Astronomy Cast Episode 42:
Magnetism Everywhere

Fraser Cain: You probably don't realise it, but magnetic fields are everywhere. We're not talking about the magnets in your speakers, your electronic equipment or on the fridge door. We're talking about the gigantic magnetic fields that surround planets, stars, galaxies and some of the most exotic objects in the Universe.

Okay Pamela. So first, let's just figure out a basic definition: what is a magnetic field?

Dr. Pamela Gay: A magnetic field is related to the electromagnetic force between two objects, where one of those objects involves charged particles that are in motion. It's really, unfortunately, something there's not a nice, one sentence, clear-cut definition of. You get a magnetic field anytime a charge moves. This means that when you're dealing with a refrigerator magnet, what you're seeing as a force that attaches you magnet to the refrigerator is resulting from all the little electrons in the atoms in the magnet all moving, and that motion is able to exert a force that holds the magnet on the refrigerator.

Fraser: In the situation of the magnet on the refrigerator, they're moving in a common direction, right?

Pamela: All the atoms manage to (or most of the atoms) manage to line up so the little electrons are all orbiting in patterns that are aligned with one another, and those alignments create a unified magnetic force.

Fraser: So if I have a rock – just a regular rock, not a magnetic rock – it has atoms and those atoms all have electrons whizzing around them, but because they're not lined up, the rock doesn't stick to my fridge door.

Pamela: Exactly. All those electrons are creating their own magnetic force, but if all those forces are aligned in different directions and pulling in different directions, you end up with a net force of about zero. It's sort of like if you have a whole bunch of different people pulling on a pillow from different sides, the pillow's not going to go anywhere, because the net force cancels out.

Fraser: That's the weirdest analogy you've used so far.

Pamela: Okay!

[laughter]

Fraser: How's it relate to electric fields? We've got electricity, we've got electrons moving through wires, and there's a connection between that and magnetism, right?

Pamela: Every electron, every proton, every charged particle has both an electric field associated with it, and (if it's in motion) a magnetic field associated with it. When we look at the net electromagnetic force, it's the sum of those two different components, and the electric field and magnetic field are always perpendicular to one another. For instance, a photon (a particle of light) moving through space is going to have both an electric field and a magnetic field that are perpendicular to one another, and perpendicular to the direction of the photon's motion (it's very mathematically ugly).

Fraser: Yeah, well we're not going to get into the math. I'm sure we'll link to some stuff in the show notes. More importantly, we want to talk about how a magnetic field can get around a large object. As I said, if I have a rock and the rock won't stick to my fridge, how come the Earth can have a magnetic field? Can I stick the Earth to my fridge?

Pamela: Well, unfortunately the Earth's magnetic field is a lot weaker than the magnetic field of, well, your standard three-year-old's letter 'L' that sticks to the fridge quite successfully.

The magnetic field of the Earth is coming from (like all of them) charged particles in motion. We have a molten metal core to our planet, and as the molten metal swirls and rotates, it's motion is (in ways we don't fully understand) able to create this magnetic field. It's only because we have a molten core that we have a magnetic field. Eventually our planet is going to cool off enough that the molten metal solidifies, volcanoes go dormant, no more cool funky magma. When that happens, the magnetic field is going to slowly fade away.

Over time all magnets lose their magnetism. Initially, when the metal stops moving, there'll be a residual magnetic field from things that have had their atoms get aligned just by having magnetic field lines pass through them for so long.

It's sort of like if you stick your scissors on top of a fridge magnet, the magnetic field will slowly cause the atoms in the scissors to align one another so your scissors become magnetic. But if you bang your scissors on the counter enough, the atoms will re-randomize themselves so the scissors are no longer magnetic. Our planet will, for awhile, have a residual magnetic field, but over time that will go away.

When we look at the planet Mars, once upon a time it had a magnetic field. Today, that magnetic field is gone because the planet has cooled, it no longer has a liquid core, and the residual magnetic field is also gone.

Fraser: Losing your magnetic field is a very bad thing.

Pamela: It's a very bad thing. We need our magnetic field to protect us from the Sun. as charged particles get flung off the Sun toward the planet Earth, our magnetic field says, "aha, I've got you!" grabs the charged particles, and forces the charged particles to move along magnetic field lines that keep them out of our atmosphere, keep them from destroying our atmosphere. As they stream across the magnetosphere, we see these amazing aurora (the northern and southern lights).

If we didn't have that magnetic field we wouldn't have the northern or southern lights, and those charged particles would hit our atmosphere directly and end up knocking chunks of our atmosphere out into space.

Fraser: So here on Earth, we're protected by the Earth's magnetic field, so all those charged particles from space go right around the Earth and don't hit us. If you were sitting on the surface of Mars, you might as well just be in space. You're getting hammered by particles from the Sun whether you're on the ground or up in space.

Pamela: This is also part of the reason why there's a much higher radiation level on the surface of Mars. Astronauts going to Mars don't have to worry about the cold nearly as much as they have to worry about the radiation and lack of oxygen. If it was just a lack of oxygen problem, you walk around the surface of Mars wearing a warm jacket and an oxygen mask.

You have to worry about the low vacuum of space causing you to bruise violently because of the pressure difference, but in a pinch… you bruise, you run to the next thing, you suffer a little bit, but you survive. The radiation levels you encounter on Mars, that's a real problem that's not as easy to defend against. We have to figure out really effective radiation shielding if we want to have people live successfully on the planet Mars.

Fraser: Does the Earth's magnetic field stay constant? I've heard it's flipped in the past.

Pamela: We don't fully understand why it does what it does, but yeah. We have geologic indications that when rocks formed at one point in the past, the Earth's magnetic field was different. As the rocks formed out of molten materials, the magnetic fields within the rocks aligned along the Earth's magnetic field. Rocks that formed far in the past have a different orientation than the magnetic field of today.

We don't know how often the Earth's magnetic field flips, or why it flips – we just know that now and then it flips and we can actually observe the north magnetic pole slowly wander over time. Currently it seems to be on its way to Siberia, of all places.

Fraser: That's an amazing piece of science, that geologists can observe the lava that comes out, and measure its magnetic field. I can imagine what happened: the lava came out, it was still in a liquid state, it got aligned by the Earth's magnetic field, and then it hardened and created a record like a fossil.

Pamela: That's pretty much exactly what happens. I have to admit, I'm not a geologist. I don't know what specific types of volcanoes, what types of instances this occurs in. what I do know is if you take any metal, and you heat it up, and pass a magnetic field through it while it's at a critical temperature (Curie point) you can end up, as it cools, it will end up gaining the magnetic field that is passing through it and have its own magnetic field when you take it and walk away with it somewhere.

At the same time you can take a hunk of metal that's working perfectly well as a fridge magnet, heat it up, and when you heat it up again to this magical Curie point, if there's no magnetic field around it will lose its magnetic field. So anytime you heat up material, you can either put in or take out a magnetic field depending on the environment while the metal is cooling off.

Naturally occurring magnets come in the form of lodestone, but we can create magnets out of a lot of different types of magnetic materials.

Fraser: Let's talk about other magnetic fields here in our solar system, because I know we're not alone in having a magnetosphere.

Pamela: No, in fact magnetospheres are one of those things that crop up all around the solar system. Surprisingly, the most magnetic object in our solar system appears to be the planet Jupiter. Jupiter has a rotating metallic hydrogen interior. This rotating interior gives Jupiter a field that is many times stronger than the Earth.

At the surface of the Earth we have a magnetic field of about 0.3-0.6 Gauss. This is the magnetic effect that is just able to move your compass, as long as your compass is nowhere near a refrigerator magnet.

On the surface of Jupiter, the magnetic field is more often measured to be between 11 and 14 Gauss at the surface. I have to admit that in trying to look up measurements of Jupiter's magnetic field, I found numbers all over the place, so when you're reading these numbers you have to be careful to ask where they're measuring the field. Are they asking what's the magnetic field inside of Jupiter, or at some specific point. Depending on where you look, you find different numbers. From what I found, at the surface of Jupiter it's 11 to 14 Gauss.

The surface of the Sun is just twice what we have here at the surface of the Earth – about 1 Gauss on average. If you want a really strong magnetic field, the best place to look is a sunspot: a specific spot on the surface of the Sun where a magnetic field line is poking through the surface. Within a sunspot you can end up with a thousands of Gauss field. You have very strong fields associated with sunspots.

Fraser: what's the mechanism that creates those Sunspots?

Pamela: We don't fully understand these things.

Fraser: Is this that hardest kind of science there is, or hardest kind of space science there is?

[laughter]

Pamela: Yeah… this is where you start getting into magnetohydrodynamics. Somewhere inside the Sun, probably at the boundary layer between where heat is transported via radiation (where it just goes from atom to atom to atom toward the surface), to being moved via convection, where you have (large scale) a chunk of hot material rises to the surface (because hot material is less dense) and cold stuff comes down… somewhere in the boundary between the convective region and the radiative region, we think, is where the solar dynamo, the solar magnetic field originates. We're not entirely sure how this works.

Whatever is going on, it doesn't create a nice, friendly, bar magnet where you have the Sun's north pole, the Sun's south pole, and nice, pretty, perfect field lines. Instead, the inside of the Sun ends up creating this tangled web of magnetic fields. Different parts of the Sun are rotating at different rates. This is probably part of the reason the magnetic field lines are so tangled.

When parts of these tangled fields twist up and end up coming through the surface of the Sun, you end up with sunspots. So the sunspots are marking the location where a tangled glob of magnetic field is coming up through the surface.

Fraser: How does that turn into a coronal mass ejection then?

Pamela: These tangled bits of magnetic field can actually funnel plasma through them. When the field gets tangled up so tightly that it rearranges itself by breaking and rejoining, that plasma gets shot off into space during the moment where the field lines break and they stop funnelling the plasma.

Imagine you have your backyard hose cranked up to full blast, and you make a nice arc out of it, and for some reason you decide you're going to cut the hose at the centre of the arc. Even if you've just turned off the hose, but it's still filled with the pressure of the water inside, that water is going to blast off in all directions (and get you wet).

In this case, we have a hose filled with plasma and when the hose breaks, that plasma gets shot off into space.

Fraser: Doesn’t that plasma still maintain a magnetic field?

Pamela: It's charges in motion, so it will have a magnetic field, but it's dominated by other things. Any charge that's in motion has a magnetic field, it's all a matter of scaling, however. If I have one lone electron zipping through my room from a cosmic ray, its magnetic field is going to be nothing compared to the magnetic field of my refrigerator magnet, or a coil of wire hooked up to a battery.

With the Sun, the magnetic field loops that are creating this coronal mass ejection are significantly stronger than the magnetic field associated with the moving charges inside the plasma. That plasma is really just shooting off from the Sun, heading off in (hopefully) a mostly straight trajectory (or we don't understand physics) until it interacts with something either gravitationally or magnetically and gets its path changed.

Fraser: All right, so we've talked about the solar system; we've talked about the Earth, Jupiter and the Sun. Let's find out – what are some other places where we find magnetic fields out in the Universe?

Pamela: Anywhere you have material moving, you can start looking for magnetic fields. One of the best ways to create a strong magnetic field is to get things moving in loops.

Fraser: One question for you, before that… you say we look for magnetic field – how can we see a magnetic field?

Pamela: (laughing) I was wondering if you were going to ask that.

Fraser: I mean, obviously you can feel it with a magnet, but if the magnetic field you're looking at is across the Universe, how can you feel it?

Pamela: We look for it in two different ways: the easiest way to look for it isn't a direct detection of the magnetic field – it's to look for jets. If you have a magnetic field created by a loop of charged material (and an accretion disk is really nothing more than a whole bunch of loops going together) you can end up with magnetic fields that are perpendicular to the disk and point in and out of the centre of the disk. So we can look for jets: jets are probably a product of a magnetic field.

Again, that's just a sort of a, "it looks and smells like a magnetic field, so we're going to call it a magnetic field". The way to directly say, "yes, I know with certainty this is a magnetic field" is to look for effects on how electrons change energies within atoms. We can do this using spectroscopy.

If you take the light from something – anything – and you spread it out, you see lines that correspond to places where electrons and atoms have absorbed part of the light of the object. Those lines you see occur in very specific locations where each atom has its own fingerprint of allowed colours at which it absorbs light.

The allowed colours, if there's no magnetic field, have one fingerprint that's nice and simple. If you induce a magnetic field, the electrons suddenly end up with a slightly different fingerprint, where what might've been one energy before might suddenly become three very slightly different lines.

So the fingerprint changes. It gets spread out into multiple versions of itself when you induce a magnetic field. The stronger the magnetic field, the more these lines split. This is called Zeeman splitting in some cases. One line becomes three lines and the separation between those lines increases, as the magnetic field gets stronger.

Something else we can look for is polarization of the light. Since light has a magnetic field, and an electric field, as part of its characteristics, the light will become polarized as it goes through a sufficiently strong magnetic field, because it will rotate. One way to think of it is we do these weird things with our hands called the "right hand rule" in physics.

If you take your (right) hand, and point your thumb and fingers out straight so that everything forms a plane with your palm flat on the table, then your fingers are currently pointing in the direction of motion. If you then bend your fingers in, that is the direction of the electric field. If you point your thumb straight up, that's the direction of the magnetic field.

You can rotate your entire arm, and if we have a whole bunch of light moving toward us and the light is unpolarized, then any of the directions of your thumb and fingers are allowed as long as your arm keeps pointing in the same direction and your palm is pointing along the direction of your arm.

If you induce a magnetic field, if you have the light moving through a magnetic field, suddenly everything will rotate so all the thumbs are pointing the same direction (if you have a whole bunch of arms representing a whole bunch of photons) and all of the fingers will rotate so that they're all pointing in the same direction. When you get all your photons lined up in the exact same way, they're polarized and we can see that polarisation with our telescopes.

Did I lose you?

Fraser: No, no… I understand the technique. We've got the jets, we've got the polarisation, and we've got the changes in the chemical constituency of the light coming from the object. From that, you can try and get a gauge of whether there's a magnetic field working here and what the strength is.

Pamela: Exactly.

Fraser: See, I paid attention!

Pamela: Okay! Cool – you're working toward that degree!

Fraser: I had my thumb out, looked like I was hitchhiking…

[laughter]

Now we kind of understand how scientists look for them. Let's go back and talk about where are some of the crazy places that we see these magnetic fields

Pamela: In astronomy, we have these things called accretion disks that seem to crop up just about everywhere. When you take a cloud of gas and dust and condense it down to form a star, as it spins, and condenses, part of that disk will flatten out into a pancake and in the centre you end up with your proto-star. That accretion disk can create a magnetic field. The spinning star that is forming can create a magnetic field, and these magnetic fields will couple to each other such that everything's rotating together.

We see these magnetic fields in T Tauri stars. What's neat is the magnetic field of the T Tauri star can actually lock onto the material and cause it to get dragged out of the accretion disk such that your accretion disk always ends up with a specific sized hole in the centre around the T Tauri star. That hole is created by the magnetic field.

This might be a way to explain the fact that hot Jupiters migrate toward the star and stop. That point at which they stop might indicate the point at which the proto-star's magnetic field had its affect on yanking material out of the accretion disk and created the hole in the accretion disk.

Fraser: I get it, so the hot Jupiter is bumping into particles in the rest of the accretion disk, so it's slowing down and by slowing down it's spiralling into the star. Then it hits this empty zone where the star has been so kind as to clear out all the space, and so the planet doesn't hit anymore friction, so it just stays at that position from that point on.

Pamela: Exactly.

Fraser: That's cool.

Pamela: It's very cool. We think there might be similar types of things associated with quasars. These are the disks of material around supermassive black holes where material is coming off of the disk, falling into the supermassive black hole. There's a magnetic field associated with the accretion disk causing jets out of galaxies (in this case).

So before, we just had these little tiny stars in the process of forming. Now we're talking about entire galaxies that have these disks.

We also find these disks around white dwarf stars. So we have stars that are forming have these, stars that have just finished dying have these – accretion disks are a great place to look for magnetic fields.

We also find magnetic fields associated with special types of neutron stars called pulsars and magnetars. These are fast-rotating, hot objects. They have ionized atoms in them (these are charged atoms). They're rotating, we don't fully understand why they have magnetic fields (this is again, magnetohydrodynamics, very scary, very hard to do), there's people working on the problem.

Pulsars and magnetars have the strongest magnetic fields in the Universe. The Sun has approximately 1 Gauss at its surface. Pulsars have somewhere between 10^12 and 10^14 Gauss fields. These are just huge, extremely strong magnets.

Magnetars have 10^15 Gauss fields. These are huge fields – they're the most magnetic things we know of. If one was nearby, it wouldn't just rip all of the magnets off every refrigerator on the planet, it would actually rip apart water molecules, because water molecules have different magnetic ends.

Fraser: What causes the magnetic field to get so strong? Wasn't this once a star like our Sun, with a 1 Gauss field?

Pamela: It all comes down to how fast is the thing rotating. Our Sun rotates about once a month, on average. A pulsar can rotate in some cases, a thousand times a second. The faster a charge is moving, the stronger the magnetic field it creates. The denser you pack together all of these moving particles, the stronger the magnetic field you're going to get.

You can actually do a slight experiment with this if you want to. You can get what's called magnetic wire at Radio Shack. If you make a bunch of loops of it around a soda can, pull out the soda can and attach the loops to a small battery, you can get a small magnetic field. If you then attach it to a large battery, you can get a large magnetic field. If you attach it to a car battery, you can fling a fridge magnet a couple feet across your desk. It's kind of cool.

Fraser: I'll do that right away! That sounds cool! Science we can use!

[laughter]

You mentioned in the show prep that you wanted to talk about some galaxy clusters. How big can these magnetic fields get?

Pamela: Magnetic fields are actually getting found permeating through all of space. There is work being done to study magnetic fields in galaxy clusters. Here we're not quite sure what the origins of the field might be. One thing we know for certain is if you take something that's magnetic and you put a bunch of iron filings near it, the iron filings will line themselves up and become magnetic. You can then bring more magnetic filings in and they'll become magnetic. You can create these long filaments of magnetic material where you start with just one magnet, and the magnetism gets communicated through the different material.

In our Universe, we have these filaments of magnetic field, where we think this might be residual magnetic fields from the early moments of the Universe, that as things have formed, they naturally align themselves along these magnetic filaments. We don't see the charge and motion, it seems there's just these natural magnetic filaments left over from some cause that we haven't fully understood. Things just align themselves along these filaments, and as they align themselves alone the filaments, they continue to maintain these fields.

Fraser: Perhaps there's some information in the Cosmic Microwave Background Radiation.

[laughter]

Pamela: I'm sure people are looking. Everything eventually points to the Cosmic Microwave Background.

Fraser: That's great. I think if there's something to take home here, there's magnetism everywhere.

Pamela: Exactly.

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