# Astronomy Cast Episode 204
## Temperature

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**Fraser:** Astronomy Cast Episode 204 for Monday October 25, 2010, Temperature. Welcome to Astronomy Cast, our weekly facts-based journey through the cosmos, where we help you understand not only what we know, but how we know what we know. My name is Fraser Cain, I'm the publisher of Universe Today, and with me is Dr. Pamela Gay, a professor at Southern Illinois University Edwardsville. Hi, Pamela, how are you doing?
**Pamela:** I'm doing well. How are you doing today, Fraser?
**Fraser:** Doing great! Of course when this is being recorded, or when people listen to this, we will have finished our presentation in Washington, and I will be flying back to Vancouver. So, I hope it went well.
**Pamela:** Here's definitely to hoping for that.
**Fraser:** So, we're going to answer a question that a 4 year old might ask. What is temperature? Why are things hot? Why are they cold? How hot or cold can they get? How is this all important to astronomy? Alright, Pamela, so when we think about that temperature, right, like I reach out with my hand, and I touch a piece of metal and the metal is hot or the metal is cold...what's going on?
**Pamela:** At the most fundamental level, if you could get down and peer at things at the level of electrons and atoms vibrating in molecules, what you'd see is that metal is filled with atoms and electrons that are a little bit excited to be alive and they're vibrating their little hearts out, zipping around and moving quickly within the metal. And it's this combination of motions and the energy those motions can then transfer to your hand, that's the hot part... or if they're not moving at all, that's the cold part.
**Fraser:** But in both cases they are moving....
**Pamela:** Yes.
**Fraser:** And so just to think about that situation... you've got the cold metal... they're still moving and they're still giving off energy. Then in the hot they're still moving but faster, more vigorously, and still giving off energy, right?
**Pamela:** Exactly. So hot stuff is fast moving; cold stuff is slow moving. At the end of the day, when we talk about temperature, what we're talking about is nothing more than how particles are moving.
**Fraser:** And if we heat the metal up, really hot, it turns into a liquid.
**Pamela:** Right. In this case we're breaking down bonds. Atoms... they tend to clump up and they do this in ways that we give the words "covalent" and "ionic" to. These are just fancy ways of saying that they're sharing electrons in different ways. These bonds... just like if two people start running across a field together and get out of sync, their hands will tear apart if they're holding hands while running. Two atoms, if you heat them up enough, their motion will break the bond that's holding them together. When we chill things down, we're allowing them the opportunity to share electrons, to bond together into solids. Then when we heat them up, we're loosening those bonds... making them more fluid... more like square dancers who switch partners as they go round and round. If you heat something enough it becomes a gas, and now there's no connections between the atoms at all.

**Fraser:** Right, they're free to flow around and fill up whatever space they're inside.
**Pamela:** Exactly.
**Fraser:** You could blow up a balloon with iron gas... a very special balloon and a very... you know...
**Pamela:** Exactly.
**Fraser:** But all of the elements go through those phase changes. But, are there limits to temperature? How cold can you get?
**Pamela:** Basically we're limited by how much energy can an object give off so that eventually it's, for the most part, sitting there going... yeah, ok, I've got nothing left here. So we talk about this as the term "absolute zero." This is the point where you have cooled an atom so much that all of its electrons are in the lowest possible energy level and the atoms really don't have any kinetic energy that they can impart through collisions... they're just sitting there.
**Fraser:** So have they completely stopped moving, then?
**Pamela:** The electrons are still in their lowest energy level, they're still slowly chugging their way around the atoms, but this is a different state of matter that we can't actually get to. So yeah, there is motion, but it's not useful motion that you can have collisions in.
**Fraser:** Right. I see. So there's still motion there, but you couldn't get any more energy out of it.
**Pamela:** Right.
**Fraser:** So then this concept of absolute zero... it's theoretical, right, because we happen to live in a universe and we could never hit it.
**Pamela:** It's not so much a condition of our universe as we don't have the ability to get something isolated enough that you can achieve absolute zero. And we don't have a way to suck all the energy out of something. This is one of those hard-to-think-about things. It's easy to heat up a room. You flow electricity through a set of wires, the wires heat up, they give off energy into the room around them. Energy naturally goes from hot to cold. You can do a whole lot of things to heat a room up... you can light something up on fire. The energy stored up in molecular bonds will get broken down and released as energy, and you have a warm room. The only way to suck the energy out of something is to... often we use various pressure rules... you can expand a gas and the energy is now spread out over a larger volume. This is kind of weird and funky but if you imagine spraying yourself with a can of canned air, the air that comes out of the canned air is always cold. This is because it suddenly gained space to move around in. It's energy got spread out and it's temperature dropped. Now we have to take cold stuff that we make cold through various... usually pressure interventions.... and flow it through something slightly warmer. The cooling tubes in your refrigerator... they're not giving cold to your refrigerator, what's happening is the warmth that you let in when you open the door... that warmth is flowing into the colder tubes. Now, to get something down to absolute zero, that means you have to somehow get something colder than absolute zero to suck the energy out because the energy will flow from warm to cold. We can't do that. So, we're stuck.
**Fraser:** So, how cold have scientists gotten temperature? I know we can't hit absolute zero, but how close can we get? How do they do it?
**Pamela:** Well, we can actually get within fractions of zero. Most things that we deal with are within a couple degrees of zero. This is where we start talking about Bose-

Einstein condensates and this cool extra condition of matter that we create in laboratories that doesn't behave like a solid, doesn't behave like a liquid, doesn't behave like a gas or a plasma, but in our pursuit to keep making things cooler and cooler using techniques either involving magnet cooling or laser cooling, we essentially stop particles in their tracks. By trapping them in specific resonances we can get them to lower and lower temperatures and get them to behave in new and fascinating ways. What's kind of interesting is that the universe itself is warmer than what we're creating in the lab.
**Fraser:** But in this case you've got a handful of particles that you've cooled down to that temperature, not a block of metal or a block of ice... you know, but it's... yeah... theoretically... Ok, well that's the cold side. Let's turn things around and look at how hot we can get. How hot can we get... is there an absolute high temperature?
**Pamela:** Not so much an absolute high temperature as we eventually just sort of run out of the energy to get things that hot. As we look out at the clusters of galaxies, the pressures are so high, that atoms are in constant collision and these constantly colliding heated up by various effects... by jets from black holes and other different effects.... this shock-heated, jet-heated, compressed down gas... it can get to billions of degrees. It's giving off gamma rays, it's giving off x-rays. We're not exactly sure of the absolute limit of how hot something can get, but we know things can get very hot, and the limits on heat are simply the limits on how much energy can you inject into a system before that system starts expanding out. That's the problem you run into is you heat something up, the atoms start moving around and breaking out of the area that they're in and expanding to larger and larger volumes. So you have to both hold the material in and heat it up at the same time.
**Fraser:** Right, I can imagine blowing up a balloon with gas that's millions of degrees... that's going to have a lot of energy and really want to expand that balloon.
**Pamela:** Right. This is where you start dealing with pressure containers. When you fill up a container of oxygen gas, of any type of gas, the gas gets hot as it goes in and these containers are always at high risk for exploding. Don't ever drop a compressed air cartridge because it can go boom with a lot of violence. So you have to have both the containment and the pressure to get to the high temperatures.
**Fraser:** And in a practical sense, this is used in fusion power experiments here on Earth. You don't have to look all the way out to the middle of the universe to find some really high temperature gas. I know that that's one of the conditions they use for trying to replicate fusion here on Earth.
**Pamela:** This is one of those fascinating things where we mentioned a few moments ago that we used lasers to cool things off... well, fusion actually uses laser to heat things up. What's happening is you're taking all of this light, often from more than one laser, focusing it down on a very small point... often a little tiny glass bead that's specially seeded with other elements... The pressure that you can create with this light is what's generating, hopefully, fusion.
**Fraser:** But even, say, the center of the sun is like 15 million degrees Kelvin... I mean there's some pretty hot temperatures out there. So then if there isn't a maximum theoretical temperature, what are some of the hottest things in the universe?
**Pamela:** Gamma ray bursts. Basically, the bluer the light, the higher the temperature. This is one of those things that is really confusing to beginning introductory students. When you look out at the universe... when you see something red, that's a cool object.

Just like your red-hot burner on your stove may seem hot, but it can also get white hot, and that's a whole lot hotter than the red hot. So as we look across the universe, it goes from red as nice cool stars to yellow as warmer stars to (there aren't green stars) big blue flaming hot stars. As we get to shorter and shorter wavelengths... as we get bluer and bluer such that we're passing out into the ultraviolet, the gamma ray, and the x-ray, that's a reflection of the temperature going up. One of the ways that we measure temperatures is by looking at the color of the objects in the sky.
**Fraser:** And so the highest energy things out there are these gamma ray bursts which in some cases can let off more energy in a few seconds than their entire galaxy is giving off.
**Pamela:** Exactly. And that's the other side of this is these extremely short wavelength photons that are getting released in these very high energy events, they carry a lot more energy in them. So you can have two photons, two identical particles by name side by side, but if one of them is a radio photon, no big deal... it can pass right through you and you're not in danger of death. But that gamma ray photon... that one gamma ray photon can bust up a piece of your DNA and potentially trigger cancer in the future. So gamma rays are highly dangerous because of how much energy can get imparted in just one photon of light.
**Fraser:** And it's this energy that's moving with photons that can then be transferred back to matter, and you get temperature.
**Pamela:** Right. It's through collisions that in some ways all the magic happens. As light form stars, from exploding stars, from a variety of different sources passes through gas, the different constituents of the gas each absorb light at their own specific frequencies, their own specific colors. We've talked about this some before where atoms have specific, allowed... I'm just going to keep using the word specific... have their own specific, allowed transitions. So you might see one set of lines that corresponds to hydrogen, another set of lines that corresponds to carbon monoxide. We're able to tell what atoms, what molecules are in a cloud of gas by looking at the specific colors that are absorbed out of that gas. Now at the same time, though, you can also have a bunch of dust particles. Dust... it's happy to absorb light at all different colors. But put together, we're able to figure out what our universe is made of.
**Fraser:** And I guess this is the next big question... how do astronomers use temperature in their studies? What does temperature tell an astronomer and how do they determine temperature?
**Pamela:** Well, determining the temperature is a matter of looking for these atomic transitions and looking more importantly at which ones are stronger and weaker. So if I'm looking at a star that has a whole myriad of different atoms in it... stars are mostly hydrogen, some helium, and then trace amounts of other atoms... of metals, titanium lines, however even though this is a very small fraction of the star, these atoms are able to suck light out left and right. So if you look at a stellar spectrum, it's just riddled with these titanium lines, it's just riddled with iron lines. And we know that when you heat these metals to certain temperatures, they start losing electrons. The set of lines that you get directly corresponds to what electrons are present which corresponds to temperature. So I can look at something and go... ok, I have this set of titanium lines which occur at temperatures between A and B. I have this set of iron lines which occur at temperatures between D and E where D actually happens to be colder than B because I'm using strange numbers. Looking at all these different parameter spaces, you sort of get a Venn diagram

where when you overlap all the different possible temperatures for this set of lines, that set of lines, it allows you to focus in and say, often within just a couple hundred degrees, exactly what the temperature of the surface of the star is. With gases we can do the exact same thing. We can start to tell what is the temperature of the gas in terms of what atomic transitions are taking place.

**Fraser:** And so without those other chemicals mixed in with the gas, would it be really difficult to tell... I mean, I know that, for example, astronomers can find cold neutral hydrogen.

**Pamela:** And the thing with cold neutral hydrogen is at least it has the dignity to have what we call a spin flip where when we look at this hydrogen gas, occasionally the one sad lone electron associated with that hydrogen gas... it will decide to it wants to flip on its head. This small little very rare transition... we can see that energy. We can see the energy given off when that spin flip occurs. That allows us to map out where the gas is located. It requires radio telescopes, but that's ok. We have radio telescopes.

**Fraser:** But once again, we're really just using that property of the matter to give us an idea of the temperature. We're looking for places where this is happening and that tells us what the temperature is. Are there other situations? What about finding temperature here in the solar system?

**Pamela:** Within the solar system we get to use an additional part of physics.... the black body concept. This is what you see when you watch really old Star Treks and Captain Kirk shines a laser beam... shoots his phaser in all reality... at a rock and the rock heats up red. Well, what's happening is as the rock heats up, as elements on an electric stove heat up, the atoms as a population are increasing in temperature. Some of them are going to be hotter than others, and some of them are going to be cooler than others. If you were to make a plot of color vs. how much light is given off at that color, you get some things that are bluer than others, some things that are redder than others. The majority of the light coming off will be at one central color. The shape of this distribution is what we call a black body distribution. It's a little quicker rising on one side, if you make a plot, and a little slower tapering off on the other side, if you make a plot.

**Fraser:** There's a good analogy with light bulbs. Certain temperatures give off a cool light or a warm light, and that's following that black body curve. I know you get... I forget what the exact temperature of a light is... it's like 5000 degrees.

**Pamela:** And if you have a dimmer switch... as you dim your incandescent light bulb, which you shouldn't be using...

**Fraser:** As you dim your LED array...

**Pamela:** Yeah, that doesn't work. As you dim your "you shouldn't be using it" incandescent light, it gets redder. As you increase the electricity flowing through that filament, it gets hotter and the light itself gets bluer. But, if you look at it through a prism or through those funky glasses that you can get that make everything into rainbows at carnivals, what you see is... it's actually a full rainbow, but the majority of the light is coming out at one color in the rainbow. The shape of this curve... the shape of this black body distribution is directly related to the average temperature of the object... the black body temperature of the object. When we look at something, and we measure very carefully how much light it gives off across all the colors of the rainbow... by looking to see this one gives off most but not all of its light in the blue... it's hot. This thing gives off most but not all of its light in the red... it's cooler. We can very accurately get the temperatures of rocks, of planets. Now there's caveats... rocks aren't perfect reflectors so there's going to be colors they don't really reflect that well, colors that reflect better than others. So we have to correct for all of that using chemistry... which isn't fun, but we can do it to figure out the temperatures of different objects.

**Fraser:** So we have a set of tools... astronomers can look for the really, really hot stuff. They can look for the temperature of stars, and they can also figure out the temperature of objects close to home in the solar system. I suppose when they land spacecraft right onto those worlds, like the Mars rovers, they can actually use a thermometer.

**Pamela:** Right. And all the thermometer is doing is when you get it cold, the mercury is going (or the alcohol, depending what type you have) is going oh, I'm cold, I'm not going to move very much, I'm going to compact myself down and be very small. But when you heat it up, the motions increase, and with that increased motion it takes up more space and expands out. So we're just looking at how things move.

**Fraser:** And at the end of the day, that's really all that temperature is is the motions of atoms and molecules.

**Pamela:** It's kind of simple to break down some of the ugliest quantum mechanics you'll ever see, but at the end of the day...

**Fraser:** I mean they only really understood what's going on in the last hundred years, right? Thanks, Einstein!

**Pamela:** Well, this isn't so much Einstein. Temperature... predates. But it's only with the advent of quantum mechanics that we're able to understand at the atomic and molecular levels exactly what's going on and relate temperature to vibrations, to spins, to the flipping of electrons, to understand exactly what goes on in all the different possible densities of materials.

**Fraser:** Alright, well, thanks a lot, Pamela. I really appreciate that, and we'll talk to you next week.

**Pamela:** Sounds good, Fraser. I'll talk to you later.