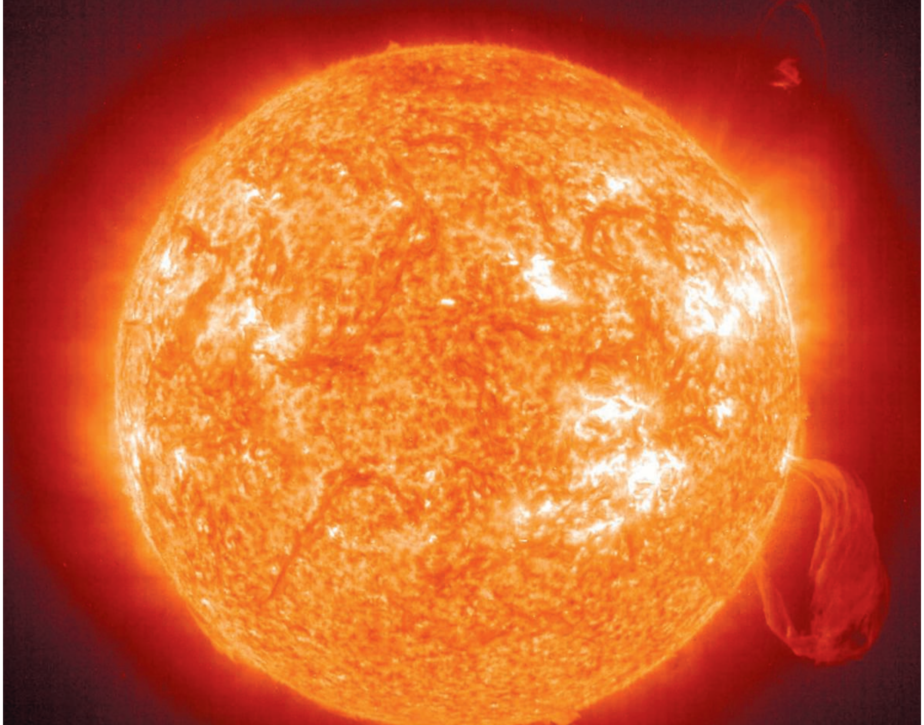

Hot topic. The sun's chemical composition is a key yardstick for astronomy.

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ASTROPHYSICS

An Unsettled Debate About The Chemistry of the Sun

Researchers thought they knew the sun very well. Now, they are squabbling over the abundance of different elements in it

On a cloudless August morning, Martin Asplund is sitting in the sun, taking a coffee break from an astronomy conference. The day is so blazingly bright it makes Asplund squint and turn away from the sunlight. But the 40-year-old astrophysicist is not shying away from a heated solar debate that he ignited a few years ago.

In 2005, Asplund came out with a new picture of the chemical composition of the sun. His calculations showed that the abundances of carbon, nitrogen, oxygen, and neon in the star—the most plentiful elements in it besides hydrogen and helium—were about half as high as researchers had previously worked out. The new values solved a puzzle, because the previous calculations had always made the sun's chemistry seem oddly out of sync with that of its galactic environment. But when researchers plugged the new abundances into models of the solar interior, the resulting predictions about the sun's temperature profile no longer matched observations. The mismatch led to a debate over which of the two was right: the new abundances or the models.

Five years later, the question has not been resolved. "We're left with a conundrum," says Asplund, who is a director at the Max Planck Institute for Astrophysics in Garching, Germany.

Getting the abundances and the models correct is not just important for studies of the sun. It has implications for other fields of astronomy, such as how stars evolve and what interstellar gas is made of. That's because the sun's elemental composition is used as the yardstick for measuring the composition of everything else in the universe, from distant galaxies to blobs of gas inside the Milky Way.

Asplund's abundances have both fans and critics among other researchers. In the past 5 years, continued skepticism—mainly by astrophysicists who model the sun's interior—has forced Asplund's group to rework its calculations using more detailed physics. As a result, the values have shifted closer to the old abundances, as Asplund and colleagues reported in a 2009 paper in the *Annual Reviews in Astronomy and Astrophysics*. But the abundances are still only about two-thirds of the older ones, and the problems that creates remain fundamentally unchanged. Researchers have tried in vain to fine-tune models of the solar interior to match the new abundances.

The debate provides a glimpse into the messy world of modeling, where results are often fraught with uncertainty and temporary truths are hammered out by the tweaking of parameters and grudging consensus. "It makes us realize that we do not understand the sun—and by extension other stars—as well as we believed," says Aldo Serenelli, a solar modeler who works with Asplund at Garching. However, he is optimistic that the effort to reconcile solar models with the new abundances will eventually lead to new insights about the sun and other stars. "This is a very healthy exercise; it's what science is about, questioning our knowledge and understanding," he says.

A star is born

The sun was of no special interest to Asplund when he got his Ph.D. in theoretical astrophysics from Uppsala University in Sweden in 1997. He was developing models of the atmospheres of old stars so that he could use those stars as markers of galaxy formation and evolution.

Previous researchers had already modeled the sun's atmosphere, simplifying their computations by flattening the solar sphere into a disk. Asplund, however, thought three-dimensional modeling of stellar atmospheres would be more accurate. Taking advantage of advances in computing, he developed a 3D picture of the turbulent gas flows and energy transfer in a star's atmosphere, taking into account the interaction between radiation and plasma.

To test his models, Asplund turned to the star for which the most data are available: the sun. Over decades of study, researchers have developed a detailed picture of how this brilliant inferno works. At its core, millions of tons of hydrogen fuse into helium every second. The energy generated by this fusion radiates outward. At about two-thirds of the way to the sun's surface, the temperature becomes cool enough (about 2.3 million kelvin) to make the gas considerably more opaque to photons. Now, convection becomes dominant. Thermal columns carry hot material up to the surface, beyond which lies the solar atmosphere. Some of the energy eventually ends up as sunlight.

Asplund's models accurately predicted the variation in the sun's brightness across the solar disk (a function of the solar atmosphere) and the intensity of sunlight at different wavelengths. Then Asplund applied a third test: checking whether his models could generate a detailed solar spectrum that matched observations. To do so, he needed to combine his models with a scheme other researchers had developed, mapping the cascade of events that occurs as radiation emanates from deep inside the sun. This scheme, known as a line formation code, describes how photons of different wavelengths interact with molecules and atoms in the gas; for example, getting absorbed by certain atoms that in turn emit other photons at new wavelengths. Together with the atmospheric models, it yields a unique spectrum for a given chemical composition.

Asplund's models passed this test as well, generating a spectrum that looked like the real one. But they also yielded abundances of carbon, nitrogen, oxygen, and neon radically lower than the previously accepted values. That was a surprise, Asplund says: "I thought things would only change a little bit as a result of 3D modeling of the atmosphere."

Asplund made a splash with the new abundances at a symposium in Austin in June 2004. The work appeared a year later in the proceedings of the conference; one of the co-authors was Nicolas Grevesse of the University of Liège in Belgium, who had been involved in calculating the earlier abundances. Stellar astrophysicists embraced the lower values, largely because they matched what researchers expected from a star that formed 4.5 billion years ago, when the galaxy was poorer in heavy elements than it is today.

Sound and fury

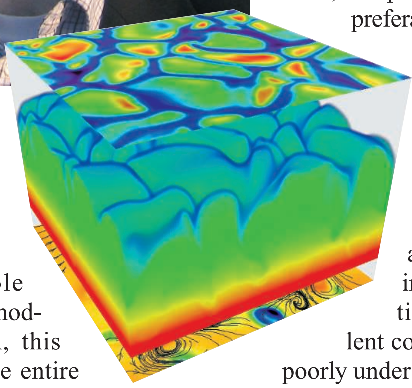
It wasn't long, however, before the new values came under attack from solar modelers. In the late 1990s and early 2000s, the old abundances had gained a foothold by helping astronomers solve a number of problems about the sun. Using them in models of the solar interior developed by Princeton University luminary John Bahcall and others, scientists had successfully predicted the characteristics of sound waves produced by the sun.

Helioseismologists can measure the speed and other features of these waves from minor changes either in solar brightness or in the position of spectral lines as the sun's surface expands and shrinks ever so slightly. From these measurements, they can infer how the temperature and density varies with depth below the solar surface. The same measurements help determine where the inner boundary of the convective envelope lies.

With the new abundances, researchers could no longer get the interior models to spit out sound speeds that matched observations. With less carbon, nitrogen, and oxygen in the mix, the material inside the sun became more transparent than previously thought. As a result, the boundary where the cooler gas became opaque to radiation—the base of the convection zone—was now pushed out toward the surface.

In August 2006, Asplund was an invited speaker at a helioseismology conference in Prague, at which the problems were discussed. "I knew that there would be some hostility," he says. Sure enough, his talk touched off a barrage of probing questions. It was clear that "they didn't believe our results, just as we didn't believe their models were correct," Asplund says. One of the skeptics in the audience—Marc Pinsonneault, an astrophysicist at Ohio State University in Columbus and an expert in modeling the sun's interior—suggested that Asplund and his colleagues had gone wrong by simulating only a small rectangular slab of the solar atmosphere instead of the whole thing.

"I decided we're going to redo everything," Asplund says. He and his colleagues



It's complicated. Asplund (*above*) developed a 3D picture (*inset*) of the sun's atmosphere.

developed "whole new atmospheric models" from scratch, this time simulating the entire solar atmosphere. "We tested them against even more observational constraints." By 2008, Asplund felt certain that his models were not the problem.

That year, Aldo Serenelli, who had worked with Bahcall on interior models, applied for a position in Asplund's lab. Asplund was enthusiastic about working with somebody from the opposition camp, especially as he himself had no experience with modeling the interior. "I hired him not to convince him but to see whether we could find a solution that may have been overlooked," he says.

Serenelli says he joined Asplund with an open mind. "The agreement between solar models and helioseismology measurements was astonishingly good with older abundances, so it was hard to dismiss those results," he says. "On the other hand, Asplund's work was by far the most sophisticated and realistic study of the solar atmosphere."

In the past 2 years, Asplund and Serenelli have only grown more convinced of their respective positions. Meanwhile, Serenelli and others have tried a number of solutions to make the interior models work with the new abundances.

One approach assumes that elements such as neon and iron in the sun have a higher opacity (or lower transparency) than researchers have assumed. That shift would wipe out some of the gain in transparency resulting from the lower abundances. "It solves a fair amount of the problem, but it isn't enough," says Sarbani Basu, an astrophysicist at Yale University.

Researchers have also played with how quickly heavier elements sink down in the sun. That has not done the trick, either. Basu says researchers could also try modifying the equation of state describing the fundamental behavior of a gas under extreme temperature and pressure conditions, which astrophysicists have to borrow from experiments at nuclear-weapons labs. But that would be fine-tuning too many parameters to make Asplund's abundances work, she says. "I'm not willing to do that. At some point, you have to raise Occam's razor," the principle that simpler solutions are preferable to more-complex ones.

Others think the problem lies with models of the solar interior. "I think the standard solar model is missing something," says W. Dave Arnett, a researcher at the University of Arizona in Tucson. Arnett and colleagues are working to improve interior models by getting a better handle on turbulent convection in stars, which is still poorly understood.

Meanwhile, Asplund's 3D models of the sun's atmosphere are no longer the only game in town. Other researchers have developed sophisticated models of their own. One group, led by Hans-Günter Ludwig of the Paris Observatory, has produced abundance values somewhat higher than Asplund's, although still much smaller than the old values.

The continuing discrepancy "would suggest either new physics—exciting, if unlikely—or major errors in the existing physical ingredients of the models, which would have to be tracked down," says Pinsonneault. It's hard to predict what the outcome of such efforts would be, he adds, "but it could be very important for our understanding of the physics of stars."

–YUDHIJIT BHATTACHARJEE

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