Solar conundrums

Richard D. Petrasso

Blinded by the Light: The Secret Life of the Sun. By John Gribbin. *Bantam: 1991. Pp. 226. £14.99.*

THE Sun, from ancient to modern times, has been pre-eminent in developing man's understanding of the Universe. In the fifth century BC, Anaxagoras showed it to be a 35-mile-diameter ball of fiery stone orbiting 4,000 miles overhead. In the late nineteenth century, Lord Kelvin (William Thomson) limited its age to a mere 25 million years. And today, exotic particles called WIMPs are hypothesized to orbit within its core. Of course, Anaxagoras's and Lord Kelvin's conclusions proved to be far off the mark, yet both men made mathematically impeccable calculations based on the best though flawed assumptions of their eras. And what about today's WIMPs? Are they, as claimed, the basis of a solution to the outstanding solar neutrino problem?

Such issues and questions form the grist of *Blinded by the Light*. By focusing on the conundrums of the Sun's energy production and age, Gribbin paints an engaging picture of how science evolves, pivotal false starts and all. And for those with an interest in the dramatic interplay between physics, biology and geology in the nineteenth century, no more-illuminating episode exists than the controversy over the age of the Sun and the Earth.

This controversy, as Gribbin notes, pitted Charles Darwin against Lord Kelvin. Darwin was greatly influenced by Charles Lyell's 1830 treatise on the immeasurably vast times needed for geological evolution and by the immense timescale needed for his own theory of biological evolution. On this basis, he qualitatively estimated that the denudation of the chalk cliffs of the Weald in Kent took roughly 300 million years and, therefore, that the age of the Earth was much greater. By contrast, Kelvin, having quantified Herman von Helmholtz's hypothesis of heat generation by way of nebular gravitational condensation, obtained 20 million years as the probable duration of the Sun's energy production. In an article published in *Macmillans Magazine* in 1862, Kelvin belittled Darwin's estimate:

> What then are we to think of such geological estimates as 300 million years for the 'denudation of the Weald'? Whether is it more probable that physical conditions of the sun's matter differ 1000 times more than dynamics compel us to suppose they differ from those of matter in our laboratories; or that a stormy sea, with possibly channel tides of extreme violence, should encroach on a chalk cliff 1000 times more rapidly than Mr. Darwin's estimate of one inch per century?

Through this and other quotations and discussion, Gribbin effectively highlights this debate. But I disagree with his view that Darwin's wealden estimate was "rather careless". This misses a fundamental point. In a subsection of the first edition (1859) of *The Origin* entitled "On the Lapse of Time...", Darwin admirably and severely reined in Lyell's immeasurably vast times by intelligently discussing the accumulation and denudation of geological features, ending with the wealden estimate that he freely admits is both "crude" and "highly imperfect". Nonetheless, this was an original accomplishment and a serious effort to establish a concrete timescale based on a geological record. (20 million years is the upper limit for a present-day estimate of the wealden denudation.)

So why did Kelvin so high-handedly attack Darwin's estimate? Part of the answer is rooted in the seductive rigour afforded by his own calculations, and the lack thereof in Darwin's. But undercurrents in Kelvin's written work indicate still more was involved. Specifically, Kelvin goes on to admit in his 1862 article that, owing to material uncertainties, an extreme upper limit of 500 million years exists for the solar duration. From this and other inconsistencies, I am left with the impression that Kelvin was annoyed by Darwin's *Origin* because he thought it challenged his own deep-rooted belief in the ordained status of the "race of intelligent beings".

It is unfortunate that neither Gribbin nor most other recent writers on the history of solar science consider the seminal contributions of the physicist Homer Lane. While Kelvin and Helmholtz were treating the Sun as a white-hot fluid of generally unknown properties unamenable to detailed analysis, Lane published in 1870 in the *American Journal of Science* a detailed calculation of the Sun's temperature and density. By assuming the validity of the perfect gas law and hydrostatic equilibrium, Lane obtained a central temperature and density of the order of 20×10^6 K and 30 g per cm^3, a stunning achievement considering today's values of 15×10^6 K and 150 g per cm^3. This is all the more impressive when one considers that Lane could not have known that the Sun consists of a plasma of electrons and ions also subject to the perfect gas law and hydrostatic equilibrium. Even Kelvin was struck by the "great power" of Lane's calculations. Nevertheless, in his 1887 address ("On the Sun's Heat") to the Royal Institution of Great Britain, Kelvin argued that Lane's estimate of the central density (but not temperature) should be "much reduced". (Here Gribbin also errs in claiming that in that address Kelvin did not properly credit Helmholtz for the condensation model.)

Gribbin then goes on to describe how Henri Becquerel's revolutionary discovery in 1896 of radioactivity demolished Kelvin's age estimates for both the Sun and the Earth. Savour the irony of subsequent developments when the astrophysicist George Darwin, son of Charles and nonetheless younger col-

Mary Evans

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The conundrum over the age of the Earth and Sun pitted Kelvin (left) against Darwin. Because Darwin's theory of evolution required vast periods of time, Darwin was increasingly pained by the apparent invincibility of Kelvin's shrinking estimates for the solar duration, which eventually converged to about 25 million years.

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league of Kelvin, conjectured in 1903 in this very journal:

> We have recently learnt the existence of another source of energy, and that the amount of energy available is so great as to render it impossible to say how long the sun's heat has already existed, and how long it will last in the future . . . I think we have no right to assume that the sun is incapable of liberating atomic energy to a degree at least comparable with that which it would do if made of (Becquerel's) radium.

Indeed, radioactivity is the driving force behind the Earth's heat, and 'atomic energy', in the form of fusion, powers the sun, not gravitational condensation as Kelvin and Helmholtz had assumed. With this and the advent of radioactive dating, the age of the Earth and the Sun unequivocally jumped to the order of 1,000 million years. (Early in Gribbin's book, an unfortunate misprint indicates 1,000 billion years.)

Arthur Eddington took one of the next critical steps when, in his 1920 address at Cardiff, he suggested that the "transmutation" of four protons into helium, through which 0.7 per cent of the proton mass is converted to energy, is the crucial solar reaction. As Gribbin notes, Eddington's idea was received with scepticism because classical arguments showed that the repulsive Coulomb barrier between protons could not be surmounted at the relatively cold temperature of 40×10^6 K, a value Eddington calculated for the solar core. Furthermore, the chemical composition of the Sun was (erroneously) viewed in this period to mirror the Earth's, thereby implying a paucity of solar hydrogen. Gribbin quotes Eddington's defiant retort to his critics:

> The helium which we handle must have been put together at some time and some place. We do not argue with the critic who urges that the stars are not hot enough for this process; we tell him to go and find a hotter place.

Eddington was to be proven correct about the fusion of protons into helium. But it is with this oft-quoted riposte that Gribbin misses the opportunity to point out that Eddington's adamance was driven by a serendipitous misconception: the helium that we observe and to which Eddington refers derives not from stellar fusion but from the fusion occurring in the first moments of the Universe. Without this misconception, the discovery of fusion might well have been postponed for several years. (Also, Gribbin mistakenly lauds Eddington, not the forgotten Homer Lane, for the first application of the perfect gas law to stars.)

In the decades following George Gamow's insight in 1928 that penetration of the Coulomb barrier is allowed quantum-mechanically, there was a sequence of remarkable discoveries that led to a detailed picture of both stellar fusion processes and stellar interiors. One important consequence, as recounted by Gribbin, was the quantitative prediction of the flux and energy spectrum of fusion-generated solar neutrinos, ghostly particles that were originally postulated by W. Pauli in 1930 to conserve energy and momentum in laboratory β-particle decays. Because of their weak interaction, neutrinos immediately escape from, and convey information about, the solar core. In contradistinction, fusion energy deposited in the solar core from γ rays and from energetic charged particles requires some 10 million years to reach the Sun's surface, a period fittingly known as the Kelvin–Helmholtz time. Truly we are warmed today by prehistoric energy. But it is these elusive neutrinos that give rise to the prominent solar conundrum: after 25 years of meticulous measurements and calculations, why is the flux of neutrinos that reach the surface of the Earth between one-third and one-half the number predicted? Are both the Brookhaven and Kamiokande neutrino experiments in serious error? Or, alternatively, are we in a situation akin to Kelvin's, in that our rigorous calculations omit an essential, albeit hitherto unknown, element of physics?

Unabashedly, Gribbin takes the latter perspective and advances the imaginative hypothesis based on WIMPs. In essence, WIMPs enhance the transport of thermal energy from the Sun's core to just outside. This reduces the central temperature from 15×10^6 K to 13.5×10^6 K. Since neutrino production is strongly dependent on temperature (to about the seventh power for detected high-energy neutrinos), this ten per cent reduction in core temperature would halve the flux of neutrinos, thereby reconciling theory and experiment. But herein begins the first delicate balancing act: one cannot just lower the central core temperature without also notably reducing the fusion power, which also is strongly dependent on temperature (to about the fourth power). So to maintain a fixed solar output, the central reduction in power needs to be exactly matched by an increase farther out. Supposedly WIMPs do all this and more, prompting John Bahcall in his book *Neutrino Astrophysics* (Cambridge University Press, 1989) to quip that if one must invent a particle, the WIMP at least has the virtue of utility. Bahcall in fact advocates an alternative solution to the neutrino problem that is based on neutrino oscillations, the so-called Mikheyev–Smirnov–Wolfenstein effect. These oscillations, which would render a large fraction of neutrinos unobservable, have just gained further support from the Soviet–American Gallium Experiment (SAGE).

WIMPs have other strengths, according to Gribbin. For example, they have also been proposed as candidate particles for the dark-matter in the Universe. In this model, 90 per cent of the mass of the Universe resides in weakly interacting particles, their ethereal presence betrayed only by gravitational effects on clusters of galaxies and gas clouds orbiting galaxies. Notwithstanding, I believe that the WIMP hypothesis will remain unconvincing unless WIMPs are directly detected or a compelling theoretical framework is obtained for their existence. The latter, for example, was what Enrico Fermi did for Pauli's neutrinos some 20 years before their direct detection.

To his credit, Gribbin skillfully weaves into the fabric of this story many important physical concepts and concrete numbers without stifling the book's flow. Overall, blemishes are infrequent, although three warrant comment. First, in his discussion of the WIMP hypothesis and the gravitational condensation model, Gribbin implicitly overemphasizes the importance of black-body radiation pressure in comparison to kinetic pressure (that due to electrons and ions). For *solar-mass* stars, the core kinetic pressure is three orders of magnitude larger. Gribbin apparently gets his emphasis from Eddington who, in *The Internal Constitution of the Stars*, gives a value of the kinetic pressure only one magnitude larger than the radiative pressure. Second, although radiative energy transport dominates the first three-quarters of the radial distance of solar-mass stars, the 'resistance' (that is, opacity) to the black-body photons is due to electrons (not protons), electrons in the field of ions, and other mechanisms. And third, the proportion of the Sun's energy flux immediately escaping the solar core via neutrinos amounts to about two per cent, not ten. Surprisingly, perhaps, if it were ten per cent, it is unlikely that any of us would exist. This is because solar evolution and light output would be slightly altered.

Certainly these few points do not detract from the enjoyment and edification provided by the book, and I recommend it. In particular, the recalcitrant solar-neutrino problem, described well by Gribbin, should be viewed as a distinct opportunity for science because it pushes us decisively against the very limits of our knowledge of neutrinos, stellar interiors and particle physics. In his prescient address of 1920, perhaps Eddington overstated the case when he remarked that we know more about the fiery globe overhead than the cooler one underfoot. □

Richard D. Petrasso is at the Plasma Fusion Center, Massachusetts Institute of Technology, 167 Albany Street, Cambridge, Massachusetts 02139, USA.

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