Astronomy Cast Episode 45:
The Important Numbers of the Universe

Fraser Cain: This week we wanted to give you a basic physics lesson. This isn't easy physics, this is a lesson on the basic numbers of the universe. Each of these numbers define a key aspect of our universe. If they had different values the universe would be a changed place, and life on earth would never have arisen.

All right Pamela, read for this?

Dr. Pamela Gay: I hope I'm ready.

Fraser: Can you explain the concept of what these basic numbers are? Why are these different than all of the other numbers that arise in physics, math, chemistry and all that?

Pamela: There's certain things that define how our universe works. For instance, when we have two masses, they attract each other and the amount they attract each other by is related to the force of gravity. There are constants that you put in front of the units you use to define mass and distance that get us at the number of the gravitational force.

There's also constants that we use when we're dealing with the electromagnetic attraction between objects that allow us to calculate that force.

These constants that allow us to relate everything in whatever unit system we choose to work in, aren't defined by anything other than measurement. These are things that are built into the universe that aren't changing with time, it's just how the universe does things.

Fraser: I guess an example would be pi? Where pi is just a ratio?

Pamela: Pi is just a ratio. It's the relationship between the circumference and radius of a circle.

Fraser: Right, so if I was an alien on another world, I would probably come up with pi as the same number.

Pamela: The thing with pi is you can get pi no matter how the universe is defined. If you go to another universe with 38 dimensions in it and you ask, "what is the relationship between the circumference and the radius of a circle (which is a two dimensional object no matter what universe you're in)?" You're still going to get the same pi value.

These other things, the relationship that defines how strong gravity is, that's somehow built into the fabric of space. You could go to an alternative universe and the gravitational constant would have a different value. Gravity could have a different strength.

So pi is just a geometric manifestation. The constants we're talking about are something that's built into the fabric of our universe, but they aren't dictated by anything that we know of.

Fraser: They don't have any nice, round number to them either. They seem totally random.

Pamela: There's one that looks like it's trying to be an integer, but in general these are just numbers that have to be painstakingly culled out of data in a lab.

Fraser: All right. Let's start moving through the numbers then. What's the first one that helps define our universe?

Pamela: There's just the simple fact that we live in a three-dimensional universe. Our three dimensions of space… it doesn't have to be that way. We could have 5, 11, 10988 dimensions of space that we live in, but we don't. we just have three. There's no reason we know of that dictates we have to have three spatial dimensions.

Fraser: Really? That's one of those things that's so hard for the human brain to wrap itself around – any number of spatial dimensions above three.

Pamela: (laughing) This is one of these things where it's what we're used to, it's the only thing we really know how to define in our mind's vision of the universe, but the physics itself in no way dictates it has to be this way.

Fraser: What might be the implications then of more dimensions?

Pamela: That's where you start to get into science-fiction. It would certainly change how we'd handle things kinematically, spatially… because we live in a three-dimensional universe, I have to admit I haven't paid a lot of attention to the consequences of having more than three dimensions.

Things like string theory look at particles and say the aspects of the particles we see in our three-dimensional universe are actually reflections of higher order spatial dimensions or rather, in this case, non-spatial dimensions for these particles. If we could see them in a higher number of dimensions, we could see they're strings, but all we're able to see are the tips of the strings in our three-dimensional universe.

Fraser: The physics only works when you reach those higher number of dimensions.

Pamela: Exactly.

Fraser: Right. Okay, keep going. What's the next one?

Pamela: We also have different values that define the fate of our universe.

There's the ratio between the amount of mass in the universe and what's called a critical mass. If our universe has this critical amount of mass, this critical density to it, then we're pretty much going to just keep slowly expanding toward a zero rate of expansion. I say toward because in infinite time, it should come down to zero, but we never get to infinite time.

So this omega parameter, this density of the universe, if it was higher than it is now, the early universe would have started to expand and then all of the gravity would've glommed onto each other and gravitationally pulled each other back together and we would've had a very early on great crunch.

If the mass-density of the universe was substantially lower, then as the universe was expanding, there wouldn’t be anything slowing that expansion and the universe could've accelerated itself apart much earlier on to the point that gravity never had a chance to form galaxies, gravity never had a chance to form stars.

By setting the mass-density to just the right value, we're able to have a universe that didn't crunch itself down, didn't blow itself apart, but was instead able to (in a timely way that allowed life to form) form galaxies and stars.

Fraser: If the amount of mass was just a little lower, the mass-density at the beginning, you'd just have this spray of particles expanding and they could never glom together to form larger and larger objects.

Pamela: They would've gotten too far apart by the time that things slowed down enough that gravity could start having the interactions.

Fraser: Or maybe if it went the other way, and the density was higher, you might've just ended up with black holes everywhere

Pamela: Or one giant black hole if everything just went crunch.

Fraser: Or one giant black hole. Right.

What impact does dark energy have on that? I know dark energy has been accelerating the expansion of the universe.

Pamela: This gets us to the next parameter. Nowadays when we try and talk about what omega means to the fate of the universe, it's not as clear as it was when I was in graduate school. When I was in graduate school, we said the cosmological constant is 0 and if omega is greater than one the entire universe will someday collapse. If omega is less than one, the universe will expand forever.

Now we have, layered on top of that, this thing called dark energy that is adding an accelerative push to the entire universe. Every cubic metre of space is pushing every other cubic metre of space, and causing the entire universe to grow.

This cosmological constant, lambda, says we're just actually going to keep expanding forever, even though we have what appears to be critical mass-density which would mean we would stop someday in our expansion (if it weren't for the cosmological constant). We're just going to keep expanding.

Fraser: I see, so with our current understanding of the universe, if we only looked at omega, there would be enough mass-density in the universe that at some point (infinite time), eventually the expansion of the universe would slow to a halt and all of the mass would be pulling all of the other mass and would eventually be pulling all of the other mass and eventually crunch the universe down to a single point. Because we've got lambda, this cosmological constant that's pushing, it's working against what should be the natural compression of the universe again.

Pamela: Not quite. The three possibilities for if there were no cosmological constant are: if omega is less than one, then it expands forever; if omega is greater than one, it collapses down; if omega equals one it just stops - it eventually reaches the point where the expansion and contraction are balanced against each other and it stops, hanging out there at infinite time (but we never quite get to infinite time, so we never quite stop).

We have an omega equals one universe (as near as we can tell from the cosmic microwave background radiation). So if there were no cosmological constant, at infinite time (which we can never quite get to) the universe would stop expanding, but we have this cosmological constant, so the universe even at infinite time is going to keep expanding. In fact, it's going to accelerate in its expansion because of this cosmological constant.

Fraser: In the past, they thought the omega had to be perfectly one, and the universe would hang out in space. But what's actually occurred, because there's this cosmological constant, could omega be lower than one and it would still expand out infinitely? Or is it just that it would compress immediately because it was greater than one, and you would never get the universe as we know it?

Pamela: In the omega-greater-than-one situation, the universe has lots of mass trying pull itself back together, and you can end up with all sorts of strange balancing acts. You can end up with omega just overpowering lambda and the universe goes crunch.

You can also end up with this new way that the mass is trying to balance out against this cosmological expansion, trying to accelerate each other apart. In the end, the cosmological constant is going to win, but it changes how long it takes for it to win. So you can end up with a period of time where the universe's expansion is slowing due to the amount of mass. How long that slowing takes place is going to depend on how much mass we have.

Fraser: Okay, let's move on. What's the next important number?

Pamela: The next number we have dictates how big things are allowed to get. This is a ration called N (for lack of any creativity), and it's the ratio between the electromagnetic force holding things together and the gravitational force holding things together.

So electrons are flying all over the place all the time. When they get close to one another, there's huge forces that repel them, currents are able to flow, you can hover magnets on top of each other if you get them lined up just right, and this is all because the electric force is huge. It can exert great amounts of force between two electrons.

Now, if you take those same two electrons that are able to fly each other across the room because of the repulsion of their two like-charges, and compare that to the gravitational attraction between these same two electrons, there's a difference of one followed by 36 zeroes. So the ratio between the electromagnetic force and the gravitational force is 1*10^36. I don't even have a word for how large a number that is.

Now, if gravity were stronger, if gravity were able to exert more force, a lot of chemistry wouldn't work the same way. How currents work wouldn't work the same way. We'd end up with all sorts of drags and basically life as we know it couldn't exist because chemistry as we know it couldn't exist, and this is a bit of a problem.

So we require for the universe we live in that the electric force has to be significantly stronger than the gravitational force.

Fraser: So if it's a 1 followed by 36 zeros, that sounds like it's a very fine-tuned number.

Pamela: Mm-hmm.

Fraser: That sounds like if it were any stronger or any weaker, life wouldn't exist as we know it.

Pamela: Exactly. If gravity went up, only very small things would be able to exist. If gravity were much stronger than it is, black holes would form much more readily.

Basically, everything breaks down. We live in such a fine-tuned universe that it's hard to imagine what would happen if things weren't designed the way we're used to them being designed.

Fraser: Right, so each of these numbers is so critical across every aspect of the universe that it's hard for us to even comprehend the implications of what would happen to the universe if they weren't the way they were.

Pamela: Yeah, it's just sometimes our imaginations aren't up to the task, because we have only ever seen this one universe we live in.

Fraser: Okay, let's keep going.

Pamela: One of those other ratios that can cause the universe to go boink.

We've dealt with the electromagnetic and gravitational forces, the other ratio forces that's important is the ratio of how strong the weak force is compared to the strong force. In this case, we call this ratio epsilon (slightly more imaginative than N, but not much).

If the weak force were weaker than it is, then we'd have protons and neutrons randomly decaying. It would be really hard to build the chemical elements that we have currently. If the strong force were stronger than it is then hydrogen atoms would randomly grab onto each other and bond.

So by having the ratio of the weak to the strong force that we currently have, the Sun is able to work. Atoms stay together in a way that makes sense. We don't have to worry about all of a sudden becoming a pile of neutrons and energy instead of staying a human being made of protons and carbon.

Fraser: It sounds like that's the exact same situation as the relationship between gravity and electromagnetism. In this case you have the strong nuclear force and the weak nuclear force, once again defining how matter is made up at its constituent level.

Pamela: Exactly.

Fraser: If these numbers were different, the universe would be vastly different in ways we can't possibly imagine (and won't even try for this podcast).

[laughter]

All right. What else?

Pamela: We have other ratios to look at. The next number we look at is named Q (we love these single letter meaningless identifications in physics and astronomy).

Fraser: I guess they fit nicely in a mathematical formula.

Pamela: They fit beautifully in a mathematical formula.

Fraser: If you had to keep writing out, "the ratio between…" it would get a little boring, so I think that's why they did it.

[laughter]

Pamela: So Q is the ratio between the gravitational binding energy in something. This is the amount of energy that it takes to go from having a planet to having a loose conglomeration of atoms that are in no way associated to each other. The amount of energy you'd have to insert to this system to shred the planet into no longer bound-together atoms is the gravitational binding energy.

If you compare the gravitational binding energy in something to the mass energy (if you take all that mass and turn it into pure energy with E=mc^2), the ratio of those energies is 1/100,000. If you changed this ratio, you'd have things turning into black holes in ways that, perhaps, wouldn't be good. You'd also end up with things not gravitationally binding themselves together at all.

So we have to tune this such that it doesn't take too much gravity to hold together a planet, it doesn't take too much energy to hold together a planet, versus it takes too little energy to hold together a planet and they just fall apart.

So somewhere in between too much and too little, we end up with the universe we have and we end up with black holes not forming too often, and planets not falling apart in general.

Fraser: All right, I've been counting. I think we've got one more, right?

Pamela: On my personal list (which isn't the end-all, be-all of lists), the other ratio that's needed to try and define our universe the way it is, is what's called the fine-structure constant, alpha. It's the one that looks the most like a real number, 1/137.

This is the ratio of the electrons' velocity in a standard atomic model to the speed of light. It defines how electrons change energy levels. It defines a lot of different characteristics of quantum mechanics. Pretty much everything we know about how electrons and atoms interact, a lot of the things we know about quantum mechanics, would cease to work if this number changed at all.

Fraser: I heard there was recently a controversy about whether or not alpha had remained constant since the beginning of the universe, or if it was changing over time.

Pamela: There are people trying to figure this out. As near as we can tell, it hasn't changed, but it's hard to diagnose all of these things in the past. How do you read into something what the changes are? As near as I can tell from the research I've read, it doesn't look like it has changed over time.

Fraser: What I'd heard was there was at one point in the distant past, there was a natural nuclear – like a certain amount of uranium had gotten together and had a natural reaction and briefly created a nuclear reactor that's been discovered, and they were looking for evidence in the way the particles were decaying in that time.

Pamela: That's cool – I'm going to have to read it, and I'm guessing I can read about it on Universe Today.

Fraser: Yes you can. I don't remember when the story was, but I'm sure we'll try and find a link for the show notes.

Let's try and bring this all together then and talk about all these numbers. We talk about how they're fine-tuned, they have to be the way they are for life to exist, so what is the underlying explanation for why these numbers are the way they are?

Pamela: The numbers themselves are really quite boring to discuss and try and explain. It's the consequences of the numbers that are really interesting.

We live in a universe that has a lot of parameters that if we changed them 1%, 0.01%, just these fractional changes would cause our universe to suddenly no longer be functional for life as we know it. Either it would've collapsed down before stars with the appropriate metallicities ever had the chance to form, or it would've expanded apart such that stars never even formed to begin with.

We don't know why these values are what they are. There are basically three possibilities to explain it, and only one of them can, as we understand physics, be addressed with physics today.

The first option is there's a layer of physics that we just haven't got to yet that says these values have to be what they are based on first principles. If you set the universe in motion, these values fall out naturally of all of the different processes that happened to get from the big bang to today.

Fraser: So there could be one underlying number or formula or something that everything else is derived from.

Pamela: Exactly.

Fraser: So if you changed the alpha, then lambda would be messed up, and the formula wouldn't balance anymore.

Pamela: Right. So perhaps there's an underlying physical explanation that makes it such that this is the only way physics works. We haven't found that. Physics as we know it allows these values to be changed.

So if these values could be changed, what if instead of there only being one universe, there were an infinite combination of different universes existing in parallel, side-by-side, springing in and out of existence? What if we live in a multi-verse?

Suskein says perhaps we live in a multiverse where as you look across the multiverse there are multiple valleys and in each valley there is a different parameter set.

In this idea, every possible set of values for all of these different numbers exists somewhere. That somewhere just doesn't happen to be here, and that makes sense because we couldn't exist if those values weren't what they are.

So the fact that we're seeing these values is just a coincidence because we couldn't exist if they weren't like this. Should we step out of this universe into another one, we could die instantly because the values were wrong. We probably would, because the majority of the universes out there won't have these numbers.

Fraser: When you say it's a multiverse, people imagine these parallel universes where you could travel by wormhole to other universes and everyone's got little beards and they're torn apart by violent black holes and gravitational forces.

But it could also be serial, couldn't it? Just one universe after another. Let's say there's infinite time, you could have one universe with the gravitational rate too high, it collapses down, there's another big bang, it's too big and it never gets going, and so on. There's just an infinite number of these big bangs happening until finally you get the one that we happen to be in, where we can talk about it.

Pamela: Exactly, and Andre Lynd has this really great diagram where he looks at it in terms of this inflationary epic after the big bang, in which our universe radically ballooned in size. What if that inflation stopped in the majority of the universe, but in some little pocket of space it continued and a different set of parameters spilled out of existence there? What if there are all these different branching universes that are connected to one another breeding new universes as they spread out in time, space, dimensions, parameters and everything else?

Fraser: All right. You said three, what was the third possibility?

Pamela: The third possibility which science can't address in any way, is there is something out there tweaking our universe to be just so. We are in a locker in the movie *Men in Black*. We are somebody's laboratory experiment, there's a God out there.

Science can't address this, or the multiverse, because we can't study anything not in our universe. So we're left in this bad position where we have three options and science as we know it can only address one, so we don't know what the truth is.

Fraser: Right, but that's not going to stop science.

Pamela: it's not going to stop us. We're still going to try. There are people out there working on multiverse theories or looking for the underlying physics.

You know, if a god out there decided to come down, stand here and tweak parameters in front of us, that would work too.

Fraser: (laughing) Perfect! I'll wait for that.

Okay, great Pamela. Thanks a lot. Now we know how special the universe is that we live in, and look forward to next week.

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