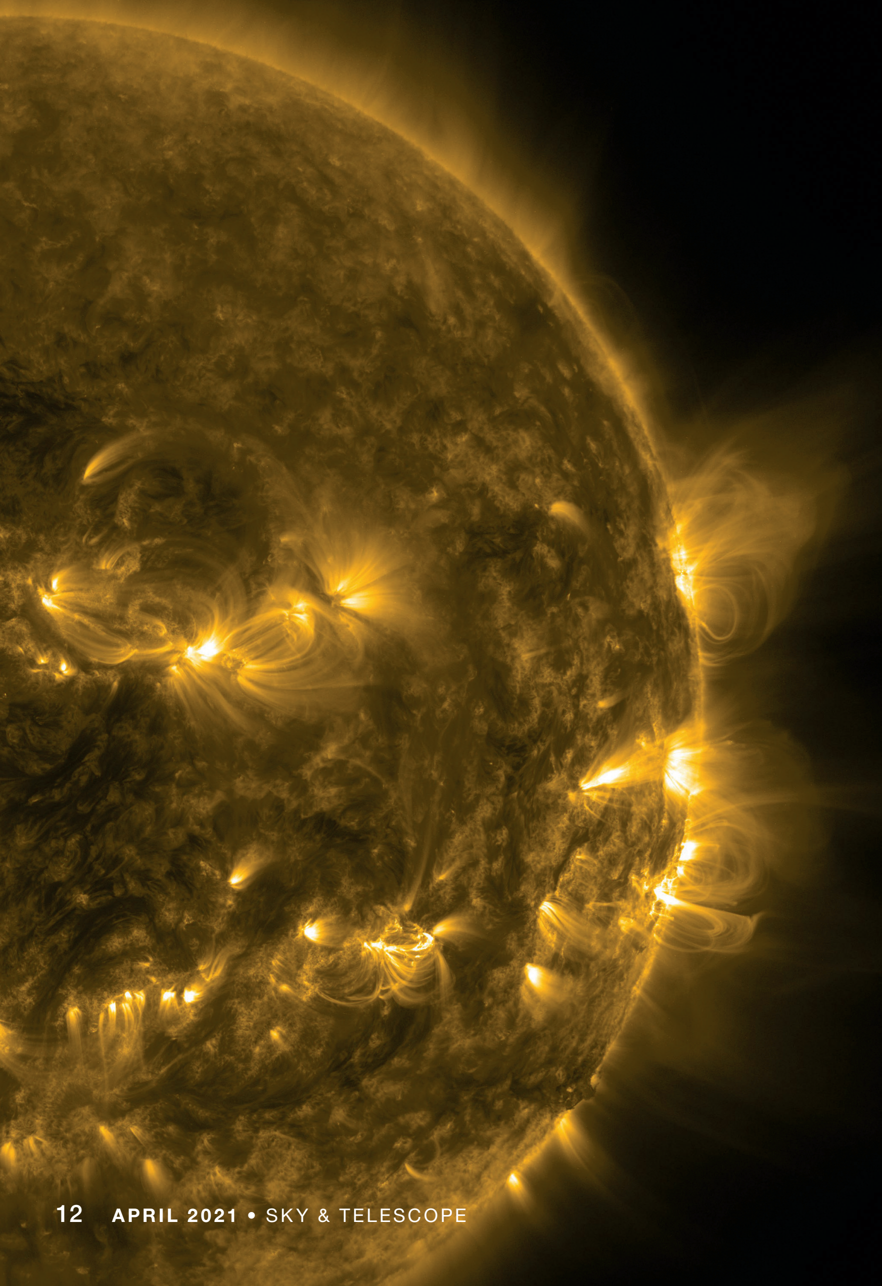
How Well Do We Know the Sun?

Even though the Sun is our nearest star, we may not understand it as well as we thought.



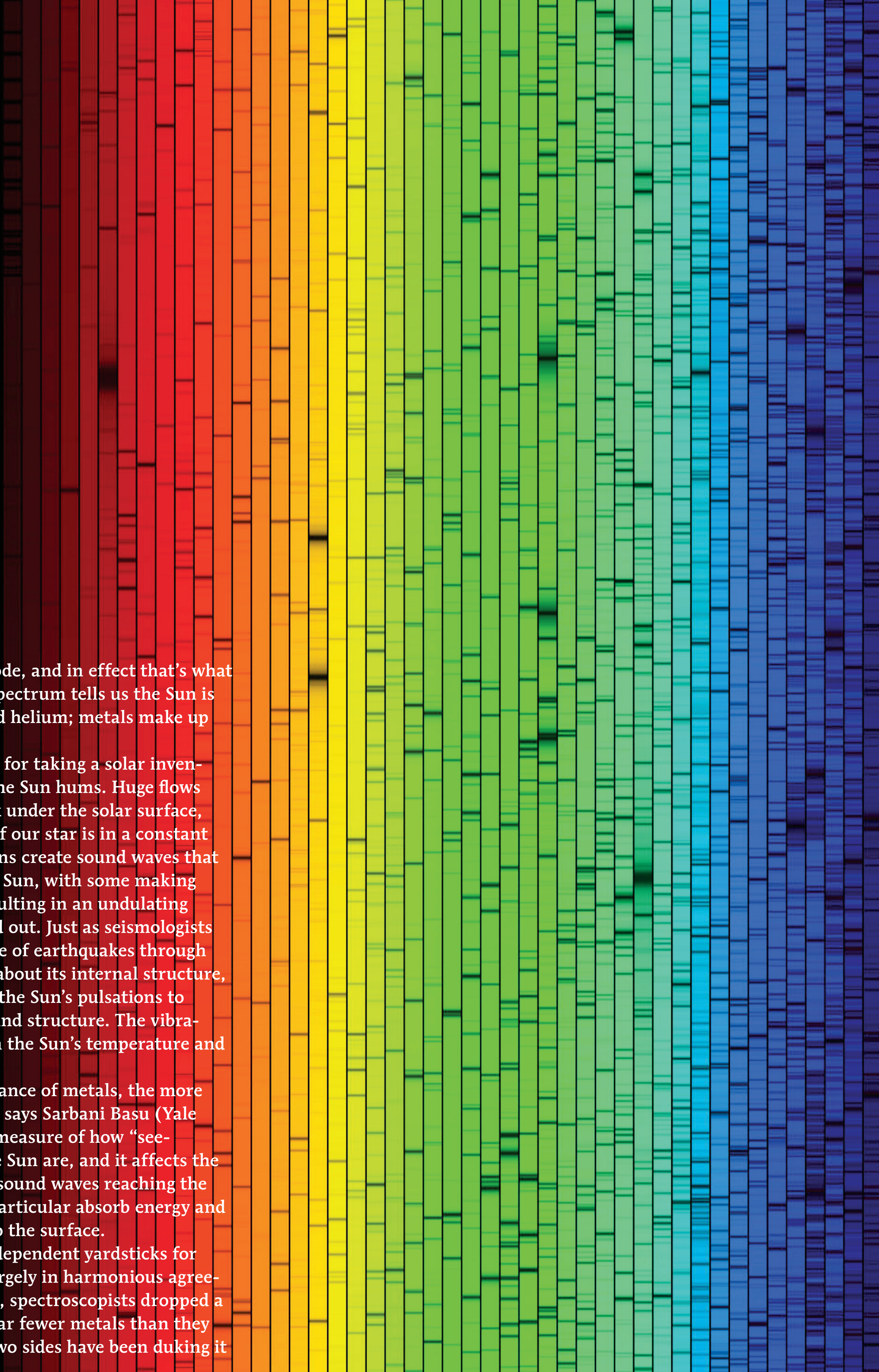
NASA / SDO

There's a problem with the Sun — or at least, a problem with our understanding of it. Rival groups of astronomers are racing toward a solution, adamant they each have the correct answer. Who turns out to be right could have huge consequences for the way we understand the Sun, other stars, and their planets.

At the heart of the issue is what the Sun is made of. Our nearest star is 1.4 million kilometers (870,000 miles) wide, a goliath of roiling, churning, seething plasma that has a surface temperature approaching 6000 kelvin (5500°C). This plasma is mostly hydrogen and helium but has a smattering of heavier elements, which astronomers call *metals*. The question is, how many?

Taking a sample is, of course, impossible. Instead, astronomers have turned into detectives, teasing out clues about the Sun's composition from the evidence provided by a suite of solar observatories both on the ground and in space and the sophisticated models of the Sun they help inform.

Those dedicating their careers to finding out the Sun's makeup fall into two camps. The first — the *spectroscopists* — rely on the sunlight we receive from the *photosphere*, the Sun's visible surface. Passing sunlight through an instrument called a spectrograph separates out all the familiar colors of the rainbow, but they're strewn with a series of dark bands called absorption lines. They are simply missing colors — precise frequencies of light swallowed by the 67 different elements found in the Sun. At first glance it



▶ The Sun emits every wavelength of visible light, but elements in the solar atmosphere absorb specific wavelengths, imprinting the spectrum with dark bands. While these absorption lines provide insight into the Sun's chemical composition, understanding the interior is a far more difficult task.

NIGEL SHARP (NSF) / FTS / NSO / KPNO / AURA / NSF

looks like a colorful barcode, and in effect that's what it is. Scanning the solar spectrum tells us the Sun is at least 98% hydrogen and helium; metals make up the remaining 2%.

An alternative method for taking a solar inventory focuses on the way the Sun hums. Huge flows of material swell and sink under the solar surface, meaning the underbelly of our star is in a constant state of flux. These motions create sound waves that bounce around inside the Sun, with some making it to the photosphere, resulting in an undulating surface that throbs in and out. Just as seismologists on Earth track the passage of earthquakes through the planet to learn more about its internal structure, *helioseismologists* can use the Sun's pulsations to uncover its composition and structure. The vibrations are sensitive to both the Sun's temperature and its composition.

"The higher the abundance of metals, the more opaque solar material is," says Sarbani Basu (Yale University). Opacity is a measure of how "see-through" the layers of the Sun are, and it affects the speed and pattern of the sound waves reaching the solar surface. Metals in particular absorb energy and impede the waves' path to the surface.

For years these two independent yardsticks for the Sun's makeup were largely in harmonious agreement. Then, in the 2000s, spectroscopists dropped a bombshell: The Sun had far fewer metals than they had originally said. The two sides have been duking it out ever since.

Astronomical Standoff

Nicolas Grevesse (University of Liège, Belgium) was a coauthor on what is now a landmark paper. He explains that the change in abundance measurements was due to advances in calculations. "Twenty years ago, we were only using one-dimensional models of the photosphere," he says. Computing restrictions forced astronomers to simplify their models and assume that the photosphere was in thermal equilibrium, with no sudden changes in temperature.

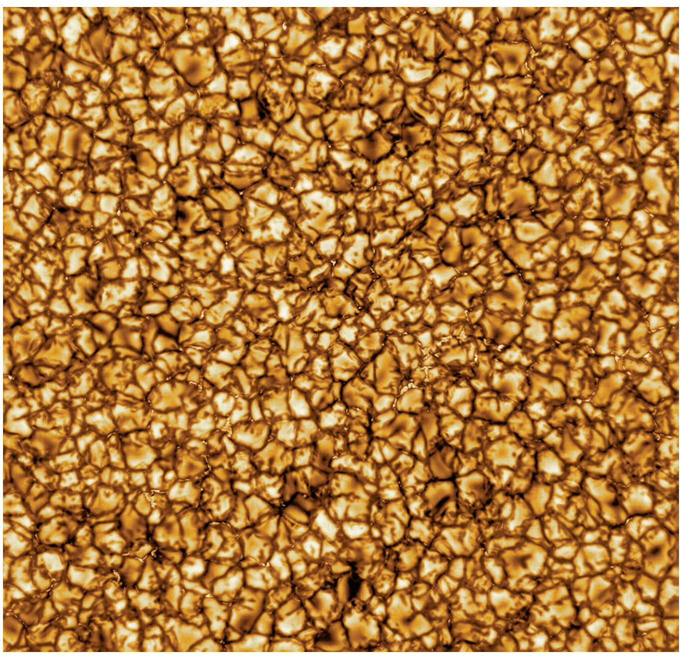
However, the surface layers of the Sun are constantly evolving, with hot, new material bubbling up all the time. Once Grevesse and his colleagues started using 3D models and dropped the equilibrium requirements, it became clear to them that their original abundance estimates of carbon, nitrogen, and oxygen were wrong. The overall metal content of the Sun dropped from 1.8% to 1.3%; a revision to oxygen abundances accounted for almost half of that shift.

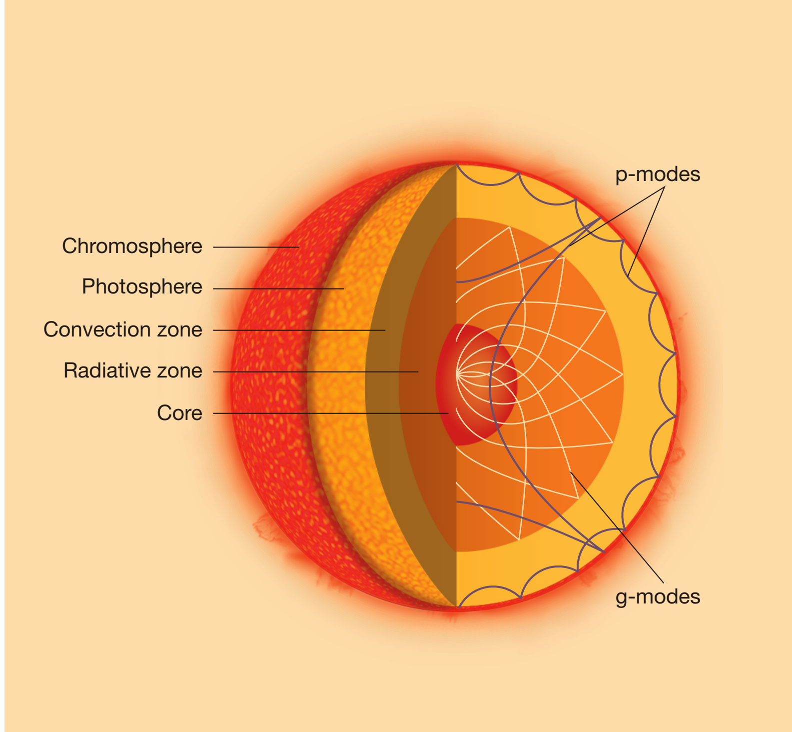
Suddenly, spectroscopists were at odds with helioseismologists, and the so-called *solar abundance problem* was born.

The consequences are dramatic. The mass of metals sliced from solar models is equivalent to around 1,500 Earths. Stars with fewer metals burn through their nuclear fuel much faster. If the spectroscopists are right, the Sun will die a billion years earlier than we'd anticipated.

It isn't just our understanding of the Sun and its longevity that are in jeopardy, though. The Sun is the only star we get to see up close; the next-nearest star is more than 268,000 times farther from Earth, more than 4 light-years away. As a result, we use the Sun as a benchmark for understanding every other star in the universe. "It affects the precision with which we infer the mass, age, and radius of other stars," says

▼ **SOLAR SURFACE** Plasma on the visible surface of the Sun churns within cells, each roughly the size of Texas.





Gaël Buldgen (University of Geneva, Switzerland). If we've misunderstood these parameters for the Sun, then we've got them wrong for *all* stars. According to Buldgen, fewer metals would mean a decrease of up to 10% in mass and radius and up to 20% in age for Sun-like stars.

These differences affect our studies of planets beyond the solar system, too. Astronomers estimate exoplanets' masses and radii from those of their host stars. In recent decades we've found potentially habitable planets around distant stars. But a planet previously thought to have a rocky surface and a nice warm temperature — and possibly liquid water — may turn out to be very different if the size of its host star is not what it seems.

The stakes are clearly high, so who's right? Both sides are stubbornly sticking to their guns in an astronomical standoff.

"It shouldn't even be called the solar abundance problem," says Anish Amarsi (Uppsala University, Sweden), who is on the spectroscopists' side. "You should call it the 'solar modeling problem,' as the abundances are sound." Different spectroscopic indicators all point to the same abundances, he says: "We have checked them again and again, and we keep landing at the same answer."

The spectroscopists also point to meteorite samples containing pristine material from the same cloud of gas and dust that formed the Sun. These, they claim, show generally good agreement with the revised solar abundances.

The real problem is that helioseismologists are underestimating the opacity of the solar plasma, Grevesse and Amarsi both say. "This missing opacity acts in the same way as changing the abundance," says Amarsi.

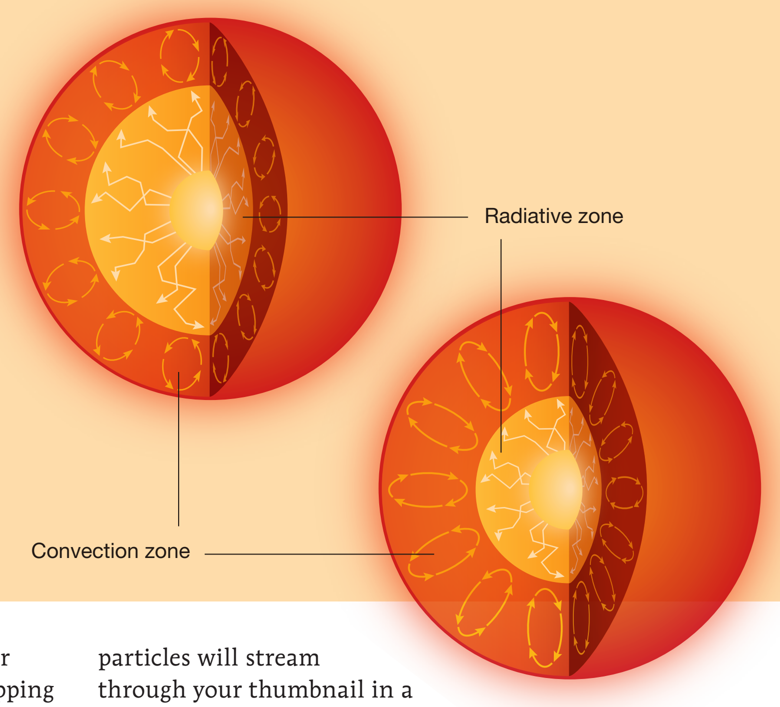
For her part, Basu isn't having any of it. "To me, this is a spectroscopists' dispute," she says. "Every helioseismic measurement gives a higher abundance."

The opacity would have to change by around 15% at the base of the convection zone (the layer of the Sun directly

SOLAR SURFACE: NSO / AURA / NSF; SOLAR INTERIOR: LEAH TISCIONE / S&T, SOURCE: ESA

◀ **INSIDE THE SUN** This cutaway diagram shows key regions of the solar interior. The *chromosphere*, part of the Sun's atmosphere, is outermost. Beneath that is the visible surface or *photosphere*. Within the Sun, a turbulent *convection zone* surrounds the more stable *radiative zone*. Deep inside is the core, where hydrogen fuses into helium. Waves slosh within the Sun, some of them (known as gravity waves) restricted to the inner regions. Other waves, known as pressure waves, connect the interior to the visible surface.

▶ **DEPTH CHANGE** The new solar abundances imply a shallow convection zone *(left)*, but sound waves indicate a deeper convection zone *(right)*. (The change in depth of the convective zone in this diagram is exaggerated for clarity.)



below the photosphere) and 5% in the core to bring solar models in line with the revised abundances, she says. Upping the opacity would change our understanding of the Sun's interior structure. Solar energy travels outward from the Sun's core by the process of radiation, before it transitions into being carried by convection as the temperature and density of material drops closer to the surface.

The chance that the helioseismologists' numbers are a fluke outlier of the spectroscopists' numbers is just 1 in 20 million. If they are wrong, then they are spectacularly wrong.

"That boundary depends on how opaque solar material is," Basu says. "If we use the new abundances, then the convection zone is very shallow." It would begin at 72.5% of the way from core to surface. But the way the sound waves bounce around suggests the convection zone is deeper, starting at 71.3% of the Sun's radius. That may sound inconsequential, but the helioseismologists claim their work is accurate to 0.1%. The chances that the helioseismologists' numbers are a fluke outlier of the spectroscopists' numbers are just 1 in 20 million. If they are wrong, then they are spectacularly wrong.

The Neutrinos Will Decide

According to Basu, there is a way to settle this impasse: solar neutrinos. Neutrinos are tiny, almost massless particles generated in the same nuclear fusion reactions that produce sunlight deep in the Sun's core. Each and every second, 683 million tons of hydrogen are churned into 679 million tons of helium. Solar fusion generates so many neutrinos that if you hold your thumb up to the Sun, 65 billion of these ghostly particles will stream through your thumbnail in a second. A billion trillion will pass through your body over your lifetime, approximately the same as the total number of stars in the entire observable universe.

Elaborate experiments around the world have been snaring solar neutrinos since the 1960s, allowing us to be confident of the Sun's inner workings. Labs go to great lengths to achieve this by sheltering underground, shielding themselves from other kinds of particles that can't make it through the bedrock. Most neutrinos, on the other hand, pass straight through Earth and continue onward into space unhindered. In fact, a light-year of lead — some 9.5 trillion kilometers long — would only have a 50:50 chance of halting a neutrino.

For decades, these unusual experiments have picked up solar neutrinos produced as part of the *proton-proton* (pp) chain — the main set of nuclear reactions that generate the Sun's energy. The vast majority of these reactions only involve hydrogen and helium, but a rarer set includes the metals beryllium and boron. In 2018, the team conducting the so-called Borexino experiment in Italy announced they had picked up neutrinos produced by all possible pp-chain reactions, including the rarer two involving metals, and so could infer their abundances. What they found favors the helioseismologists' higher metallicity estimate. Maybe it is a solar abundance problem, after all.

Borexino could provide a more definitive answer in the years ahead. A rarer form of fusion called the *carbon-nitrogen-oxygen* (CNO) cycle generates less than 2% of the helium created in the Sun. In June 2020, Borexino scientists announced that they had also picked up neutrinos produced by the CNO cycle for the very first time. Working out how many of these scarcer neutrinos the Sun produces will offer up an independent and invaluable way to work out the solar abundances of carbon, nitrogen, and oxygen.

LEAH TISCIONE / *S&T*, SOURCE: APS / ALAN STONEBRAKER

"Carbon-nitrogen-oxygen neutrino fluxes will be the cleanest test," Basu says. But she cautions against a quick answer. Although the first tentative results don't look good for the spectroscopists, she says "it may take a few decades to get the error bars down. It's a waiting game."

The Devil's in the Details

In the meantime, others have been searching for alternative solutions — some of them highly speculative. Qian-Sheng Zhang (Chinese Academy of Sciences) thinks that we can keep spectroscopists' lower abundances and match helioseismic measurements if we revise the way we model the Sun. This requires resolving the entire abundance problem, which isn't solely about a discrepancy in the amount of metals — the amount of helium is also in question.

Standard solar models using spectroscopists' lower metal abundances usually result in a lower amount of helium in the convection zone; otherwise the Sun would be the wrong brightness. But less helium is at odds with helioseismic measurements. In August 2019, Zhang's team presented a revised model of the Sun's interior that employs lower metal abundances while also increasing the amount of helium in the outer convection zone.

Currently, our picture of the convection zone is that material at its base heats up, rises to the surface, then cools and sinks back down. As the plasma boils, some helium settles out due to gravity, dropping into the radiative zone. But Zhang's team suggests that if some boiling material overshoots the lower boundary, it will drag the base of the convection zone deeper inside the Sun, preventing helium from settling as much and keeping the convection zone richer in helium. Accounting for this process allows the Sun to have lower metallicity while still maintaining the deep convection zone that helioseismologists measure.

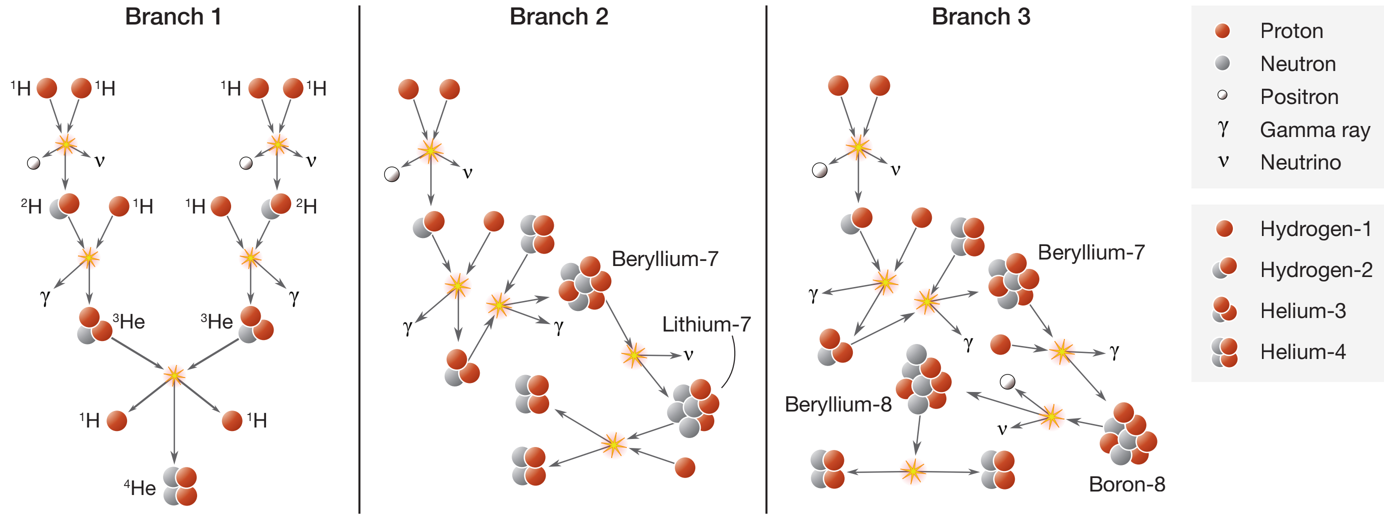
Helium was discovered by spectroscopists on the Sun before chemists identified it on Earth. That's why it's called helium: Helios was the Greek god of the Sun.

Another factor to consider is the solar wind, the stream of material blown outward by the Sun. Solar models don't typically include it, but it also affects helium abundance. Evidence from missions such as Ulysses suggests the solar wind is helium-poor compared to the normal solar surface composition. If models incorporate this effect, they see a boost in helium's abundance in the convection zone.

Finally, Zhang and colleagues found they also needed to reduce the amount of helium in the radiative zone, deep inside the Sun — a fundamental change likely made early on: The material falling onto the infant Sun would have had to be

VOLKER STEGER / SCIENCE SOURCE

▲ **LITTLE MESSENGERS** The Borexino experiment is housed underground in the Gran Sasso National Laboratory in Italy. Photomultiplier tubes line the walls of the chamber pictured here. The flashes of light they detect within a central sphere of liquid signal neutrinos coming from the Sun.



▲ **RARE REACTIONS** Most solar fusion occurs through the proton-proton chain, which fuses hydrogen into helium. About 70% of proton-proton fusion occurs through the string of reactions in Branch 1, with the rest following Branches 2 and 3 (30.9% and 0.1%, respectively). By detecting neutrinos coming from the latter two sets of reactions, the Borexino experiment has provided tentative evidence that helioseismologists are right and that the new solar metal abundances are too low. Detections of neutrinos from another, even rarer set of reactions involving carbon, nitrogen, and oxygen would provide more definitive evidence.

helium-poor. “We’ve already seen evidence of this happening with other young stars,” Zhang says.

Combined, the three processes create a complex interplay that explains observations from both sides of the standoff.

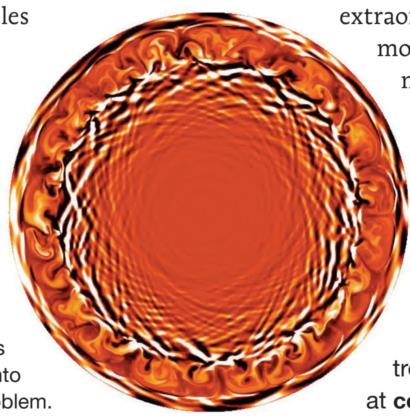
“Our model gives a perfect match to the results from helioseismology,” Zhang says. The catch is that these processes have to happen in just the right proportions to make all the pieces fit. “The range of values needed to make it work is small,” he says, “but we think it is reasonable.” It’s a rare suggestion that would see both the spectroscopists and the helioseismologists vindicated.

Anton Sokolov (Institute for Nuclear Research of the Russian Academy of Sciences) believes he has another solution, albeit one that relies on an idea far from mainstream scientific thinking. He looked for ways to change the opacity of solar material without tweaking the abundance of metals. One option is to make the radiative zone a little cooler and denser, in turn making it opaquer. To achieve this, Sokolov looked beyond the Standard Model of particle physics — scientists’ cookbook for the way particles and forces interact with one another. Physicists have long suspected there are particles beyond what the Standard Model prescribes, not least because they need them to explain dark matter, the invisible glue thought to bind galaxies like our Milky Way together.

According to Sokolov’s calculations, conditions at the top of the radiative zone are ideal for turning some of the ordinary photons the Sun creates into particles called *dark photons*. Crucially, dark photons don’t interact with ordinary solar material; instead, they stream out freely in all directions, robbing the radiative zone of energy. However, this energy loss needs to be compensated for elsewhere in the Sun to tally with observations.

For that, Sokolov turned to another so-far-hypothetical entity: *millicharged particles*. They are the product of dark matter that has settled in the solar core after being hoovered up by the Sun as it journeys through the Milky Way. According to Sokolov’s theory, these particles produce energy that warms the core and balances the heat lost farther up in the radiative zone. “Such a process would solve the solar abundance problem,” he says.

Sokolov’s solution is an extreme one. After all, as Carl Sagan famously espoused, extraordinary claims require extraordinary evidence. Yet the solar abundance/modelling problem has been a thorn in astronomers’ collective sides for nearly two decades. Although the recent Borexino CNO neutrino haul has provided a real shot in the arm, it’s clear there is much work left to do to resolve one of the trickiest issues in modern astronomy. Nothing short of our understanding of stars depends on it.



▶ **DEFINING BOUNDARIES** A 2D slice from a computer simulation shows the convection and radiative zones in the Sun. Some of the convective plumes spill past the boundary between the zones, carrying material deeper into the radiative zone. This phenomenon is known as *overshoot*, and taking it into account could help resolve the solar abundance problem.

■ **COLIN STUART** (**@skyponderer**) is an astronomy author and speaker. Get a free ebook at **colinstuart.net/newsletter**.

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