DJORGOVSKI: What's relevant for star formation is the cold part of the interstellar medium-- the part that can condense. And this is a picture from Herschel satellite that is mapping a particular giant molecular cloud in several different wavelengths. And again, you can see that these clouds are nothing like spherical, and they have this knobby structure. So all the dense spots are the densest clouds is where stars can form.

So the way we study is through millimeter wavelengths, mostly, from planet Earth. And that's usually done with Interferometers telescopes, which have receivers in the range of wavelengths of the order of 1 to a few millimeters. Caltech-- jointly with a few other universities-- is operating one of these arrays in California. It's called CARMA, for California Array for Millimeter Astronomy. And the world's biggest is now operating in Chile. That's Atacama large millimeter array. There are others, too. Interferometry is the popular way of doing radio astronomy because it allows you to resolve things with separations of antennae, not limited by the resolution of an individual antenna.

And the typical molecules that we see out there are, first of all, molecular hydrogen-- atomic hydrogen being the most common thing. Molecular hydrogen is not likely to lag behind. But then there'd be carbon monoxide-- not dioxide, monoxide-- and ammonia, and a whole bunch of other stuff, including some very, very complex organic molecules.

And it was at first surprising why such complex organic compounds are found in interstellar space. But now astrochemistry is explaining most of these things fairly nicely. Actually, that fact that there are large clouds of organic material in interstellar space prompted thinking among some people that the life may have originated in interstellar space And just got accreted on planet Earth. Now I don't think this is likely to be correct. But there is plenty of organic material in the universe, and a lot of it ends in planets, too.

So we know from direct observations that star formation like Orion Nebula-- famous picture of it-- they are always associated with giant molecular clouds in all galaxies near us. This need not be the case with very, very first stars and galaxies of high redshift. But from most of the observed universe this is a correct statement.

And clouds are sitting there. Somehow they have to start collapsing and making stars. Usually that requires some physical cause to push them over a critical density limit. And that could be say, density wave or spiral arm. Could be a shock wave supernova. Could be just the tidal force between two passing by molecular clouds. And then once you start collapsing them, they carry on and make stars.

Here is a beautiful picture of individual clouds. These are remnants of the much bigger cloud that created those bright stars behind them, which have light reflected from-- well dust fuzz around them and plenty of red ionized hydrogen. But these are the densest cores that they still haven't managed to evaporate. They are called Bok/Thackeray Globulae, and they were seen in optical pictures before any of this was really clarified.

So the question then is why do these clouds collapse in the first place and make stars? And the process of this is called core collapse. And it's intrinsic to all physical systems that are bound by gravity. That in fact, would be the case for any attractive interaction.

And it works like this. So you have a cloud of gas, and it's in some equilibrium. That means the thermal kinetic energy of molecules has to balance the gravitational potential energy. And this will generally will be the case. It would be the highest in the middle, because that's where most of the boiling potential will.

So the cloud-- or star, for that matter-- would be in hydrostatic equilibrium if you have exact match between thermal pressure of the material and gravitational pressure that pulls it down. Think you squeeze it little bit.

That means that the core of it will get a little hotter. It will emit more radiation. If this is long wavelength radiation that can go through this material-- say long wavelength infrared that can penetrate dust clouds-- it will escape, thus carrying away some kinetic energy. Because now some kinetic energy is being radiated away, the cloud shrinks some more. That brings it closer, again, to hydrostatic equilibrium, which again, leaves it with a slightly hotter core, which then shines more light, and so on.

And it's a runaway process. In case of stars, it stops because a new source of energy opens up in the middle-- the thermonuclear reactions. Otherwise, these clouds would collapse into black holes. But at some point you start burning hydrogen into helium. That releases goodly amount of energy. And that more than compensates for the amount of energy that's been escaping from this collapsing protostar.

So the core collapse leads into ignition of star in the middle. And then, that's it. Then all manner of other interesting physical things happen.

Interestingly enough, exact same thing happens in globular star clusters. We can think of them as a gas cloud of stars. What serves as a source of energy there are binaries-- but we'll get to that later.

So that's some very basic physics of star formation. So what's at play here? Obviously gravity. That pulls things together. Pressure has to balance it. But other things that can also fight gravity are magnetic fields because they're hard to squeeze, or just bulk motions-- kinetic energy in a different packaging.

And so if you have one of these clouds which is sufficiently dense to collapse, it collapses according to the free-fall time scale. Which is if you were to drop something at the outermost shell, how long will it take to come to the middle? And because the shells inner to it are accelerated more, there are more shell crossings. And so all you need to do is take one test particle at the edge of your cloud, such as it is, and let it go.

And the expression for that's given here. And the time it takes to do is also given here. And so you notice that time is inversely proportional to the square root of mean density. And that kind of makes sense because denser clouds will have stronger gravitational attraction. So they'll collapse faster.

Now the other concept that's important here is so called Jeans mass. And deriving the formula is beyond the scope of this class, but its physics is simple. You have thermal pressure that balances pull of the gravity. What is the minimum mass that will push this over and make cloud collapse? And James Jeans was the first one to evaluate this. And he came up with this formula.

There is so-called Jeans mass. It's a function of two variables-- temperature and density. Now that little R inside-- Rg is gas constant from pv equals rt. It's not radius. And mu is the mean molecular mass in atomic units.

So if you look at this formula, it says it's going to be proportional to temperature 3/2 powered-- by that power, it doesn't matter. And that again, kind of makes sense because if you have a hotter cloud, it will require more mass to push it over into a collapse.

Contrary to that, if your cloud is denser, then it wouldn't need as much, and the mass will go down. So it'd be inversely proportional to this weak power of density.

Plug in the typical numbers that we observe for interstellar clouds and assume it's molecular hydrogen. It doesn't really matter if you take a mix of carbon monoxide. And amazingly enough, it produces a value that's pretty close to the mass of our sun.

Now most stars are actually less massive than our sun. There are many more low mass star than high mass stars. And so this is kind of amazing. Just if you know the temperature and the density of the protostellar clouds, characteristic mass of stars comes out.

Now, stars don't come in one mass. The stellar mass function is not a delta function. And that's because the clouds are not perfectly uniform, et cetera, et cetera. So there'd be some range of densities, and temperatures, and magnetic fields, and God knows what else. But this is very simple application of thermodynamics and gravity in deciding how stars are made.

Just as we define a mass, there is also a characteristic length. And that's called the

Jeans length. That will be the typical scale of clouds under which things start to collapse. And so if we just solve it so that it's function of radius and not temperature, and not mass, you get formula which is similar to the previous one.

Proportional to some weak power of temperature again, because hotter clouds will tend to-- you need to have a bigger cloud in order to get enough mass to collapse-- and inversely proportional to a weak power of density, denser clouds will collapse sooner, so you don't need very big. And that happens over the free-fall time scale.

Now typical sizes of these protostellar clouds are of the orders of tens of thousands astronomical units. So they're bigger in solar system, by far. And if you plug in the numbers you find out that for this toy example, it will take approximately half a million years for the protostellar cloud to collapse. And that's good because that's just barely shorter than the lifetimes of massive stars.

Why is that important? Because stars are disrupting star formation. So you make some high mass stars very luminous. They do two things. First they shine UV that will ionize the gas. The gas will be too hot to partake in formation of stars. There'll be just too much kinetic energy in the gas.

And as they do this they essentially eat the dust. They evaporate the dust. And so you form a bunch of stars. And at that point, star formation is more or less over. These young stars will preclude any more stars being made in that same region.

And so you often see these clusters that they're embedded into these nebulae. And this is picture of Rosette Nebula. It's like the unusual coloring. And you see a cluster of bright young stars. There are many fainter ones, as well, but it's the brightest ones that dominate this process.

So this also tells you that stars tend to get made in clusters, in groups. The reason for this is that a given cloud will fragment into multiple pieces because you've seen them. They're not spherically symmetric homogeneous. They have this complicated geometry with many little dense knots. Each of those can give rise to a star.

And so more or less all of them will do their thing simultaneously. And however many those dense cores you have, that's how many stars you're going to make. And then as soon as the big stars start shining, game over.

So star formation is self-regulating because these stars last millions of years, and collapse process is half a million years, or something. That means that there will be regulation. Once you start making stars you can't make new stars until those massive ones are gone, and then you can start making more stars.

Well, so radiation is one thing. They ionize the gas. The second thing is, they like to explode. And what that does in addition to photoionization is there is sheer kinetic energy that's being implanted now in that gas cloud. That's approximately 10 to the 51 ergs for a typical supernova.

And a shock wave just clears out the dust. Sweeps it out. And so this is where those bubbles you've seen in pictures of interstellar medium came from. But they begin like this. And so the moment first supernova goes off in your star forming regions, that's it.

So stars eat clouds first. They're made out of that material, and then once they're made, they just destroy the rest. And you can also have a shock wave from explosions. So this is a cartoon of what that might look like. And this is an actual picture of one such thing taken with Hubble. So we have a pretty good idea how stars form.

Now stars do something else interesting and important and that's highly relevant for formation of planets. Which is stuff falls in, settles into a protostar. But if there is any angular momentum, that angular momentum cannot be radiated away. So the material, which had excess angular momentum, has to settle into the lowest energy state for a given amount of angular momentum.

And as you'll probably recall, when we were talking about the origin of Kepler's laws, that essentially means circles. And so material with too much angular momentum will settle into a thin disk around a newly minted star, which is made out of stuff that didn't have much angular momentum.

And this is artist conception, but we actually have seen the real things. And these are all taken with Hubble in the Orion star forming complex. And they're not necessarily symmetric, but there really are little protostellar discs with young stars embedded in them.

Another thing that they do is they drive so called bipolar outflow. If there is any magnetic field-- and usually there is some-- inside of that protostellar cloud, as it collapses it will get bunched up and threaded through this disc. The disc will keep spinning and tightening it even more. That creates a preferred axis along which you can accelerate charged particles.

This is very similar to what happens in quasars and active galactic nuclei, but a much lower energy scale. And so the protostar consists of essentially three pieces. There is this actual protostar in the middle that's igniting, starting thermonuclear reactions, surrounded by a thin disk of leftover material, which soaked up all the angular momentum, and then outflow that happens along the rotation axis.

And that's not fantasy, either. Here they are. These are actual protostellar jets from young stars as observed with Hubble, but there are other things.