DJORGOVSKI: All right. Well, welcome again. So today we will talk about three different things. We'll talk about distance scales in space and how do we start measuring them. And we'll talk about Kepler's laws and where do they come from. And there will be an interesting simple application of physics onto astronomical phenomenon. And then we'll talk about coordinate systems in the sky, because that's sort of how we find our way around.

So let's begin with the distances and scales. First, let me introduce some of the commonly-used units, and this is some of the very few numbers that you will actually have to remember. First, the distance. The basic distance unit that we use is the astronomical unit. And it's the semi-major axis, or we can say radius, of the Earth's orbit around the Sun, and it's about 150 million kilometers. So this is what's commonly used inside the solar system.

Then, of course, you know about light years. Well, we never use light years. That's just a popular astronomy unit. Instead of that, we use parsecs. And parsec is defined in this weird fashion that this is a distance from which the radius of Earth's orbit, that is 1 astronomical unit, subtends an angle of 1 arcsecond, which is a teeny-tiny angle. And that turns out to be about 200,000 astronomical units.

Also, it's 3.26 light years, so you can always convert that. So if I say, well, some galaxy is about 20 megaparsecs away, how many millions of light years is this? Anybody knows? 20 million times 3.26. So that'd be about 70 million light years. That means light took 70 million years to come from there to here, and that means it started when dinosaurs were ruling the Earth, in that immediate neighborhood, if you will.

All right. One thing that you should remember is that a parsec's about 3 times 10 to the 18 centimeters. Astronomers use CGS units because they got used to them before SI units became fashionable. But for sure we don't use the imperial system. And so since you all know how to convert from centimeters to meters and so on, I'll be usually using centimeters.

Now, later in the class, we'll also be using units of mass and luminosity. Mass is kind of fundamental parameter for many astronomical objects, and we usually use solar mass as a unit. And that turns out to be about 2 times 10 to the 33 grams. Also a good number to remember. Now, all these will, of course, be available to you on the website, so you can always refer to them. But if there aren't any, you should remember these.

And then Sun shines, and it's bolometric luminosity, meaning if you add up over all wavelengths it is about 4 times 10 to the 33 ergs per second. Now, can somebody tell me how many gigawatts is this? Whoever guesses that gets a prize. How many ergs per second are in a watt? 1, 10, million, 10 million? Yes? No? Yes. Now, for sure you need to convert that.

So a joule is 10 to the 7 ergs, and so 4 times 10 to 33 ergs per second will be 4 times 10 to 26 watts. And I asked for gigawatts, so that'll be a few (4) times 10 to 17 gigawatts. A nuclear reactor produces about a gigawatt. So the Sun shines at the rate of about a billion billion nuclear reactors per second. OK. Cool little numbers to remember. We'll work more with those on Friday during these sections.

So let's take a quick tour of the universe to put these scales in a context. So 1 astronomical unit, obviously, is distance between Earth and the Sun, and other planetary distances are kind of commensurate to it. The outermost real planets, not dwarf planets, are about 50 astronomical units from the Sun. And so that kind of defines the inner solar system.

But much beyond that, there is first a thing called Kuiper belt, and then a thing called Oort cloud, which is more spherical. And that consists of little bits and pieces that are left over from making solar system. They're mostly chunks of dirty ice. Sometimes they get into the inner solar system, develop tails, and we call them comets.

Well, the Oort cloud is inferred from dynamical arguments, and so we're pretty sure it's there from the rate that comets are coming. And that's about 1,000 astronomical units out. This is where you can think that sort of interstellar space really begins.

Now, some people are thinking that Earth-- I'm sorry, the Sun may have a companion dwarf star, which was even given the name Nemesis. And the idea was that every 70 million years or so, I forget, 23 million years, doesn't matter, the orbit of Nemesis brings it close enough to give a tidal kick to a whole bunch of comets, and then we have a shower of comets coming into the inner solar system.

When they hit planet Earth, they cause mass extinctions. And so that's apparently what did the dinosaurs in. Now, it's probably true that there was an asteroid or comet impact that did the dinosaurs in, but the existence of Nemesis is pretty much excluded by now from direct observations. OK.

How far are the stars? The picture here is actually the closest star to us. It's called Proxima Centauri, and it's a little dwarf companion of the much more famous and brighter Alpha Centauri. And anybody knows how far that is? How far is the nearest star?

STUDENT: 4.2 light years.

STUDENT: 4 plus.

DJORGOVSKI: Yeah, that's right. How many parsecs is this?

STUDENT: 1 measured--

DJORGOVSKI: Yeah, OK.

STUDENT: A little over 1.

DJORGOVSKI: 1 and 1/2, roughly speaking. So that's the nearest star. So nearest stars to the Earth are from a few parsecs on outward. And the most distant stars you can see with the naked eye, those will be super giants far away, are up to about a kiloparsec. Globular clusters, which are a very popular astronomical object, tend to be a few kiloparsecs away-- a few to a few tens.

So if the stars are of the order of parsecs to kiloparsecs away, how many astronomical units is this? Yeah, anybody?

STUDENT: Couple hundred thousand?

DJORGOVSKI: Couple hundreds thousands is 1 parsec. That's right. And so multiply from there. So interstellar separations are vastly bigger than the size of the solar system, and even more so compared to the size of the stars, which is why stars almost never collide. They do in some very special conditions, in some very dense stellar systems. But by and large, if you mush the galaxies together, they'll just pass through each other, and that does happen.

So this is what our galaxy is roughly like, a picture taken from *Starship Enterprise.* Ah, sorry, I forgot we cannot use that. So it's an artist's conception. And our solar system is about 8 kiloparsecs away from the galactic center, and that's a pretty well-established number by now. We'll go over how that's measured later.

Our Milky Way galaxy extends to maybe 20 to 30 kiloparsecs in radius. Now, it depends what you call the end. They don't have a real end. They kind of fuzz out, and if you count all of the dark halo or not. But that's roughly the size of a good, big disc galaxy, few tens of kiloparsecs.

And the nearest other galaxies to us are first there are dwarf galaxy satellites of the Milky Way. The two famous ones discovered by Magellan back in early 16th century are Magellanic Clouds, and those are two dwarf galaxies that are about 50 kiloparsecs away. So about a size of the Milky Way away from us. Other dwarf galaxy satellites are roughly similar distances from us.

But the nearest big galaxy, sort of commensurate with the Milky Way, is the Andromeda, also known as Messier 31. And that is 700 kiloparsecs away. How many light years is this now? Yeah, I'm sure we can multiply small integers. All right. So it's a little over 2 million light years away. So light from Andromeda, the one we just took in this picture, started 2 million years ago.

All right. And then our immediate extragalactic neighborhood continues to the Virgo Cluster, which is the center of a bigger structure called the Local Supercluster. We'll go over that later. And that is about 16 million parsecs away. So 16 times 3.26, well, that's kind of pushing 60 million light years. So yeah, some dinosaurs were probably still walking around when this light started.

OK. So the extragalactic world is tens of millions of parsecs away, and parsec is roughly distances to the nearest stars, and those are about a million times the size of the solar system. Yes?

STUDENT: Speaking of distances and size, approximately how big would a constellation be? In other words, one of the other--

DJORGOVSKI: OK. The question is, how big are constellations? Well, the question doesn't have a well-defined answer because constellations are just projected images on a celestial sphere. They're not physical groupings of stars. And so stars that are parts of some constellation could be at vastly different distances from us. In fact, they are.

And then, of course, depends on where you choose. So in Orion I think, typically, those stars would be a few hundreds of parsecs away from us. And the size of Orion, it's some tens of degrees. So 1 radian is 50 some degrees, so this would be a small fraction of a radian, let's call it a tenth of a radian. And so then the distance to Orion would be 10 times a couple hundred degrees, a couple hundred parsecs. That's about right.

Constellations are something that used to be popular. They're just expression of human need to see patterns in the sky, patterns anywhere, stock market, sky, doesn't matter. And they're arbitrary. They're just a mnemonic device used to help people navigate, and also set up the calendars. They also produce the very productive industry of astrology, which is making lots of money out of nothing. And in that sense, it's like Facebook. Right?

[LAUGHTER]

But constellations do not have physical meaning. We still use them in some cases because, originally, when astronomers started charting the sky, they started giving names to stars and other things according to in which constellation they happened to be. So a star will be called Alpha Cygni or something like that, and a variable star might be called BL Lacertae, and so on and so forth.

OK. So let's step even further. This is a picture of one of the Ultra-Deep Fields done by Hubble Space Telescope, so-called GOODS field. And every little bright dots you see there is a very distant galaxy. The typical distance is a few gigaparsecs from us. So the furthest reaches of observable universe are of the order of 10 gigaparsecs.

Well, it depends, what do you mean how far? Because in an expanding universe, that can have different meanings, and we'll address those. But anyway, think of 10 gigaparsecs. So this is 10 billion times distances to nearest stars. Ah, universe is big. I told you that.

So that's kind of roughly a scan through this logarithmic distance scale-- what's where. But let's now talk about how do we actually measure that. Well, the first step in measuring how far stars and other things are is trigonometric parallax. And that was figured out even by ancient Greeks. Now, parallaxes are too small and they couldn't possibly measure them, so they knew that stars are far away. So did Galileo.

And the idea here is that if there is a star, like the one hanging above the solar system, and then you look at it six months apart, the angle of that line of sight will change a little bit. And here it's grossly exaggerated, right? The stars are much, much, much further out. So the typical parallaxes will be a tiny fraction of a arcsecond, right? Because if that star was one parsec away, what would be the size of this parallactic angle? What was the definition of a parsec?

STUDENT: An arcsecond.

DJORGOVSKI: Yeah. That will work. That would be 1 arcsecond. But that's closer than Proxima Centauri. So stellar parallaxes will be all smaller than an arcsecond. This was a very hard angle to measure because even in best telescopes, atmospheric blur makes stellar images a couple arcseconds in size. And so you have to center that and then compare with many others and so on.

But this is the only real way of measuring interstellar distances and beyond. Everything else gets calibrated on the basis of the stars to which we do measure trig parallaxes because this is a pretty simple geometry. Everything else is some indirect manner, and as we go along, I'll point out some of the ways in which this is done. So today, state of the art is about 1 milliarcsecond. So we can, in principle, measure distances out to a kiloparsec or thereabouts.

OK. Well, the history of this was astronomers keep trying to do this because up until, well, 19th century, we actually didn't know how far the stars are. We just knew they were far away. And the first one to succeed was Bessel. He was a mathematician, astronomer, physicist. And he measured parallax to the star called 61 Cygni in the constellation Swan, and he got it within a few percent, right? So it's about 3 parsecs away. It's pretty close.

But ever since then, things got better and better. And from the ground-based measurements using optical interferometers and things like that, we can do a milliarcsecond, but only over small scales. In order to do better than that, you have to be free of Earth's atmosphere. And this is why now the frontier of astrometry, which is the part of astronomy that deals with measurements of stellar positions and such, has moved to space.

The first space mission that made a real difference here is called Hipparcos. It was launched by the European Space Agency, and it scanned the sky for a few years and measured parallaxes to about 100,000 stars with milliarcsecond precision. And that was completely revolutionary at the time. So that let us recalibrate all manner of astrophysical distance scales.

Now, just launched is a better version of it called GAIA, and the GAIA will scan the sky for several years and will measure parallaxes of a billion stars, going up to maybe 10 kiloparsecs out. And that gets to be vastly more interesting because you can see even past the galactic center. You can see the globular clusters with that, and it will certainly improve our understanding of the galaxy and stellar astrophysics as well.

So anyway, the current state of the art is a few hundred parsecs, maybe 1,000 in best cases. But that sort of immediate neighborhood because remember, Earth is 8 kiloparsecs away from the center of the Milky Way. So we're just measuring distances within our immediate galactic neighborhood. Never mind the extragalactic world.