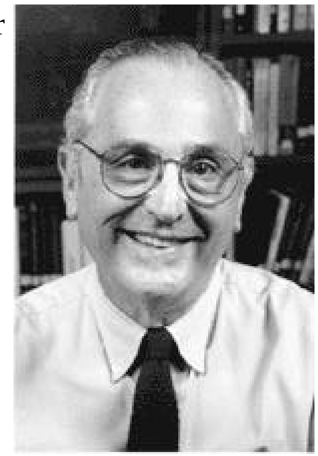
Universe, 5th Ed., by W. J. Kaufmann and Roger Freedman (New York: W. H. Freeman, 1998), pp. 452--453

JOHN N. BAHCALL

Searching for Neutrinos Beyond the Textbooks



When John N. Bahcall went in search of solar neutrinos, he applied atomic and nuclear physics to the stars. In his many areas of expertise, in fact, Dr. Bahcall studies just that interplay between the theories of physics and our understanding of the heavens. At the Institute for Advanced Study in Princeton, New Jersey, he has looked at emerging models of our Galaxy, dark matter, stellar evolution, and the spectra of quasars. He has also received the NASA Distinguished Public Service Medal for his work with the Hubble Space Telescope.

After graduate school at Harvard University, Dr. Bahcall joined the faculty of the California Institute of Technology, where he remained until 1971. A former president of the American Astronomical Society, he recently chaired the National Academy Design Survey Committee for astronomy and astrophysics. His research on solar neutrinos earned him the Heinemann Prize of the American Astronomical Society.

In attempting to understand how the Sun shines, physicists, chemists, and astronomers have been confronted with a mystery -- the case of the missing neutrinos. These exotic particles travel at essentially the speed of light. They are so elusive that they can traverse a thousand light-years of lead before being stopped.

Physicists and astronomers believe that the Sun shines because of the conversion of hydrogen nuclei (protons) into helium nuclei (alpha particles), with the subsequent release of a substantial amount of nuclear energy. The same basic process, _nuclear fusion_, produces the explosion of a hydrogen bomb. We think that about 600 tonnes (or 6 x 10^5 g) of hydrogen are converted to helium every second in the Sun's central regions, providing the energy that we know as sunlight and making life on Earth possible.

In the early 1960s, Ray Davis and I proposed to test the theory of how the Sun shines. Ray, a chemist at Brookhaven National Laboratory, had developed a neutrino detector that uses a cleaning fluid containing chlorine. Using standard theories of physics and astronomy, I calculated the rate at which neutrinos are produced in the Sun. I could then predict the rate at which neutrinos should be captured in the largest detector Ray could build. If my calculations matched experiment, they would confirm that the Sun shines by nuclear fusion in its interior.

The actual experiment used a 100,000 gallons of perchloroethylene, about enough to fill an Olympic swimming pool. Ray Davis and his collaborators put their detector in a deep gold mine, to shield it from other particles that hit the surface of the Earth.

To everyone's surprise, Ray's chlorine detector captured many fewer neutrinos than I had predicted. The results were challenged and checked repeatedly over the following three decades, but always with the same result: many neutrinos appear to be missing!

The case of the missing neutrinos has grown stronger with time. Three other experiments, each with a different type of detector, searched for neutrinos from the Sun. They all found fewer than I predicted.

What could be wrong? Where have the neutrinos gone? There are three possibilities: either the experiments are wrong, the standard model of how the Sun (and other stars) shine is wrong, or something happens to the neutrinos after they are produced. New experiments are now underway in Japan, in Italy, and in Canada to test these hypotheses.

Right now most people working in the field think that the last of the three explanations is most likely to be correct: only physics beyond the standard textbooks can describe what has happened to solar neutrinos. Somehow, most physicists think, neutrinos created in the solar interior change into neutrinos that are more difficult to detect as they pass out of the Sun and travel to the Earth. They change their personalities, so to speak! If this is correct, it would be the first experimental demonstration of a process beyond the standard model of particle physics.

So far, the evidence for new physics is only circumstantial. We know only that the results differ markedly from the predictions based upon our understanding of how the Sun shines. Future experiments are designed to search for a "smoking gun" -- unequivocal evidence of processes not in the physics textbooks. These new experiments will use the fact that neutrinos come in different types. Most easily detected are the so-called _electron-type_ neutrinos; more difficult to detect are _muon-type_ and _tau-type_ neutrinos. Suppose some from the Sun convert into neutrinos that are easier to detect as they pass through the Earth at night on their way to the detector. The change would make the Sun appear brighter at night than in the day. If that were seen, it would provide a dramatic demonstration that unconventional physics is occurring.*

If a smoking guns is found, it could offer a clue to new laws of particle physics, the laws governing the smallest scales of matter. Observations of solar neutrinos, together with laboratory experiments still to come, might reveal evidence that neutrinos have tiny masses. Conceivably, their masses could then account for much of the pervasive "dark matter" in the universe.

I do not know the correct explanation for the missing neutrinos. However, the particle-physics explanation has a mathematical beauty and simplicity that are very attractive. If the deity has not chosen this solution to the mystery, then he or she has missed an excellent opportunity to enrich the laws of the universe.

However, the real message of the experiments on solar neutrino is even more remarkable. It is that working on the frontier of science, you may stumble across something that is beautiful and unexpected. We do not yet know if this has indeed happened in the study of solar neutrinos, but we do know that future experiments will solve the mystery for us. Their outcome might point the way to a better understanding of fundamental physics and the stars.

Note added in proof*: Just as this book was going to press, scientists at the Super Kamiokande neutrino observatory in Japan reported having observed an effect of just this type. Their results indicate that electron-type and muon-type neutrinos can indeed transform into each other as they pass through matter, an effect called *neutrino oscillation*. The most recent results from Super Kamiokande can be found on the World Wide Web (http://www.phys.washington.edu/~superk/** or **http://www.phys.hawaii.edu/~superk/**).