DJORGOVSKI: So how do telescopes work? This will be a very quick rundown of geometrical optics, which I think you're also getting in some of your physics classes. But let's just go through some of the basic concepts.

The first one is the refraction. When light rays encounter a boundary between two different media, three things can happen to it. They can get absorbed, they can get reflected, or they can go through but under a little different angle. The reason for this is that the speed of light in any finite medium is less than the speed of light because photons get absorbed or scattered internally. And so the net propagation of light is less than the speed of light in a vacuum.

Now that is the so-called index of refraction, which is the ratio of the speed of light in a vacuum to the one in a given medium. And so for the air it's three parts in 10,000, so air is almost like vacuum. But for water it's like 4/3, which is if you try to look under water, say swimming, you're extremely nearsighted. You can't buy glasses that'll be good enough. So this is why you have to wear a mask.

And the so-called Snell's law that gives the relation between the incoming and outgoing angles. This can be easily derived. We don't have time to go through this, but you can do this.

Now it's obvious that if you hit the surface at a sufficiently oblique angle, then you will not be able to go through the surface, but be just internal reflection. And this is how optical fibers work. The light just keeps bouncing along in the fiber. It never goes out until the end.

This is the actual, approximate formula for index of refraction of the air. And you'd think this would make no difference whatsoever, but now that we observe objects which we see at very large red shifts, the rest frame light that started from them was from ultraviolet. We observe it on planet Earth in the air. So we have to make this correction. It turns out to be an important correction.

Now the real problem with the air having an index of refraction that's not unity is that blobs of air that are slightly denser would act like little lenses, irregular lenses. And as the star light propagates through Earth's atmosphere with all of its turbulence and blobs, you'll be like if you're looking through one of those uneven glass sheets like sometimes they put on doors and so on. This is why we have so-called adaptive optics. I'll come to this in a second. Just to define a few terms here.

For a lens, or mirror for that matter, there is the focal length, which is the distance from this optical element in which the rays converge. Could be in front side or back side. Now, the set of all of those points, depending from which angle you're looking at, form the so-called focal plane, which is not really a plane, it's a little curved, but tangentially it's pretty close to a plane. And for a single lens, the images are inverted.

So way back even in the 17th century, people who built glasses and spy glasses and telescopes figured out the so-called lens maker's formula, which relates the focal length of the two lenses and the magnification power. This is pretty simple trigonometry, so I will just leave that for sections to work this one out. But the thing to remember is that the magnification be essentially the ratio of the two focal lengths of the two lenses. And the scale of what angle corresponds to what linear scale in the focal plane would be given by the small angle formula. It will be 1 over the focal length.

Now lenses and some mirrors have so-called aberrations. Not every part of the reflecting or refracting surface will send the rays in the same direction, and so-- Also, the speed of light in glass will depend on the wave length, so that means the focal length will be different for different wavelengths. And that's called chromatic aberration.

The deviations from perfect symmetry are a different kind of aberration, the distortions. They're all really well worked out, and a lot of skill in designing modern optical systems-- whether it's your camera that you take pictures with or big telescope-- is how to match minimum number of these optical elements with minimum amount of distortion.

A couple things to know about the reflecting telescopes. If you just have a spherical mirror, which is the easiest one to polish, light rays from different radius relative to the optical axis will intersect in different places. So the focal point will move depending on where the impact of the light ray is. This is not the case for parabola, and only for parabola. This is why most telescope mirrors are polished as parabolas, because then there is a unique focal point.

Now where do you send the light? defines so-called operational focus. This is a cross section of the 200 inch telescope at Palomar. The simplest thing is so-called prime focus. Light comes in, bounces off the primary mirror, is focused in a point up there where that person is sitting. It's called prime focus cage, and you directly observe it from there.

Alternatively, you can put another mirror right there, send it back down. There is a hole in the primary mirror, and behind it we can put heavier instruments and that's called the cassegrain. Or you can put a mirror in between, send it off to the side, and that's called a nasmyth focus. All of those have various uses depending on what the purpose is.

Well, OK, so how sharp can you see? Here is an important formula to remember. There aren't very many formulas for you to remember. This one really is important. When you take a picture of a point source, absolutely point source, with the telescope, the image you get is not point. It has a finite size and looks like this Bessel function. And the reason for this is that an image collected by telescope is really Fourier transform of the aperture. The point is that there is a finite width of the light distribution, and that width is proportional to the ratio of the wavelength to the diameter. So for a given wavelength, say visible light, the bigger telescope, bigger resolution. OK?

Let's see if we can figure this one out. So this is in radians, of course. 1.22 is approximately equal to 1. And so let's say 5,000 angstroms, which is 500 nanometers, wavelengths of visible light, and there's a 5 meter diameter telescope.

What would be the angle that corresponds to the absolutely best resolution you can in principal have? Right?

500 nanometers is 5 times 10 to the minus 7. Right? A meter-- So, divided by 5, is 10 to the minus 7 of radian. And a radian is how many arc seconds? How many astronomical units are in a parsec? That's the same number. It's about 200,000.

So this would be a tiny fraction of an arcsecond. However we never see that. Because the atmosphere blurs it out to about one or two arcseconds. And the reason for that is that size, typical sizes of these blobs of air that pass in front of your telescope is of the order of a few centimeters. So it doesn't matter how big your telescope is. It's these distorting little blobs of air, it's their size that matters.

OK. So this is why we see the blur, and things don't really fall into focus. The way people fight this is so-called adaptive optics. And it works like this. Suppose there is a really bright star. You may be looking at that star or something near that star. You know that it's supposed to be a point. You make a little segment in mirror and certain sensor, and you find out what was the distorting surface, so to speak, of this air lens to make it blur at any given time. Then you compute this backwards, you readjust the surface of this small deformable mirror to exactly compensate to whatever atmosphere has done. And then bring that in focus. In fact in that way you would untwinkle the stars.

That actually works amazingly well. And here is an example from the Keck telescope. This is a surface plot indicates the intensity of light on focal plane. And the one on the left is just ordinary images blurred up by the atmosphere. This is magnified heavily. You turn on the adaptive optic system and kaboom, it gets into this tiny spike which is almost, but not quite like the diffractional image.

Well, what if you don't have a bright point source next to the one you want to observe? Well in that case, you can put one there. You can shine laser up. These are relatively powerful lasers, and they're tuned to the wavelength of the sodium, you know, like those ugly orange streetlights. The sodium doublet of 5,980 to 8190 angstroms.

There is sodium in the upper atmosphere. It comes from burning meteors. And there's a thin layer of sodium ions about 100 kilometers up and serves as a screen. So it's like having a laser pointer from a telescope exactly where you want it. It creates this little spot which is artificial star, and now you can deploy your adaptive optics system to correct it. Amazingly enough that works, too. And now this is becoming almost the standard way of observing in astronomy, removing turbulence of Earth's atmosphere.