DJORGOVSKI: Well first, let's go over the contents of our solar system. And this was a recently famous picture from Cassini spacecraft looking from the backside of Saturn. And you can't see on the slide, but there are little dots that are labeled. And those are-- the Earth and Moon was one dot, Mars and Venus was the other. So this was looking from the outside solar system in. There are also mosaics from the Voyager. So we actually took pictures. And we know really where the planets are.

The basic architecture of the solar system is-- well, there are orbits of major planets which are nearly circular, all orbits are Keplerian. There is increased spacing as you go out. So the top here you have a kind of zoom in to the inner solar system, and then squeezed down where the outer plants are. The size of some planets are obviously not to scale here, it's just the radii of the orbits. And you can see that there is recently demoted Pluto as the formally outermost planet, now as one of the new family of dwarf planets. And its orbit is tilted, unlike all of the rest of them.

You may recall that the planets form from protoplanetary disks. And the disks form because of the conservation of the angular momentum. So therefore planets will inherit the same dynamics as the material from which they've formed. And they'll tend to move to nearly circular orbits, just like particles in the disk would. But then in the outer parts of the disk, maybe things haven't quite settled. So you expect to find things that are a little different. Now planets used to be really part of astronomy, unquestionably.

But over the last few decades planetary science has really became much more akin to geology than astronomy. Because once you start banging with hammer on another celestial body or drilling holes, rolling in rovers, that's not quite the same thing as looking through a telescope. That's all good. And the comparative planetology is useful because by learning about other planets, we can understand our own little better. On the other hand, planets are interesting in their own. So? This really is a different era of exploration. And I should point out that Caltech has pioneered, along with JPL, what we now call planetary science, generalizing geology into other planets first in our solar system, and now in other solar systems.

Well in our solar system, there's three kinds of planets. The traditional two are the rocky planets, such as Earth and Mercury and Mars and Venus. And then in the outer solar system there are gas giants. There is quite a dramatic difference between them. The rocky planets tend to be smaller, lower mass, obviously then higher density. And they have heavier elements in their composition, like iron and silicon and what have you. Whereas gas giants are bigger, fluffier, lower density, and they have a lot of hydrogen-based inorganic compounds, such as first of all a lot of hydrogen and helium, and then ammonia and carbohydrates and other things.

And then finally in the even more outer solar system is this new type of dwarf planets, some of them drop deeper in like Ceres, formerly an asteroid. Pluto is of course the best known one. But our own Mike Brown has revolutionized this field, first with observations from Palomar discovering a whole new family of these objects, and now many other people are studying them. They are also composed out of lighter element, sort of just like the gas giants are. But they're frozen, they're small. Many of them are not even very spherical. And they tend to be, of course, in much, much larger orbits. So we now think that they're essentially leftovers from some of the planetesimals in the protosolar system. We'll talk about that in a second.

But first just a quick photographic tour. This is Mercury. We've now seen it, had spacecraft fly around it and take pictures. And if you didn't know, you think this is moon. Because it looks pretty much the same as our moon. There is no atmosphere. And all of the craters from meteor impacts are nicely preserved. Mercury, however, has much higher density than our moon. And the reason for this is that there is a stratification of heavier elements in protosolar nebula. The heaviest elements tend to be in the middle, and the lighter ones out. Which kind of helps explain a little bit of the composition of different planets.

But also there's some thinking that Mercury was a product of a collision in the early solar system. Where its parent planet, if you will, got so disrupted that most of its outer layers with lighter rocks got evaporated away. And only the dense core of Mercury remains. Going beyond Mercury is Venus. And you never see Venus like this. This is a picture generated from radar images from Magellan spacecraft, I think. The real picture of Venus is very cloudy. Pioneer spacecraft took pictures up close. I'm sure you see the clouds. And now we know that in Venus there also is kind of volcanic landscape, somewhat similar to Mars. Because Venus does have a very thick atmosphere. And that atmosphere generates the mother of all greenhouse effects. Which is a good warning for us.

This is our moon, technically not a planet. But in fact it's so much larger than most of the other moons, certainly all our solar system ones, that you can consider Earth and Moon as a dual planet or binary planet, almost. And Moon also having essentially no atmosphere, has a very thin one, preserves the crater record of all the bombardment that it has received. We now know that these dark areas, called maria-- which in the olden days people thought could be oceans and seas-- really were actually oceans of molten lava.

And they're covered with dust called regolith. And it has lower albedo, it reflects less light. Whereas the mountainous regions are covered with craters, some of them fairly large. And after Apollo program we understood Moon much better. Its composition is very similar to that one of the outer parts of Earth's composition, Earth's crust and mantle. And now there is a good model that explains why this is. Just a moment.

Then there is planet du jour, Mars. Very fashionable, probably the best explored by now of all extrasolar planets. Actually, amazingly enough, we now have a better elevation map of Mars, topographic surface, than we have of planet Earth. Because there is no atmosphere. And the spacecraft which map the surface features with lasers can really do a high precision job. I think you've all seen enough about Rover and the Sun. There is, of course, big hope that there may be life found on Mars.

We think that very likely there was some. Because we now have very good evidence that there was liquid water on Mars sometime in the past. And the reason why there is no liquid water now is that Mars has lost its atmosphere, which serves as a thermal blanket, essentially. And so it's much too cold to have liquid water now. But there could be a lot of frozen water under the surface. And that's one of the goals of exploration. Whether or not that could actually sustain life, nobody knows at this point. But that's one of the things people want to find out.

So Mars is also singled out as the most likely next planet to colonize, because it's not unpleasantly hot like Venus. You can always generate heat with your friendly nuclear reactor or something. But it's very hard to refrigerate living quarters in Venus. It's even worse than, say, Pasadena in August. There are problems, such as there is no air to breathe. It's kind of far away. And a few other problems, too. But there are enthusiasts like Elon Musk, who really wants to colonize Mars.

Personally I don't really see why do we need to rush about this. Because if you really want to settle to an outer celestial body, moons will be much easier. And same problems as you have on Mars. On the other hand, there is also plenty of things you can do on planet Earth. If you want to be adventurous, colonize ocean bottom, or wherever the heck. Nevertheless science fiction tends to imprint things on people's minds. And someday certainly we will colonize Mars. But I think it will be a little while.

Then we jump over the asteroid belt into the realm of giant planets. This is of course Jupiter. And it has these belts. Their origin is essentially they're winds that move laterally around the planet. And then there are gigantic cyclones, such as the famous Red Spot. It's a big planet. The little dots that you see in the lower left is the shadow of one of its satellites, which is almost like the size of planet Earth. And so things kind of tend to last a longer period of time. So the tornado of Red Spot has lasted, I think now, a few centuries. And smaller ones come and go.

Now Jupiter, just like the other gaseous giants, does have hard, dense core in the middle. Some people would think that there may be metallic hydrogen core in it. But hydrogen at such a pressure, it turns into a solid. It has a magnetic field unlike most other planets-- Earth is one of the few that do-- and all manner of other interesting properties. But it doesn't have a solid surface, really. You just have this really thick atmosphere that gets denser and denser and denser. So it's highly unlikely anybody will ever land on Jupiter. You can sink into Jupiter.

Fortunately there is more interesting stuff to do around that, and that's the Jovian moons. These are the first four, the four that Galileo saw that fateful night in 1609. And they are Io, Europa, Ganymede and Callisto. We now know several tens of smaller moons around Jupiter. Jupiter is very good at capturing passing by asteroids by its gravity, and turning them into tiny moons. But these are sufficiently big that they are like little planets. And they're very interesting in many different ways. Io tends to be squished by tidal forces of Jupiter as it goes around. And that creates the heat that melts its interior. So there are active volcanoes on Io and a sulfuric atmosphere. It's geologically-- Iologically, I guess, a very active world.

Europa may be the single most interesting body in the solar system outside of the Earth. Because we're now pretty sure that it has an ocean under the icy crust. And who knows what happens in that ocean? Then Ganymede and Callisto seem to be a little more crater-y. But Europa is everybody's favorite. How many of you have seen the Europa Report movie? It's a really good science fiction movie, check it out. Some day soon, hopefully, there will be actually probes going to Europa, drilling holes through the ice and dropping cameras in to see is anything swimming in there?

Actually, if you want to look for life in a solar system Jupiter's moons will probably be the best place to go outside the Earth. Because there is heat from tidal friction, there is radiation belts from Jupiter's magnetic field, and that causes mutation. There is liquid water, obviously. And there are a lot of carbohydrates. So in some sense it's like a really cold version of the primordial soup on planet Earth, depending which satellite you go to. But my bet is that we will probably find some sort of primitive life on Jupiter's moons before we do it on Mars, if ever.

And Saturn is a somewhat smaller, less glamorous version of Jupiter in terms of physical properties. But it's got nice rings. The rings are ground up satellites. They consist mostly of ice and dust and smaller rocks. And they form this nice fine structure with gaps which are due to tidal effects due to Saturn's own satellites. Saturn also has a handful of famous old ones that look like small planets. And lots of others, between the ring particles and others.

These are two that are currently very exciting because of the Cassini spacecraft. The one on the left is Enceladus. That, too, probably has at least partly an ocean under an icy crust. The crack that you see in the surface, it's the same thing you see in Europa, are probably parts where there was actually breaks in the ice crust. And then some water comes out. And it refreezes as different colors. But you can see there are also craters. So it's not ocean everywhere. The one on the right is Titan.

Titan really is like a small planet. It has a dense core, its surface, right? But it also has very thick atmosphere, mostly of methane and ammonia. And because it's so cold you get to see lakes, not of water but of liquid methane. Which is like compressed gas that you use in grill, except it's so cold out there that methane or other carbohydrates can flow freely. And Cassini probe, which circles southern system, dropped also probe onto the surface of Titan, which ESA built called Hugyens. And so we actually landed a probe on one of those gaseous giant satellites. And here is a picture from the surface of Titan. So this is actually kind of amazing that we can do that.

We wanted to land things on Venus, and Mars, and of course the Moon-- well, also a comet or two. But if you were to pick one place to go and fool around looking for life or what other things planets might do, I would say aside from Europa, Titan will probably be the most interesting. Then moving out, these are Uranus and Neptune. Uranus has thin rings, set of rings. Their beautiful colors are due to not the molecule, but the Jet Propulsion Laboratory Image Processing Lab. Because they chose to color it in this particular fashion. And that actually has some meaning if you had infrared eyes.

But so they're like smaller versions of Jupiter or Saturn. We don't know very much about them. One interesting thing about Uranus is that unlike all other planets in solar system which spin roughly in the same plane as the orbital plane-- well in Earth's case that's tilted by 23 odd degrees. But by and large most planets spin in the same plane. Uranus is almost orthogonal. It looks like it's rolling on its orbit. Now how do you flip a planet to change its angular momentum like that is a very interesting question. There are models that involve fly by of another earlier planet. And some-- but I don't think this has been really well established.

Then beyond these we get into the realm of-- oops. What happened to my-- there we go. Dwarf planets. The big picture is completely an artist's conception. Real pictures from out there look more like the one on the right, which is actually a telescope image from Hubble showing Pluto and its moon Charon. Which is pretty big relative to Pluto. So Pluto and Charon are also kind of like a duo planet. And the two recently found ones which have been named through crowd sourcing, Nix and Hydra. And there was a contest online how to name them. And there were many interesting suggestions, like Tweedle Dee and Tweedle Dum, and other things that are not necessarily printable in public releases. But anyway Nix and Hydra they are.

So now we know that there are many Pluto-like things out there. And they don't really belong to the solar system proper but more to the outer region called the Kuiper belt. Here are pictures of some of them. Eris, also found by Mike Brown, is about the same size as Pluto. This is what really prompted International Astronomical Union to demote Pluto, because suddenly we started finding all these other things. And so how many planets in the solar system, 8? 9? 15? 300? So at some point, they had to draw the boundary.

And there is no well-defined statement, what makes a planet? It has to be big enough to be round so gravity pulls the stuff together, keeps it kind of spherical. It has to clear out its orbit from the debris by attracting all the other pieces. And it has to move around the Sun at nearly circular orbit. Because there are things in highly elliptical orbits that come in from these Kuiper belts. So here are some of the recent more famous ones. Many of them have satellites too. And their study is a very active area of research. Because they're almost pristine material from the formation of the solar system.

Now we actually can do better than that if we're looking for fossils of solar system formation. And first there are asteroids. They're essentially rocky planetesimals. You may recall from the last time, as you start condensing protoplanetary nebula disk, it will go from dust into bigger chunks and rocks. And stick together and make these big rocks like asteroids, which may be tens of kilometers, maybe hundreds of kilometers in size. And then they accumulate to make planets.

Again there is division between rocky and icy bodies depending where they formed in the planetary nebula. Closer to the Sun, all the lighter stuff will have been evaporated. And so the composition will be similar to that one of the rocky planets. Whereas those in the outer regions will be very much icy. So we now have fly by pictures of a whole bunch of them, and even landed a probe on one of them. We can see they look like little moons. They get little meteor impacts. Their meteors may be just little pebbles that bang into them, but nevertheless they make a little impact crater. They tend to be asymmetric. And this is because they don't have enough gravity when they were formed to assume the shape of the least energy for a given mass, which would be a sphere.

Their counterparts are the comets, which are leftover icy planetesimals from solar system formation. Most of them are housed in outer regions called Kuiper belt-- which is a fluffy belt far away, tens of hundreds of astronomical units-- and a more spherical Oort cloud. Sometimes due to gravitational perturbations they drop into inner solar system. Because they're composed mostly of ice-- water ice, carbon dioxide ice, and many other ices, some dust-- as they come closer to the Sun they start evaporating. Solar wind then pushes the evaporation trail behind them, eliminates it. Scattered light is the beautiful cometary tail.

And now from the fly bys like these two, the top one is called Hartley 2 comet, the bottom one is Halley's Comet, famous comet. You can see there are little geysers of stuff, of water being heated and erupting out from the inside of the comet. And then turning into vapor, maybe into snow, creating the tails. Comets sometimes drop way too close to the sun and get evaporated completely. There has been a recent case of that, although I think a little core of that comet has survived.

So the reservoir of comets are the Kuiper belt and Oort cloud. And the reason we believe they're there is comets just come out of nowhere. You don't follow them throughout their orbits. So they must have come from really large distances. They come at essentially parabolic orbits, meaning highly eccentric, meaning the semi-major axis has to be very, very large. And it's a natural thing to expect that in the outer regions of the solar system like that, you could preserve icy material or whatever you call those pieces of the protoplanetary cloud.

The sheer number of comets near Earth over time tells you just how much of them there has to be out there. And it's a substantial mass, which I don't remember off the top. Which is why Oort and Kuiper came up with this idea. So there is a preference for orbits closer to the ecliptic, which is why there is Kuiper belt. And then there is a more spherical Oort cloud behind it. Recently there have been claims that some of those Kuiper belt dwarf planet objects, that one of them could be out from the Oort cloud. And that may or may not be the case. I don't think it's really known yet.

As the final fossil of formation of the solar system, there is zodiacal dust. And that's dust that is piled up in ecliptic. I've shown you this far infrared picture earlier. You can see it on a really clear site right after sunset or just before the sunlight. The Earth's rim obscures the sun. But the scattered light from the dust is something you can see right along the ecliptic. And it's fluffy, it's not a thin plane. And it looks like this. Now we've seen zodiacal light around other stars, because they too have formed planets. And that actually turns out to be a noisy foreground signal if you want to look for planets around those stars. So we see directly fossil evidence of the formation of solar system even today.