

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 developed 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 and other research areas earned him the Warner, Heinemann, and Russell Prizes of the American Astronomical Society and the National Medal of Science. He is president emeritus of the American Astronomical Society and will become president of the American Physics Society in 2006.

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 6×10^{11} kg) 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. In effect, we proposed using neutrinos to look into the center of the sun in much the same way your daughter uses x-rays or ultra-sound to look into the interior of your body.

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 grew stronger with time. By the early 1990's, three other experiments, each with a different type

of detector, searched for neutrinos from the Sun. They all found fewer than I predicted.

What was 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. Since different experiments all showed that fewer neutrinos were detected than I predicted, it seemed that the culprit was either the standard model of physics or the standard model of the sun.

In the 1990's, seismic measurements made with optical light on the surface of the sun confirmed predictions of the standard solar model to high precision. The speed of sound within the solar interior that was predicted by the standard solar model agreed with the helioseismological measurements to extraordinary accuracy, to better than 0.1%. Many physicists began to acknowledge that our understanding of basic physics needed to be corrected, rather than our understanding of how the sun shines.

Finally, in the last decade of the 20th century and in the first few years of the 21st century, the mystery of the missing neutrinos was decided definitely by new experiments in Japan and Canada.

The Canadian and Japanese solar neutrino experiments show that 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. The neutrinos change their personalities, so to speak! Most easily detected are the so-called electron-type neutrinos; more difficult to detect are *muon-type* and *tau-type* neutrinos. The new neutrino detectors in Japan and Canada provide clear experimental demonstrations of physical processes, neutrino personality changes, which cannot be described correctly by the standard model of particle physics.

The peculiar behavior of neutrinos, their oscillation between different neutrino types,

offers a clue that may help lead us to new laws of particle physics, the laws governing the smallest scales of matter. The observed changes from one neutrino type to another imply that neutrinos have tiny masses. Since ordinary telescopes that detect light cannot see neutrinos, we know that neutrinos account for some of the mysterious "dark matter" in the universe. Unfortunately, the simplest interpretations of the solar neutrino experiments suggest that neutrinos constitute only about 0.1% of the dark matter.

However, the real message of the experiments on solar neutrinos is even more remarkable. The history of solar neutrino research shows that if you work on the frontier of science, you may, while looking for something quite different, be lucky enough to stumble across something that is beautiful and unexpected.