. \( \tan A = \frac{x}{93 \text{ million miles}} \) would work too.

As mentioned, this only works for a few nearby stars, and even for the nearest star (alpha centauri at \(~4.2\) ly or \(~25\) trillion miles) determining the amount of parallax is like measuring the diameter of a dime from four miles away! It’s do-able, but only if your telescope is very good, very big, and on a very large, very accurate protractor base.
One last thing about stellar distances. Assuming that the distances in this picture are correct, what does it mean about space?

No star is anywhere near a light year across – more like millionths of a light year.

If the stars are that small and the distances between them that great then most of space is virtually empty.

**Figure 29.7**
The seven stars of the Big Dipper are at distances from Earth. Note their distances in light-years (ly).
Types of Stars
(and their evolution)
If you stick the end of a metal poker in a fire and leave it, it may get hot enough to glow red, maybe orange. We say it is “red hot”. If you could get it hotter and hotter (you cannot in a normal fire, because it would lose heat faster than you could add it) it would change to orange, then yellow, then green, and so on, across the spectrum. In a high temperature torch the iron could go as far as yellow, as the picture shows. You can see where the heat must have been greatest because that got “yellow hot”, beyond the immediate reach of the flame the colors follow the spectrum down through various shades of orange and red until, at the ends of the bar, only heat (infrared) energy is radiated.
Make sure you see that the bar is glowing across a part of the visible light spectrum – the “ROY” part, but not the “G BIV” part.

A piece of metal like this cannot glow much beyond yellow unless it is still in the fire and the fire is very hot. It could go to “white hot”, but not beyond. The reason is simple: it is so small that it radiates light energy as fast as it absorbs heat energy when it is white hot, even if it’s still in the fire. It cannot gain enough heat to glow at a shorter wavelength.

Very, very massive objects, however, can do so. However, as the object gets bigger, more and more heat has to be added, throughout the object, for it to glow at all.

What is an example of a very, very massive object that does have a way of getting very, very hot throughout?

Image from: http://meganandtimmy.com/2011/10/31/31365-bloody-hell/
In the 1800’s stars were classified according to their spectral type – the kind of light they radiated and any “missing” colors in their complete spectrum. The classes are O, B, A, F, G, K, and M. (Oh, Be A Fine Girl [or Guy], Kiss Me.) Thousands of spectra were compared and could be reliably assigned to one of the 7 types.

Some stars appear Red, some white, and some blue and, it turns out, for a star with a given luminosity or intrinsic brightness, the color is related to the temperature of the star – red stars are cooler, white stars intermediate, and blue ones hottest. Of course you wouldn’t want to touch a red star because “cooler” is a relative term. You can see the shift from bluer (O) to redder (M) as well as the appearance and disappearance (or change in intensity) of the more or less faint absorption lines in the spectra.
The Hertzsprung-Russel Diagram is a plot of two characteristics, surface temperature and luminosity, for a huge number of stars – far more than this image suggests.

How it evolved from the simple spectral classification is a great story involving some very good female astronomers, but we haven’t time to follow all the logic.

Where the stars fall on this graph is not random. (This is how we realize that many kinds of things can and should be classified – they graph in interesting patterns.) The “main sequence” is where the vast majority of stars fall, the giants are more luminous and hotter than the main sequence and also fairly rare. The dwarfs are even rarer (though this may be because they are so hard to spot).
The temperature (and therefore the luminosity and color) of a star is related to its mass. An object that is too small cannot get hot enough to emit light, one that is just big enough will glow red, another that is much bigger can glow blue.

As the H-R Diagram suggests, the size and the brightness (and color) of a star are related to each other.

The brightness arises because the centers of the stars are under high enough pressure to “fuse” hydrogen atoms and turn them to helium atoms. This is no mean feat because the protons in those atoms must be brought very close together for the nuclear forces to overcome the tendency of like charges to repel. This is why there is a minimal mass for a star – less mass means less gravitational pressure in the center.

The fusion releases a great deal of heat which would boil the star away if the great mass also did not provide enough gravity to keep all the “stuff” together.

So a star is a place where fusion creates heat so extreme that everything is in a gaseous state, held together by gravity. With time, the star fuses more and more hydrogen and this means that it must eventually run out of fuel.
Our sun is presently a main sequence star, fusing hydrogen (H -- #1) to helium (He -- #2). It has been this way for more than 4.6by and can continue for as much as 10by more as a main sequence star.

**Figure 29.12**
The stages of the Sun’s life cycle are plotted on this H–R diagram. The short segment labeled Hydrogen burning lasts about 10 billion years. The later segments are much shorter.
Eventually the sun will run low on H, having fused much of it into He and fusion will cease.

As the sun cools the gravitational forces within its helium core will compress that He and heat it. This extra heat will restart H fusion in the outer part of the star and the sun will expand and begin to emit (red) light as a red giant.

Late in this phase there will be enough He in the core so that gravity can begin to fuse it into carbon (#4), a much more difficult process than H fusion.
Once (most of) the remaining H has been fused the sun will simply “go out”. Because the nuclear energy is no longer available, gravity will compress its mass in “gravitational collapse”.

It does not have adequate mass to produce atoms (by fusion) any larger than C.

**FIGURE 29.12**
The stages of the Sun’s life cycle are plotted on this H–R diagram. The short segment labeled Hydrogen burning lasts about 10 billion years. The later segments are much shorter.
Forevermore the sun will be a cooling mass of material in our part of the galaxy. (Unless another star comes by and captures us)

Bigger stars may fare differently, as we will see.

Before we get there though, the sun does actually contain elements heavier than carbon (and its planets obviously do) begging the question of where those heavier elements came from.

**Figure 29.12**
The stages of the Sun’s life cycle are plotted on this H–R diagram. The short segment labeled Hydrogen burning lasts about 10 billion years. The later segments are much shorter.
Distances to "Stars" (2)
(Really, distances to other galaxies.)
Our sun emits a wide spectrum of electromagnetic energy but not a complete spectrum. The radiant energy comes from within the body where the mass is greater, then passes through the thinner, non-radiant solar atmosphere before coming our way. The elements in the atmosphere absorb some wavelengths of light leaving black lines on a spectrogram. Most of the black lines shown below are absorbed in the solar atmosphere but the $O_2$ absorbance occurs in our atmosphere. (The solar atmosphere has no molecular oxygen – these lines don’t appear in spectra observed at the space station or the Hubble Telescope, for example.)

Other stars’ spectra display other absorbance lines, but we’ll use these as an example of what we are about to do (minus the $O_2$ lines).

Think about this: why is there iron (Fe) in the solar atmosphere?
Sometimes when we examine the spectrum of some star besides our sun we can identify the absorbance lines, but they appear to be in the “wrong” place. That is, the diagnostic pattern of spacing is correct but the color behind them is wrong.

In this example we see them offset toward the red end of the spectrum and call this a “red shift”.

What causes this?
The opposite is also possible. In this example we see the lines offset toward the violet (and ultraviolet, don’t forget) end of the spectrum as a “blue shift”.

What causes this?
When any sort of wave energy is coming toward us from a fixed location (if we are still as well) we perceive it as a given wavelength. In this example we might see green light.

However, if the source is moving toward us the waves are compressed. What this does to visible light is to shift it toward the blue end of the spectrum. The same source of light we saw as green from a fixed source now appears blue because it’s wavelength is shorter.

If the source is moving away from us the waves are dilated and shifted toward the red end of the spectrum. The same source of light we saw as green from a fixed source now appears orange or red.

The absorbance lines don’t shift, only the wavelength of light on which they are superimposed.
You are undoubtedly familiar with this effect (called the Doppler Effect) from the behavior of sound waves. Even at 1.5 years old my grandson was, though he didn’t understand the physics (yet).

When he sees motorized vehicles he calls them “vroom-vrooms” because of the sound they make as they pass by.

When a car (or better yet, a train with its whistle blowing) approaches you the sound waves are compressed in front of it and you hear a relatively high pitched sound. After it passes the waves behind are dilated and these longer waves you hear at a lower pitch.

The car or train, of course, is not emitting different sounds in different places, it’s all in your perception of the sounds. You hear exactly what the car sounds like to the people in it at that instant when it is just beside you, moving neither toward nor away from you.

This effect is pretty subtle with most cars on most streets, but it is very noticeable at a race track. The cars whistle toward you and zoom past – yeeeeeeooowwww.

Can you think why this should be more noticeable with faster cars?
To understand this let’s focus on just one line. The others would do the same thing of course. In the unshifted spectrum the H line is in the orange-red part of the spectrum.

If the line is red-shifted by a certain amount then the redder (less orange) color behind it is being perceived with a longer wavelength.

If the line is red-shifted by an even greater amount then the even redder (~no orange) color behind it is being perceived with an even longer wavelength.
So the progressively redder background to the line results from the wavelength of the light “behind” it.

What causes the waves to dilate and what might make them dilate more in one case than another?

The same thing that compresses or dilates sound waves in approaching or receding sound sources does this. Stars moving toward us are blue-shifted and those moving away from us are red-shifted.

What causes the differing degrees of red-shift (or blue-shift in an approaching star) is the rate of relative motion. Faster moving stars have more dilated (or compressed) waves than slower moving ones.
Hubble’s Law is a well verified description of the relationship between an object and us (or any other object) and how fast it recedes or approaches. The equation is:

\[ v = Hd \]

(where \( v \) is the velocity of the object, \( d \) is its distance from us, and \( H \) is a constant, whose value is known.)

Of course the velocity with which an object is moving toward or away from us can be determined from its Doppler shift (red or blue). A given size of the red shift means the object is moving away from us at a certain velocity, giving us “\( v \)”. “\( H \)” is a constant, so its value is always the same, leaving only “\( d \)” as an unknown.
The experiment done in class, if done carefully, can illustrate Hubble’s Law. If we make marks on an uninflated balloon and measure the distance from some of them to a single dot, then inflate the balloon, we can see that the farther a dot is from the “base” dot initially, the faster it moves away from the base dot during inflation.

In this example, distances from dots B, C, and D were measured from dot A. The table of data gives those distances at 0%, ~50%, and 100% inflation. The graph shows the result: D moved away from A faster than C, which moved away faster than B.
Another way of graphing this is also interesting, though you lose some interesting insight. The graph below simply plots original distances between the dots (mm) against the final distance. There is apparently linear relationship that suggests the rate at which two points separate from each other depends upon how far apart they started. That is, two dots close together separate less rapidly than two points farther apart do.

What would this mean if you were “on” one of these dots during expansion and could measure the red shift of light from the other dots? The red shift of B would be greater then that of C, which would be greater then that of D.

Because of the linearity, the slope of this line is a constant for any segment of the line. That slope is what you have to multiply by to predict from one point to another how the y value will change. A constant is a powerful thing in science and this relationship between distances is where Hubble’s constant came from.

This leads us to the best and most famous application of Hubble’s Law.
Within any galaxy the stars are in motion, some converging, some diverging, some actually colliding or pirating material from another during a “close” passage.

Among galaxies this is not the situation. All galaxies are moving away from each other, like raisins in a rising raisin bread dough, or dots on an inflating balloon. We see this because all galaxies (except the Milky Way, of course) are moving away from us and we see their red-shifts. Some are large shifts and some are small, meaning that some galaxies are receding faster and others slower from us.

If we pick one galaxy and see determine how it is moving away from us we can tell how long it would have taken that galaxy to get as far from us as it is using Hubble’s Law. The time it would take for that galaxy to go that far would be expressed by the equation \( t = \frac{d}{v} \), where \( t \) is the elapsed time, \( d \) is the distance to it, and \( v \) is its velocity.

Remember that Hubble’s Law says that \( v = H d \) and substitute this into the equation, giving us \( t = \frac{d}{Hd} \).

This reduces (dividing by \((d/d)) to \( t = \frac{1}{H} \).

Assuming that the universe was “born” in a big bang, that galaxy actually \textcolor{red}{has} moved away from us since that moment. If we plug in the value of \( H \) and solve for \( t \) the result is the age of the universe – \textcolor{red}{presently estimated at nearly 14 by}. Because we get the \textcolor{red}{same} result no matter which galaxy we choose at the outset, the idea that all of them started in the same place seems very likely.
If we look at the Sun (only in the proper way, remember) the light that our eyes perceive left the sun a little over 8 minutes earlier. If the Sun went out right now we would not know it for 8 minutes or so. (Relax.)

The light we see coming from Alpha Centauri left there about 4.2 years ago. That star could, in fact, be gone and we would not know it until the last of its light reached us.

The farther away a star or galaxy is, the longer its light has been traveling to reach us, so when we look at more and more distant objects we are seeing older and older things, not what’s happening in the present.

This is a time machine. It’s one of several that we’ll examine this semester.
ONE (OR TWO) LAST THING(S)
There are two observations we made earlier that appear to be in conflict with each other and we should see if we can resolve the issue.

1) When talking about the Sun’s future we mentioned that it doesn’t have the mass (and therefore the internal gravitational pressure) to fuse He into heavier elements than C. That’s why it will become a white dwarf and not something else after its future gravitational collapse – insufficient mass.

2) When we examined the absorbance spectrum of the sun we noted that there are prominent absorbance lines for Ca, Fe, Mg, and Na. (And there are lines for even heavier elements as well.)

This begs the question of where the heavy elements came from if the sun cannot make them.
In 1054 Chinese observers saw a new star appear in the sky, barely in Taurus, almost in Gemini.

The “star” was gone in a very short time – a real flash in the pan sort of phenomenon.

What is in that location now is the Crab Nebula, a picture of which is shown above. The origin of this nebula, and of others whose origins were seen and recorded by astronomers, was a **supernova**.

There are two ways these can happen, but both involve a star of very large mass – much more massive than the Sun.

When such a star goes into its gravitational collapse stage the excess mass is enough to force the fusion of He to heavier elements, C at least (for lower mass stars) and heavier ones in more massive stars.

This fusion releases huge amounts of energy and literally blows the star to smithereens. Instead of becoming a white dwarf the star becomes a supernova. The crab nebula is just the smithereens of the 1054 supernova.
You’d think that that would be the end of that star, and in some cases it is. Much of the mass of the original star spreads outward and some is propelled with enough force that it will continue drifting out into interstellar space, lost to the star.

But not all of it. Gravity does eventually pull some of the matter back together, forming a large central mass with, possibly, smaller masses orbiting it. If enough matter recollects in the center it may be able to reignite, starting the H fusion again. Now there is a new star with planetoids revolving around it.

This second generation star and its planetoids are made of the stuff the original star was made of, including the heavier materials that formed during the earlier supernova phase.

If the star is exceptionally massive this process could repeat more than once – there may be third or fourth generation stars out there somewhere.

Given that the universe is 14 by old and the solar system is not much more than 4.6 by old, and that the sun contains elements too heavy for it to have manufactured, it is logical to conclude that the Sun is at least a second generation star.
Calculations suggest that elements no heavier than helium would have been formed in the Big Bang.

This means that a first generation star only somewhat larger than our sun might have been able to fuse He to elements as heavy as C, but no heavier. Indeed, even more massive stars would have fused C before proceeding to heavier elements.

If one of those stars went into gravitational collapse (as they all do), becoming a white dwarf (or a nebula too diffuse to reignite) then the carbon atoms in its core would be able to crystallize. They would do so under very high pressure and temperature, and what mineral would result? (What high P/T mineral is made of C?)
Diamond, of course. Diamond was presumably the first crystalline material to exist in the universe, that is, the first mineral.

Ordinarily you don’t think about chemistry and mineralogy evolving over long expanses of time, but they do! Most of the minerals we discuss later in the semester could not have existed until at least second generation stars had evolved because their elements did not exist.

There are diamonds in the sky but they don’t twinkle.