Astronomy Cast Episode 16:

Across the Electromagnetic Spectrum

Fraser Cain: This week is going to be one of those foundation episodes that we'll be referring back to time and time again in the future, so pay attention, take some notes, we'll try to make this as entertaining as possible but it's going to be some work so listen carefully.

So as human beings, we perceive the Universe in visible light. We can feel infra-red as heat, and our skin burns because of ultra-violet (although that's not a very good scientific instrument). There's a whole electromagnetic spectrum out there, ranging from radio waves to gamma rays. Different kinds of objects and events produce different kinds of radiation and tell us more about the story of the Universe.

So Pamela, let's start with a really simple question: what is light?

Dr. Pamela Gay: Light is a particle and a wave that is called a photon. It's this little bit of energy that's capable of moving at the speed of light that we perceive as light. It can have all sorts of different wavelengths or energies, which correspond to the colours that we see.

If you have a low-energy bit of light, a low-energy photon, you might perceive it as a radio wave by turning on your radio and seeing what incoming signals your antenna can apprehend. You might perceive it as visible light, by taking a picture of your child during the holiday season and then sending it to all of your relatives. You might perceive it as microwave light by turning on your microwave and sending lots of photons with a microwave wave-length at your food and watching your food cook.

Fraser: So our eyes are just photon detectors.

Pamela: That's all they are.

Fraser: And a radio is a photon detector at a different wavelength.

Pamela: And our microwave is a light just like our lights are lights. Radio antennas out in the middle of fields, those are a different type of light. They are emitting radio waves.

Fraser: So what's the difference between a radio wave, and why can't I see a radio wave when I can see visible light?

Pamela: Different detectors are sensitive to different colours. Our eyes are sensitive to the specific colours around 400-800 nanometres that correspond to optical light. Those nanometres are how long the given wavelength is. At the same time, light that comes from say, my favourite radio station here, 90.7MHz (it's an NPR station), its wavelengths are 33 metres long. So we're going from something that is 0.000 000 0007 nanometers – a really, really red colour your eye can perceive, out to 33 metres long, which is what your radio antenna can receive when you turn your radio on at home.

Fraser: So is it that your eye isn't equipped to see the photon because it has such a long wavelength, it can't put it together?

Pamela: That's exactly what it is. What's cool is, different creatures eyes are actually sensitive to slightly different colours. Some forms of snake can actually see slightly redder colours. They can see into the infra-red more than the human eye can because they're adjusted to be able to find mice at night and mice are basically warm little objects running around in a cold forest at night. Anything that's warm gives off infra-red light. You and I are giving off infra-red light as we're sitting in our offices, just because we're warm.

Fraser: Okay so, how does this move to astronomy then? How do astronomers use this for finding stuff in space?

Pamela: The different colours correspond to different types of interactions. The colour of an object can depend on how hot it is: warm things like human beings, we give off light in the infra red. So do stars that are forming – really young stars that haven't really started to generate a lot of heat on their own, they give off light in the infra red.

Really hot stuff starts to give off light that is optically visible. So things that are visible to the human eye typically have temperatures between 3600 and 7200 degrees. So hot things (really hot things, things that would more than cook your car if you touched them) those are visible to our eyes.

Even hotter things, things that are capable of giving you sunburns and stuff, those correspond to larger temperatures greater than 10 thousand degrees. Really, really hot, young stars give off the majority of their light in the ultraviolet.

Fraser: Hold on. So, if I'm in my room in the dark and turn on a light bulb and can see everything in my room, that doesn't mean that everything in my room is 5 thousand degrees.

Pamela: No, but what it means –

Fraser: But the lightbulb –

Pamela: The light bulb has light that corresponds to temperatures that are really really hot, and those photons are flying off of your really hot light bulb and reflect off surfaces. Some photons will reflect and some will get absorbed. What we see as colour is simply the characteristics of what photons get reflected and absorbed by different surfaces.

Fraser: Right, so it all depends on the source of the photon, it can then bounce around from that point on, but the photon has been given that energy.

Pamela: What's cool about light bulbs is some light bulbs are actually cool. Some fluorescent bulbs, you can touch them – no big deal. These aren't giving off light because of temperature, they're giving off light because the electrons inside are getting excited by electricity. Excited electrons have high energies, but nothing can stay excited for a long time. We all crash eventually, including electrons. When those electrons come down from those excited energy levels, that energy has to go to something. In human beings, we generate heat. Electrons generate photons when they drop to lower energy levels.

The fluorescent light bulbs give off photons because the electrons inside are changing energy levels, and that's another way we can get light: through electrons transitioning from energy level to another, either while roaming around free (that's called "free-free", or "bremsstrahlung" emission (that's just a fun word to say)) and we can also get atomic molecular lines and just plain old atomic lines, where you have an atom or a molecule and the electrons are changing energy levels and give off very specific colours. This is where we get "Open" signs that are red made out of different gasses. We can get all sorts of different neon lights that correspond to different gasses with different energy levels.

Fraser: Okay, let's go back to astronomy then.

Pamela: Okay. So, when we go outside, we can use all sorts of different instruments to look up at the sky and detect all these different colours of photons. Any of you, who've seen the movie *Contact* with Jodi Foster, saw that she used an array of giant radio dishes, as well as one ginormous dish in Puerto Rico. She actually filmed (along with everyone else in the crew) at the Arecibo Observatory in Puerto Rico as well as the Very Large Array in New Mexico. These are both radio observatories, and they use their dishes to look for all different colours of radio light coming from stars, galaxies and cold gas.

So radio emission comes from a bunch of different things. One of the neatest places it comes from is molecular transition lines. We don't think of it very often, but the sky is filled with things like ammonia and formaldehyde and carbon monoxide. When these molecules have electrons that change energy levels, they give off radio emissions. For instance, ammonia has a 12cm wavelength, or 23 GHz radio line. So we can go out, tune our antennas to 23 GHz and tune in to listen for ammonia in giant clouds of gas and dust.

Fraser: So do most objects in space give off radio waves?

Pamela: Most cooler objects give off radio waves, due to these molecular transitions. Molecules are kind of fragile. If you heat them up, they turn into their individual, constituent atoms. These individual atoms often give off light at shorter wavelengths, for example in the optical or ultraviolet. But molecules have these lower transitions and those are visible in the radio.

We also get radiation in the radio from star forming regions where we have electrons that are running free that as they change directions, there's actually energy involved in changing directions, and that can get given off as radio emission. We also have star-forming regions that give off radio emissions. So galaxies that either have active galactic nuclei (which means there's a black hole consuming things – but that's two shows away, when we talk about black holes), and places where stars are forming, we get this radio emission.

Fraser: And also, we know that the further away you look at things, things can be redhsifted away, so can't things that maybe started out in a different spectrum be redshifted out to the radio spectrum?

Pamela: You have to be moving away from us at a fairly large rate to get redshifted all the way into the radio, but there are lots of optical things that get shifted into the infra red, and UV things that get shifted into the optical and near-infra red. So, we do see things at colours other than the ones that they're actually giving off due to this Doppler shifting of our Universe's expanding, so further away objects appear to be moving away from us and their light gets shifted because of that.

Fraser: I guess you explained a bunch of interesting things in the radio, aren't there pulsars and stuff that are giving off radio waves?

Pamela: A lot of that comes from the electrons interacting, these free-free / bremsstrahlung reactions. Electrons that are excited into different states, when they de-excite, they give off the radio emission and we find this in some cases around pulsars. The magnetic fields in the pulsars can cause the electrons to change directions and the effect is we see radio emission. It's just a really neat way of seeing what's going on at the atomic level in objects that are so far away we can't really make out the details of what they look like, but we know what their atoms are doing.

Fraser: Okay, let's pump up our photons, a little more energy. What else can we see now as we move up the electromagnetic spectrum?

Pamela: The next chunk of the electromagnetic spectrum we hit is microwave radiation, and this is where we find our Cosmic Microwave Background. One of the things we haven't talked about in detail is how temperature and wavelength and frequency are all intertwined.

So when we're talking about the colour of something, we can use a lot of different terms. We can say that it has a wavelength of 14.48 GHz, that's formaldehyde. Or we can say it has a wavelength of 21cm. You get these two numbers because wavelength times frequency just happens to work out (because of the way the Universe was formed) to be the speed of light. One of the other neat things that comes out of physics, is if you heat an object and it's what's called a perfect black body… a rock is a good example.

If you heat a rock, it gives off light in all different colours, but the maximum colour it gives off, the colour that gives off the most number of photons is going to correspond to the temperature of the rock. If you go back and watch some of the original Star Trek episodes, you'll see Captain Kirk heating rocks with his phasor, because that's what he did. As you heat the rock it gets brighter and brighter in the reds. It's a warm object. If he keeps shooting it with his phasor, it will eventually turn blue. That colour that we see corresponds directly to the temperature.

So when people talk about the Cosmic Microwave Background, they usually talk about its temperature, which turns out to be about 2.7 degrees Kelvin. If you look at the equation that describes the maximum wavelength that corresponds to a given temperature, that works out to be about one millimetre, so the wavelength of the Cosmic Microwave Background is one millimetre, which is microwave. So in theory, you could use the Cosmic Microwave Background to heat food – not effectively, it's not tuned exactly right, but still, it's just microwave radiation.

Fraser: And the microwave background radiation is what was redshifted from the visible light back at the beginning of the Universe.

Pamela: That's one of those cases where something that was once really hot, bright temperature, good, easy to see (probably quite dangerous to the body) radiation, over time has gotten stretched out, now being in the microwave.

Fraser: Is there anything else that we can see in the microwave spectrum?

Pamela: There are these neat things called "mazers". These are cases where you have some sort of molecule hanging out either sometimes in a comet, sometimes in galaxies, in molecular clouds, and these molecules are hanging out in an excited stage.

Molecules and atoms are allowed only to have specific energy levels. It's sort of like stair steps. They jump from one level to the next and they can't be anywhere in between. It works out that if one of these molecules is at a higher step and a photon comes along with the exact energy corresponding to between that high energy and the energy below it, it can hit it just right that the molecule jumps down an energy level, gives off a photon, and that original photon (or at least, some photon with the exact same energy) also comes off.

So one photon comes along and suddenly it turns into two photons. Those two photons can hit another excited molecule, and now we have four photons. This ends up magnifying the amount of light at a given colour that's coming out in a straight line. It's sort of like a laser beam, except in this case it's in the microwave radiation.

Fraser: Is that because the energy is being spread out? Sort of one photon has a lot of energy, but then it gives it to a whole pile of other photons, but they're going to come at it with a lot lower energy.

Pamela: It works out as this weird amplification process. You have all these things that are hanging out at a higher step, and one thing comes along and it knocks something off a step and it gets another photon with it. It comes along, hits something else on a higher step, knocks it down, now we have more photons at that same energy going along. It's causing a cascading reaction of all of these excited molecules that are in an unusual state. They cascade down, and then give off this photon as they go.

Fraser: So we're seeing "mazers" in the microwave spectrum.

Pamela: We see them in the microwave spectrum and they're just kind of cool. The Universe creates its own lasers, but in the microwave regime.

Fraser: All right, let's keep crawling sort of up the spectrum. What's next?

Pamela: The next place we land is in the infrared. This is generally just warm stuff. What's neat about the infrared is dust and gas scatters light. Light is more likely to get scattered if it has a very short wavelength, or a high frequency. Stuff we can see with our eyes easily gets scattered by dust. Stuff with really long wavelengths, like in the infrared or radio, can pass right through dust – not a big deal.

When we look out in the Universe using the infrared, we can see through a lot of different dust clouds, and we can see things that are embedded in the dust clouds that we can't normally see using optical light. So we look out and we can see stars embedded inside of nebulas, we can see background objects, we can peer into the centre of our galaxy just by going into the infrared and looking at this light that doesn't easily get scattered.

Fraser: The invention of infrared was quite a revolution in astronomy, wasn't it?

Pamela: It allowed us to suddenly see things that we never thought we'd ever be able to see. It's just a matter of getting detectors that are tuned to the right colour photons. Nowadays, it's common technology. Night-vision goggles are just infrared detectors. They allow you to see the cooler photons that come off of warm objects. This is why you see warm bodies as ghostly shapes where the dark spots correspond to cold objects on the person's body.

This allows us to see things with temperatures in the range of human body temperatures. We look out and can also find things like stars that are just starting to form, things up to 1 thousand degrees, 2 thousand degrees – not a big deal in terms of hot objects, but a big deal in terms of the science that comes out of it. We can see stars before they have nuclear reactions going on, and start to figure out what are all the different stages in star formation.

Fraser: You could have an object, say even a planetary system. There's nowhere near enough energy there for us to be able to see with a visible light telescope, but it's getting warm enough just through the friction of the dust that it's starting to form and we can see it in the infrared spectrum. Maybe even, it's covered in dust – enshrouded in dust – and the infrared lets us peer through that dust when normally it would be blocked in other telescopes.

Pamela: It's this wonderful form of the old "get your x ray glasses" comic book glasses, but in this case it was really the infrared that was needed. We're peering through dust that was otherwise opaque to see objects that were otherwise invisible.

Fraser: And most of the new instruments htat are being built are focussing on a lot of the infrared – Spitzer, I know the new James Webb telescope is going to be significantly in the infrared

Pamela: This is for a couple of different reasons. One of them is it allows us to look through dust, and that's just useful. It opens up whole new areas of the sky, places we can now go and explore. It lets us look at star and planetary formation.

The other reason is the most distant galaxies have had the majority of the light they're giving off redshifted into the infrared, so now things that may be bright blue on the very edge of the Universe, far back in the past, their light has gotten shifted as it travelled toward us, so now it appears in the infrared. We can see the earliest days of the Universe by looking in these other wavelengths.

Fraser: So next up…

Pamela: Next is the good, old fashioned, boring optical.

Pamela & Fraser: Boring!

Pamela: This is what we see everyday of our lives. Again, nice. Warm temperatures, again. Here we're looking at the few thousand to about 7 thousand degrees. This is where our Sun gives off a lot of its light. It's just good old fashioned thermal emission.

Now you also start to get atomic lines in here. You get some neat – the hydrogen bomber series, which is a good way of looking at a star and telling how fast it's moving because you know exactly where these lines are.

It's a good way of telling the temperature of the star, because the strengths of the lines vary with temperatures. You get things that are very excited at high temperatures, or very excited at lower temperatures because as they go up to the higher temperatures the electrons fly away and you no longer have transitions.

There's all sorts of really cool quantum mechanics going on. You start to get things like iron atoms get excited. You get metallic lines going on.

So there's lots of neat ways that when you spread out the light of a star and look at the individual colours, you can start telling exactly which atoms go into making up stars. This is all very easy to do in the optical. You have lots and lots of lines to deal with and easy to detect because our technology's driven in some cases by what is commercial and most useful.

Everyone wants to take a picture of their kid, so we figured out how to make optical detectors. All of that commercial technology has gotten transformed and used in astronomy. We have all of this great equipment we can use to study the stars, and study what atoms make up the stars, what light is getting absorbed and emitted by the individual atoms in those stars.

Fraser: All right, let's move beyond the visible light. What's next?

Pamela: Next is where we get our sunburns, that's the ultraviolet light. This is again, a good place that we can study the individual atoms in the stars. We also get UV light specifically in its largest amounts, in really hot places.

When you have lots of star formation going on, you have lots of young, really, really hot, really, really massive stars just blasting ultraviolet radiation. It's these hot, dense areas with these young, young stars that give off lots of UV light. So when we look at starbursting galaxies, they're not just blue, they're ultraviolet. Ultraviolet is you just keep going hotter from the blue and you land there.

It's a dangerous place interms of the human body doesn't cope so well with ultraviolet. These are high energy photons, so when they hit things, they can knock electrons out, they can do lots of damage. Ultraviolet photons can actually damage your DNA if they hit one of your molecules in just the wrong way. We need to be careful when we start getting into these high energy photons.

We also start to see ultraviolet in places like the cores of galaxies that have active galactic nuclei that are doing lots of consuming and there's high density gas. Anyplace where the gas gets really dense you start to get high energy photons.

Fraser: So we're going to be seeing ultraviolet in fairly exciting places.

Pamela: Very exciting places. We also start to see x rays in some of thse very exciting places.

Fraser: Right, that's next on the list.

Pamela: X rays, we start to get from hot gas. We also get x rays when you heat metals up really, really hot. When we look at the cores of clusters of galaxies, in these places, the gas gets compressed so much, and the temperature gets so high that they start giving off x ray emission.

We also get x rays in places where there's really strong magnetic fields. As electrons get accelerated by the magnetic fields, this acceleration… you end up with an energy change. This energy change corresponds to photons – to light being given off. We end up with magnetic fields being sources of x rays. When we look at stars with really large magnetic fields, we also start finding x rays. When we look at supernova remnants, where we have, in some cases, magnetic fields, and where we definitely have lots of accelerated stuff, we find x rays.

Fraser: So the magnetic fields are boosting the energy levels of the photons around them.

Pamela: They're accelerating them.

Fraser: and hurling the mass.

Pamela: Exactly.

Fraser: Wow. There's more?

Pamela: There's one final category; Everything that is higher energy than x rays is called a gamma ray. No matter how much higher you go, it's still going to be called a gamma ray.

Fraser: That's how we get the Hulk, right?

[laughter]

Pamela: Something like that.

Gamma ray emission is again, something we find associated with magnetic fields. We find gamma rays in supernova remnants again, but gamma rays also come from the most magnificent explosions in the Universe.

When you have some supernovas that funnel the majority of their energy along the axis of rotation of the star that's exploding, if we just happen to be along that axis, we can see this burst of high-energy light, high energy photons, gamma rays, funnelled straight at us from the explosion. These are the mysterious gamma ray bursts that had been befuddling astronomers for decades, that we think we finally have a handle on.

If you get a couple of neutron stars to collide, they give off gamma rays because the energy of the explosion is so high, the photons get accelerated to the point that they become gamma rays.

Fraser: Wasn't there a mystery that gamma rays have been detected with energies so high that we don't even know where they might be coming from?

Pamela: There's always these mysterious "what could have done this?" It could just be that you hit something with a photon that's going at a really large rate. This is the old what happens when you send a two-year-old on rollerskates at a sumo wrestler? They bounce off. Now, if the little kid goes into a running sumo wrestler, they bounce off with a really high velocity. If you have a regular, everyday, happy electron chugging through the Universe at not to high a rate, and it gets blasted by a high speed photon, a cosmic ray from some sort of an explosion or something, the energy change could correspond to ginormous levels that end up giving off gamma rays. We're not entirely sure what would cause that to happen. There's always these mysteries.

Fraser: I know there's a new observatory being built in Chile

Pamela: There's all sorts of different ways for studying the Universe. There's new telescopes coming on everyday. It's going to be interesting to see what technology allows us to discover in the next 10 years or so.

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