DJORGOVSKI: So now let's leave our solar system and look at planets outside our solar system. This has been a booming industry and one of the most active areas of astronomy over the last decade or so. Because technology finally got there, we can discover such planets.

As of yesterday, I looked and there about 1,800 confirmed extrasolar planets, and there are 1,100 planetary systems. So around some stars, we found more than one planet. There could be more, but we just haven't seen them yet. And there is another 3,000 possible planets that people still have to check. So that's actually pretty good.

And the reason why we would like to study them, in addition to our future or science fiction interests, like exploring those planets directly or settling on them, is that by learning about other planetary systems, we'll get to understand our own a little better. Turns out that our solar system is somewhat unusual in some of its properties, but that could still be a selection effect.

So there are four ways in which we can look for planets around other stars. The first obvious thing would be, well, let's take a picture and take a look. The problem with that is that the scattered light of the parent star, say due to seeing it in Earth's atmosphere, or even scattered light in the optics, is so much brighter than the reflected starlight from planet itself, about a billion times for a typical case, that this is almost impossible.

However, if you go into the infrared, then the thermal emission from the planet itself comes in. And so planet shines, its own energy, and that makes the contrast much more favorable. So a lot of imaging that's now done for extrasolar planets combines these two things, somehow suppressing, scattering, and turbulence, and also looking at infrared. I'll show you pictures.

The first way in which actually we found any extrasolar planets is the Doppler shift technique, radial velocity technique. As star and planet actually orbit common center of the mass, then there is a little bit of velocity jitter for the star itself in its radial velocity. And if you have very precise spectroscopy, you can measure that.

Then you can look for eclipses if you happen to be in the ecliptic plane of that planetary system. Then as planets transit the disk, you're going to have teeny tiny eclipse. And by looking for that with very precise photometry, you can find planets. And this has now been by far the most productive method from Kepler satellite, but also from the ground-based measurements in some cases.

And a somewhat unusual way is through gravitational microlensing. And I'll show you a diagram of how that works. But that is relatively rare, and also imaging is so hard that the bulk of the planets we have found is these two in the middle, the radial velocity method and the eclipses.

Let me show you some pictures of this. So on the top right is illustration why direct imaging is a problem. That if you took a picture and planet is completely lost in the glare of the star. If you took the same picture in infrared, well, star is not as bright because it's really inside of the spectrum. So star is intrinsically dimmer than those white ones, and the planet starts to shine its own thermal radiations, so the contrast improves.

Now this is still idealized. So even with the Hubble space telescope, there is no Earth's atmosphere in turbulence. They have to apply coronography, which is an instrument, or by insider telescope. You put some occulting disk or something right in the focal plane to block the parent star light. And then you just look for other things that would otherwise be lost in the glare.

Now there are a lot of faint stars and galaxies in the sky. So in order to actually claim that any one of the faint ones that you've seen is a planet, you have to monitor this. Stars move. They have their own velocities. Their planets will be coming along. And planets also going in orbits around them.

So if you take a picture, couple years apart at least, and you see that one of those things has moved, according to what could be a Keplerian orbit, then it's a pretty solid case. And here is the real case from Fomalhaut. And now there is a whole bunch of these.

You may remember Beta Pictoris, the first protostellar disk, also protoplanetary disk, that was seen. The big blue circle in the middle is artifact of that coronography obscuring the central portion. And you'll see the infrared emission from side on protoplanetary disk.

But there is also this one little source that was seen right close to the star, and that is one of the first formed planets in that system. Then there is this one called HR 8799. That's designation of the star. This is image from Keck telescope, also using adaptive optics.

So now this is done, not exactly in an industrial scale, but we've seen enough planets directly and everything kind of fits together with other measurements. So that's good.

What about the radial velocities? So when two mass points are in gravitational interaction, they will actually orbit around common center of mass. And the product of mass and velocity is the constant. So if a planet moves of its own velocity, then the ratio of planet's mass to star mass gives you the velocity of the star.

Of course, this will depend on inclination. Ideally, you'd be looking right in the orbital plane. But if you're not, then there is the inclination angle as an extra variable that has to be solved.

So if you do this for Earth and Sun, you find out that, to find Earth around Sun somewhere else you have to measure velocity of the star with centimeter-per-second precision. That's way beyond our state-of-the-art even today.

However, if you take a really big, fat planet, like 10 times the mass of Jupiter, and to make life easier you put it closer in, say in orbit of Mercury, then you have a vastly higher effect. Because it's closer, the velocity is going to be higher. Right? Kepler's Law. And because it's more massive, again, the velocity will be higher in order to balance kinetic and potential energy.

So for a hypothetical fat Jupiter like that, it'll be some hundreds of meters per second. And in fact, the first planets that had been found outside solar system were of this nature. They are very massive planets, very close in. And this is entirely a selection effect that that's the only ones we can find.

Also, you have to monitor the thing for a long time, for at least one or two periods. And in our solar system, Jupiter goes around the sun every 11 years, so you better monitor it over 11-years period. So today we can actually do this with the meter-per-second precision that's state-of-the-art.

Incidentally, you can do the same thing in astrometry. If you had the really precise measurements and positions of stars, then even if you look face-down on the orbit you can see star make little wiggle, like hellicoidal motion. Now that has never been seen yet, but with forthcoming astrometric missions and plans, that might be a possibility.

Actually the first planets outside solar system were found with a version of this method, and it involves pulsar. Pulsar timing is a very precise measurement. These are neutron stars with extremely high moments of inertia. And they spin at an extremely well-defined frequency.

So as you are counting pulses coming from pulsar, with atomic clocks and so on, if the pulsar is moving away from you, then there'll be some delay. It comes towards you. They'll be piling up. So it's like a Doppler shift, but the pulse is not easy to find.

And in fact, in '92 this was seen around the pulsar with this designation by two people in Arecibo. And people call them the Rocks Around the Clock. Where did these planets come from?

They may have been leftovers from a parent star that exploded and made pulsar. But they can be also freshly condensed planets, because supernova ejects material, some of that material cools and retains, and may make second-generation protoplanetary disk and make planets all over again. So this has been somewhat neglected, but it's actually, I thought, a result that was well worth emphasizing.

So most of the planets nowadays were found through the transits method, and most of them with Kepler mission, which was launched in 2009 and ended last year, although it's still using telescope for limited type of observations because it's lost its pointing capabilities.

So the idea here was very simple. You have a telescope with a lot of CCDs imaging a same piece of the sky, again, and again, and again. And that piece of the sky is close to the galactic plane, Cygnus.

Why do this from space? Well, because you can achieve precision in photometry from space that you could never achieve on the ground because of the stellar scintillation. And seeing the limit on ground-based photometry is rarely better than one part in 1,000. But in space you can easily do one part in a million with the proper detector.

The person behind this was Bill Borucki, and he deserves a lot of credit for making this happen. European Space Agency also had a similar satellite called Kourou, but Kepler, by far, produced many more.

So how this works is very simple. Planet comes in front of the stellar disk. You see a slight eclipse. It goes away. But flat-bottom type eclipse. In our solar system, we see that with Mercury and Venus. And so every however many years, there is transit to Venus, transit to Mercury, can see a little disk of Venus occulting part of Sun.

Now for Earth-like planet in front of Sun-like star, a radius is 100 times smaller than that one of Sun. Square of that is the area scaling, so you need part in 10,000. This is a very, very shallow eclipse. And so better measure with like 1 to million precision. And that's exactly what Kepler does. And I don't know if you can read the numbers on the y-axis, but those measurements really are of the order of part in a million.

And the final method is gravitational microlensing. We'll probably come back to gravitational lensing at some point later in the class, but the idea here is that if you put any massive object in front of some background source, say a star, general theory of relativity tells you that gravitational field will bend light rays. This is how it was proven in the first place with solar eclipse.

And essentially, the mass in front of your source acts as the lens. And it magnifies the background source, making it brighter. So if you have moving lens, say a star that crosses the line of sight towards some background star, you're going to see it brighten and dim out. And this is called gravitational microlensing, and it's now done on industrial scale. It's been seen thousands of times.

Now what happens if you have a planet orbiting the lensing star? Then this'll be like a little extra mass component to provide a little extra magnification if it was just the right triangle. And so we just see an extra spike, due to the planetary lensing atop of the stellar microlensing. And that, too, has now been seen some number of times, although it's very hard to capture. You have to monitor a vast number of stars. And then we act quickly and make sure you don't miss one of these.