# Astronomy Cast Episode 108:
# The Life of the Sun

**Dr. Fraser Cain:** This wasn't our intention but we're actually coming up with another series. We talked about the Sun last time and we're going to talk about the Sun today and maybe we'll talk about the Sun next week. I don't really know.

**Dr. Pamela Gay:** We just have too many big ideas that refuse to be confined to 30 minutes.

**Fraser:** I know. This could be one show, this could be two shows, I don't really know.

**Pamela:** We'll see where we go.

**Fraser:** Exactly, we'll just let the show decide. We've talked about the Sun before. This time we're going to look at the entire life cycle of the Sun and all the stages it's going to go through, Solar Nebula, Protostar, Main Sequence, Red Giant, White Dwarf and more. So if you want to know what the past held and what the future holds for the Sun get ready for the grim details. [Laughter] And of course this will always end on a sad note.

Okay Pamela, I think the goal here today is to go through in excruciating detail all of the stages of the Sun. It is actually really amazing all the crazy stuff that happens. So let's rewind time all the way back to 4.6 billion years ago plus plus and talk about what came first.

**Pamela:** Well, once upon a time there was nothing more than a giant cloud of gas and dust. That's the boring part. We don't know how long that cloud of gas and dust just sorta hung out doing nothing other than maybe glowing faintly. Somewhere along the line that cloud of gas and dust was caused to contract; caused to fragment and turn itself into a bunch of baby Stars.

**Fraser:** Now the key is that it was a cold cloud, right?

**Pamela:** Yes.

**Fraser:** And not a hot cloud. If you get a hot cloud of gas it will never contract.

**Pamela:** This is because temperatures related to the rate at which Particles are flying around. If you have something hot the Particles are bouncing around, bouncing off of each other and it's hard to get that to collapse down because you have this thermal pressure holding the cloud apart basically.

But if you have cold gas and dust that is just hanging out in Space and you whack it, it will start to condense. As the gas and dust fills a smaller and smaller volume, Gravity will start to drive that contraction faster.

We talk about the point at which something starts to identify itself as being the beginnings of a Star as the Hayashi track. With a Star like our Sun, it actually started out about ten times brighter than it is right now as it started to contract off of this Hayashi track.

So for several million years, we're not exactly sure how long this process takes, the Sun contracted and actually got fainter as it contracted and then started nuclear burning in its core.

**Fraser:** So before it was bright but it wasn't burning with nuclear fusion in its core?

**Pamela:** No, it was actually all thermal heat. This is sort of what Jupiter is doing. Jupiter actually gives off more light than it is simply reflecting from the Sun. If you turned the Sun off, Jupiter would still be giving off light.

This is because gas that is being held together, being pushed together, being squished together by Gravity actually emits thermal radiation for many billions of years.

**Fraser:** Right so the first few million years of the Sun, it was just a ball of Hydrogen and Helium held together by the Gravity and just headed up by that process. No fusion necessary.

**Pamela:** The best way to think of this is it's the opposite of spray air. When you spray your hand with spray air, it's really cold because the gas is expanding. In this case we're squishing the gas together and it's heating up. So, gas squished, heated up and eventually it starts nuclear burning.

This process probably started with Deuterium burning. This is where you're burning up bits of Hydrogen Atoms that have an extra Neutron in them. These actually burn a lot easier than just regular run of the mill Hydrogen.

**Fraser:** And where did those come from?

**Pamela:** Those probably came from the Big Bang. So we're burning up the building blocks of the Universe basically.

**Fraser:** The point being that it's like at early enough on you didn't have the conditions to fuse Hydrogen yet, but you still had a few left over chunks of Deuterium and those could start to fuse together.

**Pamela:** Eventually you do end up with nice friendly Hydrogen burning in the center of the Sun. Over the process of getting to that stage the Sun first overheats a little bit and then cools down to settle into a nice friendly what we call main sequence life. This is the first big main part of saying that is a Star.

So we go from protostar which is the process of going off of the Hayashi track to contracting to just settling down into nice round Star that has also along the way blasted everything out from around it.

During the early parts of the Sun's life, they go through many radical stages with lots of x-ray flares, lots of high energy output. They go through their own form of "the terrible twos" that includes High Energy Radiation.

**Fraser:** Now why are they so violent and active at that stage?

**Pamela:** As they collapse there's material streaming on to them. Our Solar System is basically an Accretion Disk at this point, a disk of material where some of that material is just streaming on to the Star in the center.

You have powerful Magnetic Fields in many cases. You can have jets coming off of the poles of the Star. All of these different interactions can lead to flares as the Star settles down.

**Fraser:** So it's almost like new chunks of material are landing on the Star and that causes flares. It wasn't that inflow of material that causes the Star to settle down.

**Pamela:** We also don't know exactly what the details of the Magnetic Field evolution at this point is because you have all these Magnetic Field lines that are rearranging themselves as well. There is lots of potential for badness to be going on.

**Fraser:** Now the Sun has finally settled down to its Main Sequence. But that was like four and a half billion years ago, right?

**Pamela:** So depending on what paper you read, the protostar stage could have taken hundreds of thousands of years or a few million years. That's a short stage to get nice solid Star formation going on and to get our Planets formed and to get everything lined up so that we have a Solar System that looked like the Solar System we live in today although the terrestrial surfaces were very different. The pieces were all there.

**Fraser:** Right, but how does the Sun look? We're still on a Main Sequence phase, how does the Sun look different when it started the Main Sequence to where it is today?

**Pamela:** Its temperature has changed slightly. It was a little bit hotter in the past – our Sun has actually cooled off some over the years. Once it hits the Main Sequence Stage, it's a fairly constant Sun. We've had a bit of cooling off but our Planets found other ways through gases and stuff to keep going in a way that works for us.

**Fraser:** But how is it changing – even though it's in the Main Sequence – it must be changing a little bit, right? Hydrogen is getting fused into Helium.

**Pamela:** There are long term changes in temperature. Over time our Sun is now heating up again. So we went from being hotter and the Sun cooled off and now slowly we're getting warmer and warmer over time. It's a gradual enough process that even over those 5 billion years; terrestrial effects have been really what have dominated the situation here on the planet Earth.

**Fraser:** Okay so the Sun is getting hotter – we're not talking like a cause for global warming – we're talking billions of years.

**Pamela:** Right, so it's only in like 50 million years from now that we're going to have to start worrying about the temperature has gone up enough that it starts to affect the planet Earth.

If you look at people who look at long term cycles in the Sun, there are a lot of them who believe for a variety of reasons that are hidden in the field of Solar Astronomy, that our Sun is actually in the process of a cooling period that has to do with how the Magnetic Field is evolving over time. There's lots of long term and short term changes in the Sun's behavior.

We think that there is currently a short term slight cooling phase going on but that's superimposed over a long term heating of the Sun that about 50 million years from now is going to start to impact us. The Sun actually will stay a Main Sequence Star for probably another 5 billion years.

**Fraser:** Right, so we're only not even halfway through the process yet.

**Pamela:** It's middle-aged still though because the periods that come after it are so short that we can start to look at ourselves as being in our mid-40s if you are talking about someone who lives to be 100.

**Fraser:** Then I guess at some point – we've talked about this before – that the heat from the Sun is going to start to really impact our Planet, right?

**Pamela:** Yeah. This is where we start having our oceans heating up. That leads to higher humidity in the air which leads to the Planet heating up more which of course heats the oceans more and eventually the oceans evaporate – total runaway Greenhouse Effect. No more life on Planet Earth. It's rather depressing but our Universe is after all trying to kill us. [Laughter]

**Fraser:** We've covered that before. [Laughter] I've seen some competing series on this but essentially 500 million to a billion years from now there will be no liquid water. Water vapor will have boiled off into Space. We'll essentially be very much like Venus, just a little cooler.

**Pamela:** Yeah.

**Fraser:** We're on our way to Venus. So, Earth doesn't matter anymore. [Laughter] The Sun is still a concern. That's still like 3 billion years from now. So when do things get interesting again?

**Pamela:** About 5 billion years from now we start to run out of Hydrogen that is readily available for fusing in the center of the Sun. When this happens the Sun is going to start contracting because there is not going to be as much pressure from the light supporting the outer layers of the Star.

**Fraser:** This is kinda interesting because even though there is tons and tons of Hydrogen in the whole Sun and if you could somehow mix it all back up again – give it a stir – the Sun could just go on for hundreds of billions of years, right?

**Pamela:** This is what happens in little tiny tiny Stars. The burning process is able to create what we call convective mixing. The entire Star essentially acts like a Lava Lamp. It's able to constantly refuel the center of the Star.

As you get to bigger and bigger Stars like our Sun, you reach the point where that mixing no longer takes place. So as you're burning Hydrogen into heavier elements in the center of the Sun, those heavy elements stay there. You end up building up a Helium core to our Sun.

Once the core is exhausted of its Hydrogen fuel the Sun will begin to collapse and it will reach the point where a shell of Hydrogen around that Helium core is able to ignite. The densities around the core get high enough and the temperatures get hot enough just from the weight of everything resting on them that we burn a shell of Hydrogen.

At this point we talk about the Sun being off the Main Sequence and the next really interesting phase starts to occur once you reach the stage that you get a Helium Flash. For awhile you have what we call a Red Giant Branch Star. This is where you're burning the shell of Hydrogen but the Star is still collapsing.

The Sun is still getting smaller and smaller and the center of the Sun is getting hotter and hotter under the weight of this collapsing material above it. The pressures are getting higher as everything is getting confined into a smaller and smaller area.

In a magical moment when it reaches a temperature ten to the 8 degrees, suddenly the Helium in the center of the Sun is able to ignite. We call this a Helium Flash. At this point the Sun becomes what we call a Horizontal Branch Star. Now you have a new segment in the evolution of the Sun. This phase can also be called the sub-giant phase of the Star. Here you have the Star happily burning Helium, it bloats itself back out. It gets hotter in the core once you get this new burning going on. You get more light pressure supporting the outer layers of the Star, Star bloats out. It also drops in luminosity here.

This is one of the neat trade-offs that is happening with the Star. It's constantly changing every so slightly in brightness and in temperature as it goes through all these different phases. So once the Hydrogen shot off, the Star got much redder. Now that you have the Helium burning, the Star gets a little bit bluer again and that's kind of cool. Eventually the Helium also exhausts itself in the center of the Sun.

All of the Helium ends up burning itself out into Carbon. Here again you end up with shell burning. So now you have this Carbon core surrounded by a shell of Helium that's burning itself surrounded by a shell of Hydrogen that's burning. So you start getting Onion15:11 of Sun. This is where we talk about the Star being a Red Giant again. Exactly what happens depends a little bit on metalisty15:19 of the Star.

In a lot of cases as it goes through these phases we can also end up with it being what's called a Variable Star where it pulsates in brightness. This happens to Stars that are just like our Sun. They can go through a phase of pulsations as they go along. As they start running out of all this fuel, this is where we call them Mira Variables. They're giant, they're bloated; the outermost layers of the Star are thinner than the Earth's atmosphere which is kind of cool to think about.

This is where you start to spread our Sun out over a volume that just fits – maybe we think – within the Earth's Orbit. We don't know for certain. And you also start getting Mass loss in Space as the nuclear burning is going on. The outer layers of the Atmosphere have expanded out so far that sometimes just a slight push from the core of the Star which is sputtering as it burns is able to cause puffs of the Atmosphere to drift away.

**Fraser:** And the red color is just coming from it being cooler, am I right? Back in the olden days the Sun was white because it was a temperature of nearly 6000 degrees Kelvin and now it's cooled down even though it's a lot larger, right?

**Pamela:** So here we're starting to get down to 4000 degrees Kelvin. This change in temperature is enough to change its color so that it's a deep red.

**Fraser:** But the overall brightness of the Sun is way higher.

**Pamela:** This is because you have a much larger surface area that the light is going through. Each bit of that surface area is able to radiate away Photons and all those Photons add up to being a much brighter Star.

**Fraser:** So even though the Sun is changed to red, it's now visible from a much further distance than it was before.

**Pamela:** This is part of why so many of the really bright Stars that we see in the Sky are these red Stars. We can just see red Stars at a much greater distance and this is a common phase for Stars to go through. What's kind of amazing is the time scales that all of this has been happening on.

**Fraser:** That's just what I was going to ask – how long does this last?

**Pamela:** Our Sun hangs out on the Main Sequence for a few billion years – like 10ish billion years. Then it only spends a few hundred millions years going through all the rest of the stages. So those are relatively short stages in a Star's life.

We refer to the Main Sequence as the majority of the Star's life and that's exactly what it is. Then it goes off and does all these really cool things but those happen essentially in the blink of a Cosmic eye. Once the Star hits the Mira phase, just maybe four or five hundred million years after leaving the Main Sequence, at that point it starts losing its Atmosphere.

It starts transitioning from being a Star that's burning and doing all the Star-like things to blasting its Atmosphere away starting to form a Planetary Nebula. A Planetary Nebula is nothing more than the Atmosphere of a Star that's been exhaled and hasn't yet drifted so far away from its starting point that we can no longer see all the gas associated with one another.

**Fraser:** What's the mechanism that actually gets the Atmosphere away from the Sun? Like what's blowing it away?

**Pamela:** It's the flickering and sputtering of these shells of burning Hydrogen and Helium. As the Star collapses down you'll get a burst of extra light that pushes things away. The Star is so big that Gravity and Light are just barely in balance and it's very easy to overcome that Gravity of the outer layers of the Star.

**Fraser:** You almost get it kicking as it's normally in balance and then it maybe sputters and gets brighter and more light pressure per second and then contracts but it's enough of a push to shove off that outside layer.

**Pamela:** There's also this constant Solar Wind that's going out where you have this light pressure pushing out and it's always able to remove some amount of the Star's Mass. We're just not entirely sure how much of the Star's Mass.

What's really amazing is we're now able to start looking at detailed maps of the environments around some of these Stars and see all sorts of crazy strange structures that have formed during Planetary Nebula phases. We don't understand what causes all of these different strange shapes.

There is different Planetary Nebula that looks like a series of nested boxes, a series of nested rings, figure eights and all of these are coming from fairly similar parent objects. But there's something that is causing it to look radically different in just how the Atmospheres were lost to form these Nebula.

**Fraser:** Magnetic Fields.

**Pamela:** [Laughter] That's the thing we always blame.

**Fraser:** Okay, so now our Sun is in this Mira phase, puffing off outside layers into Space….

**Pamela:** Eventually it reaches the point where between Mass loss and just burning up what little fuel it has, it starts to run out of Energy. The Helium burning shuts down. The Hydrogen burning shuts down. And the last of the Atmosphere just drifts away.

At this point you now have a hot cinder of a Star. That cinder of a Star collapses down. It no longer has any burning going on to support the Atoms against one another. As they collapse they actually reach a degenerate gas phase. This is where the Hydrogen and Helium Atoms pack themselves so closely together that the only way the Electrons can still exist is if they basically form a Matrix.

You end up with Stars that their internal structure is essentially a diamond of Carbon surrounded by these extremely dense – we call them degenerate layers – of Hydrogen and Helium as well. These are our White Dwarf Stars.

**Fraser:** Right and so you've gotten a situation where the Gravity is so intense that it's packing the Carbon and the Helium and all that's left into a sphere but there isn't enough Gravity to actually ignite fusion of the Carbon.

**Pamela:** In the process of packing everything together it gets so close that the pressure of the Electrons one against the other going: "no, you have the same charge as I do stay away," and the poly-exclusion principle that are working to support the Star.

If you made White Dwarfs any heavier you'd be able to overcome this and you'd squish everything down into being a Neutron Star which we will get to in a couple more episodes.

But the remnants of Stars like our Sun are supported not by light but by Electron pressure. That's kind of neat to think of Electrons supporting a star. These are the largest diamonds we have in the Universe.

**Fraser:** Is it actually a diamond?

**Pamela:** Yeah, it just might be. If you think about it, what a diamond is. It is nothing more than Carbon Atoms that have been arranged in a Matrix which is one of the tightest structures that you can get those Carbon Atoms into. That's why diamonds are so hard.

As you're creating a White Dwarf you have to pack those Carbon Atoms down into a crystalline structure. That's where you start getting something that is basically nothing more than a really HOT diamond.

**Fraser:** Right, if you could cool it down and survive the Gravity and chop pieces off you could turn them into diamond rings. [Laughter]

**Pamela:** Yes. You would have to wait a long time for them to cool off though.

**Fraser:** I'm a patient man. It's a new business. Anyone want to go into business with me [Laughter] in the Inter-stellar diamonds?

**Pamela:** You want your one Solar Mass diamond, don't you?

**Fraser:** Yeah, exactly. So then, but it's not dead yet, right?

**Pamela:** It's still radiating heat. It's still hot. This is the situation of Captain Kirk heats up the rock with his phaser and it takes a little while for the rock to cool down. Well, White Dwarfs are a lot bigger than that rock and it takes them millions of years to cool off.

**Fraser:** Billions, trillions….

**Pamela:** It depends on how cool you want to get them. So they're cooling off over time and as these White Dwarfs cool off, the Planetary Nebula they sit in the center of also fades away as it expands away. You're essentially watching the home of the Star disappear.

Its Atmosphere is dispersing moving further and further away from that Core White Dwarf. The Star itself is getting cooler and as it is getting cooler it's getting fainter and fainter.

Eventually you end up with that gas and dust in the Planetary Nebula just sort of mixes itself in with the rest of the Cosmos. The White Dwarf over billions of years cools off to the temperature of Space. It's a kinda sad future.

**Fraser:** Right and we call that a Black Dwarf, right?

**Pamela:** Yeah, it depends on who you talk to. People are kind of nervous about using the phrase Black Dwarf because too many people mix it up with Black Hole, but that is one of the terms kicking around.

**Fraser:** It there some super Scientific term?

**Pamela:** No.

**Fraser:** Okay, some kind of degenerate …..

**Pamela:** Cold White Dwarf also works.

**Fraser:** A Cold White Dwarf, okay. That's very scientific sounding. [Laughter] Now what do we see? If we look out into the Universe, how far along that do we see White Dwarfs? Are there White Dwarfs that are just now too cool for us to be able to see them? Too cool for school? [Laughter]

**Pamela:** We don't think so. The Universe hasn't quite been around that long. One of the neat things that's happening is we can look out at Globular Clusters, packages of in some case thousands of Stars, that are gravitationally bound together and are orbiting our Milky Way Galaxy. These are some of the oldest objects that we know of, formed 13 or 14 billion years ago depending on whose Stellar Evolution Models you believe.

When we look at them - we can use Hubble Space Telescope to probe fainter and fainter until we start to pull out the White Dwarfs - we can actually see what we call the White Dwarf cooling sequence.

This is where you see a sequence of Stars in a plot of temperature vs. brightness that forms a nice polite line where the brighter ones are also bluer and the fainter ones are also redder. There is a direct relationship between how bright they are and what temperature they are forming a perfectly straight line. We can see where we stop getting Stars.

This is part of how we come up with the age of these Globular Clusters is we know, okay the first Stars to be able to form White Dwarfs were Foo and they burned through their stuff fairly quickly because they were higher Mass, had large amounts of Mass loss and eventually ended up dying with only 1.4ish Solar Masses of material after all of their Mass loss.

Then they collapsed down into White Dwarfs. And then Stars that were a little bit less massive collapsed down to White Dwarfs. And then Stars that were even less massive collapsed down to White Dwarfs. The Stars that became White Dwarfs later are still hotter than the ones that formed first which are still cooler. There aren't any that have had time to reach the point that they're too cool for school as you put it.

**Fraser:** Right, so you can look at a cluster, count up the number of White Dwarfs count up the number of Stars and get a sense of how old that cluster is.

**Pamela:** This is one of the many ways that we work to confirm the ages of systems.

**Fraser:** Right. Now is there going to be any time then – I mean the Sun is going to be slowly cooling down – is there anything left? Will there be some time down the road where maybe Jupiter crashes into the Sun? [Laughter] You know the White Dwarf Sun and you get re-ignition?

**Pamela:** No, probably not. It just doesn't have quite enough Mass to do anything quite that exciting. One of the interesting questions is going to be what happens as the Sun loses Mass through it's – we call it the Asymptotic Giant Branch Phase – that period of time where it's essentially a Mira variable. It's going to be undergoing huge amounts of Mass loss as the Mass leaves the Atmosphere and starts to form another Planetary Nebula.

As that Mass is lost – first of all, it's blasting the Planets – but second of all that Mass is no longer holding the Planets in their present orbits. This is going to cause the Earth's orbit to get bigger; the Mars orbit to get bigger; Jupiter & Saturn's orbits to get bigger. It rearranges our entire Solar System.

This is part of why we think the Sun isn't actually going to consume the Planet Earth. Earth will drift out of range. So, our orbit will get consumed, but our orbit is just an artificial line around the Sun. Our Planet itself will probably escape.

**Fraser:** I think you're wrong.

**Pamela:** Why do you think I'm wrong?

**Fraser:** The latest article I read: "The Earth will be destroyed. The Earth won't be destroyed." I think the last article that we did was the Earth will be destroyed.

**Pamela:** See, I like the Mass loss people. I'm a firm believer in Mass loss.

**Fraser:** Well, no the Mass loss will still happen it's just that it won't be enough the Earth will still be destroyed. Anyway, that's the current thinking. [Laughter] We'll talk in a year and the current thinking will be: Earth will survive.

**Pamela:** Well, and you know, I'm sure that for every paper written on Earth will be destroyed, an equal number are being written at the exact same rate for Earth will not be destroyed. This is one of the areas of Science that we're still struggling to understand. We still don't know how to calculate Mass loss halfway accurately. We're trying to figure it out but it's a complicated process where you have to understand in detail how Energy is transported through the Sun.

It's a crazy situation where part of the Sun acts like a lava lamp with convection; other parts act more like light bulbs heating up the levels above them through radiative transfer and trying to figure out how all these things happen and how they change as the temperature of the Sun changes.

It's a really complicated process and we're just starting to get computer software that is sophisticated enough to answer a lot of these questions. We're finally starting to get computers that are sophisticated enough to run that software without having to wait a few years for the answer.

**Fraser:** Right we can just keep coming back and forth with the controversy then. Five years more of AstronomyCast [Laughter] and you know, we'll have flipped the position five times. I think that's the wonderful thing about Science you know, that it isn't known. More evidence keeps getting brought to the table and the situation just keeps changing back and forth as more evidence is brought in.

As more evidence is thought through and argued and that's Science and I love that it's how that all works. It's different like should you drink red wine or not? [Laughter] It's like where you're changing your drinking habits the fate of the Sun doesn't really play into the day-to-day habits that I have.

**Pamela:** It's fun to watch how Scientists in general – a lot of us are willing to go yeah we're not sure what the answer is but I'm going to go with this one because I like it – until we have more solid Science.

When I first started studying Astronomy in college we didn't know what the expansion rate of the Universe was and the choice was 50 or 100. It was often: "Children use 100, it makes the math easier." [Laughter] We now know it's around 70 kilometers per second per mega parsec. But I'll never forget that: "Children use 100, it makes the math easier."

**Fraser:** Even though it's completely wrong, could be off by you know…

**Pamela:** But we didn't know if it was 50 or 100 and there were people fighting to the death over those two numbers and it turns it was halfway in-between.

**Fraser:** Alright, well I think next week we wanted to look at Stars that are smaller and Stars that are bigger. The way those events unfold change dramatically depending on the Mass of the Star that you're dealing with.

So we'll probably go through that whole process again but there's things that will get a lot more exciting and a lot more boring; mostly more exciting.

**Pamela:** But there will be explosions involved.

**Fraser:** There will be. Okay we'll talk to you next week.

*This transcript is not an exact match to the audio file. It has been edited for clarity.*
*Transcription and editing by Cindy Leonard.*