Astronomy Cast Episode 36:
Gamma-Ray Bursts

Fraser Cain: This week, we're going to talk about the most powerful explosions in the Universe (I love saying that): Gamma-ray bursts. But before we talk about what they are, why don't you give us a little history? How were they first discovered?

Dr. Pamela Gay: Well, like a lot of the great discoveries of the space age, it all came down to trying to check on the Soviets. Apollo came out of trying to beat the Soviets and the discovery of Gamma-ray bursts came out of trying to discover if the Soviets were trying to beat up on us with nuclear weapons. Specifically, there was a nuclear test ban treaty signed and we wanted to make sure that the Soviets (and everyone else on the planet) adhered to this nuclear test ban treat. One of the best ways to look for nuclear testing is to look for the gamma rays that are given off during the nuclear explosion.

In 1963 we launched the Vela satellites to monitor for gamma-ray bursts, and the bursts they were looking for were going to be terrestrial, but the bursts they actually found were cosmic in origin: they seemed to be coming from all over the Universe.

Fraser: Now was this a bit dangerous? Were we on the brink of nuclear war for a while there?

Pamela: We were rather suspicious. Luckily though, the distribution of gamma rays from gamma-ray bursts of cosmic origin don't look the same and don't have the same time profile as the gamma rays that you get from nuclear tests. So people looking at the stuff could go, "this doesn't look quite right."

Fraser: Okay, so the Americans launched the Vela satellite, designed to look for gamma-ray bursts on Earth but picked up flashes coming from the Universe?

Pamela: Exactly. The first flash was detected in 1967, but it wasn't actually de-classified until 1973. For a while, the scientific community outside of people at top-secret bases didn't even know these things were going on.

Fraser: Don't tell the UFO conspiracy theorists about this...

[laughter]

…that the government was actually keeping some astronomy confidential.

Pamela: Ohh, it happens all the time.

Fraser: Oh, okay.

Pamela: But the folks at Los Alamos were able to look at the Vela detections and determine that they had to have a cosmic origin; they had to be coming from somewhere outside of our solar system, somewhere either in the galaxy or outside of the galaxy, and this started a whole new field of astronomy that no one had ever imagined. In 1974, the Soviet Konus satellite confirmed that the Soviets, too were detecting these gamma-ray bursts from the rest of the Universe.

Fraser: Oh, so the Soviets had the same plan.

Pamela: Exactly.

Fraser: Right.

[laughter]

Pamela: We can't trust them, they can't trust us… always useful.

Fraser: We're both launching gamma ray telescopes…

Pamela: Exactly!

Fraser: Right.

Pamela: At least some good science came out of it.

So, for a long time everyone was like, "what's going on? Where are these things coming from? Are they coming from the halo of the galaxy? Or from some sort of known object?" In 1976 there was a network of satellites creatively named the Interplanetary Network that were set up to try and triangulate the positions of gamma-ray bursts and figure out where exactly in the sky these things were coming from. They were able to figure out that these gamma-ray bursts weren't related to known x-ray emitters or any other known objects of astronomical interest. So the more we learned about these things, the more questions we had. That's the picture for basically 20 more years.

In 1991 the US launched the Compton gamma ray observatory with the BATSE detector on it, and this amazing satellite was able to detect over 27 hundred gamma-ray bursts in the nine years it was orbiting. What it found was the distribution of these gamma-ray bursts was uniform across the sky. This means that if they were something related to our galaxy, then they'd either have to be something we don't quite understand because things related to our galaxy tend to pile up along the disk of the galaxy.

Fraser: Oh I see, so if it was related to the Milky Way then it would show up in the bulge, the galactic bulge and the disk that we can see in the night sky when we see the Milky Way.

Pamela: Exactly, but that wasn't what we found.

Fraser: So the bursts had to be coming from outside the galaxy.

Pamela: It wasn't certain; it could be something that was associated with the halo, like globular clusters are fairly uniformly distributed. People were starting to think these probably were extra-galactic and this was finally confirmed when we started being able to get spectra of these things in the late 1990's.

The BeppoSAX satellite was able to identify a gamma-ray burst fast enough, and identify its location using an x-ray telescope well enough, that people with optical telescopes here on Earth could zoom in and really fast find what it was and where it was, and go back after the burst had faded away to take spectra of what turned out to be the galaxy the gamma-ray burst appeared in and figure out how far away these things are.

These things seemed to be coming from the earliest moments of the Universe all the way up to fairly recently but not really recently. So these things are really distant, hugely energetic and it took us 60+ years to figure out exactly where they were coming from.

Fraser: All right. And so, let's talk a bit about what's going on then. How did astronomers go from being able to detect them to starting to get a sense of what they are?

Pamela: Well it was a long process. Looking at these things we see that they tend to fall into two different categories. There are short-duration gamma-ray bursts that typically last a little less than two seconds to a lot less than two seconds. Gamma rays are all high energy bits of light but some of them have higher energy than others so we call these hard gamma rays and soft gamma rays.

Fraser: Would that be like the equivalent of visible light and looking at red or blue as the two ends of the spectrum?

Pamela: We have the bluer gamma rays and the redder gamma rays, all of which are bluer than x-rays (we're just going to use blue and red to mean higher and lower). What we usually say is the higher energy is a harder energy and the lower energy is the softer energy. With the short duration gamma-ray bursts, there's a lot more high energy, there's a lot harder of a spectrum.

There's a couple of differences: the time and distribution of the energies of the photons is a lot harder. With the long duration, you have things that last more than two seconds, sometimes more than a couple hundred seconds. The spectrum in these cases is a softer spectrum, a lower energy spectrum.

Fraser: So these short ones are happening under a second – milliseconds - to let out that much energy?

Pamela: Yes.

Fraser: And the long ones can take seconds to a couple of minutes to let out that energy.

Pamela: Yes.

Fraser: And then that's it.

Pamela: Yes.

Fraser: So what could've been letting off this much energy?

Pamela: There's a couple of different causes. You have two different types of bursts: two different types of progenitors – possibly three different progenitors, but two that we're fairly certain of.

In general we think that the short duration, hard spectrum gamma-ray bursts come from two compact objects merging, for instance two neutron stars merging or a neutron star and a black hole merging. When these two things merge together there is a huge energy output as you end up forming either a bigger black hole or a brand new black hole where there used to be two neutron stars.

Fraser: I see. As we said in the black hole episode, neutron stars don't have quite enough mass to fall into a black hole but if you mash two of them together then you get double your mass and you might very well cross that limit – five stellar masses I think – and you're able to make your black hole.

Pamela: These things can happen locally: they can happen in our galaxy, in Andromeda, anywhere that you have old stars in binary systems you can end up with a short duration gamma-ray burst. They still seem to be extremely rare – we're still working on the statistics – but it's kinda creepy to know they can happen locally, and the places they can happen are kinda hard to notice. Two neutron stars aren't that easy to find. We are finding them, but if neither of them are a pulsar and neither of them have an accretion disk, you're talking about two little, tiny, faint objects orbiting one another potentially waiting to explode in violent and dangerous ways.

Fraser: All right, let's talk about the long duration ones. The short ones are two compact objects – a neutron star and a black hole, or two neutron stars or could you do a white dwarf and a neutron star?

Pamela: No, those the energies aren't quite sufficient in that case to end up forming a gamma-ray burst.

Fraser: Okay. Let's talk about the long duration one. What's causing those?

Pamela: Here we think it's a special type of supernova, created by a giant star that is in the process of collapsing, a type Ib or Ic supernova.

You have 10^44 Joules of energy given off and it's funnelled out the two poles of the star and the area that these are funnelled out is as small as sometimes two degrees in an opening angle. That means you go off the pole, measure two degrees out, make a circle and funnel all the energy out that small circle.

Fraser: How could all the energy just get funnelled out of that circle?

Pamela: It's jets. It's all about the magnetic field.

Fraser: So the star, as it turns into a supernova is able to create a magnetic field powerful enough to siphon all that energy out those jets.

Pamela: These jets typically have opening angles between two and twenty degrees. It's vast, vast amounts of energy. We're talking the same amount of energy as if we took the mass of the Sun and converted it spontaneously into energy all at once.

Fraser: Where do we draw the line then, between this kind of a supernova, becoming a gamma-ray burst and a regular, plain old supernova, where a star with a mass 100 times the Sun goes kaboom?

Pamela: There are a lot of people trying to figure out how to make that definition. If you look through the literature, there's different people going in slightly different ways. Some people talk about collapsars, some talk about hypernova… exactly how it happens, I think isn't cleanly defined yet. Unfortunately most of the gamma-ray bursts are occurring so far away that we can't get good, high-resolution images of the supernova remnant that's left behind. So we're working on limited data, and we're starting to find cases where we can actually follow the evolution of the resulting supernova that comes a few weeks after we see the gamma-ray burst, but we're still developing that picture.

So somehow, in some systems, you have, as the system collapses down, it's able to funnel the energy out through the poles and form this gamma-ray burst. It's a special sub-class of supernova.

Fraser: You hinted on this a bit, but what are the big unknowns about gamma-ray bursts? What are astronomers still trying to figure out? I think that five years ago it was one of the greatest mysteries in astronomy, now astronomers have a pretty good handle on it but what do they still want to understand?

Pamela: We're still trying to figure out… we know it's related to supernovas but we know it's not all type Ib and Ic supernovas. We have hints that perhaps these are more common in more metal-poor systems. If you start looking at the types of galaxies that are having gamma-ray bursts occur in their star forming regions, you get the gamma-ray bursts associated with star forming regions because these are young, hot, hot, very short-lived stars forming gamma-ray bursts. So, some of the stars are still in the process of forming. The smallest stars in the star forming region are still in the process of forming as the gamma-ray bursts are starting to go up and disrupt the entire system. In these systems, when we look at them we say "aha, we know this system had a gamma-ray burst" then we go in and measure how much metal is there, how much carbon, how much iron. We're finding that the gamma-ray bursts are occurring in more metal-poor systems and they're occurring preferentially in the early, first few billion years of the Universe.

Fraser: Is that because the first few generations of stars just didn't have a lot of metals in them?

Pamela: It took time for the metals to build up, and we also think that when you have a more metal-poor system, it's easier to form extremely massive stars. So you have perhaps a chicken and the egg problem: is it that you have more massive stars when you have lower metals, or do you need lower metals to get hypernovae? So we're still sorting out how all these different factors play together.

Fraser: You just dropped a term and I'm going to call you on it. What's a hypernova?

Pamela: A hypernova is one of the things that we call the sub-class of supernova that form gamma-ray bursts.

Fraser: What distinguishes that from a regular supernova, or from the gamma-ray bursts?

Pamela: That it has a gamma-ray burst?

Fraser: Okay, so a hypernova is a supernova that also has a gamma-ray burst.

Pamela: Yes.

Fraser: Okay. How close have these gamma-ray bursts gotten to the Milky Way? Has one ever been seen in the Milky Way?

Pamela: Not that we know of, but there is some evidence that it's possible that (and I'm going to destroy the pronunciation of this – this is one of those things where you read the word but never hear anyone say it)… it's possible that the Ordovician-Silurian extinction event 450 million years ago may have been caused by a gamma-ray burst. Or at least, this is what some of the folks at NASA and Kansas State University are thinking.

So it's possible 450 million years ago a gamma-ray burst went off within our Milky Way galaxy, pointed at the planet Earth and it killed a lot of life.

Fraser: Hold on a second here. You're talking about it going off *inside* the Milky Way. You know that I'll inevitably get to this kind of question –

[laughter]

How close does one of these have to be to cause a problem here on Earth?

Pamela: As near as we can tell, as long as it's more than 30 or 40 thousand light years away, we're safe. But that leaves a whole lot of our Milky Way within harm's way.

Fraser: Hold on, hold on, let's do some math here. How big is the Milky Way across – 100 thousand light years across?

Pamela: Something like that

Fraser: So that's almost anywhere in the Milky Way, if a gamma-ray burst went off, we'd get hit – in a kill a lot of light on Earth kind of way.

[laughter]

Pamela: Anywhere within the 50% of the Milky Way nearest us… yeah, we're toast.

Fraser: Okay, alright. Now what kind of damage – what would happen? How would the gamma-ray burst ruin us? Would we actually get hit by the blast of gamma rays?

Pamela: The primary problem is what it does to our atmosphere. It ends up causing the generation of nitrogen oxide compounds that deplete the ozone. Our ozone is necessary to protect us from UVB radiation. If the UVB radiation gets through the atmosphere and hits us, our DNA is toast and we all die of cancer.

Fraser: So how long would it take for the gamma-ray burst to wipe out our ozone layer?

Pamela: Well, it can do enough damage to effectively cause an extinction in just the ten seconds that the gamma-ray burst is going off.

Fraser: So the gamma-ray burst is going off, ten seconds later the Earth has no ozone layer –

Pamela: Or at least not enough to be useful

Fraser: And here comes the radiation.

Pamela: And here comes the radiation.

Fraser: Wow. And so, this may have happened in the past… is this for both the short and the long duration ones?

Pamela: I think the distances are different between the two. The distance that I quoted you is the distance for a long duration gamma-ray burst. The short duration gamma-ray bursts are a lot less energetic so they'd have to be closer for them to toast our atmosphere.

Fraser: So is it just a matter of time, like an asteroid hitting, that we're going to get hit by a gamma-ray burst?

Pamela: There are people working really hard to try and calculate that. There are unfortunately a fair number of neutron star/neutron star binary systems and neutron star/black hole systems that we've already discovered and probably a whole lot more that we haven't discovered in the halo of our galaxy.

There are people trying to figure out, first of all how many of these things do we think there are, where do we think they are, what the average energy of these is, and just how much danger are we actually in. The nice thing is that the people who have systematically stared around the nearest part of our galaxy haven't been able to identify any long duration gamma-ray burst progenitors. Eta Carina could potentially be a hypernova, but its poles aren't pointed toward us. So even if Eta Carina turns out to be the right type of supernova to become a hypernova and a gamma-ray burst, we're okay because it's not pointed at us.

Figuring out the neutron star/neutron star problem is a bit more difficult and I don't have an easy answer I can give to you. I can tell you there are people working on it and I can also tell you that there's a good chance we just might miss the one that decides to destroy us.

Fraser: I think the good news is that the Milky Way is fairly high in metals, compared to what there was in the early Universe

Pamela: Yes

Fraser: So if that connection between low metals and gamma-ray bursts is true, it's almost like we're out of the bad years.

Pamela: Yes. And in general, even in the systems where these things are happening, the probability is about one per galaxy per 100 thousand years.

Fraser: Can we talk a bit about how gamma-ray bursts are being detected right now? I know there's the SWIFT satellite which was recently launched. How does that work?

Pamela: What it does is it picks out a certain area of the sky that it's going to look in. It points and it sits there waiting for gamma rays to come in and when the gamma rays come in it, really quickly, turns on its x-ray cameras. With x-ray cameras you can get better directional information than with gamma rays.

Gamma rays really don't like to be focussed. You can't just put a lens out and focus the gamma rays onto a detector and then say, "aha, I know exactly where that came from." Instead you sort of get the vague notion that the gamma rays came from somewhere over there, which might be an area of the sky several times bigger than the Moon. That's not a small enough area for most people to point their telescope at the sky and be able to find anything new and interesting.

So then they look with the x-ray cameras. The x-rays give them better pointing information. Once they have better pointing information from x-rays, then really fast they flip in an optical light camera and they can get accurate coordinates. Once they have those coordinates they relay them down to networks of observers here on Earth who turn in their optical systems and they follow how that optical afterglow changes with time.

Fraser: How long does that whole process take? How quickly can SWIFT respond to an explosion?

Pamela: Under a minute.

Fraser: Under a minute!

Pamela: Oh yeah

Fraser: The telescope just sits there waiting, it detects gamma rays, swings around, focuses in, swapping out instruments, finds the target, relays the coordinates and telescopes here on Earth point at it as well. All within..

Pamela: under a minute

Fraser: …within minutes. Wow.

Pamela: What's really cool is there are amateur astronomers who will look up where on the sky SWIFT is looking tonight and then pick their scientific targets of interest to be near that area of the sky so when they do get an alert from SWIFT they don't have to move their telescope very far to get on target. The amount of time it takes you to slew your telescope across the sky might be the amount of time it takes for a gamma-ray burst after-glow to fade by a factor of ten or more. These things are very quickly fading away.

Fraser: I guess this must be a little bit frustrating because you're working on your science and then a gamma-ray burst shows up and you've got to swing over and catch that as well. They must have a lot of researchers on the paper because whoever was working on some other project at the time gets dragged into the research because they had to give up their telescope time.

Pamela: This is one of those times where the amateur astronomers are truly vital. To them, the really cool sexy science comes out of catching the gamma ray afterglow, whereas if you're observing on Keck, you might have three nights that you fought for the past six months to be able to get, it's finally here, you're out observing, getting all the data you need – perhaps it's the last run you have on some grant on your dissertation, and all of a sudden you get a phone call that you're supposed to go off target and switch to doing something totally unrelated to what you're doing. It's not a phone call any professional observer wants to get, but it happens. Everyone knows you're supposed to actually slew the telescope and go observe the gamma-ray burst even if you don't want to, but it's the amateurs who can already be almost entirely pointed and be on target the fastest.

What's nice is the amateurs who have the smaller telescopes and can get on target the fastest are the most able to observe extremely bright moments in the optical afterglow. As the afterglow fades, the amateurs can't see it anymore with their perhaps 20" backyard telescopes (or backyard observatories in this case) whereas the professionals with their multi-metre observatories it may take a few minutes to get on target. It's when they're on target a few minutes later that the amateurs can't necessarily still be following the object. So it plays out quite nicely.

Fraser: I guess having to hustle isn't something that astronomers are used to, I think. Now it's become this high stakes, go, go, go kind of game in astronomy.

Pamela: Yeah. Totally. It's been a really fascinating few years with the new discoveries that are constantly coming out. These things were first really discovered in 1967 and we couldn't even say they weren't happening inside our galaxy until 1997. In the ten years since 1997 we've now been able to say, "okay, we know the short ones are two compact objects, we know the long ones are related to supernova, we've seen the supernova." We've made amazing progress in just ten years.

Fraser: What do you think the future holds for this?

Pamela: Oh I don't know. One of the neatest potential uses for gamma-ray bursts was a report I saw at the Washington AAS meeting by Dr. Brad Schaefer of Louisiana State University. He's looking for ways to use gamma-ray bursts as standard candles. To use them the same way we use supernova to measure distances to the farthest corners in the Universe.

What's really neat about this is these suckers are scary bright and some of them are so bright and so far away that we're picking them up but we can't see the host galaxy they're in. We know they're in a galaxy, but the galaxy is so far away there isn't a telescope on Earth capable of detecting it. We might be able to measure… we know there's a star capable of having a gamma-ray burst that formed just 500 thousand years after the Big Bang.

If we can figure out how to use gamma-ray bursts as a standard candle, we'll be able to extend the Hubble diagram to huge numbers. Right now we can only get out to redshifts of about 1.2 – 1.3 with supernova. With gamma-ray bursts we're getting out to redshifts of 6. That's getting us out to over 12 billion years in the past.

Fraser: Right. So the gamma-ray bursts with these low-metal stars could be the first stars that formed as the matter came out of the Cosmic Microwave Background Radiation. The first matter formed and then went straight into stars and then these things started detonating as gamma-ray bursts.

Pamela: If we can find them in systems where we can measure the redshift of the host galaxy and measure the distance to that host galaxy using gamma-ray bursts, this allows us to probe the changing acceleration rates all the way back to pretty much the beginning and that's kind of exciting to think about.

Fraser: I see, that could give astronomers a better sense of how dark energy has been changing over time.

Pamela: How matter and radiation have played against each other, when matter dominated, when dark energy dominated… all sorts of really neat cosmological questions that would require not just multi-metre but multi-tens of metre telescopes, we might be able to figure out how to probe using gamma-ray bursts, if we can figure out some way to calibrate them as standard candles.

Fraser: It's fascinating stuff.

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