NQUIRY: AN OCCASIONAL COLUMN

Absolute Hot

- By Peter Tyson
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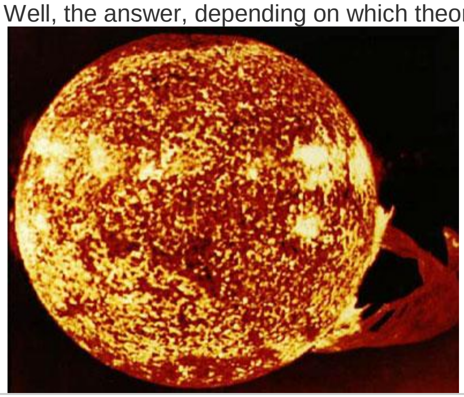
Is there an opposite to absolute zero, the lowest possible temperature?

The question *Is there an opposite to absolute zero?* seems innocent enough, right? Absolute zero is 0 on the Kelvin scale, or about minus 460°F. You can't get colder than that; it would be like trying to go south from the South Pole. Is there a corresponding maximum possible temperature?

Well, the answer, depending on which theoretical physicist you ask, is yes, no, or maybe.



For many of us, the hottest thing we could think of might be the core of the sun. But broiling as it is at roughly 10^7 degrees, it's a full 25 orders of magnitude colder than the current highest temperature that physicists propose. Enlarge Photo credit: Courtesy NASA Johnson Space Center

Huh? you ask. Yeah, that's how I felt. And the question doesn't just mess with the minds of physics dummies like me. Several physicists begged off of trying to answer it, referring me to colleagues. Even ones who did talk about it said things like "It's a little bit out of my comfort zone" and "I think I'd like to ruminate over it." After I posed it to one cosmologist, there was dead silence on the other end of the line for long enough that I wondered if we had a dropped call.

I had touched a nerve, because, unbeknownst to me, the highest-temperature question gets to the heart of current inquiries and proposed theories in cosmology and theoretical physics. Indeed, scientists who work in these fields are zealously trying to answer that question. Why? Because, in some sense, nothing less than the future course of physics rests on the answer.

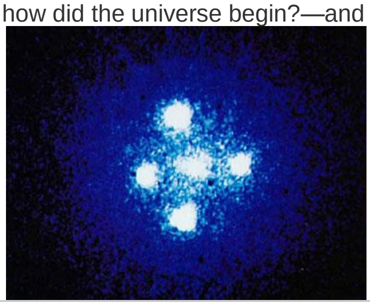
CONTENDER #1—10^{32} K

Certain cosmological models, including the one that has held sway for decades, the Standard Model, posit a theoretical highest temperature. It's called the Planck temperature, after the German physicist Max Planck, and it equals about 100 million million million million million degrees, or 10^{32} Kelvin. "It's ridiculous is what it is," said Columbia physicist Arlin Crotts when I asked him if he could please put that number in perspective for me. "It's a billion billion times the largest temperature that we have to think about" (in gamma-ray bursts and quasars, for instance). Oh, that helped.

Truthfully, when contemplating the Planck temperature, you can forget perspective. All the usual terms for very hot—scorching, broiling, hellish, insert your favorite here—prove ludicrously inadequate. In short, saying 10^{32} K is hot is like saying the universe occupies some space.

Whatever the highest temperature is, it might be essentially equivalent to the coldest temperature.

In conventional physics—that is, the kind that relies on Einstein's theory of general relativity to describe the very large and quantum mechanics to describe the very small—the Planck temperature was reached 10^{-43}seconds after the Big Bang got under way. At that instant, known as one Planck time, the entire universe is thought to have been the Planck length, or 10^{-35} meters. (In physics, Max Planck is the king of the eponymous.) An awfully high temperature in an awfully small space in an awfully short time after â€¦ well, after what? That's arguably an even bigger question—how did the universe begin?—and we won't go there.



Quasars, such as this one appearing quadrupled through the "gravitational lensing" effect of an intervening galaxy, are among the most energetic, hence hottest, of celestial objects. But even they pale next to the temperature right after the Big Bang. Enlarge Photo credit: Courtesy NASA Johnson Space Center

A BRICK WALL

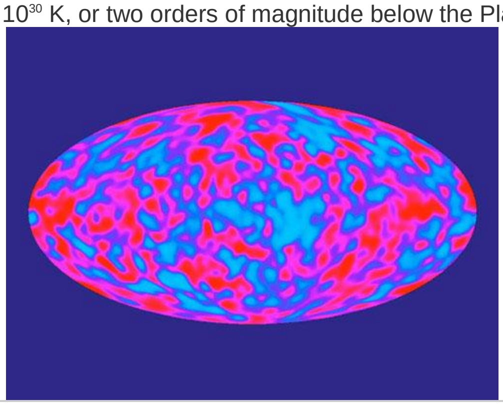
The Planck temperature is the highest temperature in conventional physics because conventional physics breaks down at that temperature. Above 10^{32} K—that is, earlier than one Planck time—calculations show that strange things, unknown things, begin to happen to phenomena we hold near and dear, like space and time. Theory predicts that particle energies become so large that the gravitational forces between them become as strong as any other forces. That is, gravity and the other three fundamental forces of the universe—electromagnetism and the strong and weak nuclear forces—become a single unified force. Knowing how that happens, the so-called "theory of everything," is the holy grail of theoretical physics today.

"We do not know enough about the quantum nature of gravitation even to speculate intelligently about the history of the universe before this time," writes Nobel laureate Steven Weinberg about this up-against-a-brick-wall instant in his book *The First Three Minutes.* "Thus, whatever other veils may have been lifted, there is one veil, at a temperature of 10^{32} K, that still obscures our view of the earliest times." Until someone comes up with a widely accepted quantum theory of gravity, the Planck temperature, for conventional physicists like Steven Weinberg, will remain the highest temperature.

CONTENDER #2—10^{30} K

String theorists, those physicists who believe the universe at its most fundamental consists not of particles but of tiny, vibrating strings, have their own take on temperature. I spoke to Robert Brandenberger, a theoretical cosmologist at McGill University in Montreal. Along with Harvard string theorist Cumrun Vafa, Brandenberger has proposed a model of the early universe that's quite different from that of traditional Big Bang models. (I should note that there are many models out there; I'm touching on only a few here.)

Called string gas cosmology, this model posits a maximum temperature called the Hagedorn temperature. (It's named after the late German physicist Rolf Hagedorn.) "This is the maximal temperature which string theory predicts," Brandenberger told me. While string theorists don't give a specific number for the Hagedorn temperature, Brandenberger has reasons to think it's about one percent of its theoretical cousin, the Planck. That makes it about 10^{30} K, or two orders of magnitude below the Planck.



Even after 14 billion years, a remnant of the Big Bang's beyond-astronomical levels of heat exists in the cosmic background radiation (CBR), which has cooled to just three degrees above absolute zero. Here, the CBR is "seen" in a NASA image. Enlarge Photo credit: NASA Goddard Space Flight Center

CONTENDER #3—10^{17} K

I learned of yet another highest possible temperature from Brandenberger's former graduate student, Stephon Alexander. Now an assistant professor of physics at Penn State, Alexander is one of many physicists who are eagerly awaiting the day that officials at CERN on the Swiss-French border switch on the Large Hadron Collider, the world's largest particle accelerator.

One reason why they're excited has to do with temperature. As Alexander told me, "It may be that the [highest possible] temperature is—as I believe—the temperature or the energy right around the energy that the LHC will be probing." The LHC will operate at 14 trillion electron volts, or terra electron volts, designated TeV. Fourteen TeV equals 10^{17} K, thus 15 orders of magnitude below the Planck.

Why could the LHC help determine this? As Brandenberger explained to me, string theory predicts that space-time has more than four dimensions, either 10 or 11. "Now, the other dimensions, which are hidden to us, could either be very, very tiny—they could be strings or Planck scale—or else they could be TeV scale." And if these extra dimensions prove to be TeV scale, he says, then the topmost temperature will be TeV scale too.

If there is a hottest temperature, whatever it is, how about something even hotter? No problem!

I asked Alexander what it would mean for physics if the Planck temperature turned out to be TeV scale. "Oh my God, this would be one of the biggest breakthroughs of our species—you know, Einstein stuff," he said. "It'd be as big as the discovery of relativity and quantum mechanics itself." Brandenberger, for his part, thinks it's a "very, very long shot" that temperature's upper terminus is TeV scale. Regardless of who's right on this score—if, in fact, either is—it will be nail-bitingly suspenseful to see what arises from the LHC, which is slated to begin operation in 2008. Says Alexander: "I've got my stock invested."

Could absolute cold and absolute hot—whatever it is, if it even is—be manifestations of the same physical phenomenon? Here, an ultraviolet image of the sun's corona. Enlarge Photo credit: NASA Goddard Space Flight Center

CONTENDER #4—0 K

As if at least three different possible opposites to absolute zero weren't pause-giving enough, what Alexander told me next really set my head spinning. Whatever the highest temperature is, he said, it might, just might be essentially equivalent to the coldest temperature. "In other words, zero temperature is the same, in a sense, as the Planck temperature."

Come again?

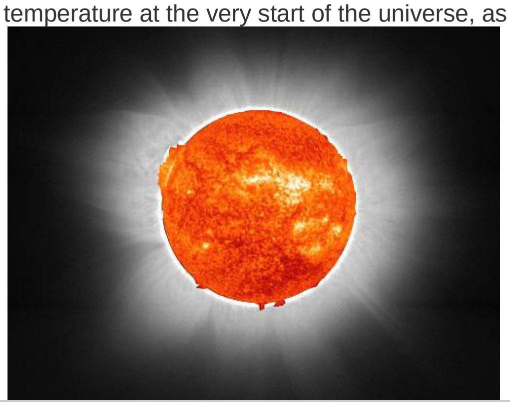
Alexander described two potential ways the universe began. Either it was at the Planck temperature and then inflated and cooled to create what we see today. Or it started off at zero temperature and speeded up as it expanded. "So one of two situations could have happened," he said, "and it would be interesting if, indeed, both situations are really the same underlying phenomenon."

That is, could the physics of the coldest possible temperature be equivalent to the physics of the hottest possible temperature? Considering that beyond both limits—below one and above the other—space and time start to do those strange, unknown things, Alexander believes it's "a logical conclusion, a logical possibility. Why not?"

BEYOND THE BEYOND

Why not, indeed? After chatting with Alexander and others in his rarefied field, I was up for anything. How about something theoretically hotter than the Planck? Sure! I asked Jim Gates of the University of Maryland. "All we know is that above the Planck temperature, the rules change, but â€¦ we don't know what the rules change to," he said. "If someone figures out such consistent rules, then yes, it's conceivable that there will be hotter temperatures."

How about a boundlessly high temperature? Great! After all, classical general relativity calls for an infinitely high temperature at the very start of the universe, as well as in the centermost point, the singularity, of black holes.



In the end, no one knows if there's a hottest-of-all temperature. But that uncertainty only fuels physicists' speculations. Above, a composite image of the sun during the total solar eclipse of June 21, 2001. Enlarge Photo credit: NASA Goddard Space Flight Center

Or, if there is a hottest temperature, whatever it is, how about something even hotter? No problem! In theory, a hotter temperature than a hottest temperature can exist—it's a negative temperature. As Charles Kittel and Herbert Kroemer write in their classic text *Thermal Physics*, "The temperature scale from cold to hot runs +0 K, â€¦, +300 K, â€¦, +âˆ ž K, -âˆ ž K, â€¦, -300 K, â€¦, -0 K."

Almost giddy now, I again turned to Arlin Crotts for help. If, theoretically speaking, you go above the Planck to an infinitely high temperature, the next step beyond infinity is minus infinity? "Well, you're not talking about thermal distribution anymore," he said, "but if you keep pushing it, you basically go through infinity over to minus infinity and then come around on the other side." *Wow!* "What you really should be paying attention to," he added, "is 1 over T [where T is temperature], because one over infinity and one over minus infinity are basically the same thing." *Totally!*

CONTENDER #5—WHO THE HECK KNOWS?

As you might have guessed, by this point the physicists had lost me—if not at the very beginning. I was *way* out of my comfort zone.

In the end, perhaps the best answer to my question came from Lee Smolin of the Perimeter Institute for Theoretical Physics in Waterloo, Ontario. "It may be that the most you're going to be able to say is that there's a possibility that there's a highest possible temperature," he told me. "But let me mull it overâ€¦."

This feature originally appeared on the site for the NOVA program Absolute Zero.

Peter Tyson is editor in chief of NOVA Online.