Astronomy Cast Episode 103: Electromagnetism

Fraser Cain: Yeah and you're off to Dragon Con. I know we've been saying this over and over again, but this is it.

Dr. Pamela Gay: I'm going to be at Dragon Con and there will be an International Year of Astronomy booth over in the Marriott Hotel and Pod casting science space and a whole lot more over in the Hilton.

I even got myself onto one of the Star Wars panels where we're going to be talking about, "Could the Star Wars Galaxy really happen?" It's going to be a fun packed week and I'll have all the details up on my blog probably Wednesday or Thursday.

Fraser: Alright and Phil's going to be there and all the folks from Skepticality. It's going to be a lot of cool people there. I get to take a week off because you'll be recording the show, so it will be great.

Actually it probably won't be a week off because we'll probably do our show next week and then we'll probably post the Dragon Con show the week after that.

Pamela: We'll see what happens.

Fraser: Yeah we'll figure it out. There will be something every week forever. All right well let's move on. Our series on the basic forces of the universe continues. Last week we covered gravity and this week we'll handle electromagnetism.

You probably know electricity and magnetism are just two facets of the same force and they play a huge role in some of the most energetic places in the Universe. You can't talk Astronomy without understanding these.

All right Pamela so we're ready for Part 2. I'm going to guess we learned about magnetism first so maybe you should give us just a little bit of background.

Pamela: Well, the fact that these are forces is one of those things that confused us for no end. There was first this whole that there are rocks out there that can pick up other rocks and they cause attraction and repulsion and this was just highly confusing.

But, it allowed us to do things like build compasses. Compasses were probably one of the most useful things right after fire in terms of helping human beings expand out across the planet. Compasses allow us to find our way across water.

With society growing up around the Mediterranean, being able to navigate by sea was kind of important.

Fraser: I guess that must have been a pretty amazing discovery to think that you'd float a little piece of metal or rock on water and it will always point in the same direction.

Pamela: You've got to wonder what sort of magic and gods and all sorts of other mythology was involved with that. It's something that we didn't really understand until the 1800s, but we've known about for basically forever. That's just one of the strange, why do things fall? Well they do. Well why do magnet's needles point north, well they do.

It took a long time to sort it out. Trying to bring magnetism and electricity together was one of those things that actually first started to happen out at sea. Sailors were being subjected to St. Elmo's fire, to lightning, to all of these electrical effects and noticing in the midst of all of this chaos that their compass needles are going haywire too.

Here you know how these poor superstitious sailors, who don't have the education to know any better, watching their magical compass needles spin crazily, watching their masts start to glow with built up electric charge and then quite often all of this leads in their ship getting struck with lightning.

They had to have evoked all sort of craziness and now we have the science to explain the craziness. The moral is you don't want to be the tallest thing on the ocean during a storm.

Fraser: So from electricity, how did they start to understand that?

Pamela: There are all sorts of neat things but it often all boils down to cat fur and amber, or wool and amber. There are different things you can do to build up static electricity. This can lead you to doing all sorts of neat experiments.

For instance, if you rub cat fur on amber or plastic you can start to build up charge. You can transfer this charge if you have a metal cylinder. One really neat experiment we do in a lot of freshman physics courses is we take a metal cylinder with a piece of glass on both ends of it.

Going into the metal cylinder we usually have a little finger of metal with a piece of foil attached to it. There's usually an insulator of some sort to protect the piece of foil from the little metal finger going into the cylinder.

If you rub plastic with wool and then touch the metal cylinder it will deposit charge and you can do this over and over and over again. Very slowly as the charge builds up you can start to deflect the small piece of foil in the center. This is the type of experiment that they could have done a couple hundred years ago.

Fraser: Actually I have a great experiment for every one. If you want to pause the pod cast. Find something long and plastic like a knitting needle or something like a straw. Rub it against cotton or wool ideally and then turn on your water off your tap really lightly so you have a thin little stream coming down.

Once you've rubbed the plastic with the wool hold it right next to the stream of water and you will actually find the water bend sideways. It freaks the kids out. [Laughter]

Pamela: The reason that works is because there's charge in the water. It's not all neutral and you're actually getting attraction. That's a really cool demo I'm now going to have to try with my students. I didn't know about that particular demo.

There are all sorts of neat little things you can do with electricity and magnetism. For a couple hundred years all sorts of people including perhaps most famously here in the United States, Benjamin Franklin, looked for all sorts of different ways to experiment with electricity and find new and interesting ways to hurt themselves in some cases.

Fraser: How do they get the sense that they were connected?

Pamela: This whole lightning strikes and compass needle goes crazy was indicative that there was something going on. You can actually start to generate electric current through wires by using magnetic fields. If you have a moving magnetic field near charge then you can get the charge to move too. It's one of those cool things.

Take a loop of wire move a magnet through the wire and you'll end up getting current moving through the wire. This is in part how generators work. You take and you either rotate the wire around the magnets or the magnets around the wires and you can start generating all sorts of different types of current depending on how you have the wires set up. There's this clear, physical, tangible experimental evidence that something is going on.

Fraser: Right, so once again I think the experiment reads you take a coil of wire and then you move a magnet through the middle of the coil and assuming you have a light bulb on the end of it, the light bulb will glow every time you move the magnet in and out of the coil of wire.

Pamela: The other thing is once you start figuring out how to generate electricity, if you run electricity around and around a coil; that generates a magnetic field. You have two different sides of a coin facet to this where magnet going through wire generates electricity, electricity going through coil of wire generates magnetic field.

This is actually in part what's happening in stars. We don't so much have a coil of wires, but instead there are plasmas (charged particles) moving in circular motions around the insides of stars and this motion of the charged particles generates magnetic fields. That's what leads to sun spots eventually, that's what leads to the Earth's magnetic field.

Everything seems to come down to what happens when you take an electron, what happens when you take a proton, what happens when you take a calcium atom that's missing a few electrons. What happens when you get this charge moving is you get magnetic fields.

Fraser: Back to my question, how do they come together?

Pamela: It all came down to a rather brilliant man by the name of Maxwell who was working on trying to figure out how to mathematically pull all of these pieces together. We had laws describing mathematically how magnetism worked. We had laws describing mathematically how electricity worked.

Maxwell sat down and realized that all these sets of equations could be brought together into a single formalism that combined both the electricity and the magnetism through basically four different equations.

Fraser: So we've got then four different equations that then allow you to calculate how the electricity and the magnetism in some situation are going to be interacting.

Pamela: It all comes down to, "How do charged particles move and how do magnetic fields change?" If either of these two things is happening, if either a charged particle is moving or the strength of the magnetic field is changing, you're going to generate electric fields. You're going to generate magnetic fields and you're going to get all sorts of neat secondary effects.

One of the things we don't think about as we're wiring up our houses is if you had direct current, if you had current that was always flowing in one direction and somewhere in your house and you ended up with too much wire and you coiled it up you could end up with small pockets of magnetism in your house.

As it is with alternating current, we can still end up with small pockets of magnetism but the direction of the magnetic field is constantly changing so that's not as likely to do weird things to your house.

If you leave a nail inside of a magnetic field that's constant for too long you can actually transform that nail into a magnet because over time that magnetic field can actually change the alignment of the atoms in the nail.

Fraser: Let's bring it back to Astronomy then. What role does electromagnetism play in some of the biggest forces in the universe?

Pamela: Magnetic fields are pretty much where it's at. One of the scariest parts of the field of astrophysics is something called magneto-hydro dynamics. It's the study of basically, if you have stuff that's acting like a liquid and there's charge in it, it generates magnetic fields, let's describe this in three dimensions using fancy computer models. It's probably the most complicated thing to try and study.

It's necessary because things like the accretion discs around Black Holes generate magnetic fields. Stars generate magnetic fields. The faster rotating the star, the stronger the magnetic field. When we pull all of these pieces together, it leads to side effects.

There are jets. The jets of a Super Massive Black Hole are nothing more than the North and South Pole of a giant magnet and particles are getting streamed out that northern and southern pole. Charges are getting carried along and flung out the ends. These are violent, violent behaviors.

Hyper nova and gamma ray bursts, are considered to be in part, driven again by jets potentially again driven by magnetic fields. Where there's violence, quite often there are magnetic fields. Understanding these things allows us to understand some of the coolest most high-energy events hanging out scattered around the Universe.

Then there are just low-level magnetic fields that could have different effects on galaxy formation. We're still working to try to figure this out. We know that there are magnetic fields permeating through Galaxies. We're still working to figure out how does that effect star formation.

How does that effect the streaming of material that's getting spit out as super novas shock the nebula that they sit within? We're still sorting all of these secondary things out and we have to understand the magnetic fields to understand what's happening.

Fraser: I know one of the more recent theories about Super Massive Black Holes is that those jets that are coming out of them are helping to see the Galaxy and help collapse star formation and seed some of the heavier elements. Those big magnetic fields operating from the Super Massive Black Holes might have a big impact as well.

Pamela: It's basically like a giant magnetic sprinkler head. We have all of these nuclear reactions going on generating heavier and heavier particles and they are not neutral.

They don't have enough electrons to balance out all of their protons in a lot of these extremely hot dense environments. Any time a particle is charged it's susceptible to magnetic fields.

So it's possible that these Super Massive Black Holes can basically scoop up the charged particles, shoot them out through the magnetic fields and let them rain back down on the Galaxy.

Fraser: Can we get a sense of scale here? We've got a bar magnet or the Earth's magnetic field, how does that compare to say the magnetic field of the Sun or a Pulsar or something like that?

Pamela: Here on the surface of the Earth your standard bar magnet can totally overwhelm the effects of the Earth's magnetic field or of this little tiny magnetic field. It's like order of a few tens of a few micro-teslas. It's not that big. We can generate in the lab thousands of teslas if we feel like it.

The Sun is measured in micro-teslas. It's about a hundred more powerful in general. Once you start getting out to some of the bigger things out there such as Pulsars, Neutron Stars that are rotating quickly, accretion discs and things like that you can start to get to thousands of times stronger, tens of thousands of times stronger.

In fact the magnetic field of magnatars, are measured not in micro-teslas but measured in giga-teslas. The micros are like fractions and fractions and fractions of teslas where as the giga is billions of teslas.

Fraser: So we're talking trillions of times more powerful than the Earth.

Pamela: Yeah. You might say that we really don't want to be anywhere close to a magnatar. When the magnetic fields and magnatars rearrange themselves there is so much energy involved that, one that did this on the other side of the center of the Milky Way a few years ago was actually able to damage satellites orbiting the Earth because it let off so many high energy particles, so many high energy gamma rays. There's a lot of energy tied up in all of these magnetic fields.

Fraser: Okay I'm going to channel my six year old daughter here for a second and ask the kinds of questions that she would I'm sure would want to know. I just have to say why? Why is there magnetism and electricity? What is the underlying reality at work here?

Pamela: At first glance it's the way the universe was built. When you start looking at the way particle physics describes it all of these forces are immediated by different particles.

So last week with the force of gravity we had the graviton running back and forth being – you, you be attracted to this and pulling things together. With the electromagnetic force we both have things flying apart and coming together. That's one of the really cool things about the electromagnetic force.

Just like with gravity, the electromagnetic force can work over huge distances. Just like the electromagnetic force it gets weaker with distance. It turns out that just like the force of gravity, the electromagnetic force has a mass-less particle running around going – you go over here, you come over here and in this case that particle happens to be the photon, the particle of light.

When you have two magnets repelling each other across the table you don't see a beam of light going back and forth between the two of them. This is where we start talking about exchange particles and virtual particles.

Mathematically we describe everything with the exchange of photons but that's not actually something we're generally going to see. We can actually see how light effects matter. The electromagnetic force is the one that holds together pretty much everything around us.

The reason I'm not falling through the chair I'm sitting on is because the electromagnetic force is bonding all the atoms together with covalent and ionic bonds, which is just a fancy way of saying different atoms are sharing electrons.

The reason that I am able to stretch some things and fold others is because of the fluidity of how the atoms are bonded together. All of these things are determined through the electromagnetic force and I can start to change things.

I can start to remove electrons; I can start to basically change how atoms are structured to the point of even causing fusion if I just hit them with enough light.

This was part of the photoelectric effect that Einstein got his first Nobel Prize for. If I shine a nice happy red light on a piece a metal there is a pretty good chance that I can beam that piece of metal all day long and not necessarily get any electrons flying off.

If I change the color of that light and change it more to the blue and more to the blue and more to the blue making the light higher and higher energy, eventually I'm going to start knocking electrons off of those atoms.

What was realized is that light, while appearing to be this stream of flowing color is actually not waves but individual particles. Each packs an individual little punch where red light carries less of the punch than blue light.

Atoms have electrons that are held in place and with a certain amount of energy can get knocked to a new place. Just like having ten million little puppies butting their little heads against my leg is probably only going to make me slightly bruised and ten million pit bulls will cause me to fall violently to my knees, the blue light is perfectly capable of moving electrons.

Whereas the red light just causes the electrons to go, "Yeah, so go on, do your best." It's that energy that can cause electrons to get removed from atoms.

Fraser: So how do the photons relate to the magnetism and the electricity?

Pamela: They work to carry the force. Here is where it starts to sound more like magic than science unless you start getting into the nitty gritty quantum mechanics of all of it.

The photons basically working as virtual particles getting evoked in lots of fine diagrams are going back and forth communicating from one electron to another; you too should be repelling one another. Communicating from one electron to one proton, you two should be attracting one another.

In this way they are the carriers of the force. They are the ones that communicate what's going on and through their motion at the speed of light they are also able to communicate in some ways the distance between things.

Magnetic fields don't move instantly. If I move a magnet it's going to take the magnet that's interacting with it time, the amount of time it takes a photon to move from one magnet to the next to realize that there has been a change in the force it's experiencing.

Fraser: So magnetism works at the speed of light just like we know electricity goes at the speed of light.

Pamela: Yes, so we have gravity, we have electricity and we have magnetism, all traveling at the speed of light because they are communicated by particles with no mass.

Fraser: So when you said that everything that we see in the Universe, all the light that we see, all of the forces that are holding together the atoms that we see, the molecules, that's all electromagnetism.

Pamela: That's all electromagnetism with gravity sometimes mixing it up a little bit. We have gravity out there changing the color of light, changing the path of the light. But the structures we see are all electromagnetism. The structures we're sitting on, our computers, all of that is electromagnetism.

Everything that allows the computer, the I-Pod the I-River, the whatever it is you are listening to us on to function. All of that is described through electromagnetism. Through various sets of rules that define how circuits work, and how one charged electron interacts with different properties in atoms.

This is perhaps one of the most complicated forces. Gravity is quite happy to say, you have mass, okay I'm going to pull on you. With electromagnetism you start to get into the individual characteristics of different atoms.

You look at what are the geometries of the electrons? What is the susceptibility of a particular substance to having its electrons moved around?

Electrons move readily in metals. Metals become magnets. Metals conduct electricity. All of these things are united together. At the same, pick take up a hunk of wood and it could care less if you have a magnetic field or a flow of electricity. It's just going to sit there and be wood and refuse to conduct and refuse to repel and refuse to attract.

It's all the electromagnetic force and the structure of atoms define how that electromagnetic force is able to do all the amazing things that it does.

Fraser: All right so let me see if I understand this correctly. I could take for example a magnet pulling on some other magnet onto some piece of metal and I could turn that into electricity, right, either by moving the magnets through the wire or whatever.

I could turn that electricity into light or also magnetism here or I could use that electricity or magnetism to knock electrons off of some atoms to make them either stick together or break apart and this is all just the same force acting?

Pamela: This is all the same force even down to light bulbs where when you try and get electricity to flow through things that are more resistive to its flow like carbon filaments.

The friction is the wrong word, but it's the one people try to use, don't say friction. The resistance of that carbon fiber to having the electricity flow through it is going to cause the atoms to move, to heat up, and to generate light.

That's again electromagnetism where as the electricity flows through something that conducts easily, a normal every day wire, to moving through something that is resistive like a filament we generate light.

All of these things are electromagnetism and it all boils down to the structure of the material the electricity is attempting to flow through or the magnetic field it is attempting to interact with.

Fraser: Now we're treating it as a separate force from gravity. Is there any inter-relation between electromagnetism and gravity, or are we not ready for that yet?

Pamela: No, we wish we understood how these two things could come together, we don't. At the earliest moments in the first fractions of a fraction of a fraction of a second of the Universe, all the forces were one.

Then gravity went off and went its own way. The other three forces hung out together for a while and electromagnetism is not related to gravity. Gravity can affect how light changes, but magnetism and electric forces are their own happy little things.

Fraser: So I guess we're going to have to wait until the last part of this series where we win our Nobel Prize [Laughter] to unite the forces.

Pamela: Exactly.

Fraser: All right, well we'll look forward to that then. Be patient everyone, that's coming.

Pamela: We condensed the entire topic of four college courses into 30 minutes. So if we were vague and we didn't dig into details it's because I don't have a blackboard. There are some excellent books out there.

There's E & M by Griffith if you ever really want to learn more about E & M than your calculus-knowing mind thought it wanted to know. If you really hate yourself, Jackson's E & M is a book that has put the fear of E & M into pretty much all grad students who have studied physics at one point or another.

Fraser: I don't think that people really understood how it's all inter-connected. Pretty much all of the things you are interacting with are all generated from this one force in different facets. In fact we talked about this before, that you can take light and freeze it into matter.

Pamela: Exactly. We talk about quantum mechanics as if it was dealing with its own separate little set of forces. It's not. Quantum mechanics deals in part with how the electromagnetic forces dictate how electrons move.

It deals with how light is generated, how things come together, and how electrons are able to go through different potential wells, how fusion and fission, how all of these different things are able to take place.

This is all electromagnetism and it took quantum mechanics to explain how all of these different things come together.

Frazer: We've got two more forces to go so I think that will be maybe one maybe two more weeks. I don't know how much we have to talk about.

Thanks Pamela and maybe there will be a Dragon Con episode next week, it's all going to be a mystery so stay tuned, we'll figure it out.

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