Distances: Crash Course Astronomy #25

Crash Course: Astronomy
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Oh. Hey! Sorry, I donâ€™t mean to be rude. Iâ€™m just trying to figure out how far away my thumb is. How? Parallax. Centuries ago, people thought the stars were holes in a huge crystal sphere, letting through heavenly light. It wasnâ€™t clear just how big the sphere was, but it was pretty dang big. I have some sympathy for them. By eye, and for all intents and purposes, the stars are infinitely far away. If you drive down a road youâ€™ll see trees nearby flying past you, but distant mountains moving more slowly. The Moon is so far it doesnâ€™t seem to move at all compared to nearby objects â€" and itâ€™s easy for your brain to think itâ€™s much closer, smaller, and actually following you, which is a bit creepy. Sometimes people even think itâ€™s a UFO tailing them. Finding the distance to something really far away is tough. Itâ€™s not like you can you can just pace off the distance. Or can you? The ancient Greeks knew the Earth was round and there are lots of ways to figure that out. For example, ships sailing over the horizon seem to disappear from the bottom up, as youâ€™d expect as they slip around the Earthâ€™s curve. But how big is the Earth? Over 2000 years ago, the Greek philosopher Eratosthenes figured it out. He knew that at the summer solstice, the Sun shone directly down a well in the city of Syene at noon. He also knew that at the same time, it was not shining straight down in Alexandria, and could measure that angle. Thereâ€™s a legend that he paid someone to pace off the distance between the two cities so he could find the distance between them. But more likely he just used the numbers found by earlier surveying missions. Either way, knowing the distance and the angle, and applying a little geometry, he calculated the circumference of the Earth. His result, a little over 40,000 km, is actually amazingly accurate! For the very first time, humans had determined a scale to the Universe. That first step has since led to a much, much longer journey. Once you know how big the Earth is, other distances can be found. For example, when thereâ€™s a lunar eclipse, the shadow of the Earth is cast on the Moon. You can see the curve of the Earthâ€™s edge as the shadow moves across the Moon. Knowing how big the Earth is, and doing a little more geometry, you can figure out how far away the Moon is! Also, the phases of the Moon depend on the angles and distances between the Earth, Moon, and Sun. Using the size of the Earth as a stepping stone, Aristarchus of Samos was able to calculate the distances to the Moon and the Sun as well as their sizes. That was 2200 years ago! His numbers werenâ€™t terribly accurate, but thatâ€™s not the important part. His methods were sound, and they were used later by great thinkers like Hipparchus and Ptolemy to get more accurate sizes and distances. They actually did pretty well, and all over a thousand years before the invention of the telescope! And I think it also says a lot that these ancient thinkers were willing to accept a solar system that was at least millions of kilometers in size. But at this point things got sticky. Planets are pretty far away and look like dots. Our methods for finding distances failed for them. For a while, at least. In the 17th century, Johannes Kepler and Isaac Newton laid the mathematical groundwork of planetary orbits, and that in turn made it possible, in theory, to get the distances to the planets. Ah, but there was a catch. When you do the math, you find that measuring the distances to the other planets means you need to know the distance from the Earth to the Sun accurately. For example, it was known that Jupiter was about 5 times farther from the Sun than the Earth was, but that doesnâ€™t tell you what it is in kilometers. So how far away is the Sun? Well, they had a rough idea using the number found by the Greeks, but to be able to truly understand the solar system, they needed a much more accurate value for it. To give you an idea of how important the distance from the Earth to the Sun is, they gave it a pretty high-falutinâ€™ name: the astronomical unit, or AU. Mind you, not â€œanâ€• astronomical unit, â€œtheâ€• one. Thatâ€™s how fundamental it is to understanding everything! A lot of methods were attempted. Sometimes Mercury and Venus transit, or cross the face of the Sun. Timing these events accurately could then be used to plug numbers into the orbital equations and get the length of an AU. Grand expeditions were sent across the globe multiple times to measure the transits, and didnâ€™t do too badly. But our atmosphere blurs the images of the planets, putting pretty big error bars on the timing measurements. The best they could do was to say the AU was 148,510,000 km -- plus or minus 800,000 km. Thatâ€™s good, but not QUITE good enough to make astronomers happy. Finally, in the 1960s, astronomers used radio telescopes to bounce radar pulses off of Venus. Since we know the speed of light extremely accurately, the amount of time it takes for the light to get to Venus and back could be measured with amazing precision. Finally, after all these centuries, the astronomical unit was nailed down. Itâ€™s now defined to be 149,597,870.7 kilometers. So there. The Earth orbits the Sun on an ellipse, so think of that as the average distance of the Earth from the Sun. Knowing this number unlocked the solar system. Itâ€™s the fundamental meter-stick of astronomy, and the scale we use to measure everything. Having this number meant we could predict the motions of the planets, moons, comets, and asteroids. Plus, it meant we could launch our probes into space and explore these strange new worlds for ourselves, see them up close, and truly understand the nature of the solar system. And itâ€™s even better than that. Knowing the Astronomical Unit meant unlocking the stars. We have two eyes, and this gives us binocular vision. When you look at a nearby object, your left eye sees it at a slightly different angle than your right eye. Your brain puts these two images together, compares them, does the geometry, and gives you a sense of distance to that object. And you thought your teacher lied when she said math was useful in everyday life. We call this ability depth perception. You can see it for yourself by doing the thumb thing: as you blink one eye and then the other, your thumb appears to shift position relative to more distant objects. That shift is called parallax. The amount of shift depends on how far apart your eyes are, and how far away the object is. If you know the distance between your eyes â€" weâ€™ll call this the baseline â€" then you can apply some trigonometry and figure out how far away the object is. If the object is nearby, it shifts a lot; if itâ€™s farther away, it shift less. It works pretty well, but it does put a limit on how far away we can reasonably sense distance with just our eyes. Stars are a bit beyond that limit. If we want to measure their distance using parallax, we need a lot bigger baseline than the few centimeters between our eyes. Once astronomers figured out that the Earth went around the Sun rather than vice-versa, they realized that the Earthâ€™s orbit made a huge baseline. If we observe a star when the Earth is at one spot, then wait six months for the Earth to go around the Sun to the opposite side of its orbit and observe the star again, then in principle we can determine the distance to the star, assuming we knew the size of the Earthâ€™s orbit. Thatâ€™s why knowing the length of the astronomical unit is so important! The diameter of Earthâ€™s orbit is about 300 million kilometers, which makes for a tremendous baseline. Hurray! Except, oops. When stars were observed, no parallax was seen. Was heliocentrism wrong? Pfft, no. Itâ€™s just that stars are really and truly far away, much farther than even the size of Earthâ€™s orbit. The first star to have its parallax successfully measured was in 1838. The star was 61 Cygni, a bit of a dim bulb. But it was bright enough and close enough for astronomers to measure its shift in apparent position as the Earth orbited the Sun. 61 Cygni is about 720,000 astronomical units away. Thatâ€™s a soul-crushing distance; well over 100 trillion kilometers! In fact, thatâ€™s so far that even the Earthâ€™s orbit is too small to be a convenient unit. Astronomers came up with another one: The light year. Thatâ€™s the distance light travels in a year. Lightâ€™s pretty fast, and covers about 10 trillion kilometers in a year. Itâ€™s a huge distance, but it makes the numbers easier on our poor ape brains. That makes 61 Cygni a much more palatable 11.4 light years away. Astronomers also use another unit called a parsec. Itâ€™s based on the angle a star shifts over the course of a year; a star one parsec away will have a parallax shift of one arcsecondâ€"1/3600th of a degree. That distance turns out to be about 3.26 light years. As a unit of distance itâ€™s convenient for astronomers, but itâ€™s a terrible one if youâ€™re doing the Kessel Run. Sorry, Han. The nearest star to the sun we know of, Proxima

Centauri, is about 4.2 light years away. The farthest stars you can see with the naked eye are over a thousand light years distant, but the vast majority are within 100 light years. Space-based satellites are used now to accurately find the distance to hundreds of thousands of stars. Still, this method only works for relatively nearby stars, ones that are less than about 1000 light years away. But once we know those distances, we can use that information on more distant stars. How? Well, like gravity, the strength of light falls off with the square of the distance. If you have two stars that are the same intrinsic brightnessâ€"giving off the same amount of energyâ€"and one is twice as far as the other, it will be Â¼ as bright. Make it ten times farther away, itâ€™ll be 1/100th as bright. So if you know how far away the nearer one is by measuring its parallax, you just have to compare its brightness to one farther away to get its distance. You have to make sure theyâ€™re the same kind of star; some are more luminous than others. But thanks to spectroscopy, we can do just that. A starâ€™s distance is the key to nearly everything about it. Once we know how far it is, and we can measure its apparent brightness, we can figure out how luminous it is, how much light itâ€™s actually giving off, and its spectrum tells us its temperature. With those in hand we can determine its mass and even its diameter. Once we figured out how far away stars are, we started to grasp their true physical nature. This led to even more methods of finding distances. The light given off by dying stars, exploding stars, stars that literally pulse, get brighter and dimmer over time. All of these and more can be used to figure out how many trillions of kilometers of space lie between us and them. And we see stars in other galaxies, which means we can use them to determine the actual size and scale of the Universe itself. And all of this started when some ancient Greeks were curious about how big the Earth was. Curiosity can take us a great, great distance. Today you learned that ancient Greeks were able to find the size of the Earth, and from that the distance to and the sizes of the Moon and Sun. Once the Earth/Sun distance was found, parallax was used to find the distance to nearby stars, and that was bootstrapped using brightness to determine the distances to much farther stars. Crash Course Astronomy is produced in association with PBS Digital Studios. Head over to their YouTube channel to catch even more awesome videos. This episode was written by me, Phil Plait. The script was edited by Blake de Pastino, and our consultant is Dr. Michelle Thaller. It was directed by Nicholas Jenkins, edited by Nicole Sweeney, the sound designer is Michael Aranda, and the graphics team is Thought CafÃ©.