DJORGOVSKI: So today we'll start talking about how do we actually measure stuff in astronomy? The data are of course the basis of every science, and in astronomy we get data by observing, and that means we have to use a variety of telescopes.

So first let's talk about telescopes in visible light. Often people call them optical, but the same thing applies for ultraviolet or most of the infrared. Now, Galileo did not invent the telescope. It was some Dutch person, and this is actually the first known drawing of a telescope from a book in 1609. It's pretty much what Galileo will figure out how to do.

So, Galileo made the first usable telescope, and that was a refracting telescope using lenses, which we usually think of as telescopes today. Then Newton came up with a reflecting telescope that uses curved mirrors instead of curved glass to bend light rays, and those are the telescopes that are most used today.

So if you look at the history of telescopes, they get bigger and bigger. And the reason for that is the collecting area. The bigger the collecting area for your telescope, the more light you gather per unit time, and therefore the fainter things you can see. The human eye has a pupil diameter a few millimeters. That doesn't give you much of a collecting area. It's also not a great detector, either.

But this is a log linear plot, so you can see that the collecting area of telescopes kept increasing exponentially. At first they were all refractors, telescopes based on lenses, but then reflector started coming in. And for the past couple centuries at least, that's pretty much the only astronomical telescopes that are really being used.

Some of the famous ones are noted here. Hale is the 200 inch telescope at Mount Palomar from 1948. It was superseded by the Soviet 6 meter, which has never produced much science to begin with. Which shows that size is not everything. Hubble, which is one of the most productive if not the most productive telescope in history, is not very big. It's 2.4 meter diameter mirror. But as they say in real estate, it's location, location, location.

And state of the art today are the twin Keck 10 meter telescopes in Hawaii. There is a very similar one in the Canary Islands called Grantecan. And the future, telescopes are following same design. The 30 meter telescope, or TMT, which was built by Caltech, UC, Canada, China, India and probably other partners.

So what are the issues that we worry about making telescopes? First of all, those mirrors tend to be pretty massive, and that has several different problems associated with it. First, mechanical issues of moving the damn thing. But then they also bend under their own weight. And finally, things expand when they get warmer, shrink when they're cooler, and that changes the shape. So a lot of the skill or improvement in technology of making telescopes was in making the mirrors lighter and easier to manipulate.

So first they started removing pieces of glass they didn't need. Palomar mirror is like that. I'll show you this in a moment. Then today they're like thin meniscus mirrors. And then there are the multiple segmented designs. And there are also crazy ideas like spinning a dish full of liquid mercury. And so because of the spin, it will assume a parabolic shaped surface, and they can use, it's a telescope that looks straight up. Mercury being toxic, this is not always a good idea.

The important thing is that in order for telescope to actually produce good quality images, the deviations from the perfect figure, which is usually a parabola, can't be any larger than about 1/10 of the wave length. Now, think what that means for a, say, 10 meter telescope in Hawaii. That means, a wave length-- so, typically of the order of, I'll say, visible light is 500 nanometers, so the biggest bumps you can have are 50 nanometers. 50 nanometers, that's 5 times 10 to the minus 8. So divided by 10. So it's 5 parts in a billion.

Now if Keck telescope mirror were the size of the planet Earth, what would be those biggest bumps that we can tolerate? So the diameter of planet Earth is, let's say to first order, 12,000 kilometers. Well, it's 12,000 kilometers, 12 million meters, and 12 billion millimeters. So 5 times 12, it's 60 millimeters. So the biggest uncertainty, uh imperfections, you can tolerate will be of the order of 3 inches for the whole primary size of planet Earth. This is how precise they have to be done.

Here is the mirror from Palomar, 200 inch, when it was still being made. You're looking from the top. It is a perfectly smooth surface through which you look. The weird stuff underneath are holes, cavities that were put there to remove the excess volume of the glass. And then the top surface was polished with great precision. That pretty much is the end of how big you can make them. 8 meter mirrors are the biggest mirrors people make today.

And then they can support them with active optics, a lot of little pistons pushing, keeping the figure just right as the telescope turns around. And a completely different approach is segmented mirror design. Instead of having a single monolithic mirror to be a primary, you chop it up into a whole lot of hexagonal pieces-- well, you don't cut the mirror, you build the pieces, put them together-- each of which is the appropriate segment of the parabola. And then you have to control their position with similar accuracy to what I told you earlier.

So this is how the two Keck telescopes were built, and this is a design that's now being copied elsewhere, including for next generation of space telescopes, because it's a very clever idea. The person who developed this idea was Jerry Nelson. He was a Caltech undergrad, so we expect every one of you to come up with equally revolutionary idea to students from astronomy.

Where are we going in the future? There are telescope that look at individual targets or small fields really deep. But also there are telescopes that sweep large areas and do sky surveys. The preeminent of those now under design is so-called Large Synoptic Survey Telescope, or LSST. And it has this strange design. Usually if you want wide field, there are some tricks in optics you have to play. So even though it's 8.4 meter diameter, it's really equivalence of 6 and 1/2 meter, because of all these holes and so on. And the idea is that that telescope will survey the sky, will be based in Chile, and will produce 30 terabytes every night. It will essentially produce one Sloan Sky Survey every week, more or less. And people will select targets from their bigger telescopes.

An example of the next generation big telescopes is the 30 meter telescope that's being developed here at the University of California, now with all these other partners. And it's essentially a gigantic Keck. But Kecks have 36 segments, each of which is about size of a person. This one has 738 segments, a little smaller, and they'll still have to be adjusted in a very precise fashion.

The competition for the 30 meter telescope is so-called the Giant Magellan telescope, which is built by our friends over at Carnegie Observatories across the freeway, and Arizona. And they think they can do this with a small number of large mirrors, 8 meter glass mirrors. They'll probably work just fine, and we'll see who gets to build one first.

These toys get to be very expensive. The price tag of one of these is over a billion dollars now, and they'll probably take upwards of $50 million per year to operate. To put this in context-- Keck telescopes are roughly $100 million apiece, and they cost about $20, $30 million per year to operate two of them. So astronomy is really big science today.

And the Europeans are planning European Southern Observatory, ESO, or European Extremely Large Telescope. They're just very unimaginative coming up with these names. They called the VLT, Very Large Telescope for 8 meters they have. Now this is Extremely Large Telescope. And it has to be bigger than the American one, so this is why it's 40. I predict it's going to be a 31 meter by the time they're done.

Now, there are problems in doing astronomy from the ground. Obviously the weather is an issue. This is why people go to things like really dry deserts in Chile and so on. But also this. This is an actual composite, when there are no clouds, of the United States taken from the orbit. And you can see exactly where the people live and where the roads are. So you want to go to places that are really dark. The big bright splotch on the lower left is of course Southern California, Los Angeles. Clearly not a good place to do astronomy. But somewhere in the kind of dark part next to it is Mount Palomar. And you can barely see Baja peninsula below, and there is a really excellent Mexican observatory there, San Pedro Martir.

So, this planet is good for many things, but it's actually not all that great a place to do astronomy because of the presence of atmosphere. Things like oxygen and water vapor, and so on. Which is why we send telescopes in space. So this is Hubble Space Telescope, which was up there since 1990, is still going strong, and is truly revolutionary to astronomy. Even though the size is not large, the absence of atmosphere, which removes all the turbulence, essentially, and also ability to go to ultraviolet that doesn't go through its atmosphere. That's what makes Hubble so successful.

Currently under construction is the next generation space telescope called the James Webb Space Telescope or JWST, which is 6 and 1/2 meter diameter. As you can see, it's just like Keck. It's one of the segmented designs. The strange contraption on which it sits is a thermal shield, and there are solar panels on the back.

And the idea is that this telescope will not be in Earth's orbit. It would be actually in Lagrange point behind Earth, so that Earth will be shielding it in part from sunlight. And it will be observing from there. Now, a problem with this is that once you send it to Lagrange orbit, there is no fixing it. Hubble's been serviced many times very well. There will be a problem to service something like this. So, it's going to work perfectly the first time. And it will be optimized for near infrared.

We also go to space to observe wavelengths that don't go through Earth's atmosphere, like much of the thermal infrared. And Pasadena, Caltech and JPL are leaders in this game. This is a picture of the Spitzer Space Telescope, one of NASA's great observatories which is run out of that building. And it's been producing fantastic science, is still going on.

The one on the right is GALEX, for Galaxy Evolution Explorer, which was the ultraviolet observatory also run out of here from this building by Chris Martin and his team. And that really surveyed sky in ultraviolet better than was ever done. Now that telescope has run out the course if its life. There have been many, many good missions that observed sky in variety of wavelengths that don't go through Earth's atmosphere. We'll talk a little bit about some of the high energy ones in a bit.

So, questions about this. Yes, please.

STUDENT: Was there something [INAUDIBLE] from the surveys on the land based systems where it's-- why are people applying so much money into connecting them to colleges here instead of sending one into space?

DJORGOVSKI: I'm sorry. The question is why do we spend so much money on ground based telescopes when it's better to go to space?

STUDENT: Yeah.

DJORGOVSKI: Well, space telescopes cost a lot more than ground based telescopes. To launch one of these things is probably a cool billion dollars right there. Just for a rocket or space shuttle. To develop it is probably a few times that much. I don't know what price tag on Hubble is by now, but it's certainly upward of $10 billion. And I think the construction tab for James Webb Space Telescope is of the same order, maybe more. So things are always much more expensive in space. You go to space only if you really cannot do it in any other way, such as Earth's atmosphere absorbing stuff.