Astronomy Cast Episode 38:

Neutron Stars and their Exotic Cousins

Fraser Cain: First I'd like to let everyone know that Pamela and I were interviewed on *The Skeptic's Guide to the Universe* last week on their episode 95. *Skeptic's Guide* … if you haven't heard of it, it's one of my favourite podcasts dealing with science and scepticism. It's a completely different show from us, with this great collaborative group and they hash out various topics on science and scepticism. They interviewed us for about 45 minutes about dark matter, astrobiology, scepticism in astronomy and a bunch of other topics. Kind of like a 45 minute episode of *Astronomy Cast*. You can find their site at www.theskepticsguide.org and we'll probably be doing more stuff with them in the future, so stay tuned.

On to the show. This week, we're talking about some of the most bizarre objects in the Universe: neutron stars and some of their even weirder cousins: pulsars and magnetars. You've heard the terms, now learn the science.

Okay Pamela, what's a neutron star?

Dr. Pamela Gay: A neutron star is a star made of neutrons.

Fraser: Oh, come on!

[laughter]

Pamela: It was just too tempting!

Fraser: I know. Okay, *more*!

Pamela: So seriously, you take a four to eight solar mass star, let it evolve and eventually it's going to build up an iron core. An iron core isn't capable of generating more energy, and when a star runs out of the ability to generate energy it explodes as a type II supernova.

The stuff that's left (if there's enough of it left – if there's somewhere between 1.4 and 3.2ish solar masses) is going to start to collapse. As it collapses, the electrons and the protons aren't going to be able to push each other apart. They're going to collapse down and end up, for every electron and proton, producing one neutron and one neutrino. In this process, roughly 10^57 neutrinos are going to carry away a whole lot of energy, and what's left is going to collapse down into a neutron star.

These objects are tiny. They're about 5-20km in radius and they get smaller the more mass you throw on them because they squish down. When they first form, they're about a million degrees, which makes them x-ray objects. Some of them are spinning at as much as 1000 Hz – they're spinning 1000 times per second.

How's that for an explanation?

Fraser: All right, that's good.

[laughter]

Now, if I remember my supernova conversation with you, if you get a star that's too big, 50 times the mass of the Sun, it just detonates and goes kaboom, right? And there's nothing left.

Pamela: Right. Yes, exactly.

Fraser: But if it's smaller, as you say, if it's in this four to eight solar mass range, it explodes as a supernova but something's left. If it gets any bigger, is that where you get a black hole?

Pamela: That's where you get a black hole.

Fraser: Okay, it has more mass than our Sun – which is just going to become a white dwarf, right?

Pamela: Right.

Fraser: So if it's in that in between range, four to eight solar masses, it doesn't have enough mass to become a black hole, but I guess the process is kind of the same, right? It's collapsing down and then it just goes beyond a neutron star and turns into a black hole. So we're talking about those lucky stars in the four to eight solar mass range that can turn into a neutron star.

Pamela: The really, really big stars… they don't even quite get to the iron core part. They just blow themselves apart. The slightly smaller stars will actually end up becoming black holes, and it's the even smaller ones (that are still on the huge side of the stellar mass distribution) that become the neutron stars. So there's a whole continuum of ways that stars can blow themselves to smithereens.

Fraser: And we've got gravity overcoming the strong nuclear force, is that right?

Pamela: Yes.

Fraser: So normally you've got a proton and an electron and it just gets mashed together into a neutron?

Pamela: It gets mashed together into the neutron. This is actually the weak force at play when you're transforming the arrangement of the quarks, where you're going from one configuration of up and down quarks to another configuration of up and down quarks and flying off neutrinos.

Fraser: So if I could see a neutron star, what would it look like?

Pamela: They are just hot objects, so when we look at them we don't see anything in particular that's different about them because they're primarily neutrinos. In fact, they have an outer metallic shell around the neutron core. They glow really, really hot and we see them as what's called a black body.

A typical example of a black body is a rock. If you take a rock and you heat it up, it will eventually start to glow red. This is sort of like what Captain Kirk likes to do with phasers when they're abandoned on strange alien planets. If you keep heating the rock up with Capt. Kirk's phaser, it's eventually going to glow white. If you keep going, the rock will probably vaporize. If you keep going and you're dealing with something that doesn't vaporize, it will eventually be hot enough that it's giving off light in the x rays.

With neutron stars you have an object so hot that they're emitting light in the x rays. They're also giving off light in other colours, but it's in x rays that they particularly stand out all across the sky. There's actually some pretty neat Chandra images that look like you're looking at Christmas tree lights through fog because all the slightly different shades of x ray they artificially make different colours. It's a quick and dirty way to find lots of neutron stars quickly – with x rays.

Fraser: So they artificially turn low energy x rays into red and high energy x rays into blue?

Pamela: …Yeah, something like that. They make some decision on this is this, this is this.

Fraser: Right, so they're blazing in the x rays, but they're not necessarily blazing in the lower spectrum at all.

Pamela: They're just too small to give off a whole lot of light that we're going to notice above the background of everything else. You have something that’s basically the size of Manhattan. It's giving off vast quantities of light per square metre, but it only has so many square metres. When you look out across the sky, you can have a neutron star happily emitting light, but it's competing against things like Sirius, Betelgeuse, Rigel – all these bright objects – against nebulas, background galaxies… so they're going to get lost.

If you instead turn Chandra at the sky and start looking around the sky in x rays there's not a lot of stuff out there that's hot enough to be emitting x rays. All of a sudden neutron stars start springing up against the background sky.

Fraser: Now can neutron stars be part of a binary object, is that another way you can see them yanking a star around with it's gravity?

Pamela: You can see them yanking stars around with their gravity, and they can also build up accretion disks. If one of these high mass objects gets too close to their companion star, they can start stripping material off of the companion star. This will make them what's called a cataclysmic variable: a star that strips off material, forms an accretion disk and periodically the accretion disk undergoes it's own related nuclear reactions and flares up into a nova event.

Fraser: So you might have mini pieces of stars – reactions like fusion reactions going on outside the neutron star as it's dragging this material in.

Pamela: Exactly. You get this pancake disk where within the disk the densities and temperatures become identical to the centre of the star. So you have the nuclear fusion process going on within the accretion disk.

Fraser: I guess if the neutron star gets too much mass it might tip over the limit and turn into a black hole.

Pamela: That is also a problem to be considered, and when you get two neutron stars that end up orbiting together and eventually collapsing together, that's another way to form a black hole. In that case you get a short duration gamma ray burst in the process.

Fraser: Right, which we talked about a couple of weeks back.

Pamela: Exactly.

Fraser: All right, so what is a pulsar and how is that different from a neutron star?

Pamela: Well, all pulsars are neutron stars, but not all neutron stars are pulsars.

If you have a generally young, just formed neutron star that has a fairly strong magnetic field and is rotating quickly, that magnetic field can channel materials through the field. Electrons, other charged particles… they're going to follow the magnetic field lines. Because pulsars are rotating and because rotating charged particles generate magnetic fields, there's all sorts of complicated, scary physics going on… you can end up with very strong magnetic fields that create basically jets of particles.

These jets of particles appear in radio observations. So when you look at a pulsar in the radio, you can use them as some of the most accurate clocks in the Universe. We look at them and every time we hear a beat of the clock, what's happening is the beam of the pulsar is passing in front of our telescope.

One of the neat things about this is we could be looking at a neutron star and never know it's a pulsar because it's pointed away from us. We only see pulsars as pulsars when that magnetic field's poles are pointed at the planet Earth and our radio telescopes are able to intercept the radio signal.

Fraser: So it's kind of like a lighthouse turning and so we will only know there's a lighthouse over there when the beam from the lighthouse passes over our boat.

Pamela: Exactly, and this is one of the weird cases where you have to imagine a lighthouse where one side of the two-sided spotlight points slightly up to the sky, and the other part points slightly down toward the water. If you're a person at the foot of the lighthouse looking up at the lighthouse, you're only going to see one of those two beams: the one that's pointed down toward the water.

But if you're flying over the lighthouse you're only going to see the one that's pointed up at the sky. So in the case of pulsars, the magnetic fields' pulls aren't necessarily (and in fact we don't think they are) lined up with the rotational axis of the star.

Fraser: How fast can they be rotating?

Pamela: This is where they're going 1000 Hz – 1000 rotations per second. They slow down over time, though.

Fraser: How can you have… Our Sun, doesn't it take days to rotate?

Pamela: It rotates on roughly a one month schedule.

Fraser: Right, so how can a neutron star rotate thousands of times a second?

Pamela: Well… anyone who's watched an ice skater spin in any of the competitions (the worlds, the Olympics), they hold their arms out and gracefully, slowly spin around smiling, and then they pull their arms in and start whipping into vastly faster speeds. Now, they're just going from having arms extended to arms in. That's not a huge difference in the grand scheme of things.

We're looking at a four to eight [solar] mass object that ends up admittedly being only 1.4 to 3.2 solar mass object, that's going from normal star size down to the size of Manhattan. So in the process of squishing down, it takes all of its angular momentum, it takes all of its rotation and the rotation speeds up as the object compresses smaller and smaller.

The process of the supernova itself can also give the star a kick and increase its rotation rate. It also sometimes kicks it out of the supernova remnant, which means we're sometimes finding pulsars that are sort of roaming freely, and we also find supernova remnants that don't have a neutron star or black hole in their centre.

Fraser: Now, you mentioned briefly that a pulsar slows down. How does that happen?

Pamela: The energy it's giving off in the process of pulsating has to go somewhere. As the material is getting streamed out, it's carrying the rotational energy away and turning it into kinetic energy. We're just changing the type of energy and as the energy goes away from the pulsar, then you also end up with the pulsar slowing down with time.

Fraser: Right, okay.

Pamela: It's all about the energy. Think of it as… you're standing there throwing rocks while you're rotating. As those rocks go out in straight lines, your rotation is going to slow down.

Fraser: I'm just surprised that astronomers would be able to detect that slowing down of speed. It must be tiny.

Pamela: Well, they're such precise pulsaters, that we can detect changes on the order of fractions of a millisecond and some of them have been observed for enough decades that we can start to see noticeable changes in their pulsation rate. So in the course of a year they're as accurate as an atomic clock. Looked at over the course of years, those fractional changes build up, and we can see the changing period.

Fraser: Wow. Okay, so then what is a magnetar?

Pamela: A magnetar is this new thing that we're just starting to understand. It was first put forward theoretically back in 1992 by Robert Duncan and Chris Thompson. Rob Duncan was actually at the University of Texas where I was. I got to hear some of the early talks in the mid-90s, which was kind of cool.

These are a special type of neutron star that has an especially strong magnetic field. Not all stars are created equal, that's what makes the Universe exciting. Some stars start off with an intrinsically large magnetic field, and when you collapse down the star you also collapse down the magnetic field, confine it to a smaller area, and it gets stronger.

I have to admit understanding what's called magneto-hydro-dynamics, the study of how magnetic fields arise in stars and all that sort of stuff is a bit beyond my ability to get at the mathematics of. They say in astronomy there's two ways to confuse anyone: one is you ask how does this magnetic field affect that and the other is asking how does that look in three-dimensions. Understanding magnetars requires that you understand both magnetic fields and three-dimensional fluid modelling of degenerate mass, which is just a lot of scary words which means: it's hard.

These folks, they figured out, using complicated modelling, that you can talk a star with a strong magnetic field and create a neutron star that initially has an uber-strong magnetic field. They estimate that perhaps only one in ten neutron stars, when first formed, has the potential to be a magnetar, and of those that actually become magnetars, they'll only last for about 10 thousand years, which on cosmic scales is a really short period of time.

So you have a neutron star, that has an anomalously high magnetic field for a short period of time and they do weird things. Some magnetars are considered to be what are called anomalous x ray pulsars. These are slow rotating. They rotate every 5-12 seconds instead of the 100 or 1000 times per second you'll see in some of the fast rotating ones. They have extremely high B-fields, and periodically they'll give off bursts of x ray energy.

Fraser: Sorry, what's a B-field?

Pamela: Sorry – magnetic field. I slipped into astronomy jargon. They'll have an extremely high magnetic field, which physicists call a B-field for no obvious reason that I know. We're starting to find these. So we have these anomalous x ray pulsars.

We also have things called soft gamma ray repeaters; there's only four of these known. These are objects that give off low-energy x rays randomly, and repeatedly. So, here we are: we have a sub-class of neutron stars, and then we have two sub-classes of that. All of these are short-lived, very special events that can be very dangerous.

There was an object that went off December 27 of 2004. This particular object, SGR 1806-20 gave off enough energy that it sort of went through the sides of some space telescopes and still managed to get detected. So the energy didn't go in the front of the telescope, where energy should enter. It instead went through the side, side-hit the detector, and still managed to blind the detectors. It was a gamma ray event that was very determined to be seen. These things can give off as much energy in a tenth of a second as our Sun released in 100 thousand years.

This particular object (which was just the other side of the centre of the Milky Way, only about 50 thousand light years away), gave off so much energy that our ionosphere actually bloated up. It changed the ionosphere of our entire planet from 50 thousand light years away. If that same object had been ten light years away, the Earth's ozone layer would've been completely destroyed. It would've been an event similar to 12 kilo tonnes of TNT nuclear blast at 7.5km.

Fraser: Everywhere.

Pamela: Yeah.

Fraser: So that's similar to like, we talked about the gamma ray burst going off and your neighbourhood just disappearing and the ozone layer letting in the radiation.

Pamela: Yes. It's just frighteningly huge amounts of energy in very, very short amounts of time. If we'd been able to see in gamma ray light, it would've been the largest explosion observed by humans since Kepler's supernova back in 1604. This object would've been several times brighter than the full Moon. If you look at it in terms of total energy, it was brighter than the full Moon. We just don't see in gamma rays, instead several satellites took it for us. From the blighting their detectors temporarily incurred, we were able to know what happened.

Fraser: Now you brought this up, not me.

[laughter]

I'll run with it. That's one way these things can kill us. Now, what if we had a pulsar reasonably close, firing out its jets? Would that be dangerous?

Pamela: It would be kind of dangerous. There's worse things in life that could happen. Being near two of these things that are coalescing is much more dangerous. The actual pulses coming off of a pulsar, in the grand scheme of things, are fairly low energy. It's radio lights. Our atmosphere can protect us from radio fairly well, so that's not too huge of a danger. Luckily, there's no magnetars that are known to be near us, so we don't have to worry about it too much.

The real problem is if one of the magnetars does get too close, just its magnetic field can start to tear stuff apart. What you have to worry about is the rogue, high-magnetic field more than the pulse of the pulsar. Your typical magnetar might have a magnetic field of about 10^11 teslas, or 10^15 gauss. That's a huge magnetic field. For comparison, the Earth's magnetic field is about 30-60 micro-teslas, and just 10 giga-teslas at the distance of the Moon would wipe out everybody's credit cards. So we're talking that one of these in our solar system and all of our plastic money no longer works.

Fraser: Catastrophic!

Pamela: Yeah.

Fraser: But I'm sure like, your computers don't work, your television doesn't work, your radios don't work, your car doesn't work…

Pamela: More importantly, the magnetic field of a magnetar at a distance of about 1000 km would start tearing apart human tissue because of the magnetic properties of water.

So, yeah. Dangerous magnetic field.

Fraser: Yeah, but the chances of a neutron star getting within 1000km …

Pamela: Yeah, not going to happen, but it's cool to think about.

Fraser: It's cool to think about!

Now I wanted to talk a bit about how pulsars are used for predictions. Aren't pulsars being used to help confirm relativity?

Pamela: Yes. We look at them in all sorts of different ways. So, first of all there's the basic idea where you have a pulsar in a binary system. It's a high mass system, you start to get relativistic effects into the orbits. You have to take these into account in looking at the timing of the pulses.

As the object is orbiting, there's two different things going on: first of all, its distance is changing, and because the distance is changing, the amount of time that different pulses take to reach the Earth changes. So we see some change in the frequency of the pulses just due to the changes in the distance. The other thing that happens is you also end up with relativistic effects caused by the velocities involved. So we can use these to say how the timing is being effected in different ways that prove and (so far) don't disprove relativity.

Fraser: So this is the situation, I think, didn't Einstein call it "frame-dragging"?

Pamela: So, frame-dragging you get from fast rotating objects. These are fast rotating objects, so they're something we can pay attention to, to look at frame-dragging. We can also look at them in terms of if you have a pulsar and a black hole orbiting one another, you can start to see things like gravitational radiation. As gravity radiates away from the system and the orbits change over time, and you can get very accurate orbital measurements using pulsars to time the measurements.

Fraser: I have one last piece of research. Weren't planets discovered around a pulsar?

Pamela: That's actually one of the first ways that first we incorrectly and then did correctly find planets around another star. The first object that was a real set of planets was B1257+12, and this was a discovery made in 1992. I actually remember the day that the discovery was announced because I was working at Haystack Observatory in Massachusetts was all excited and wanted to buy me a beer, but I was 18 so he left.

Fraser: You were working in an observatory when you were 18??

Pamela: I'm a freak.

[laughter]

Fraser: Just dedicated. I think I was working in a comic book store when I was 18.

[more laughter]

Pamela: Yeah, I've been a freak for a long time, but it's *fun* to be a freak. Yeah, no I was working at Haystack Observatory in my home town, Westford Massachusetts doing basic data reduction of T Tauri stars. I was sitting there, minding my own business, measuring different parameters and great excitement broke out and I was too young to celebrate. It was sad. But, I remember the discovery and it doesn't have just one planet, but it has three planets associated with it and potentially comets. They're still sorting that out.

What's neat here is we're looking at the smallest known planet-like things. In one case, the mass, compared to Jupiter, is 0.000063 Jupiter masses – tiny, tiny thing.

Fraser: Is that smaller than Pluto?

Pamela: I don't know, but we can put that in the show notes. It's tiny. I don't think it's quite smaller than Pluto, but I could be wrong and we'll put the answer to that question in the show notes.

The other two objects have more realistic masses. They're 0.014 and 0.012 Jupiter masses. Now what's cool about these objects is their potential histories. These are either things that survived a supernova explosion, in which case they're probably the rocky cores of former gas giants. So take Jupiter, blast it with a supernova explosion and the core that's left behind might be what one of these three objects are. The other possibility is the material that was given off during the supernova explosion re-coalesced to form a new generation of planets out of the freshest recycled material you can imagine.

Fraser: Sort of like a change of life baby.

Pamela: Yeah, exactly.

Fraser: But it must be a pretty awful existence, you can imagine the poor planet that's just being bathed in x ray radiation and pulsating radio waves. Wouldn't be a good place to live.

Pamela: Yeah, it's not exactly… yeah, DNA wouldn't survive real well, but it's still neat to think that planets really can be found just about anywhere.

Fraser: Even around a neutron star.

Pamela: Even around a neutron star.

Fraser: What would you say are the biggest unknowns right now, what needs learning more about?

Pamela: We're still trying to sort out the soft gamma ray repeaters and the x ray pulsars. What causes these different subclasses to form, what is their life expectancy, what is their frequency? It's just something new, some new idea to follow up on and learn about.

What are the mechanisms necessary to form these huge magnetic fields? We're still trying to fully understand the source behind the magnetic field in our Sun. We're pretty sure it has to do with a dynamo that originates somewhere between the radiative and convective layers, but we're not positive.

Here we are, working to piece together how magnetic fields are generated in a completely foreign type of object, something that's made out of matter that we can't even really create here on the planet (degenerate neutron material), and figure out how are magnetic fields generated with it, how do they evolve with time, how does the star evolve and cool with time?

So there's a lot of interesting stuff to figure out evolving. The first few thousands and tens of thousands of years of life after a pulsar, after a neutron star has been formed and how it changes, and then of course there's the fate of how the magnetic field damps with time, the rotation damps with time… what happens when the neutron star is cold and dead?

Fraser: So I guess anyone looking for a real challenge in research can go into this three-dimensional magnetic fields.

Pamela: Magneto-hydro-dynamics.

Fraser: (laughing) Magneto-hydro-dynamics. If you want to pick a hard topic in school, there you go.

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