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A star of contradictions

By Mark Buchanan

Recently, physicists in Japan have upgraded the Super-Kamiokande neutrino detector by dissolving a small amount of gadolinium sulfate into its 50,000-ton volume of pure water. Gadolinium absorbs neutrons, and when a neutrino interaction in the detector knocks a neutron free, a gadolinium nucleus captures it within microseconds. This in turn generates a cascade of gamma rays providing an unambiguous signature that distinguishes true neutrino events from background noise. With this improvement, Super-Kamiokande has become one of the most sensitive instruments ever built for observing solar neutrinos, allowing physicists to probe the nuclear chemistry of the Sun with a precision unimaginable only a decade ago. Super-Kamiokande's upgraded phases build on the landmark 2020 detection at the Borexino detector in Italy of elusive CNO neutrinos, produced when hydrogen fuses into helium through the carbon–nitrogen–oxygen catalytic cycle.

As a result, solar neutrinos now play a key role in refining our understanding of stellar interiors. Yet the gains in accuracy have sharpened some predictions while unsettling others. Most dramatically, they have intensified the mismatch between seismic models and spectroscopically inferred surface metallicity – the so-called solar composition problem. Measured CNO neutrino fluxes point toward a solar core richer in heavy elements than the best atmospheric models allow. Meanwhile, updated measurements of other key fusion reactions – such as $^{3}\text{He} + \alpha \rightarrow {}^{7}\text{Be}$ and $^{7}\text{Be} + \text{p} \rightarrow {}^{8}\text{B}$ – combined with improved pp-chain neutrino determinations, have highlighted discrepancies in radiative opacity, the physics governing how energy propagates outward from the core.

This new landscape is at once a crisis and a chance for reinvention. A recent review by Bijaya Acharya and colleagues (*Rev. Mod. Phys.* **97**, 035002; 2025) surveys recent progress while laying bare the tensions resulting from this precision revolution. The Sun – long treated as a solved problem – now seems full of subtle contradictions.

In 1938, German physicist Hans Bethe published the first explanation of how the Sun and other stars generate energy through proton–proton fusion. By the 1980s and 1990s, developments in helioseismology and neutrino physics had refined Bethe's ideas into a standard solar model that reproduced seismic sound-speed profiles with impressive precision. Once researchers understood and incorporated neutrino oscillations, the model accounted for all known neutrino data.

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But as Acharya and co-authors relate, this sense of completion vanished in the mid-2000s when improved hydrodynamic models of the solar atmosphere triggered revisions to the best estimates of surface abundances. The inferred concentrations of carbon, nitrogen, oxygen, and other heavy elements dropped by nearly 30%. This shift led to immediate inconsistencies: the convection-zone boundary moved to the wrong depth, the sound-speed profile lost its excellent agreement, and the predicted surface helium abundance no longer matched seismic inferences. The Sun no longer fit its own model.

Recent neutrino measurements complicate matters further. The flux of CNO neutrinos scales directly with the core's carbon and nitrogen content and provides the first empirical handle on the Sun's interior metallicity. Intriguingly, the observed flux leans toward a higher metallicity than spectroscopic models predict. This suggests that either our spectroscopic methods are flawed, or our understanding of the physics of the solar interior (including opacity, mixing and diffusion) is significantly incomplete. Future progress will depend on tightening CNO neutrino measurements, improving radiative-opacity calculations, and perhaps revising atmospheric models.

A second major issue that the authors highlight is radiative opacity, a quantitative measure of how impenetrable the solar plasma is to radiation. This impenetrability is determined by the microscopic physics that governs how the solar plasma absorbs, scatters and re-emits photons. For decades, opacity tables were trusted building blocks of solar modelling. Yet helioseismology now suggests that opacities in the radiative zone are 5–15% too low, depending on depth. Laboratory experiments using facilities like Sandia's Z machine have even found that the iron opacity – a crucial contributor – may be substantially higher than theoretical predictions. Because a small increase in opacity deepens the convection zone and alters the temperature profile, opacity underpins the solar composition problem and is rapidly becoming one of the central unknowns in stellar astrophysics.

Acharya and colleagues also revisit the nuclear reaction rates themselves, which have been improved by experiments at advanced underground labs such as LUNA in Italy and Felsenkeller in Germany. Shielded from cosmic rays, experiments at these facilities have refined the low-energy fusion cross sections for critical steps in the pp-chain. Meanwhile, inertial-confinement plasma experiments have begun to probe electron-screening effects directly under near-solar conditions – something previously not possible. Some reaction rates have shifted by a few percent, which is enough to alter predicted neutrino spectra. Even the shape of the ^{8}B neutrino spectrum, a staple of solar neutrino studies, has been revised downward in energy by tens of keV.

Therefore, the Sun is no longer the tidy, well-understood object it seemed to be a few years ago. The revolution inspired by new neutrino data reveals multiple tensions as neutrinos, seismic waves, opacities, and spectral lines tell slightly different stories. That divergence is what makes the present moment exciting. With new detectors coming online and new laboratory measurements probing previously unreachable regimes, the next twenty years may see Bethe's foundational picture not overturned but enriched. The Sun's simplicity was an illusion born of incomplete data.