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How does the Sun shine?

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Is there something new under the Sun? Has the measurement of solar neutrinos revealed new, fundamental physics or exposed poorly understood astrophysics? What can be inferred from the 10,000 accurately measured frequencies of seismological oscillations on the surface of the Sun? How accurate are the astrophysical data used in interpreting solar and stellar observations? It is difficult for a researcher working on one aspect of the Sun to be sure what is being tested using different techniques, and even more difficult to be certain what has been established firmly and what requires further investigations, which is why astronomers, astrophysicists, chemists and nuclear and particle physicists gathered recently*, with high hopes, to discuss the interior of the Sun. The result was a surprising consolidation of conventional wisdom in the face of an avalanche of new experimental and theoretical results.

The standard model of the Sun makes many quantitative predictions about the solar interior, none of which was directly testable before the introduction of the techniques of observing solar neutrinos and of solar pressure (acoustic) waves, both begun in the 1960s. Some people must have left the recent meeting thinking, as researchers have been saying for two decades because of the discrepancy between the predicted and detected flux of high-energy neutrinos from the Sun, that we are on the verge of discarding the conventional wisdom about the nature of stellar interiors. Just one more factor of two improvement in the measurements will surely reveal a fundamental flaw in our current understanding. In the meantime, the theoretical calculations improve, the data become more precise and the systematic uncertainties are better understood.

New observational and theoretical results were presented on solar neutrinos, which carry information directly from the hydrogen-burning core of the Sun. The Kamiokande II collaboration reported [1] a definite measurement of the flux of the higher-energy neutrinos which arise from boron-8. The flux is about a factor of two lower than that predicted by the standard (Bahcall-Ulrich) solar model. This provides the first experimental confirmation of the solar-neutrino problem after more than two decades of consternation based upon measurements with a single (chlorine) detector. The new result is of epochal importance because it demonstrates that the observed neutrinos do come from the Sun; the neutrinos are de-

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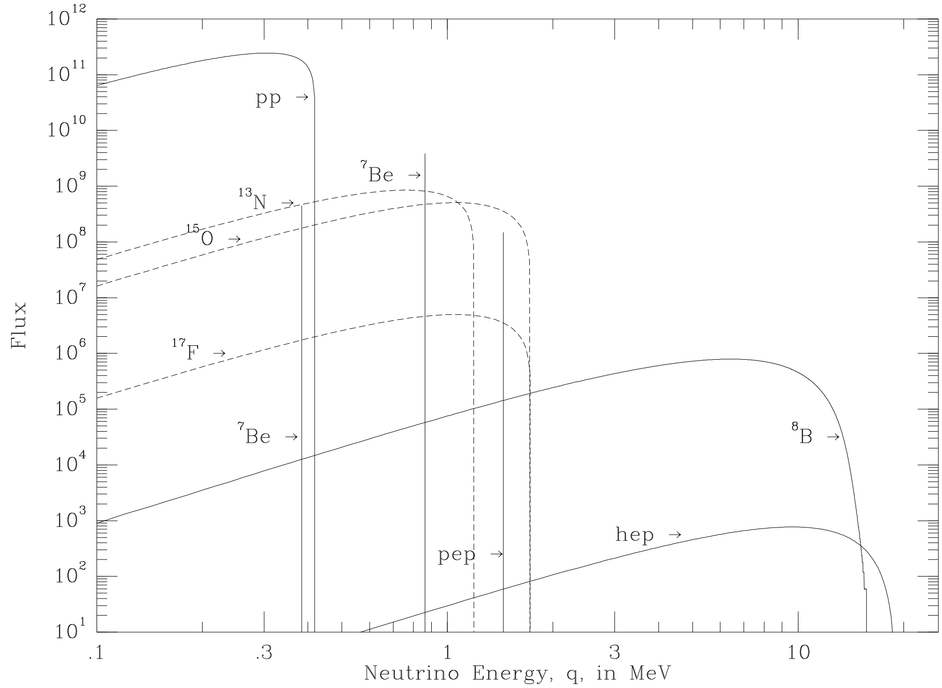
*_Inside the Sun_, IAU Colloquium 121, Versailles, 22–26 May 1989 tected by the recoil of scattered electrons, and these are observed to move in the Earth-Sun direction. The direction of the neutrinos is not revealed in radiochemical experiments such as the chlorine experiment of Davis.



An outstanding experimental challenge for the next decade is to measure accurately the form of the solar-neutrino spectrum. The figure shows the spectrum for each of the contributions included in the standard solar model. A precise spectrum should provide a decisive test of whether the solar-neutrino problem—the discrepancy between the predicted and measured flux—is caused by our lack of understanding of the solar interior or by new physics. The shape of each contribution to the spectrum will remain the same, whatever modification is made to the standard solar model, unless non-standard electroweak effects, such as neutrino oscillations have to be invoked. (From J. N. Bahcall *Neutrino Astrophysics*; Cambridge University Press, 1989).

The measurement uncertainties in the scattering rate determined by Kamiokande are, however, still too large (plus or minus 30 per cent, one standard deviation) to permit secure conclusions about either new physics or the solar model. More precise results are expected in the next few months. The first results from the Soviet-American gallium detector in the Caucasus were described. An unexpectedly large background was observed, which may be removed by further experimentation. The initial experimental measurement of the solar signal, which should go a long way towards deciding in which direction the solution of the solar neutrino puzzle lies, should be available "soon."

Pure reason scored an apparent victory at the meeting. Small discrepancies between the measured and calculated frequencies of pressure oscillations observed in optical light on the surface of the Sun led different groups, especially those at the University of California, Los Angeles [2] and at Los Alamos National Laboratory (reported by A. Cox), following an earlier suggestion by Christensen-Dalsgaard et al. [3], to the conclusion that the opacity of matter at moderate stellar temperatures had previously been under estimated. The suggested correction to the commonly used tables of atomic opacities (about 15 per cent or so at temperatures of several million degrees) is confirmed by more accurate, detailed opacity calculations (C. A. Inglesias, Livermore National Laboratory). Opacities calculated for the higher temperatures characteristic of the solar interior are now in good agreement (to within 1 per cent or less) with the values used in the standard-model calculations of the solar-neutrino fluxes.

Helioseismology yields a precise, rich characterization of aspects of the solar interior. Many thousands of oscillation frequencies have been measured with a precision approaching 0.01 per cent. A comparison of solar-model calculations with some of the earliest measurements of pressure-wave frequencies showed that the depth of the solar convective zone is somewhat deeper than previously believed.

Subsequent observations of the splitting of the frequencies of different standing waves caused by the asymmetry of the solar rotation are interpreted in terms of a relatively constant rotation rate with depth below the solar surface. No evidence has yet been obtained that there are extremely strong magnetic fields or that the solar core is rotating very rapidly, two frequently discussed non-standard solutions to the solar-neutrino problem.

Pioneering calculations for the conditions in the innermost Sun (out to a fifth of a solar radius) were presented by different theorists who have used similar helioseismological data. The independently derived numerical solutions for the physical conditions differ greatly inside the solar core, indicating that the problem of determining characteristics of the solar interior from oscillation data is not solved.

Two other problems were particularly controversial. WIMPS—weakly interacting massive particles—are hypothetical objects that could account for the missing astronomical mass and explain the solar-neutrino problem. (If they exist, WIMPs can transport energy efficiently in the solar core, lowering the central temperature and the high-energy neutrino flux as well as changing the sound speed.) John Faulkner (University of California, Santa Cruz) forcefully argued that their effects can be discerned in existing pressure-oscillation and other stellar data; several other theorists could find no such evidence in the best data.

Second, an apparent increase in the neutrino flux detected by the US chlorine detector may indicate a correlation, some argued, with the sunspot cycle, which is currently approaching its maximum. Douglas Gough (Cambridge University), who combined humour with insight in his summary talk, pointed out that it is not surprising that Ray Davis (University of Pennsylvania) finds his observations of possible variations highly suggestive and that I, having contributed to the standard model which gives no hint of an explanation of such variations, should find the data statistically unconvincing.

With new detectors to measure the energy spectrum and precise time dependence of solar neutrinos, and terrestrial global networks, as well as polar observations and space experiments to determine more precisely the spectrum of pressure oscillations, solar physics is in a renaissance period. Similar techniques have produced indications of oscillations on the surfaces of other stars and many are optimistic that definitive measurements will be forthcoming shortly. To date, the most surprising thing is that not much has been shown to be definitely new under the Sun.

Surely, new data will lead soon to big surprises concerning the interiors of stars. Won't they?

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[1] Hirata, K.S. *et al. Phys. Rev. Lett.* **63**, 16–19 (1989).

[2] Korzennic, S.G. & Ulrich. R.K. *Astrophys. J.* **339**, 1144–1155 (1989).

[3] Chnstensen-Dalsgaard, J. *et al. Nature* **315**, 378–382 (1985).