Astronomy Cast Episode 101:
Advanced Propulsion Systems

Fraser Cain: At the time people hear this I am sitting on sunny Hornby Island enjoying the Perseid Meteor Shower.

Dr. Pamela Gay: And I'm in upstate New Hampshire doing the same thing.

Fraser: Last week we talked about rockets. How they worked, how they go boom, their limitations…..

This week we're going to look at the future of propulsion systems – every other way that people theorized might be able to get us around the Solar System and even the Galaxy.

Pamela: And not all of them are realistic, but we're going to go there anyway.

Fraser: But we'll go there anyway. [Laughter] So from Ion engines that are already working to explore the Solar System to the prototype Solar Sails to futuristic technology like Magnetic Sails and Bussard Ramjets. This is how we'll travel to other stars.

Okay Pamela last time we talked about rockets. Essentially if you boil it down a rocket is throwing stuff out of the back of the rocket and thanks to conservation of momentum you move in the other direction. These advanced technologies use completely different laws of physics, right?

Pamela: Well laws of physics are generally kept constant. That's one of the nice things about the Universe. They use different techniques to try and accelerate themselves.

Although there is one exception and that is the railgun in which case you're still throwing stuff out the back end of the aircraft but you're accelerating it in really cool ways.

Fraser: Right, but at the end of the day, all of this stuff is more advanced forms of sitting on a chair on ice throwing rocks. Right?

Pamela: Pretty much, there are a few exceptions where you do things like playing with the Earth's magnetic field and using it to accelerate yourself in which case ….

Fraser: Right or people are throwing rocks at you.

Pamela: Well, that's true too. But yeah.

Fraser: So let's talk about one that really exists and that's Ion Engines. What is an Ion Engine?

Pamela: An Ion Engine is basically a device that takes atoms and ionizes them – removes the fuel electrons – which gives them a charge. If you have a charged particle and a magnetic field, you can get the thing to move. In fact, you can get it to move really, really fast.

This is essentially how particle accelerators work. If you start throwing really fast-moving particles out of the back end of your Spacecraft, you can admittedly without very small acceleration because you're only throwing particles out the back end, you can move yourself forward.

There are a few caveats though. If you strictly throw the Ions out the back end of the Spacecraft what you will do is slowly create a cloud of charged particles behind your Spacecraft and you will also slowly charge your Spacecraft. So you have the positive Ions going out of the back end, you're keeping the negative electrons and this causes you to eventually start electro statically attracting yourself to your exhaust jets.

You have to remember to also fling the electrons out. You just throw them out in a different way so that they meet up outside the Spacecraft and you end up with neutral Spacecraft and neutral cloud of exhaust.

Fraser: Right. This is where we've got this formula, mass times velocity, right? To determine your momentum and in this case you're taking very small masses but you're accelerating them at enormous velocities and using that to accelerate a Spacecraft. How efficient is this compared to a rocket?

Pamela: This is like THE absolute most efficient way that currently works that we have to accelerate ourselves. So if you look at the way we generally quantify efficiency, we look at something called the specific impulse. A solid rocket has a value of about 250.

For an Ion Thruster, you're looking at more like 3000. You're also looking at getting about 3 megajoules per kilogram of fuel out of solid rocket fuel, whereas you get about 430. So again, more than a hundred times the number of megajoules per kilogram of fuel.

Fraser: Okay so why don't we have Ion Engines launching from the ground? Why don't we just have great big Ion Engines and they're pushing with a lot less fuel and launching up into Space?

Pamela: Well this is where the whole, it doesn't accelerate you very fast part comes in. To get off the planet Earth, you have to start off with a force that is sufficient to fight against the gravitational pull of the planet Earth. If you don't have a force right off the bat; if you don't have acceleration, a change of momentum right off the bat that is greater than gravity holding you down on the planet Earth, you're never going to get anywhere.

With Ion Thrusters, I can sit in my chair that has wheels and fire Ions all day long and they have so little mass that pretty much no matter how fast I fling Ions from the device I'm holding in my lap, I'm never going to overcome the force of friction in the wheels of my chair. This is a sad statement.

Fraser: Right. I think someone mentioned that the force you feel from an Ion Engine would be the equivalent of like the weight of a piece of paper on your hand. So if you hold a piece of paper, that's how much force the Ion Engine is actually putting out. I know that some of the fastest spacecraft in the Solar System have gone with Ion Engines. How is that working?

Pamela: Well, what you do is get somewhere that the force that is on you right now is a lot less. Decrease the force on something and then it becomes much easier for the initial Ion to be able to get you moving a little bit. Or, you just start off with an initial velocity and increase that initial velocity using the Ion Engine.

You have to somehow get past the gravitational pull that you have to overcome to get yourself going. Then you have to make sure that the drag that is on you is exerting less of a force than the Ions are able to overcome. Once you're out in Space, you're pretty much good to go.

Fraser: There's no friction out there.

Pamela: There's no friction out there so just get you past Earth's orbit and then start firing the Ion drives. This is where we use chemical rockets to launch things initially into Space. Sometimes we put a booster on them to get them a little bit away from Earth's orbit and then start firing the Ion drives.

Fraser: And the other thing is time. Like I know that some of the spacecraft like Deep Space I just kept its engine firing for the better part of months on end to reach high velocity. That little force of a piece of paper really adds up over time.

In fact each Smart One which was the ESA's spacecraft that visited the Moon used an Ion Engine to slowly increase its orbit around the Earth. It increased its orbit and its orbit was so big that it included the Moon. Then it slowly started back down and was finally orbiting the Moon. It did that on a tiny amount of fuel. It just took like a month.

Pamela: So these are things that we're using. Smart One had one; the Space Electric Rocket Test was the first example of using one back in the 1970s. Deep Space I used one, Artemus used one. Dawn has one. These are out there being used. You just have to be patient with them because it takes time to get yourself up to the speed you want to be going.

Fraser: And the limit of this was thought about for a mission that would explore all the icy moons of Jupiter. It would be a very powerful Ion Engine relatively speaking with a huge nuclear generator.

It would be able to power a fairly powerful Ion Engine that could then have the spacecraft drop into orbit around each of Jupiter's icy moons, explore them from orbit and then launch itself back out of the orbit of the moon onto the next one.

That's the kind of technology it will take to do some of those kinds of missions. We're going to see a lot more Ion Engines in the future for planetary exploration.

Pamela: Yeah. One of the biggest problems we're facing right now is America at least doesn't have any small nuclear fuel sources for any spacecraft that are sitting in reserve and not being used. The military has pretty much snapped up any of them that are left or at least any with fuel sources that were left.

We aren't currently running any reactors that are producing new nuclear fuel sources for us. So this is a problem that needs to be solved. Hopefully the answer will come in the not too distant future.

Fraser: Okay, so Ion Engines, same concept, sittin' on a chair throwing rocks – what else fits in that same concept of hurling things off of you at great velocity?

Pamela: The Buzzard Ramjet that you mentioned earlier in the show is perhaps one of the strangest, at least to me, imaginings of a way of flinging things out the back of your craft that has been devised. Here the idea is basically you put the interstellar medium equivalent of a snowplow at the front end of your spacecraft and you scoop up hydrogen fuel from the space between stars.

Using magnetic fields you compress this ionized hydrogen down into tighter and tighter coils until it starts undergoing thermonuclear reactions. Then you use that nuclear reaction to fire things out the back end of your spacecraft and move yourself forward.

When this idea was first developed, people didn't know just how little stuff there are between the planets. It was thought that this would be a cool way to move around the Solar System. Then we realized that there is nothing between the planets. So, really the only way to make something like this happen in our Solar System or in general when you're not in thick part of the interstellar medium is to precede space with hydrogen.

You basically fire out a stream of hydrogen and you somehow make it go where you want your spacecraft to go. Then the spacecraft confines itself to the stream of hydrogen which means you can't make any navigational changes as you go. This is a bit sad if you're an explorer because you're confined to your hydrogen trail.

Fraser: True, but you are essentially gathering hydrogen, building a star [Laughter] at the middle of your spaceship and then using the heat and temperatures to blast out an exhaust.

Pamela: The other little problem with this is really hydrogen doesn't like to undergo fusion. It becomes much harder than was originally thought using the mix of material that is between the stars to get nuclear reactions going.

Fraser: I think nuclear fusion is always been thirty years away.

Pamela: [Laughter] Yeah and if Space was filled with nothing but Uterium and Tritium which have extra neutrons in them, this would be easy. But it's not.

Fraser: Right. Okay, any other methods of hurling stuff off of your spaceship to move?

Pamela: [Laughter] Well there's all sorts of crazy ideas out there. Well, one of the crazier ways of doing this to use anti-matter. I thought this was rather funny. You basically go out and find yourself a few positrons and make yourself a few anti-protons and confine them in a magnetic field and go up into Space carrying your carefully confined magnetic fields a pocket of anti-matter.

Whenever you want to accelerate yourself, you release a little bit of your anti-matter and let it react with some non-anti-matter so you mix a positron and an electron for instance. This gives off a huge blast of energy and you somehow funnel this energy out the back end of your spacecraft.

Fraser: This is essentially the purest form of energy generation possible, right?

Pamela: Yes.

Fraser: There is no more efficient way of creating energy than mixing matter and antimatter together.

Pamela: Right, antineutrino is not going to help. But mixing electrons and protons is the most efficient way we have of creating any sort of energy. It is just rather hard to control and the confinement systems that you have to use are rather heavy.

You're building something wants to explode, is extremely weighty in trying to get off the surface of the planet safely. So we aren't trying to build this currently.

Fraser: No and I'm not sure what the numbers are but I'm sure even with all of the particle accelerators out there building antiparticles for years you still wouldn't get much of an explosion even if you tried to. You would need to turn antimatter production into this gigantic scale economy.

But I think that would solve the problem of being able to get you off the ground and get you around in Space if you could somehow come up with a way to make as much antimatter as you needed. It would be expensive energy [Laughter] right?

It takes an enormous amount of energy to make antimatter in the first place. Then you would then burn it to get yourself around. However, it would be very light weight. You could carry just a few grams of antimatter to get a rocket up into Space right?

Pamela: Yeah, that's entirely true. The question is do we really want to expend the energy necessary to build that little tiny amount of antimatter? The amount of energy that goes into creating that antimatter far far exceeds the amount of energy that you get out of the nuclear reaction.

Fraser: But if weight is your absolute issue then antimatter might be the way to go.

Pamela: It's in the future.

Fraser: All right. So anything else while we're rolling stuff off of the spaceship?

Pamela: We talked a little bit about nuclear drives last episode and they come in a couple of different types of forms. One of them is you simply have a nuclear reactor and this is what we mentioned last week. Nuclear reactors run really really hot and you use them to heat up something else that you use as a propellant.

The other alternative is just having a nuclear drive and you just fling bits of stuff from the nuclear drive out the back end of the spacecraft. This is something that we are somewhat looking at in different ways but again we don't have a lot of nuclear reaction research going on.

One of the ways that they've considered is building a tokamak reactor which is where you have plasma that is confined in magnetic fields. It gets extremely hot and nuclear reactions go on within the plasma. Pressures build up and you release the pressure to move the spacecraft forward.

But tokamaks are big devices. They weigh a lot. The amount of energy that is going to come out of that and more importantly the amount of energy needed to confine the plasma doesn't make them practical.

Fraser: Right, aren't those kinds of reactors just barely energy neutral here on Earth?

Pamela: They're not even energy neutral.

Fraser: Here on Earth in gigantic facilities. I can't even imagine the engineering that would be required to put it on a spacecraft.

Pamela: But it is part of our fusion dream for the future.

Fraser: Absolutely. Then Mr. Fusion in my car. [Laughter] That will come later. Okay then also the railguns?

Pamela: Railguns are kinda cool. We actually had some of the back in Austin when I was a grad student. The Pickle Research Center had them that they were developing for military purposes. Railguns are just one of these cool devices.

You basically take a couple of rails and you run magnetic fields down them. You can greatly accelerate bits of metal down these rails. You can get things going at large enough velocities that it starts to become interesting as projectile weapons to the military. They just haven't figured out how to build one of these that is actually the size of a tank. They're working on it.

Someday in the future we may have tanks with railguns instead of your more classic turrets. Here the idea is you basically have a set of rails that you run a magnetic field down and you accelerate chunks of metal or anything else that happens to conduct electricity out the back end of your spacecraft. This is pretty much exactly the sitting on the ice throwing rocks way of accelerating yourself.

Fraser: This is one of the thoughts about how to move an Asteroid because a lot of Asteroids are made of metal. You would clamp one of these railguns to the side of an Asteroid that you want to move. You then just start mining the Asteroid, sticking the pieces onto the railgun and blasting them away. Each load that you fire off would move the Asteroid a tiny bit or give it some thrust in the direction you want.

Pamela: Basically what's kinda cool about doing this with Asteroids is every bit of metal that you fling out into Outer Space is a little bit more space for human beings to live inside. You get where you're going and you end up with a progressively larger house to live in as you do.

Fraser: Right. Eventually I guess you would use up all of your fuel. If you just kept flinging it out [Laughter] you would eventually run out of spaceship. It would definitely be an effective way of moving from point A to point B.

Pamela: And what do you want to do with a shell of Asteroids once you get there anyway? You might as well use it all up.

Fraser: Right. Exactly, hollow it out and live inside. That would be great. Have we exhausted all of the ways of flinging stuff off here?

Pamela: I think we have. I think we're now on to flinging things at ourselves which is a bit more traumatic [Laughter]

Fraser: Right. So think again to our poor person on the ice, shivering cold having run out of projectiles – snowballs. But all of his friends are now quite angry and now start throwing their snowballs back. [Laughter]

So there have been some ideas proposed where you are catching stuff from Space that is moving and using that as a way to get you moving. Solar Sails are the classic examples, right?

Pamela: Yes. This is one of these technologies where everyone understands how it works. We're pretty sure it will work. But no one has done it yet which is kinda frustrating. We're so close. We almost did it.

There was a private initiative involving the Planetary Society that was looking at trying to figure out how those might work. The only problem is that their spacecraft Cosmos I which was done in collaboration with the Russian Academy of Sciences failed.

So they did a summary launch which was kinda cool. They launched it on a rocket but the rock didn't carry the spacecraft all the way into space so we weren't able to test it.

Fraser: What are the underlying physics that are in play here to make a Solar Sail work?

Pamela: Okay, the idea is that you take something shiny, something that is highly highly reflective and not going to absorb the sunlight and get hot. You make a giant sail out of it just like you would make a giant sail to collect the wind. In this case what you're collecting is the light. When the light hits and reflects off of the mirror it imparts momentum to the mirror and the mirror moves.

Fraser: When the light is hitting a mirror, or even just like me. [Laughter] When I'm out in the Sun, I'm actually being buffeted by the Sun.

Pamela: Yeah. The sunlight that hits you when you're standing outside is different wavelengths of light that can react with you in different ways. The infrared light you generally absorb and get hotter.

The red light, the blue light and things like that that allows me to see you when I look at you are colors of light that are hitting your clothes and your skin and bouncing off. That reflected light is what I'm able to see with my own eyes.

With a Solar Sail, the reflected light is not only allowing anyone who happens to be out looking at the Solar Sail to see it but it's actually imparting enough momentum if the sail is big enough that it is able to get the sail moving.

Just like anyone who has ever tried to use a sailing vessel like a small sail vessel on your local lake, over time you figure out that even though the wind is only blowing in one direction you're able to steer and move around going pretty much anywhere you want on the lake just by making tack changes. You can do the same thing with the Solar Sail.

A lot of the plans for how to make these have things that look like crazy wind spinners. The little things you stick out in your gardens that have a bunch of petals to collect the wind. These have a bunch of steerable petals to collect the sunlight.

The way it works is you go in whatever direction is the angle halfway between the light comes in on and the light goes out on. So if you have your mirror straight on facing the Sun, you will move straight away from the Sun. If you tilt your mirror 45 degrees you're going to go at 45 degrees away from the angle the light is coming in. It's the laws of angle coming in equals angle going out and you move at an angle that is between those two angles. It's a neat way to be able to steer. It's a neat way to be able to get around.

The reason we're not using it, even though you basically don't have to worry about your fuel running out because the Sun is just going to sit there for awhile, the reasons are twofold.

First of all there's this whole problem that we're a bit scared that in the process of trying to unfurl the sails something bad will happen. Any of you who have been following the International Space Station or many other missions know that one of the things that happens fairly frequently is when you're trying to unfurl a Solar panel or even a telecommunications boom as happened with one of Mars Explorers, things get stuck periodically.

You have to go out and work on them and point them at the Sun to get them to change temperatures and all sorts of radical things to get them to fully expand.

With the Solar Sail you're dealing with extremely thin material that tears easily, a complex truss system that has to weight next to nothing and if things don't unfurl correctly, you can steer, you may not be able to move.

There are all sorts of ways your technology could fail you just in the unfurling process. The other reason we don't use this is the ability of these things to work falls off as the square of the distance from the Sun which is a fancy way of saying the further you are away from the Sun, the less able to move you become. So, if you want to get to Venus and you don't mind tacking into the Sun, or more importantly, you want to get back from Venus or Mercury, good technology.

If you want to go out and visit Pluto, not the right choice to be making unless giant laser beams perhaps attached to a shark that we don't currently have the technology to build are employed to artificially accelerate your Solar Sail which is, I guess now a Laser Sail.

Fraser: So, same deal, you would seed your route with laser beams and as your Solar Sail went by you would zap it and it would accelerate, accelerate and accelerate.

I guess one of the cool things about this on the upside is that a Solar Sail could theoretically go close to the speed of light. Because that's what velocity the light is hitting at, right?

Pamela: Yeah and here the only trick is how much light you can hit the Solar Sail with before either you ionize it. [Laughter] It's a problem. You're shooting laser beams.

Fraser: Yeah, get it just right.

Pamela: Or you can imagine this technology might perhaps work much effectively in a really dense star cluster. Even then, how far can you go in a straight line accelerating before you hit a star? That's also a problem.

Fraser: I think people have a bit of a misunderstanding about how the Solar Sails would work. It is very much like a sailing ship. You think of a Solar Sail sort of starting by the Sun and then zipping in a straight line out of the Solar System.

The reality is that you would put these into orbit just like Earth is in orbit around the Sun or Mars is in orbit around the Sun. Then you would tilt the sails one way and it would push you into higher and higher orbits away from the Sun. You would still be circling the Sun but then you could tilt the sails the other way and it would actually slow you down.

It would drop you into lower and lower orbits. The same Solar Sail would either let you raise your orbit to visit the outer planets or lower your orbit to visit the inner planets. There is no problem with using the Solar Sail to move down towards the Sun or back up away from the Sun.

Pamela: And just like with a sailing craft, you can't move straight towards the Sun but you just tack left and right and eventually you get there.

Fraser: You're essentially using the photons to either slow down your orbit to drop you into lower and lower orbits or using it to speed up your orbit to rise you up into higher and higher orbits.

Pamela: Right. Cool technology.

Fraser: Yeah, really cool technology. Now there's a similar technology which is a magnetic sail, right?

Pamela: Yeah, this is another one of those things that sounds really cool until you start realizing you have to build something really really big. The idea here is if you take a huge loop of wire and run electricity through it, it will generate a magnetic field. Magnetic fields can be used to attract or repel things.

Anyone who has played with refrigerator magnets knows that you can both scoot them across the counter by making them repel each other or lift something up off the kitchen counter using a magnet in the opposite orientation. Here, Space is full of magnetic fields.

We have lots of opportunities to either accelerate or repel you from some object's magnetic field, like the Earth's magnetic field or the Sun's magnetic field.

The other cool thing is Space is filled with moving charged particles. Moving charged particles interact with magnetic fields in unique ways. So, you take your loop of wire and you know that there is a wind of ionized particles you can use that wind of ionized particles interacting with your magnetic fields to deflect yourself in the direction you want to go. You simply set up your magnetic loop so that it's at a right angle to the moving particles and you move in that right angle. It's kinda cool. It's basically Physics 102 – second semester E & M.

I'm going to be torturing engineering students with this next semester. Little do they know they will be forced to understand magnetic sails. With a loop of wire and charged particles, off you go.

The problem is when you're in parts of Space that are kinda low on the charged particles, when you're not near a star that has a large magnetic field, just like with the Solar Sail the further you get from the Sun, the further you get from the source of ions the less ability you have to move forward.

It's a bit harder to see Space with ions than it is to just shoot hydrogen out there if you'd rather do the ramjet instead.

Fraser: Right. Well I think there is one last paradigm that we'll look at. We have a guy sitting on the ice throwing snowballs. We have the people throwing snowballs at that person and [Laughter] I guess you've more of a collaboration thing with the person sitting on the ice and a skater comes by and they hold hands and the skater gets them moving. Then I guess the skater slows down.

Pamela: I'm thinking you're talking about Space Tethers here.

Fraser: Right.

Pamela: There are a couple of different things that are both referred to as Space Tethers. One of them is far cooler to me than the other. There is the idea of taking a large, heavy object like a piece of ballast or something and anchor it in orbit somewhere. Then you attach a really long thin cable made of like carbon nanotubes or something to it.

You set the whole thing spinning so that this tether just shoots straight out the same way that happens if you start spinning rapidly with a long rope in your hand. The rope is going to shoot out. If you put this object in high enough orbit, and you have a long enough tether, the end of that tether just might dip down into the Earth's atmosphere to a point where you can match its velocity and altitude with some sort of fancy airplane.

You go up with your fancy airplane and you attach to your fancy airplane a capsule of some sort that you can shoot out. You match speeds with the tether just like you were trying to match speeds with a refueling jet and you attach your little capsule onto the tether. You have to do those at the exact moment that the tether is pointed directly at the Earth. It's kinda scary to think about all that you have to do it, the just rights that are involved in this.

Then you get your capsule attached to the tether and it's going to be so big, so massive and the ballast in the center is rotating so quickly that it's not going to care about the capsule that just got attached. It's going to keep swinging on by.

This is sort of like trying to grab onto a rapidly spinning Ferris wheel. You don't weigh anything compared to the Ferris wheel and you're just going to get lifted up to the top of the spin. Well, in this case the top of the spin might be another thousand kilometers off the surface of the planet Earth.

That's kinda cool. You can almost imagine an entire system of these where we have the ballasts with tethers attached at a whole series of different orbital heights such that periodically they line up just right for you to jump from one tether to the next until you reach perhaps the Moon or extremely high orbits and then use them as jumping off points.

Again, not something we've built. And again something quite scary that we don't have the technology to do just yet. In this case the building of the long tethers that we just don't quite have the ability to pull off. But it's a neat idea.

Fraser: And you mentioned there was another concept as well?

Pamela: There's another concept and this is where the whole let's abuse E & M comes in again - Electromagnetism. In this case we have a planet with a magnetic field. If you run current through a wire, that also generates a magnetic field. One of the ideas is you take a spacecraft, run a really long wire off the end of the spacecraft and as that wire moves through a magnetic field, it generates the current. The current that is generated generates its own magnetic field and these two magnetic fields work against each other and can cause a spacecraft to drop out of orbit or rise into a higher orbit depending on just where you are on the Earth's magnetic field.

That's kinda cool. That has actually been tested. It has been used to basically de-orbit part of the Delta rocket. They threw something into Space with a tether test unit on it that they didn't care about so if it didn't work everyone wouldn't be upset. And it worked. They were able to de-orbit a spacecraft using a tether.

Fraser: Awesome. Well I can't wait for all of these technologies to show up. You notice we didn't mention anything about warp drives? [Laughter]

Pamela: Yeah, that's not going to happen.

Fraser: These are the ones that the Laws of Physics permit. Well thanks Pamela.

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