Astronomy Cast Episode: 10

Measuring Distance in the Universe

Fraser Cain: This week we hoped to put everything in perspective for you, and by that I mean we want to explain how astronomers measure distance. How close is Mars, or the moon, or that nearest star, or that galaxy, or that nebula, or that galaxy cluster or that big bang? How do astronomers know how far away everything is? Pamela?

Dr. Pamela Gay: Oh, we know in lots of different ways. We have many lines of evidence. So, what object do you want me to start with?

Fraser: Let's start close

Pamela: Ok, so the moon?

Fraser: sure

Pamela: Pretty close. We bounce laser beams. Not involving sharks or unicorns. We bounce laser beams off the surface of the moon. There's a facility out in West Texas out McDonald observatory that uses a telescope and a giant green laser and they pulse the laser beam at the moon, sending a packet of photons at the moon and then they wait to see how much time it takes for the light from the moon to make it back to the planet earth, and using the fact that we know how fast light travels and we can measure how long it took that packet of light to do the round trip from here to there and back we can get the distance to the moon in just millimetres. So that's pretty cool.

Fraser: before we had laser beams, how did we know how far away the moon was?

Pamela: well in that case we were using parallax. So you and a buddy decide to position yourselves in two vastly different places on the planet earth. You both look up at the moon and you look to see what star is right next to some specific crater, and you measure the difference in which stars appear directly behind the moon, and that difference in the angel that the edge of the moon lines up with the stars in the back ground gives you a triangle where you and your buddy form the base of the triangle and your two views of the moon form the apex of the triangle.

Fraser: I think we need to have people do a silly experiment wherever they are right now to demonstrate this.

Pamela: Exactly

Fraser: So I think everyone could put out their hand at arms length with your thumb up and then look at your thumb and some distance object and then just blink your eyes back and forth. So open one eye then the other and you'll see how your thumb moves back and forth in front of objects that are behind it.

Pamela: In this case your two eyes are you and your friend, the thumb is the moon and whatever background objects that you're looking at are the stars off in the distance. So if you know the distance between you and your buddy you measure the angle that forms the apex of the triangle and use a little bit of trigonometry and you can find the distance to the moon.

Fraser: I think people are going to want us to go into the trigonometry. Just kidding. You all remember from high school and your sine and your cosine, and if you still remember that you can probably make those calculations yourself. I guess the difficulty comes in the precision of the distance, right? The measurements.

Pamela: you have to know very precisely how far apart you and your friend are. And then you need to make very careful measurements of the distance to the stars on the background between some specific point you're both looking at. Making really precise measurements is difficult on the planet earth because you have this atmosphere that's constantly jiggling things around. The moon's big enough that you can get a significant difference in two people spread out across the planet and what it lines up with. It's an easy measurement to make, it was made a long time ago. Trying to do the exact same thing with other objects, though, becomes much more difficult. We actually use this exact same technique to measure the distance to nearby stars and to other planets.

In fact, a very special type of parallax was used to try and measure the distance from us to Venus and the sun using a transit of the planet Venus. So in theory if I'm here and I have a friend go down to the Southern Hemisphere and we both look at a planet moving across the surface of the sun like mercury did a few days ago I'll see it cut across the sun in one place and my friend will see it cut across the sun in a very slightly different place and these differences are caused by how our line of sight passes through mercury and up against the sun the same way your thumb lines up differently with different objects in the background. So this triangle allows us to get a feel for what the scale distances between us, the planet and the sun are, all at once, just using the distance of me to my friend.

Fraser: So how far does this scale go? Obviously you can use it to find the planets in the solar system, but what about stars?

Pamela: Well, with stars, I can't just send a buddy to somewhere else on the planet. I actually have to move a larger distance. Luckily, the earth does this for me. If I take a measurement in June from where I'm located of a nearby star using background quasars as my reference points, so I very carefully measure the distance form star A versus twelve different nearby quasars, then I wait six months. Now, in that time the planet has gone a hundred and eighty degrees around the sun, so my baseline is the diameter of the earth's orbit. I can now, again, look up at star A and measure it's position relative to a bunch of background quasars, which are really distant, and won't appear to have moved at all with the earth. And I can see slight changes in how much that star has appeared to be separated away from these background objects.

Now, these are very slight changes. An object that's 3.26 light years away will move about the distance of the width of a piece of hair held at arm's length. That's one arc second. So we're talking really slight, tiny changes. But these are changes that we can measure and if you get outside of the earth's atmosphere, you can actually measure the more precise changes. A satellite called Hipparcos measured the slight motions of stars and it had an accuracy of about 1 milli-arcsecond, which means that under ideal circumstances, it could measure the distances to objects little over three thousand light years away. There are errors, things crop up, so this level of precision wasn't consistently there for objects a little over three thousand light years away and you had to do lots of statistical stuff with star clusters. But it still allowed us to see out to a significant distance. And to calibrate the positions to all sorts of nearby objects.

Fraser: so we've got the first step of our measuring ladder, which is this parallax method with laser beams for the, and then our parallax method, so let's say we want to go further out into space. What do we use next?

Pamela: Well, here we use what are called pulsating variable stars. Back around 1908 a woman by the name of Henrietta lavette was looking at stars in a pair of nearby galaxies, the large and small Magellanic clouds, which you can see from the southern hemisphere, and for the most part all the stars in these two nearby galaxies can be considered to be the same distance. It's sort of like if you're looking way across the football field and there's two people standing side by side. There is a slight difference between you and the person on the left and right, but for all intents and purposes both those people are the exact same distance away from you.

So when we look at these two nearby galaxies, we can more or less assume all the stars are the same distance. Now, this is important because objects appear fainter the further away they are. I can look at two objects and have them appear to be the same brightness, but if one of them is significantly more luminous and more distance, it will appear the same as a nearby faint object.

Fraser: And stars can be dramatically different in brightness.

Pamela: Thousands of time different one to the other. So Henrietta lavette was looking at these nearby galaxies where all the stars are the same distance, so any difference in apparent brightness was a difference in actual luminosity and while she was looking at these stars she noticed that this particular type of star, called a Cepheid variable star, ones that appeared to change in brightness to variant brightness, ones that appeared to vary in brightness over short periods of time had lower brightness than stars that took longer to vary in brightness.

Fraser: how was she able to confirm that? How did she know that the ones that were going quickly were less brighter?

Pamela: So, you're assuming that everything's at the same distance, so if one star has an average brightness that's fainter than another star's average brightness, since they're at the same distance the star that appears less bright is also going to be less luminous. It's like if someone walks away from you holding a twenty watt light bulb and a hundred watt light bulb, the further away they walk from you, the twenty watt light bulb is still going to appear less bright. So she had a whole bunch of different images of these galaxies taken over long periods of time, and she was able to document the changes in brightness about some average value. The ones that changed in brightness over a shorter period of time had a lower average brightness and thus a lower actual luminosity than ones that varied over a longer period of time and had a larger apparent brightness.

Fraser: So she was able to build a scale of these different stars and how bright they were to each other, but it was all kind of relative. She didn't know what absolute terms how far away things were.

Pamela: there were no absolute terms, and trying to figure out the absolute luminosity of a Cepheid has actually been kind of painful, because there aren't any that are nearby, so when we try to measure the distance to one of these things, we're using all sorts of crazy statistics, and there's lot of errors. But it's as good as we can get from the next step, so based on statistical, careful study of parallaxes to the nearest by still not quite as near as we might like, Cepheids we've built up what we use as the next rung in the distance ladder.

Fraser: So, who close are the nearest Cepheid Variables?

Pamela: There in the thousand kilaparsecs. So, you're right on the very edge of what Hipparcos is able to do. It's sort of like if you're just barely able to read the words on something because it's too far away, and someone's trying to get you to read a quote, very precisely and you're sort of guessing at what a few of the words are. You can mostly get it, but there's some errors.

Fraser: Essentially, that connects the two distances together, so you've got the parallax for the stuff that's close by and then you've got that kind of connection between that and the Cepheid variables. How far out can you go with the Cepheid Variables?

Pamela: Now that's the cool part. These things, while they don't tend to be nearby, they are very luminous. So we can see them to huge distances and the most distant ones that I know of have been found in the galaxies m100 and ngc4639 which are terribly named but very pretty spiral galaxies. M100 is fifty six million light years away and ngc4639 is seventy eight million light years away. So now we're starting to see the huge distances, large enough that these galaxies aren't gravitationally interacting with our own, so we can actually get to see how the universe is expanding and measure the relationship between some things recession rate and its distance using Cepheid Variable Stars.

Fraser: So how do we go further?

Pamela: the next thing that we look for is a new standard candle. We need a new object that we know how much light it gives off, it's luminosity. The next brightest thing that we've been able to find luckily has occurred nearby, and that's a type 1a supernova. Now, type 1a supernovae have occurred in galaxies where we've seen Cepheid variable stars, and these particular supernovas are created when a white dwarf is right next to some other type of star, and is sucking material gravitationally off of that other star. The material that it's pulling off bubbles up and over time there gets to be enough of it that the weight of it triggers thermonuclear reactions. You get carbon fusion occurring.

Fraser: you don't have to go too far into this because we'll save a whole show just for supernovae.

Pamela: Ok, so the basic gist of it, you dumb a lot of stuff onto a white dwarf, and it decides it doesn't want to be a white dwarf anymore, and it explodes.

Fraser: But there's a specific amount. There's only so much material a white dwarf can consume before it blows, every time.

Pamela: You're consistently blowing up the exact same amount of fuel. If you blow up the same amount of stuff, you get the same size explosion, which produces the same amount of light in the same way. So we look for these explosions to be occurring all over the universe, and we use these explosions to say, "that galaxy is eight billion light years away, that one is four billion light years away," and so we're able to build up a map of where galaxies are using super novae, and this, again, allows us to say, "ok, I now know how fast that's moving away from me, where it's located" and you can again start to get direct measurements of how our universe is expanding.

Fraser: and how far out can we go with this?

Pamela: well, so far we've only gotten about ten billion light years, but you know, that's a good way back to the beginning of our thirteen point seven billion old universe.

Fraser: so how do we know all the way back to the thirteen point seven?

Pamela: so there we start hoping that our understanding of how the universe is expanding is correct. At a certain point you have to look at something and say, "well, I know it's recessional velocity," and assuming that we correctly understand the universes expansion, I extrapolate outwards and can get it's distances. There are people working to develop techniques that can probe all the way back by looking for gamma ray bursts. Supernovae are bright, but they're not the brightest thing out there.

Right now gamma ray bursts are the brightest thing we know about. For a brief moment they give up enormous amounts of light, more than a galaxy. And all that light has a chance to reach us and still be bright enough that we can detect it with a telescope. With a supernova at the very edge of the universe may not be bright enough that we can detect it with the telescopes, like my eyeballs can't detect lightning bug on the moon, but the telescope can.

Our telescopes can't deal with supernovas that are at the very edge of the universe, but gamma ray bursts are brighter, so we can see them at the very edge, but we're not completely sure how to relate the observable properties of a gamma ray burst to the actual luminosity of a gamma ray burst. There's some good people working on this, Brad Schafer down at Louisiana State University is working on this.

Fraser: so they might think that gamma ray bursts are standard candles, but they're still not entirely sure.

Pamela: We know there's some sort of standard, but we don’t' know exactly how to calibrate it. It's in calibrating them, in understanding that if we see this it's this luminosity, if we see that it's that luminosity, it's getting all those pieces right that we're still working on figuring out.

Fraser: There's been some recent stories about people looking in Hubble deep field imagery with a circle around this little haze of light and saying that is the most distant galaxy we've ever seen. How do they know that that's the most distant galaxy?

Pamela: when we do that, we're using red shifts. Here the whole idea is, if everything is expanding like a loaf of raisin bread the amount of dough between me and the nearest raisin might increase one inch per hour, so if there's one inch of dough between me and the nearest raisin, in one hour there's two inches of dough between me and the nearest raisin. Now, if instead, I look at another raisin that starts out four inches away from me and the dough is growing at one inch per hour, that four inches is going to turn into eight inches, to the rate at which I see that other raisin moving away from me, it's moving away at four inches per hour, whereas the nearby one is only moving away at one inch per hour.

This translates into when I look at nearby galaxies. I see them moving away from me at fairly low velocities, because there's not a lot of stuff between me and them that is increasing, where as if I look at a really distant galaxy I see them flying away at huge velocities, because there's a lot more stuff between me and them that's expanding. So when we look at these little fuzzy blobs at the edge of the universe, we measure how fast them appear to be moving away from us and extrapolate out using the measurements that we've made using supernovae, using Cepheids, and say, "OK, I believe the universe has an expansion constant h_0 of 70km per second per mega parsec, every mega parsec of space is expanding at 70km per second right now. We can use that and a whole lot of math and extrapolate backwards and I use this to determine where other things are.

Fraser: So these red shifts can be overlaid with your supernova calculations, so you can get a sense, if you're able to detect the red shifts, you have a pretty good idea of how far away something is.

Pamela: yeah, and it's just a matter of having used all these other techniques to measure how the expansion rate is changing with time. It's unfortunately not a constant thing.

Fraser: right, I can feel you being a little slippery there and I think that's because the expansion rate of the universe is changing, right?

Pamela: Right, and that's why we can't use it alone. That's why we have to constantly double check how it's changing with time. We know what it's doing now and we just need to figure out very precisely what it's doing at the beginning moments, at the middle moments and at the current moment.

Fraser: and once again I think that's a conversation for another show where we talk about dark energy. But that one's coming too, pretty soon I think. So now you've got the major tools that astronomers use, what are some other cool tricks they can use to find out the distance of something?

Pamela: Well, not every galaxy is kind enough to provide us with a type 1a supernova, so that we can tell exactly where it's located, but some of them do neat things like rotate in a way we can measure. Spiral galaxies have this really neat feature that the rate at which they rotate is directly related to how bright they are, so if I can measure the rotational velocity of a galaxy and I multiply that to the fourth power, so it's velocity times velocity times velocity times velocity. And then multiply it by some magical constant that people have calibrated using techniques like Cepheids and type 1a supernovae and stuff I can get at the actual luminosity of a galaxy.

So I look around the sky, I find an edge on spiral galaxy, because you have to be able to see exactly how it's rotating, and it needs to be edge on to measure that, and I can go, "ah ha! I know where you are." Now, this doesn't work if you're looking at a face on galaxy. If I can see all the pretty little details in the ring, I can't use this method.

Fraser: so you're essentially measuring the velocity difference of the stars coming towards you on one side of the spiral and stars going away from you on the other side of the spiral, right?

Pamela: Yeah, and the way this works is that it actually broadens the spectral lines, so that the light that's coming towards me appears to be more blue than it actually is, and the light coming off of things moving away from me actually appears to be more red than it actually is. Over the entire disk of the galaxy I'm going to get this distribution of objects moving at different rates towards and away from me and it broadens out the color that I actually see related to one specific type of a transition.

Fraser: now we need to have galaxies that are as edge on as possible to be able to see those differences in velocity.

Pamela: and they have to be spiral, so this only works for a very small subset of spiral galaxies that are edge on.

Fraser: ok, what else?

Pamela: so, there are other galaxies out there, and we want to know how luminous those are as well, and for this we use something called the Faber-Jackson Relationship, with the spiral galaxies it's the Tully-Fisher, and for elliptical it's the Faber-Jackson relationship. Here, I look at the total distribution of the velocities of stars. So, stars in these things, some are moving faster, some are moving slower, some are moving towards me, some are moving away from me, and if I look at the velocity dispersion in how these stars are moving, raise that to the fourth power, multiply all of this by some constant that people have worked out using other methods, I can get the luminosity of an elliptical galaxy. Now I'm starting to get a lot of different types of galaxies under control, and that is pretty cool.

Fraser: Are there any tricks for stuff closer?

Pamela: For closer, I can look at individual events and I can sometimes get lucky. The Crab Nebula is a nearby supernova remnant, and if I look at it over enough years, in fact over other people's lifetimes, because I'm not quite old enough to do this real well and we have pictures of the crab nebula spanning back about a hundred years, you can look at where its edge is relative to background stars, and you can see how it's expanding in angular size across the sky, so it progressively subtends a larger angle. This means you can use a protractor and measure it's angle in the sky relative to your eye. That gives me one way that it's increasing, but I need to get a distance to make sense out of that.

What I can also do is measure the rate at which that stuff is expanding in exact terms, and here I have to assume that it's expanding to the left and to the right relative to my eye looking at the picture is also expanding at the exact same rate directly towards me. So I measure the radial velocity of the stuff in the supernova that's expanding form the centre directly towards me. I do this using Doppler shifts, and it's the exact same technology that police use to give me speeding tickets.

With that information I know exactly how fast that material is moving. If I know in miles per hour, meters per second, choose your units, how fast that material is expanding away from the centre and I can see how fast the angle of the object is growing, I can use trigonometry to get at the exact distance of that object. This works with supernova remnants, it also works light, because light echoes.

There's this really neat object called V838 Mon, and it sent out a burst of light, and we are now watching that burst of light move through dust and clouds of material surrounding that central star. Light travels at the speed of light, and it's really convenient that way. And as it lights up progressively further and further material, we can measure the angular growth of that light shell and get the distance to this really cool looking object.

If you haven't taken a look at the V838 Mon, go to the Hubble website and check it out, it's absolutely spectacular, you can see layers of dust surrounding this little star. So for things that give off a pulse of light or a pulse of material, we can use the expansion of that material or light to get to the distance of that object.

Fraser: and so I guess astronomers use these other techniques to double check some of their other calculations they've already made. To make sure that the evidence they already have for distances syncs up.

Pamela: everything is constantly getting double checked, and all these different techniques have to match up and get the same numbers at the same time for the same objects. We have all these different techniques because not every object has more than one way to measure the distance to it. But for objects that do have more than one way, we apply all of them to make sure we have our distance ladder built in a stable, correct, and well calibrated manner.

Fraser: this is still really important work and astronomers are still working to better and better calibrate this distance ladder because everything depends on everything. So if you can fine tune that connection between the closer stars and the Cepheid variables, you can make sure the rest of your calculations work out very well.

Pamela: it's a thankless job, because it's trigonometry and statistics and statistics and trigonometry, but it's the foundation of everything we do. If you're building a house, you better make sure that all of your construction workers have rulers that are calibrated the exact same way.

Well, we're building a theoretical model for the evolution of our universe, and that means that we need to be able to map out all the structures that are out there and how they change and grow as we look back in time a million years, five hundred million years, a billion years, five billion years, and we need to be able to calibrate our models all the way back and make sure all of our distances, all of our sizes, all these different numbers work together.

This transcript is not an exact match to the audio file. It has been edited for clarity.
Transcription and editing by Angela Coate.