Astronomy Cast Episode 100:
Rockets

Fraser Cain: Happy 100 Pamela.

Dr. Pamela Gay: Happy 100 to you Fraser.

Fraser: It's actually not 100 because we've got the Panspermia episode and the Kids Question shows, so it's more than that but you know the actual numbers that we're counting, it's Episode 100.

Pamela: We've been around for a long time, we're old podcasters.

Fraser: Yeah really. It feels like we just started. Don't worry we have a list of many, many more episodes. We're never going to run out.

Pamela: Yeah we have no plans to stop. Just keep sending us your questions and we're going to keep going and the universe is going to keep telling us new things. We have no concerns.

Fraser: Thanks to everyone sending in 100th Episode well wishes. We're going to hang on to them and probably read a few over the next couple of episodes, so thanks for that. Here we go. This might be the first of two parts.

To move around in space you need some kind of propulsion system and for now that means "rockets", directed controlled explosions. Let's learn the underlying science of rockets, how they work, and learn why a rocket will never let us reach the speed of light.

Okay Pamela, so I'm flying in an airplane, and flying higher and higher and higher, why can't I just fly my airplane off into space?

Pamela: Well there's this little problem known as your standard airplane happens to require air to function. Without the air to make the jet engines or even worse the propellers function you hit a certain point where the atmosphere is too thin and the plane says no I'm going to fall out of the sky and pretend to be a brick now.

Fraser: So you have the problem of not enough air to actually burn your jet fuel and you also don't have enough lift underneath the wings to make it fly.

Pamela: Take a propeller. You cut your way through the air to move yourself forward. Without air to do that, how are you going to move yourself forward and without the motion forward, how are you going to generate the lift?

Fraser: So how does a rocket solve all these problems? Why do rockets work when airplanes don't?

Pamela: They basically just start exploding things and use conservation of momentum. The idea is: sit yourself down on some ice on a chair that happens to have little tiny points at the ends of each of the legs so that it's perfectly willing to slide around.

If you happen to have a lap full of rocks for some crazy reason and you start throwing the rocks, the conservation of momentum is going to cause you to move backwards as the rocks move forward. The more rocks you throw, the more you end up moving backwards.

With rockets, you're basically taking some sort of fuel and accelerating it to extremely high velocities and throwing it out the back end. If you throw fuel out slowly you're going to move forward slowly. This is the way conservation of momentum works.

The numbers have to sum up to the same thing. You take mass times velocity going in one direction, mass times velocity in the other direction and they have to always add up to the same number.

If you throw out a heavy object at a low velocity you can move yourself. If you throw out a small object at a high velocity you can move yourself. If you throw a heavy object at a huge velocity you can seriously move yourself.

Fraser: So all rockets work by that same process, that all rockets are hurling something out of the rocket and the conservation of momentum is allowing the rocket part to move in the opposite direction?

Pamela: Exactly. There's a second part to this as well. If you look at any big rocket, it's going to have a nozzle. This nozzle is actually kind of important because there's unbalanced forces inside the nozzle.

If you take your normal balloon, the air molecules inside the balloon aren't causing it to move in any specific direction because there are air particles pushing to the left, pushing to the right, pushing up, pushing down, and pushing in all directions evenly keeping the balloon nice and inflated.

If you open the end of the balloon and let it do its thing flying frantically around the room, what's happening is you have air coming out through that nozzle and the opposite side of the balloon; the pressure of the air against the balloon is no longer balanced against anything.

That pressure is working to move the balloon forward. Most people generally think it's the air coming out the nozzle that's doing the pushing on the air that's outside of the nozzle and that's what is moving it forward.

It's actually the pressure inside the balloon against the inside of the balloon that's not balanced against pressure at the nozzle that's moving you forward and that's kind of cool.

With a rocket nozzle you have sections that are up toward the rocket that have pressure of the expanding gas inside the nozzle pushing the rocket up while there's also gas escaping out the bottom part of the nozzle that's not balanced.

So you have this unbalance of forces again and that's helping to move the rocket forward.

Fraser: Okay so what are the parts of a rocket? If you're going to build a rocket, what you need to have inside of it to make it even work?

Pamela: At the most basic level you need a fuel. This fuel is going to consist of something that wants to burn, an oxidizer, which is something that allows the burning to take place, and there's generally an ignition source. Not all rockets are equally simple.

Solid rocket boosters are perhaps one of the most simplistic types of rockets to look at. You have this "stuff", basically a gel that we call it an elastimer, which is a big scary word.

You have this plasticky stuff that is embedded within at both the oxidizer and the fuel. You inject this into your rocket mold, into your engine section. You do this in such a way that there's a burning surface.

It's often just a simple cylinder of nothing down through the center of this long cylinder of fuel. Then you ignite it such that you have burning all along this inner core and as the fuel burns it ends up creating hot gas in the center part that comes out through the nozzle at the back of the rocket.

So you have your fuel embedded in this stuff, you have your oxidizer embedded in this stuff and then you ignite it.

In more complicated systems like liquid fuel systems, you typically have a tank of oxidizer, which is often just plain old oxygen or nitrous oxide, which is laughing gas. I just love the fact that some rockets have laughing gas as one of their primary components. [Laughter]

Then the other tank you're working with is some sort of fuel. It can be something as simple as gasoline or all sorts of more complex burning things like even liquid hydrogen gets used as a burning fuel. Then you have to mix these and ignite them.

One of the tricks with liquid fuel rockets is you have to get the pressure of the fuel going into the combustion chamber to be greater than the pressure inside the combustion chamber. Otherwise the fuel is not going in.

You have to have some sort of a pump or something that drives the fuel into the combustion chamber where it is ignited gets pressurized, shoots out the nozzle. And you move forward.

Fraser: So what is the limit? How hard can rockets push? What's their limit on them?

Pamela: You have to start asking "At what point do we start exploding the outside of our combustion chamber rather than simply sending our rocket forward?" The limits that we have are more structural limits than anything else right now.

If you combine things at too high a rate you explode your rocket rather than having a controlled explosion as you said during the intro.

Fraser: So that's why you get those rockets that are exploding because they're trying to control this reaction inside the tube and it can't withstand it so instead of pushing the rocket upward, it just blows out the side or just explodes the whole thing.

Pamela: There are a lot of different points that failure can occur. For instance we lost the Challenger Space Shuttle here in America back in 1986. The problem there was the solid rocket boosters are built in segments. You have these outer shells with lots of electronics in them and they're built in several meter long sections that are then put together with O-rings connecting the different segments.

All of this has to be able to flex during the launch process because you have radical changes in temperature, you have radical changes in pressure.

Typically part of making sure it doesn't explode while all of this is going on is having flexible materials between the different segments that create what we call a positive pressure.

Basically the O-ring is sitting between the two levels, the two segments, pushing against each of them and preventing any of the gas inside the rocket from leaking out between the two segments, leaking out in the joint.

Anyone who has put together a faucet has put these little round rings inside the faucet that work very much the same way. These little round rings, when you put pressure on them they squish out the sides and where they squish out the sides water can't get out of your faucet.

In the segments of the solid rocket boosters the O-rings press out the sides and instead of preventing water they prevent exploding gas from leaking out the sides. The problem is that O-rings are just made out of different types of plastics and rubbers.

If you've ever taken a plastic cup and frozen it, it becomes brittle. There's a point at which we say that the plastic has a phase transition and it becomes more like glass.

With the space shuttle the O-rings got too cold. They became brittle. Instead of flexing, instead of maintaining this positive pressure, they sat there and said no and didn't expand the way they needed, so gas was able to escape out the sides and this is a rather dangerous thing.

The other problem with solid rocket boosters is you can't turn them off. They're one shot, let's go, go, go, go, go. That's also not exactly the safest thing. You can, in the case of the solid rockets boosters on the space shuttle, drop them off, get rid of them, no more solid rocket booster and now it works.

With liquid and hybrid engines (which we haven't talked about yet) you at least have the ability to turn off the fuel system. All you have to do with a liquid engine is turn off the pumps that are forcing the fuel into the combustion chamber. No fuel in the combustion chamber, no fuel going out the nozzle, you stop accelerating. This can be a good thing at times.

Fraser: Let's talk a bit about a rocket launch. Let's talk about the physics involved. I'll sort of think back to my engineering training and think about the balance of forces going on.

You've got a rocket sitting on a launch pad and it's being pulled down by the force of gravity and at the same time the ground is pushing back against the rocket and balancing out the forces and so the rocket just sits there. Then at some point someone gives the command, they turn on the rocket. What happens?

Pamela: The first thing that happens is the entire thing shudders. [Laughter] This is one of the really neat things to watch with the NASA videos. They turn on the rockets and they keep these things bolted to the launch pad for a few moments making sure everything fires correctly and building up all of the thrust. Then they let go and the entire thing bolts into the sky.

What's happening is, you turn everything on and make sure it's all working. When you take off you're hitting the air, which is creating drag against you. Your mass is changing as you go. You have this incredible pressure behind you and it's somewhat steerable.

The Space Shuttle engines actually have gimbles on them so that the firing of the Space Shuttle's engines, which draw out fuel from that big orange tank, the liquid fuel tank that you see on the belly of the space shuttle basically in pictures. They allow it to steer as it takes off.

The solid rocket boosters are also firing in the Space Shuttle case. The firing of the engines is actually a rather scary moment. Especially with liquid fueled rockets. You never know for certain if your igniter is going to work and that's one of the greatest points of failure in a mission.

When you're dealing with multiple rockets firing simultaneously like with a Space Shuttle, sometimes you have to within tenths of a second get all three engines firing at once. It's the bolting it down that gives you a little bit of flexibility and making sure everything is firing.

You have to have a sensor that is able to say that there's this flame going on and often one of the ways they make sure that their entire ignition systems are working is they put what's called an interlock between the combustion chamber and the ignition system.

So you light the flame, go, "Okay I have a flame" and then pull back the interlock system and let whatever you're trying to light on fire be exposed to the ignition system.

The problem is the interlock between the flame and the fuel is actually more likely to fail than the ignition system, which is one of your greatest points of possible failure. In designing rockets we have to make decisions of, do we want to have the default fail to be nothing fires or do we want the default fail to be perhaps some stuff fires and others doesn't.

What often happens is when you're worried about keeping humans alive like with the Space Shuttle you have the interlocks and you try and make sure your ignition system is working, pull back the interlocks and hopefully go into Space.

But when you're looking at instead at perhaps the third or fourth stage in a multi-stage rocket, there if you have your interlock fail instead of having your igniter fail, you're not going to reach the orbit you wanted. There it's considered, "Okay we'll take the risk of the igniter not working and not have any inter lock at all and at least there when we fail we are still moving forward."

Fraser: All right now when I see a rocket taking off, it kind of starts really slowly but you know that later on it's moving thousands of kilometers an hour. Why aren't they just leaping up into the sky? I mean you said they word leap but that's no what I see. When I see a rocket I see it starting out pretty slowly then later on it reaches orbit.

Pamela: Okay so leap compared to me the human being jumping up. It's still pretty amazing anytime you see something the size of a building going in to space even if it is moving very slowly at first. It takes time to accelerate.

Anyone who's ever taken a little tiny car and filled it with all of their belongings to move to college, which I think a lot of us have done at one point or another, your car is incapable of moving quickly once you start trying to move out of the parking lot. But, once you get out on the highway you put your foot to the floor and over the next thirty miles slowly accelerate yourself up to the speed limit.

This slowness in accelerating that you experience with your overload of little tiny beater car is similar to what the Space Shuttle experiences. You have this huge amount of mass and an engine that's trying to accelerate that mass forward and the amount of acceleration that you have is limited. But if you accelerate long enough you can eventually reach enormous speeds.

Initially you just have to accelerate faster than the Space Shuttle is trying to fall back to Earth. Basically if you can get a forward push of greater than nine meters per second squared against the backwards times your mass (mass times acceleration) compared to gravity backwards you're going to start accelerating. But its going to be a really small acceleration and it's only over the tens of miles that you start getting to large enough velocities that you can make it all they way into Space.

Fraser: I guess rockets are built jammed pack with fuel and as they're going through their fuel they're getting lighter and lighter and easier to push as they go into Space.

Pamela: Well not only that but as they get further and further from the center of the planet Earth, you're also going to have less and less gravitational effect. As you get further and further from the surface of the Earth you also end up with less and less oxygen, less and less nitrogen, less and less of all this stuff we need to breathe. That also creates a lot of drag on your rocket.

As you start to get closer to Outer Space you have less gravity dragging on you. You have less air dragging on you, and you've burnt through significant fuel so it's easier to accelerate with what fuel you have left.

Fraser: Why do rockets use stages? You see these stages falling away or you see with the Space Shuttle the solid rocket boosters falling away.

Pamela: The basic idea is get rid of the mass you don't need. If you consider for instance one of the old Saturn 5 rockets used during the Apollo missions have a whole series of really giant segments that were once upon a time filled with fuel.

You blow through all the fuel in the first segment and you're still left with this cylinder of metal, cylinder of electronics, cylinders of all sorts of stuff. That has weight, so you get rid of it. By getting rid of that excess weight it makes it easier for the fuel that's remaining to continue to keep pushing what's left of the rocket up into space.

It's sort of like when you're camping you eat through your food and hopefully have biodegradable wrappers so that you don't have to carry all your garbage. If it doesn't biodegrade and it doesn't say that it's all right to dispose of it, don't do it.

Apple cores you throw into the woods, plastic bags you throw into your pocket. You jettison apple cores while hiking because you might be creating apple trees and you don't want to carry that weight.

Fraser: Right, okay. You hinted a bit about it. We've got the liquid rockets, we've got the solid rockets and we've got hybrid rockets. What are those?

Pamela: Hybrid rockets are kind of cool. What they are is you have your solid that contains only the elastimer that holds everything together and fuel. If you try and burn that it goes yeah I can't I need oxygen. You need some sort of oxidizer to allow the combustion to take place. It's a chemical reaction.

You use a tank of liquid oxygen, liquid nitrous oxide, and you can turn the reaction on and off by introducing the liquid oxidizer to the solid fuel. It's just one less thing to fail.

Fraser: Right. So you don't have your oxidizer mixed in with your fuel that you can never turn off. You can shut the valve down if things are going badly.

Pamela: You don't have the complexity of having liquid fuel and the liquid oxidizer. You reduced your complexity a little bit and you increase your safety, it's just a nice hybrid system.

Fraser: This is the system that Spaceship I used when it made its launch up and I guess the Spaceship II will be using as well. Although there was an explosion about a year ago that killed a couple of people and they're working with their engine.

Pamela: It's also kind of cool because there's an episode of Mythbusters where they use nitrous oxide and paraphin, which is basically laughing gas and candle wax, to create a rocket to see if they could have had rockets during the civil war. They also attempted to use a salami as rocket fuel and it didn't work so well.

Fraser: So what are the limits? At the beginning of the show I mentioned that a rocket would never take you to the speed of light. Why is that? If you had a tank of fuel large enough, why couldn't you just keep firing it and firing it and firing it and just go faster and faster and faster?

Pamela: In theory you could, but it's a matter of is this practical. When we're trying to figure out what is the correct device to use, what is the correct rocket form, what is the correct engine type to use you take into consideration how much stuff you need for every pound of thrust that you produce.

In considering this, rocket fuel is one of the lease effective ways of getting yourself to accelerate. It has the advantage of chemical rockets, can get you accelerated faster than just about anything else but they're not efficient in doing this.

There are a lot of issues in terms of having a whole lot of thrust that's hitting the sides of your nozzle and not moving you forward. Chemical reactions are messy. You have all sorts of energy that gets lost in random directions that you can't recoup.

If you're trying to get going really, really fast instead of using a chemical reaction, which isn't effective, you want to look for something that for every ounce of fuel you're able to get a lot more pounds of thrust. For that you start looking at things like ion drives and fusion drives. All of these things are much more effective and require fewer resources.

One of the problems with building larger and larger rockets is you're having to carry around more and more mass to use up later. As you get bigger and bigger, you then have to start accelerating larger and larger masses and there's a limit on just how much you want to strap a giant bomb to your butt.

Fraser: I know that there was some thinking about nuclear rockets and that they would be a lot more powerful. What's going on there?

Pamela: We're definitely going to have to stretch this into more than one episode. Just to hit on it, with nuclear engines you still have a gas that you're spitting out the back end of the rocket except here instead of getting the gas hot and expanding because it's reacting and exploding in a combustion process, what you do is you flow it through a nuclear reactor.

One thing nuclear reactors do well is to generate lots and lots and lots of heat. This is where we talked about nuclear reactor meltdowns. If you don't cool them effectively they simply go through the floor of the containment building and they keep going.

So here you take a nuclear reactor and you run some sort of gas or liquid through it, there are all sorts of different models and that stuff gets heated up and that expanding material shoots out through the nozzle and it's a different way of creating thrust.

Fraser: I know it can make it a lot faster than the chemical rockets.

Pamela: Yes. There it's simply a matter of heating things up more effectively using a smaller object to heat them up. This is actually a type of engine that has been looked at as we start to figure out effective ways to get out to Jupiter and beyond.

There's the Prometheus project that NASA was running that was looking at trying to figure out how to build something to get us to Jupiter. Because they are so much more effective than the chemical rockets it allows you to carry more stuff with you when you go to other planets.

One of the greatest frustrations for scientists who are trying to get instruments to other planets is the extreme limitations on both how much energy you have to run your equipment if you're working off of solar panels and also the weight that you can carry with you is extremely limited by the chemical rockets that we use.

If you're using a nuclear reactor both to generate electricity and to also generate thrust you're killing two birds with one stone. You're generating more electricity and you're also generating more thrust. This would allow projects like Galileo, which explored Jupiter or Cassini, which is currently exploring Saturn to just go and go and go and go and go.

Both of those projects had nuclear reactors in them. By combining that also with the thrust system, it gives you a lot more ability to change your direction. With the Cassini program it's really amazing how they're using gravitational assists from all the different moons to constantly change their direction.

If you have a nuclear engine on board that you use for your thrust as well you can decide, oh Io is having a volcanic eruption (Io of Jupiter) I want to go explore that and change your direction and go explore it.

Fraser: That would be amazing.

Pamela: It would be very cool. This is also, while it's not particularly safe to be too close to a nuclear reactor for a human being, we're looking for ways to design safe ones. It is one of the things talked about as a possible way of getting to Mars quickly and efficiently.

Fraser: Yeah you could do the trip in just a couple of months as opposed to the big multi-year journey. Well I think as you hinted earlier on this is going to be two shows, maybe more. [Laughter] We want to talk about the more exotic and newer forms of propulsion systems. For example, ion engines, solar sails, kinetic sails and stuff like that. So we'll talk about that next week.

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