The Enigmatic Origins of Li in Sun-like Stars[*]

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What will happen to our Sun when it ages? Where do the chemical elements in the Universe come from, and in particular, what is the origin of the rare element Lithium (Li)? These questions are intimately linked to the processes of stellar evolution and nucleosynthesis. The recent study by Kumar, Reddy et al. (*Nature Astronomy*, 2020) seeks to answer these questions by looking at large samples of stars obtained by on-going astronomical surveys.

Out of all of the elements in the periodic table, the light element Li is quite special. It is one of the only three elements that was made by the Big Bang, alongside hydrogen and helium. Following the Big Bang, which started our Universe roughly 14 billion years ago, stars formed, aged and then died, releasing their nucleosynthesis products into galaxies. New generations of stars formed from this material, which was slightly more enriched in elements heavier than Li (e.g., carbon, oxygen, iron) than previous generations. While this story of element synthesis with cosmic time—or chemical evolution—works well for most elements, it doesn't work so well for lithium.

Why is this? Lithium is easily destroyed by proton-capture nuclear reactions at relatively low stellar temperatures, but it is difficult to create. The reaction $^{7}\mathrm{Be} + \mathrm{e}^{-} \rightarrow {}^{7}\mathrm{Li} + \nu_e$ can create the dominant isotope of lithium, ^{7}Li, where the amount created depends on the initial supply of ^{3}He, which itself is also created by proton captures via $\mathrm{d} + \mathrm{p} \rightarrow {}^{3}\mathrm{He} + \gamma$ (see *Figure* 1 for a description of the symbols and reaction chains involved). The lithium created is destroyed again by the reaction $^{7}\mathrm{Li} + \mathrm{p} \rightarrow 2\,^{4}\mathrm{He}$. This last reaction occurs at temperatures of only about 3 million degrees Kelvin, much lower than we predict for the central temperature of the Sun, which is closer to 15 million K.

Computer simulations show that Sun-like stars, which are converting hydrogen to helium at their centres, have depleted their initial supply of Li by the reaction described above. Stars in this stage of evolution are known as 'main sequence stars' (see *Figure* 2) [1]. When stars age, they expand to become red giants, where the position of red giant stars is shown on a Hertzsprung-Russell (HR) Diagram in *Figure* 2. In the process, some of the products of the hydrogen fusion reactions shown in *Figure* 1—which is devoid of all Li by now—is mixed to the stellar surface by convective currents. Convective currents mix material from deep within the stellar interior to the surface, where they can be observed by us on Earth, using powerful telescopes. [1] For an overview of stellar evolution, we refer to Hansen, Kawaler, and Trimble (2004).

What we see is that the atmospheres of red giant stars become devoid of Li as they age. On the red giant branch, the cores of Sun-like stars are compressed by contraction, and

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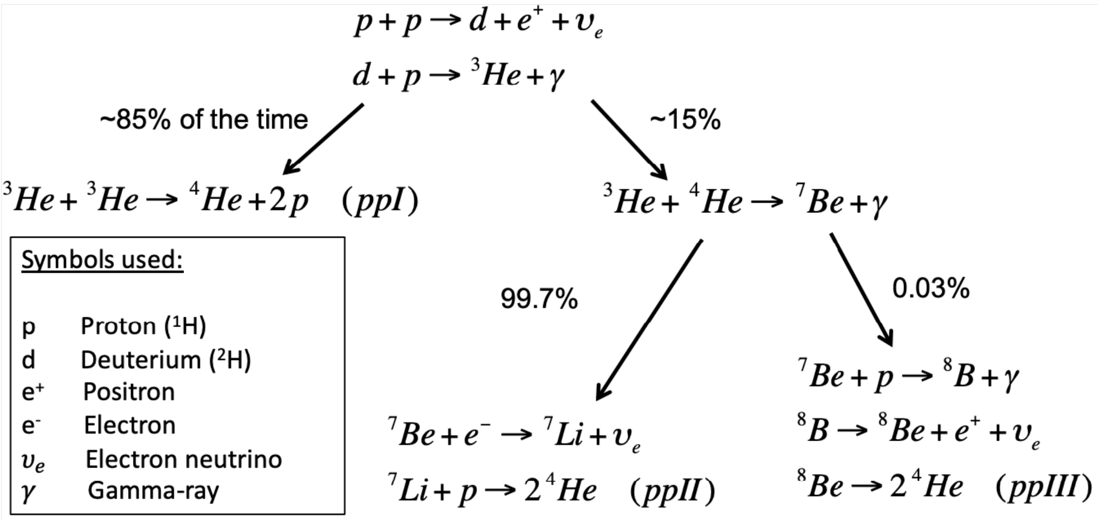

Figure 1: Reaction rates involved in the proton-proton (pp) chains. The percentages are shown for conditions at the core of our Sun.

they grow hotter until eventually, they reach temperatures high enough to sustain helium fusion reactions—about 100 million K. The net result of these reactions is that three helium nuclei combine to form one atom of ^{12}C. This phase of stellar evolution is known as the ‘red clump’ (see *Figure* 2). During this phase of evolution, the computer models predict no change to the surface composition of elements, including for the element Li.

Indeed, it is only after the star ascends the asymptotic giant branch that a special set of conditions can occur that allows for substantial Li production. These set of conditions are described by the Cameron-Fowler mechanism and requires freshly made Li to be transported out of a hot region by convection, into a cooler region of the star (say near the stellar surface). In this case, the freshly created Li will be left untouched. The Cameron-Fowler mechanism is predicted to naturally occur in reasonably massive, asymptotic giant branch stars. These stars are most definitely not Sun-like and have masses of at least 4–5 times the mass of our Sun. The Cameron-Fowler mechanism is not however predicted to occur in any phase of evolution for Sun-like stars.

One of the authors of the study (Reddy) has carved out a successful career analysing starlight to obtain Li abundances, in order to test our understanding of stellar evolution. Previous works were limited because the evolutionary status of the stars was unclear. This is because red clump stars are hard to disentangle from their red giant counterparts—they occupy similar regions on the HR diagram, as can be seen in *Figure* 2.

One of the advances of the modern era of as-

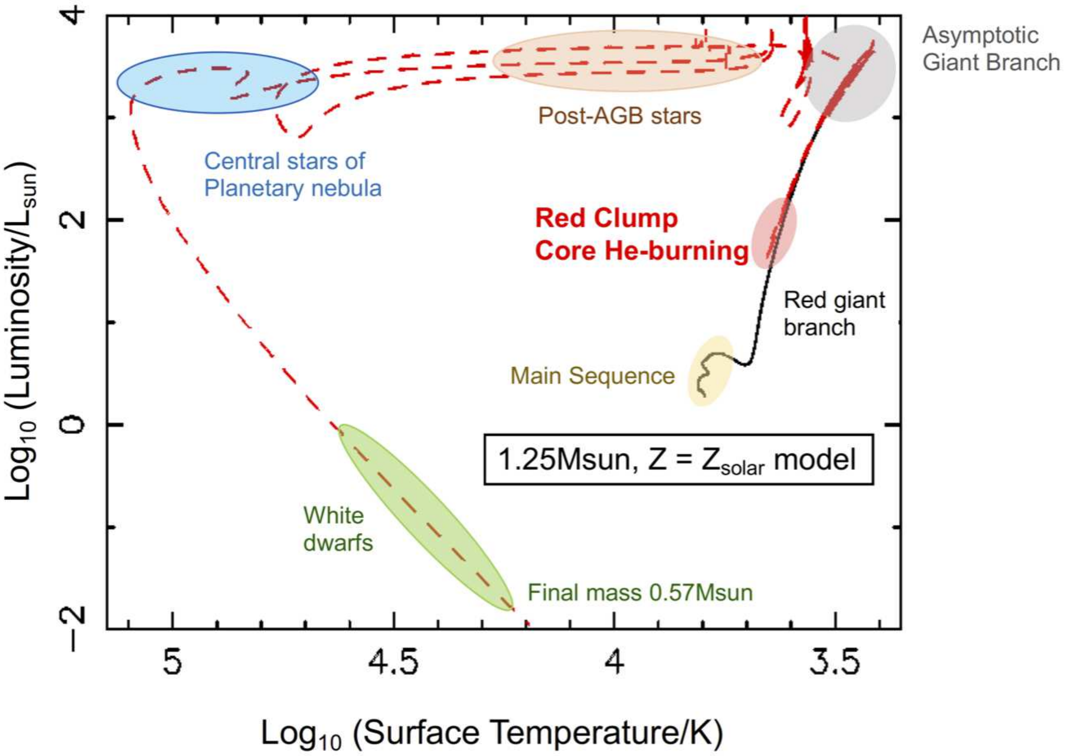

Figure 2: : HR diagram of a 1.25 solar mass star, with a composition similar to the Sun. The evolutionary track is calculated by solving the equations of stellar structure for a given set of initial conditions (Reference: Karakas 2014). The main phases of evolution are highlighted.

tronomy has been the advent of large-scale stellar surveys, which observe not just a few stars but hundreds of thousands of stars or even billions, in the case of the Gaia survey [2], which is providing accurate distances to 1% of the stars in our Galaxy. These surveys utilise a star's spectrum to reveal the chemical composition of its atmosphere through the unique spectral fingerprints or spectral lines that elements leave behind. One such survey that is on-going in Australia is GALAH (Galactic Archaeology with the Hermes spectrograph) [3], which uses the largest optical telescope in Australia, the Anglo-Australian Telescope. GALAH aims to observe a million stars in our Milky Way Galaxy in order to obtain surface compositions from stars in all phases of their life.

Using GALAH survey data cross-matched with three other different surveys (including Gaia, LAMOST [4], and Apogee [5]) Kumar et al. (2020) were able to accurately identify almost 10,000 red clump stars. The authors came to the very surprising conclusion: *All* of their red clump stars are enriched in Li! This is completely contrary to our understanding of how stars work! Computer simulations predict that once a star becomes a red giant, the surface lithium abundance should plummet and should never return to high values and indeed should be reduced even further as the star ages along the red clump and beyond. The intriguing result of the Kumar et al. (2020) study is that Li is not only produced by Sun-like stars as they age but in fact that it is commonly produced. They go further to redefine our definition of 'Li-rich' to apply to all such stars, where the super-Li rich objects, which we've known about for some time, remain only a small percentage.

You might be asking what causes Li production? Well, the short answer is that we don't know. We don't see Li production in the brightest red giant stars, which suggests that whatever the mechanism is, it must occur after the stars have ignited helium fusion in their cores and become red clump stars. This process is in fact relatively quick—for a star!—and takes only a million years or so. Kumar et al. (2020) also point to a curious prediction from computer models that suggest some production of Li can occur right around the time that stars ignite helium, but that the amount predicted is much smaller than observed. Further, theoretical predictions for Li are notoriously uncertain, as highlighted by Lattanzio et al. (2015). Li can be made or produced depending on the numerical details of the mixing scheme involved. The main issues include the fragility of Li at stellar temperatures and our lack of a first-principles understanding of mixing processes in stars. Clearly, there is much we still don't understand about stars and the production of unusual elements like Li.

Suggested Reading

[1] C J Hansen, S D Kawaler, and V Trimble, *Stellar Interiors: Physical Principles, Structure, and Evolution*, Springer, 2nd Edition, 2004.

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[3] https://galah-survey.org/

[4] http://www.lamost.org/

[5] https://www.sdss.org/dr12/irspec/

[6] Y B Kumar, B E Reddy, S W Campbell, S Maben, G Zhao, and Y.-S. Ting, *Nature Astronomy*, https://www.nature.com/articles/s41550-020-1139-7, 2020.

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