Astronomy Cast Episode 12:
Where Do Baby Stars Come From?

Fraser Cain: Most parents have had that uncomfortable conversation with their children at some point. Mommy, Daddy, where do stars come from? You hem and haw, mumble a few words about angular momentum and primordial hydrogen and then cleverly change the subject. Well, you don't have to avoid the subject any longer. Pamela, where do stars come from?

Dr. Pamela Gay: They come from giant molecular clouds. You have this big cloud of gas and dust hanging out quite often in the disk of a galaxy, minding its own business, when something knocks it out. Either a density wave hits it, a shockwave from a supernova hits it or another galaxy hits a galaxy and the two galaxies hitting one another send shockwaves that knock about the giant molecular cloud.

Fraser: What causes these density waves?

Pamela: That's another one of those we don't know answers. When you look at spiral galaxies, you see arms and definite structures of where the stars and the dust are located. There are those who believe (and I'm one of them) that these are caused by some sort of density wave propagating through the galaxy. We're not quite sure where they come from – but we know where stars come from (giant molecular clouds).

Fraser: So that density wave or supernova explosion or colliding galaxy causes this cloud to collapse.

Pamela: As it collapses, it fragments. You go from having a giant cloud of thousands of solar masses that's tens of light years across, to having smaller fragments that are less than a light year across and are made of anything from a few solar masses to tens of solar masses. It's these smaller fragments that then break down and collapse down and spin up and flatten out and form star systems.

Fraser: How do they spin, though? Wasn't it just a cloud hanging in the galaxy?

Pamela: There's this thing called torque, which likes to make things spin. The basic idea is if I hit anything and I don't hit it exactly along its centre of mass, it's going to spin. It's sort of like if I got very angry at my mic stand (because my mic stand likes to fall over periodically), if I flick it in the exact centre, it moves straight. It's hard to hit something in the exact centre. If I instead hit it at the base, then the base will cause it to rotate about the centre. If I hit it at the top, it will again rotate about the centre.

If I shock that giant molecular cloud anywhere except along its exact centre of mass, I'm going to start it spinning. So, the shockwave is bound to somehow cause the dark molecular cloud to start spinning. Each of the fragments within it will spin. As they collapse it's sort of like an ice skater pulling her arms in towards her body. As you get your distribution of mass closer and closer to the centre of the mass, an object spins faster and faster. As these fragments collapse, they get smaller and they rotate faster.

Other neat things are also going on. This giant cloud has all sorts of gravitational potential energy in it. The atoms are spread out across space, but there's a central point to the space.

As things move inwards toward that central point, gravitational energy gets converted to kinetic energy. The particles move faster and faster as they get in closer to the centre. They heat up. You have something that's spinning faster, heating up and it flattens out like pizza dough flung up into the air. As the cloud collapses it fragments and the individual fragments heat up, they spin faster and start to flatten out into disks.

Fraser: I've seen enough pictures of that. You've got this long, flattened out disk – almost like a little galaxy – with a ball at the middle where the star's starting to form.

Pamela: That's exactly what it looks like. These systems form rather quickly. You can go from fragment to a star starting to ignite hydrogen in its core in about 100 thousand years give or take (depending on the size of the star).

One of the neat things about this is you have a huge dark molecular cloud that is beginning to light up as stars form. The first stars to light up are the ones that will become the biggest, brightest, largest showboat stars in the entire cluster.

Fraser: These are the chunks of the largest of the fragments in that original cloud of gas.

Pamela: The largest fragments have the most self gravity. They collapse the fastest, and they form the largest stars. Those largest stars ignite the fastest, burn the brightest and these are the stars that you see when you look at things like the Orion nebula, which is one of the largest star forming complexes we can see in the sky.

When you look out at Orion (which is starting to become visible in the evenings this time of year), you can see the sword of Orion which is part of the Orion star-forming region.

Fraser: If you're in dark enough skies, you can see Orion with the unaided eye. There's sort of a hazy/fuzzy bit just below Orion's belt. Even with your unaided eye or binoculars you can see the fuzzy bit. We're lucky to have something so close and bright.

Pamela: This is a young star forming region with these bright objects and just a few years ago, a new star was seen to light itself up on the edge of the nebula. We could see the moment at which a star broke free of the dust and gas around it, and we could suddenly see it glowing in the sky. This is something that's going on dynamically, where we can see changes from year to year, as these stars are evolving toward becoming regular Joes like our Sun.

Fraser: So what's going on? We see the cloud collapse, we see the disk and the centre part. This is coming together quickly – the star's forming. What's going on inside the star?

Pamela: As the gas collapses down, it gets hotter and hotter. Pressure builds up in the centre.

You have gravity pushing all of the gas tighter and tighter together. Eventually you reach the point where the combination of pressure and temperature causes atoms to get slammed together at a rate that causes nuclear fusion to occur. You end up getting hydrogens going through a bunch of different reactions that lead to helium. This hydrogen burning process causes a star to start giving off light via nuclear reactions.

Prior to that, you have gravitational heating. As the gas gets compacted more and more, it heats up and a hot object gives off light. We're able to see where stars are starting to form if we look out at the gas clouds in either radio light (which is really red light) or if we look out in infrared light (which isn't quite as red as radio). Cool objects, but warmer than the background gas, give off radio.

A giant molecular cloud will only be ten degrees above absolute zero – ten Kelvin. These fragments will heat up enough that they start giving off warmer light in radio waves. Eventually, they'll heat up even more and they start to give off infrared light. When they ignite with the hydrogen reactions, you start getting visible light which is what we see when we look at the Orion nebula through binoculars.

Fraser: When this star is collapsing, what's to stop it from going all the way down to a neutron star or black hole? Isn't that what black holes are – matter that's collapsed down?

Pamela: The nuclear reactions actually create their own pressure. We're not generally aware of it, but light actually hits us and the lights from our ceiling are creating a very, very tiny, not noticeable light pressure on our body.

Within a star, there are so many photons, so much energy getting radiated away from the centre where the nuclear reactions are going on, that the pressure from the light is able to balance out the gravitational force trying to collapse the star down.

Fraser: That's amazing. The pressure of the light alone is causing that balance.

Pamela: Light balances gravity. It's this really neat process and what happens with supernova (which we'll talk about in a few weeks) is that light shuts off. The nuclear reactions shut off and there's nothing to balance that gravity anymore, so the star collapses. In young stars we have lots of fuel, we have lots of reactions going on, and the star is able to balance itself between light and gravity.

Fraser: That light makes it out and we see it as a star.

Pamela: Exactly.

Fraser: Continue on though – the star ignites, what happens next?

Pamela: There's a whole lot of different things going on during this process. One of the weird things that has had astronomers confused for a while is when we look at really young systems called T Tauri systems – these are young variable stars (their brightness is changing) that are basically what our Sun looked like when it was in the process of forming. They're approximately one solar mass objects.

When we look at them, you'd expect them to be rotating really fast. There's all this mass that collapses down and it's sort of like an ice skater holding barbells, who's spinning. When she brings those barbells in, she starts whipping around. These stars don't do that.

What we think is happening is there's magnetic fields that connect the disk of material around the star and the star. This magnetic field is causing everything to rotate differently than it would if there was no magnetic field.

Fraser: It's almost like it's acting like a brake.

Pamela: It brakes the star. In our own solar system, Jupiter holds lots of angular momentum. It has lots of this rotational momentum. If there was a magnetic field there once upon a time, that could explain how we ended up in a solar system with a fast Jupiter.

We think that magnetic fields early in the solar system are responsible for preventing the stars from rotating a little bit too fast.

There are also jets. No one's completely sure where the jets come from. Right before the star starts radiating light due to nuclear fusion, there's material streaming into the star and there's jets coming out the ends of these stars.

These jets are totally amazing. The material actually shoots out and when it hits the surrounding material, it lights up. There are things called Herbid-Harrow objects, that eject anywhere from 1-20 Earth-masses of material during their lifetime. This material streams out and hits other material that's also moving. This collision between the differently moving material lights up forming beautiful knots of glowing nebulosity around new forming stars.

It's sort of like these little tiny nebulas say, "look here – there's a star forming here."

Fraser: So the star's ignited, it's got material streaming off, it's got a magnetic field that's interacting with the disk around it. What comes next?

Pamela: Out around the star, you have a disk of material. This disk of material, when the star ignites, is going to get blasted with solar winds, with the light-pressure as well. When that happens, you start to get stuff pushed away. It clears out some of the disk of material.

Within the disk you have particles that are colliding with one another. Sometimes they stick together due to electrostatic forces, sort of like dog hair sticking to your wall. This material that sticks together can gather friends and all of these materials glom together and over time they build up planets.

You end up with, closest to the star, the rocky planets because the material that makes up the rocky planets is harder to get blown away by the star. It's also moving slower. Gases – they're tiny. When they collide, they can send each other into high-velocities.

If you take a little tiny thing like a hydrogen atom and knock it up against a bigger molecule, it's sort of like when you flick a marble at a wall. The marble just bounces off of the wall and the wall doesn't move that much.

The lightweight material is moving too fast to bond together in the inner parts of the solar system. Out in the further parts of the solar system, it's not as hot, the material's moving a little bit slower, and you can start to get gas giants.

The inner part of the solar system – the gases are moving too fast to form planets. The heavier-weight materials can form the rocky planets. In the middle parts of the solar system, gas is moving slower and can glom together so you can get gassy planets.

Fraser: It's like a bit of a race, then. You've got the material trying to glom together faster than the increasing stellar wind is coming off the star to push everything away.

Pamela: It's a real problem. You need everything to be happening all at once. These are happening in violent places – you have stars forming and supernovae going off nearby. We're still trying to figure out the details of it, but planets are still somehow able to form in this violent area. This is all happening on timescales of just hundreds of thousands of years.

Fraser: Most of the extrasolar planets discovered so far are the hot jupiters – the large gas giants close in to their stars.

Pamela: That's something of a selection effect.

Fraser: Right.

Pamela: We don't know what the typical solar system looks like, we just know what the easy to detect solar systems look like. There's no way of knowing if those are typical or not.

Fraser: The interesting discovery that's happening right now is people finding that all this happens much more rapidly than people had ever thought before.

Pamela: It's happening in much more violent places than anyone had thought before. Scientists are looking out at the Orion and Carina star forming regions and finding disks of material everywhere. This means that in high-density star forming regions, with giant, violently UV-emitting, young stars, disks and planets are still able to form. Planets are going to be everywhere. At least, everywhere there are heavy materials capable of forming planets.

Fraser: I'd like to sort of provide some variation. The situation you described is the regular, main sequence star like the Sun. What happens if you've got some of those large first-forming knots that are really large?

Pamela: For a lot of complicated reasons, stars like our Sun, which have a lot of elements in them that we don't think about (like titanium, scandium, iron and all these heavier elements) allow the stars to be smaller. When the universe first formed, pretty much all we had was hydrogen, helium, a dusting of lithium and beryllium.

These earlier stars didn't have all the materials. They weren't able to form as normally as the current stars you might say. These early stars turned out to be 200 times more massive than the normal stars today, and they only lived about 3 million years. They formed huge, burned brightly, gave off vast amounts of ultraviolet radiation (the type of light that gives us all sunburns). They lit up the universe around them and then exploded, having created heavier elements within them.

They spread these heavier elements vast distances and it was this first generation of stars' explosions and dispersal of material that allowed mixing of the heavy elements throughout the universe that allowed stars like the ones we have today to begin to form.

We've gone through many generations of stars. We can't see any of those first generation of stars – they only lasted about 3 million years. The next generation of stars (population III stars), there are people out there looking for them and finding them in the halo of our galaxy.

Little, tiny, low-mass stars that did have some heavier elements in them can live billions and billions of years. Some of these population III stars, some of this very second generation of stars are still alive.

When you look at them, you can look at the elements within them and say, "this had a supernova that contributed to it, this one had two or three." This is the result of two different types of research.

You have people who say, "okay, when you have a supernova explosion from a massive star that is ten solar masses, you get this distribution of atoms formed. When you have a different type of supernova with a different mass, you end up with this distribution of atoms formed." So we take the recipe of what we think was formed in a supernova and do very careful stellar atmosphere modelling.

Knowing the temperature and which atoms are giving off or absorbing light, we can build a model of what percentage of the star is each of the different atoms. Then we match between what the supernova give off and what we find in the stars so we can reverse-engineer how stars were made and how many supernova went into stars.

Fraser: It's like a family tree for stars.

Pamela: That's exactly what it is. It only works for the earliest stars that tend to be more of a pure-bred from a single supernova or just a couple. Once you get to stars like our Sun, so many different things went into forming it that it's impossible to detangle everything.

Fraser: How small can a cloud of gas be and still be able to form a star.

Pamela: That's a complicated question. We're still finding new places where clusters are forming. There's some recent research looking at one of the Arp galaxies – one of the twisted up, messed-up, doesn't look like normal galaxies. They were finding smaller clusters that were only about ten light years across (instead of several tens of light years across), that were able to fragment and form stars.

In general, you're not going to get a single cloud of gas and dust that is just big enough to form a single star. You do get ones that are only big enough to form hundreds of stars.

Fraser: Right and you can get brown or red dwarf stars.

Pamela: In any given cluster, you end up with a whole distribution of masses formed. There is actually a lot of work that goes into figuring out if you have a large molecular cloud, what the population of stars it produces looks like. In general, you don't get very many big stars forming, but you get tons of itty-bitty, tiny stars forming. There are all sorts of functions people have come up with to describe the distribution of masses.

When you watch clusters, our sky allows us to see snapshots of what clusters look like at different ages. We can look at the Orion star forming region and see stellar nurseries.

We can look at the Pleiades, an open cluster that's also visible at this time of year in the northern hemisphere. We can see what a region that has pretty much stopped forming stars, but still has a little bit of gas and dust left over and has many of its biggest stars still burning, we can look at it and see what its distribution of stars look like.

We can look at the Hyades cluster which is also visible, but older, and see what it looks like.

By taking these snapshots of different clusters which are all different ages, we can develop pictures for how clusters evolve over time. What's neat is you can also see how the clusters shred themselves over time.

Fraser: I was going to ask a question about that. Did our Sun start out in a cluster like that?

Pamela: Yes, pretty much everything started out in a giant star forming nursery and a cluster, once upon a time.

Fraser: Where are all our little friends?

Pamela: They've orbited away from us over time. These clusters take up space and as the galaxy rotates, things that are closer to the centre are moving at one rate and things that are further out are moving at a little bit slower of a rate. This differential rotation rate causes the clusters to slowly fall apart. We see this very dramatically when we look at the Hyades cluster which is now stretched out across the sky.

As we look at the clusters, we see them disperse (get less and less dense) and we know that’s exactly what the star forming nursery we came from went through. There are different people that work to trace back where we came from and who our stellar siblings may have been.

Fraser: So we can look at a cluster, measure how far apart things are, and get a sense of how long ago that cluster formed.

Pamela: Yes.

Fraser: That’s really interesting.

Pamela: We can also look at the ages of the stars and for the most part they’re all the same age. That’s one of the really neat things about doing cluster work: the stars in the cluster are pretty much all the same age, all made out of the exact same stuff. So when you look at stars in a cluster, the only differentiating characteristic is their different masses. We can see exactly how stars evolve as a function of mass, because they’re all the same in everything else.

Fraser: Wow. Fascinating stuff, Pamela. Hopefully that definitively answers the questions from people on where stars come from.

This transcript is not an exact match to the audio file. It has been edited for clarity.