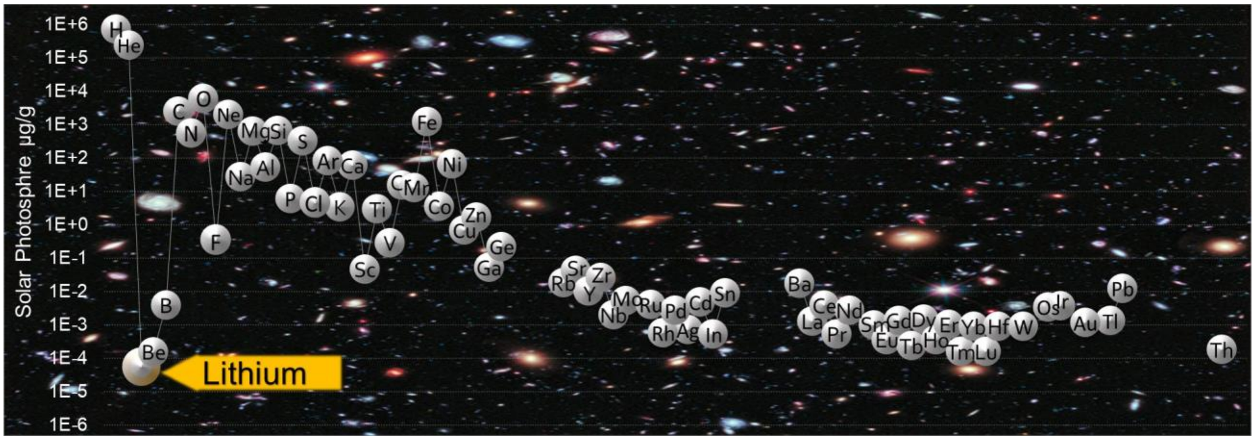
“The Cosmic Lithium Story”



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ABSTRACT:

The story of Lithium interconnects Big-Bang nucleosyntheses, the evolution of stars, and galactic chemical evolution. Lithium was the only metal produced in the Big-Bang together with H and He. Stars destroy both stable lithium isotopes easily, and it seems lucky that we still have any lithium left after generations of stars have come and gone. Ongoing Li production by Galactic Cosmic Rays and by a few nuclear Li-producing reactions and transport processes in some rare types of stars keep lithium alive in the universe.

Keywords: Lithium, Big Bang, Stars, Brown Dwarfs, Nucleosynthesis

LITHIUM ABUNDANCE – WHY SO LOW?

Elemental abundances were first studied in terrestrial samples and meteorites, and later in the sun and other stars. Harkins (1917) and Goldschmidt (1930) wondered about the orders of magnitudes lower concentrations of Li, Be, and B in the Earth’s crust (Li 18 µg/g), bulk silicate earth (1.6 µg/g), and meteorites (1.51 µg/g in CI chondrites) compared to the major rock-forming elements such as O, Mg, Al, Si, and Fe. The first quantitative spectroscopic analyses of the sun by Russel (1929) revealed the truly astronomically low abundances of Li, Be, and B. The title diagram shows Li is the least abundant by mass of the elements analyzed in the solar photosphere, in stark contrast to the most abundant elements H and He, followed by O and C.

The Sun is a good proxy for the element inventory of the solar system, except for lithium. Many rock forming elements in the solar photosphere and in chondritic meteorites (particularly in CI-chondrites) have similar element/silicon ratios within 5-10%. But the Li/Si of the photosphere is 170 times lower than in meteorites, 740 times lower than in the crust, and 90 times lower than in the bulk silicate earth. The smaller Li/Si ratio in the Earth compared to CI-chondrites is due to the slightly higher volatility of Li than Si in a solar composition gas; the higher Li/Si in the crust reflects the differences between Li and Si during magmatic and hydrothermal differentiation.

The riddle of the low Li, Be and B abundances was solved through understanding of nuclear stability and structure. The low binding energies of ^{6}Li and ^{7}Li (5.3 and 5.6 MeV/nucleon) make these nuclides fragile compared to their neighbors ^{4}He (7.1 MeV/n) and ^{9}Be (6.5 MeV/n). However, Li is more stable than D (1.1 MeV/n) and ^{3}He (2.6 MeV/n).

LITHIUM DESTRUCTION IN THE SUN AND SUN-LIKE STARS.

Spectroscopy of the sun's photosphere probes the sun's composition near the outer convection zone, but not that of the underlying radiative core, where Li is destroyed by high-temperatures. The observable amounts of Li, Be, and B in the sun and other stars depend whether stars have convective outer layers and how deep such layers penetrate inside. Current measurements show comparable abundances of Be and B in the photosphere and meteorites, and only Li is depleted strongly in the photosphere. In 1943 Biermann noted the presence of Li, Be, and B in the solar photosphere rules out a deep convection zone and extensive mixing throughout the sun. The Li, Be, and B abundances can be used as thermometers for the outer portion of the sun because fusion temperatures of Be (>3MK) and B (>5MK) are higher than that of Li (2–2.5 MK), and the Li destruction rates are very temperature dependent. Helioseismology implies the solar convection zone is a radial shell from 0.713 – 1 times the solar radius with ~2% of the sun's mass. The base of the convection zone has about the right temperature (2 MK) for Li destruction.

Over the Sun's lifetime, all elements (except H) have diffused and gravitationally settled from the base of the convection zone toward the sun's interior and continue to do so. However, this is a minor effect and the element to hydrogen ratios in the photosphere (e.g., Li/H, Si/H) are about 10-20% below the protosolar value because of element settling. Heavy elements have similar settling efficiencies, hence the Li/Si ratio in the photosphere cannot change significantly over time. Only Li-burning near the base of the convection zone can explain the dramatic difference between the Li/Si ratios in meteorites and the photosphere today.

Lithium burning occurs if the base of the convection zone is deep enough (hot enough) to be at the required temperatures of 2–2.5 MK. There should be an inverse correlation of the Li content of low to solar mass stars with their age. This was noted as early as 1965 by Herbig and has recently attracted more attention (e.g., Carlos et al. 2019 and references therein). Figure 1 shows the Li content in G-type stars like the sun – with similar masses and similar metallicity – as a function of stellar age. There is a drop by a factor of 100 in the Li surface abundances over 8-9 Ga. This strengthens the case for active Li burning in the sun. Also noteworthy in Figure 1 is that all stars have lower Li contents than the proto-solar value derived from meteorites for 4.6 Ga ago. Considering that stellar nucleosynthesis produces elements over time, an 8 Ga old star may have formed out a molecular cloud with lower metallicity and a younger 1 Ga star from one with higher metallicity. However, all these stars are "solar siblings" and have the same metallicity as the Sun (except for Li). It is puzzling that the youngest stars do not approach the protosolar value which should occur if all of them started with the same metallicity. Something else is going on. Figure 1 also shows the sun is below the trend of its siblings for poorly understood reasons (Carlos et al. 2019).

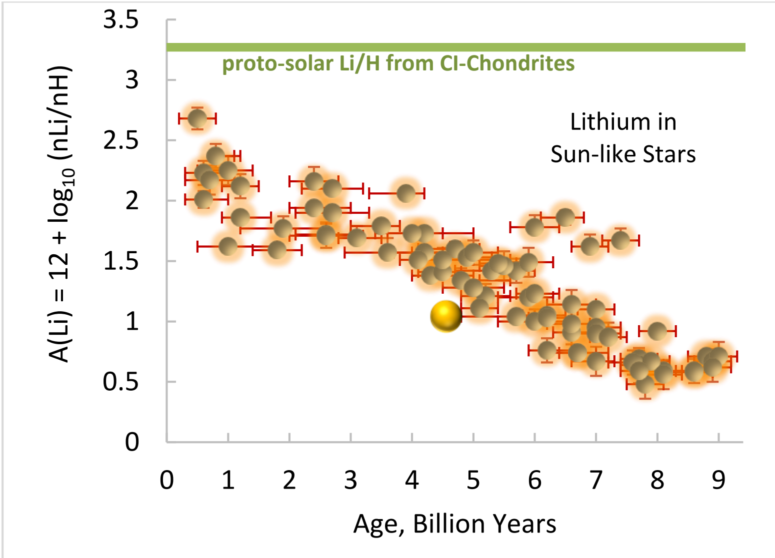

Figure 1. Li/H abundances in sun-like stars and in the sun (big yellow dot) as a function of stellar age. All stars have similar elemental abundances (other than Li), masses and effective temperatures (Carlos et al. 2019). The green line is the protosolar Li/H ratio computed from Li/Si in CI-chondrites and the photospheric Si/H ratio (no corrections made for heavy element diffusion in the solar outer convection zone).

PRE-STELLAR LITHIUM DESTRUCTION AND THE LI-TEST TO IDENTIFY SUB-STELLAR OBJECTS

Destruction of D and Li occurs before a star ignites and enters the main-sequence (MS) where hydrostatic H-burning takes place in stellar cores. Ignition requires 10^7 K and much higher densities than for D or Li-burning. Stars contract during their pre-main sequence evolution and their central temperatures and pressures allow D- and Li burning, depending on total mass of the star. Deuterium fusion occurs in the stellar core and once D is used up, it continues to burn in a shell surrounding the core. Convection throughout the proto-star supplies D for burning. Energy released from deuterium burning counteracts gravitational contraction, which helps the star to accrete more mass because core H-burning is delayed. Stellar contraction resumes when all deuterium is consumed (within a few million years), and core H-burning can eventually occur. Mass accretion onto the star stops with the onset of H-burning because stellar radiation dissipates material left in the proto-stellar accretion disk. Thus, longer D-burning increases the time for mass accretion onto the protostar, which also favors Li destruction because the D and Li fusion temperatures are within a factor of two.

The stars in the Pleiades cluster provide a temporal snapshot of lithium destruction as a function of stellar mass. These stars formed at about the same time and had about the same initial composition. Figure 2 is a plot of Li abundances against effective temperature for Pleiades stars. If all stars in the cluster have about the same age, their temperatures measure stellar mass. To first order this is a fruitful working hypothesis. The best estimate of the Pleiades' age is about 120Ma (Basri et al. 1996, Martin et al. 2001). Pre-stellar evolution for near solar mass stars is ≲50 Ma, so the Pleiades cluster should have very young solar mass stars.

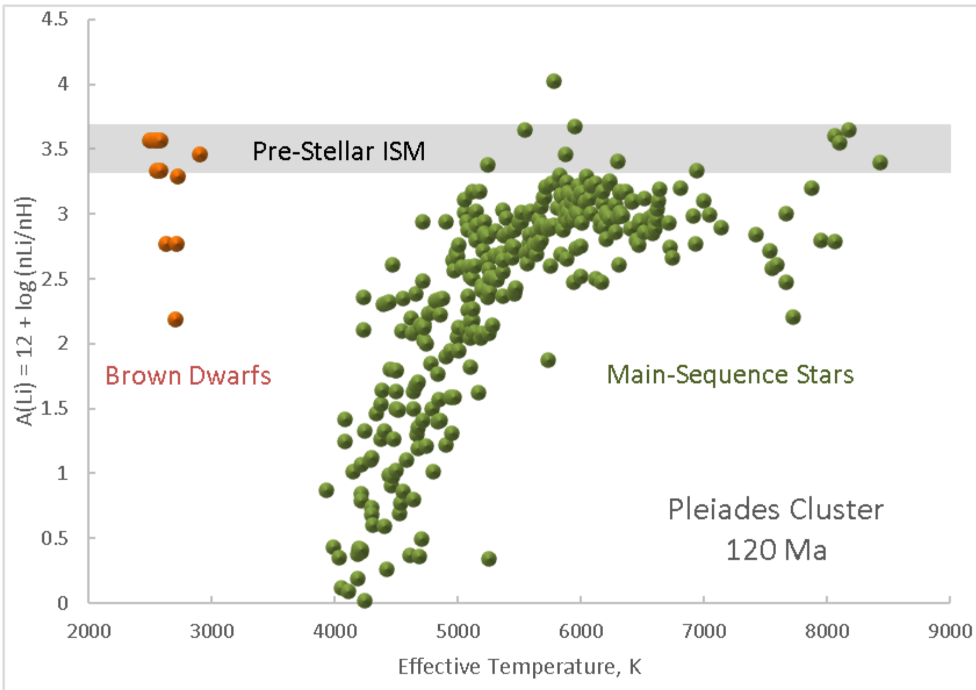

Figure 2. The Lithium abundance of stars in the young Pleiades cluster. The grey bar is the presumed proto-Pleiad Li content. The Li abundances range over a factor of 1000. Data from Aguilera-Gómez et al. 2018, Barrado et al. 2016, Bouvier et al. 2018, Burkhart & Coupry 1997, Frasca et al. 2018, Martin et al. 1994, and references therein.

The original Li content of the parental molecular cloud of these stars was about A(Li) = 3.5, higher than the protosolar value from meteorites (3.27) as one may expect from galactic chemical evolution during the past 4.6 Ga. Most Pleiad stars shown are between 5000-6000K, have masses near solar, and have factor of three (0.5 dex) lower surface abundances of A(Li) = 3. (The coolest and hottest stars and some fast-rotating stars in the middle are exceptions.) This would imply that the Sun could already have lost ~60% of its original Li after 100 Ma. More Li destruction occurs on the main sequence as time passes (Figure 1). However, we do not fully understand lithium destruction in our sun over time. A majority consensus is that the 170-fold difference between the initial (meteoritic value) and current photospheric "surface" abundances cannot be explained with pre-main sequence physics alone (if it even happens at all in stars of 1 solar mass as some may argue).

Lithium depletions in the Pleiades are more pronounced below 5000K for lower-mass main sequence stars. Lithium abundances steadily decrease until ~4000K. Less massive stars with lower temperatures develop deeper convection zones and the lowest mass objects become fully convective, in contrast to the hottest and more massive counterparts shown. Deeper mixing cycles more Li through the hot destructive interior, explaining the trend between 4000-5000 K.

The Li abundances in the hotter stars >6500 K are more variable, and fast rotating stars often have higher Li contents. The "Li-dip" occurs at ~6500K and is a real feature known for stars in this temperature range (e.g., Aguilera-Gómez et al. 2018). The scatter in Li abundances for stars in a cluster with given age and metallicity reflects how other variables influence Li transport into the stellar abyss through the tachocline (the zone between the bottom of the convection zone and the radiative interior). These variables include stellar mass, stellar rotation rates (some Li-rich ones may spin up to100 times faster than the sun), induced turbulent mixing, development of magnetic fields, and convective overshooting. The effects of rotation on stellar Li destruction and survival are currently an active research area.

THE LI-TEST FOR SUBSTELLAR OBJECTS

Figure 2 shows some Li-rich but cool objects, which are common among the Pleiades but not easy to analyze. These objects are known as "substellar objects", "failed stars" or "brown dwarfs" with masses between 13-80 Jupiter masses (0.01 - 0.075 solar masses). They burn their D for a few million years, but H-fusion never ignites in their cores. They are fully convective and as their mass cycles through the center, D vanishes. Lithium can burn if temperatures get high enough, but this is sensitive to the total mass of the object. It is tricky to distinguish cool (T < 3000K), low mass stars from brown dwarfs with similar spectral types (a measure for surface temperatures), because their observed temperatures depend on their masses and ages (see Basri et al. 1996, Martin et al. 2001). A brown dwarf of about 60-70 Jupiter masses and 100-200 Ma age would have the same spectral type as a 500 Ma old real star with a mass just over the H-burning limit (>80 Jupiter masses). The "lithium-test" helps to decide whether some cool objects are "stellar" or substellar": if the monatomic lithium absorption line is present, it is a substellar object; if it is absent it is a low mass star. However, the Li test fails for objects with effective temperatures < 2500 K, because Li-bearing molecules form. Reactions of monatomic Li with HCl or HF to LiCl or LiF decrease the Li gas abundance. In cooler brown dwarf atmospheres monatomic Li absorption then weakens and disappears because Li-bearing molecular gases and condensates form. Observation of the predicted Li halides is observationally challenging because their lines are in the far IR and millimeter regions.

SOURCES OF LITHIUM IN THE UNIVERSE

Lithium is unique with at least three different nucleosynthetic origins: Big-Bang nucleosynthesis (BBN), spallation (collisional break-up nuclei) of heavier elements such as C, N, and O by galactic cosmic rays (GCR), and production in evolved stars on the Asymptotic Giant Branch (AGB). Other potential sources to the overall Li budget are neutrino-induced spallation reactions on C, N, and O (the "ν-process") in supernovae, and Li produced in novae (not discussed further here).

LITHIUM FROM BIG-BANG NUCLEOSYNTHESIS

About 13.8 Ga ago, Big-Bang Nucleosynthesis (BBN) created H, He, and tiny amounts of Li (atomic Li/H = 4.65×10^{-10}). Afterwards, stellar nucleosynthesis in several generations of stars created all other heavier elements. To first order, younger stars have more heavy elements than older stars. Lithium is the only "metal" made in the Big Bang (here "metal" means all elements heavier than helium, in astronomical parlance). BBN did not produce significant amounts of nuclides heavier than ^{7}Li. Figure 3 displays the nuclear reactions leading to ^{7}Li synthesis within 20 mins or so of the Big-Bang. Two channels produce ^{7}Li: ^{3}H(α,γ)^{7}Li and ^{3}He(α,γ)^{7}Be(n,p) ^{7}Li. The second channel has radioactive ^{7}Be as an intermediate that reacts to ^{7}Li by neutron capture or by decay. The ^{7}Be half-life (53 days) is longer than the time of BBN, and because ^{7}Be decays through electron capture, decay was possible only after the Big Bang when nuclei had recombined with electrons. Whether the ^{7}Be channel contributed significantly to ^{7}Li depends on the baryon-to-photon ratio during BBN. The Wilkinson Microwave Anisotropy Probe (WMAP) and Planck missions determined the baryon-to-photon ratio from the cosmic microwave background. The BBN abundances from nucleosynthesis network computations for the matching baryon-to-photon ratio indicate ^{7}Li comes from both reaction channels with ^{7}Li/H = 4.7×10^{-10}; or on the astronomical scale A(^{7}Li) = 12 + log (n^{7}Li/nH) = 2.72. The expected isotope ratio of $(^7\text{Li}/^6\text{Li})_{\text{BBN}} \approx 40{,}000$ indicates only minute quantities of ^{6}Li were made in BBN (Cyburt et al. 2016, Coc et al. 2012). The network predictions are robust, but comparison to astronomical observations led to the "Cosmological Lithium Problem" that still awaits full resolution.

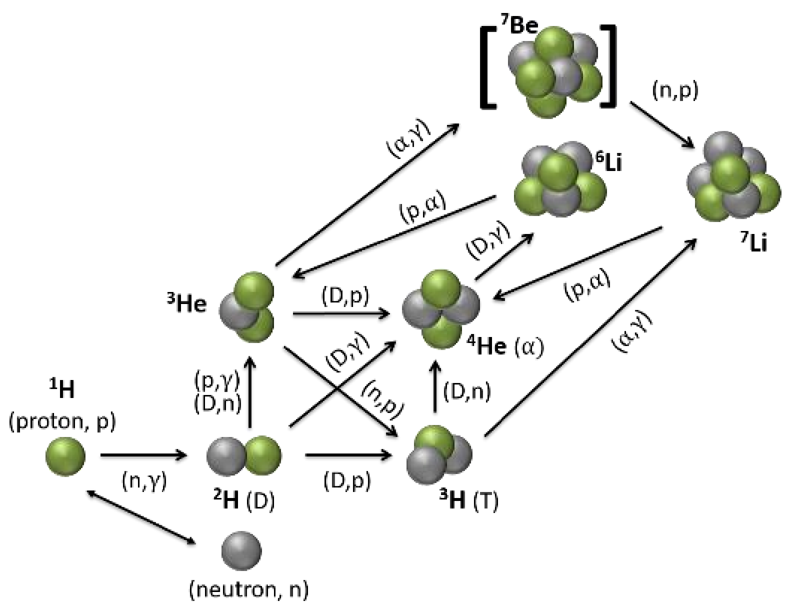

Figure 3. Reaction network for Big-Bang nucleosynthesis of ^{7}Li (major) and ^{6}Li (minor). The reactions are written as target nucleus (projectile, outgoing particle or radiation) product nucleus; e.g., the reaction of tritium to ^{7}Li by helium capture and gamma emission is written as ^{3}H(α,γ)^{7}Li. Neutrino emissions are typically not included in the notations.

The Lithium Problem for Big-Bang Nucleosynthesis

The standard BBN model predictions of the primordial ^{4}He mass fraction, the ^{3}He/H, and D/H ratios agree with observations, but the calculated BBN Li abundance based on the WMAP and Planck results (^{7}Li/H $=4.7\times10^{-10}$, A(Li) = 2.67; Cyburt et al. 2016, Coc et al. 2012) is about three times larger than observed (Figure 4). Spite and Spite (1982) discovered that Li is present at about a constant level (^{7}Li/H $= 1.58\times10^{-10}$, A(Li) = 2.2) in many old stars. The “Spite plateau” as it has become known, shows nearly constant Li abundances for metal-poor stars with effective temperatures above 5500K and only 1/300th to 1/10th of the solar metal content (also written as -2.5 < [Fe/H] < -1; where [Fe/H] is metallicity, the logarithm of the stellar (Fe/H) ratio over the solar ratio). Many studies confirmed the Spite plateau for stars in old clusters and isolated galactic halo stars (e.g., Lind et al. 2009, Gonzales Hernanez et al. 2009, Roederer et al. 2014; Figure 4). but in some extremely-metal poor stars with metallicities below 1/1000th solar ([Fe/H] < -3), Li is substantially lower than in stars on the Spite plateau (Sbordone et al. 2010, Bonifacio et al. 2015, Spite et al. 2015). The lithium problem then became: Do the BBN models produce too much ^{7}Li because of insufficient knowledge about nuclear physics, or are the observed stellar values not representative of the primordial Li abundance?

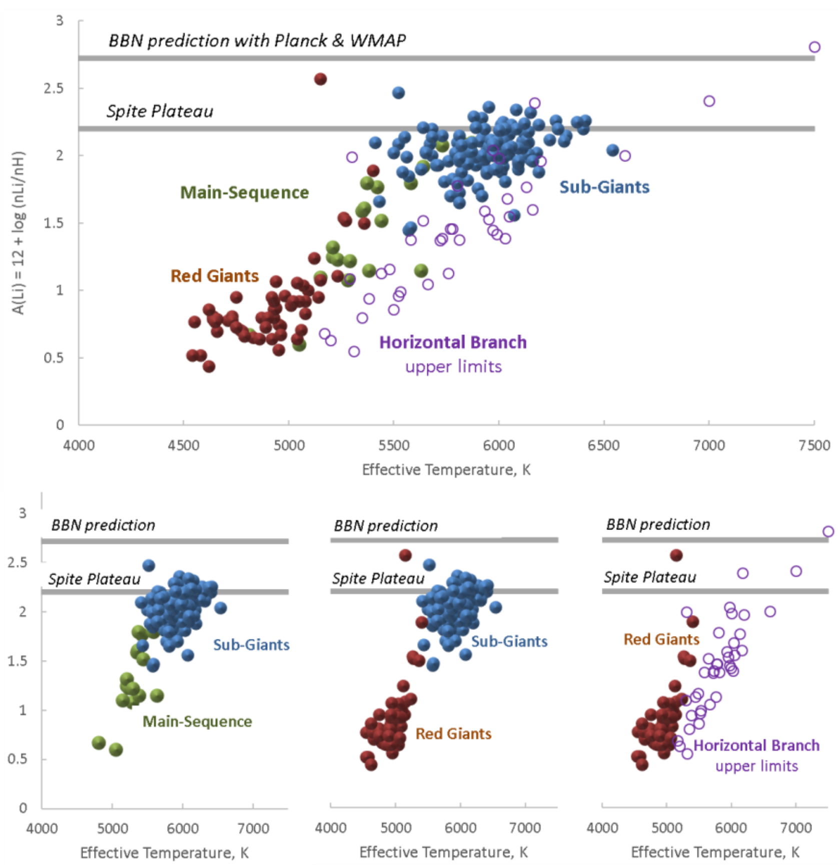

Figure 4. Lithium abundance in old halo stars of different age, masses, and metallicities of -4.5 < [Fe/H] < -1. Stars are color-coded following evolutionary sequences: main sequence (green) → sub giants (blue) → red giants red) → horizontal branch stars (open purple). The evolutionary stage of a star depends on mass and age. Data from Roederer et al. (2014).

A constant Li content was unexpected because the Li depletion in solar-metallicity stars like our sun is well known (see above). Older metal-poor main sequence stars of low mass should be even more depleted in Li if the same nuclear reactions destroy Li in younger and older stars.

Subgiants and main sequence stars plot about the Spite plateau, but several stars are depleted in Li compared to the plateau value. Lithium abundances in red giant and horizontal branch stars (which burn He in their cores) vary by more than a factor of thousand. Analyses of lithium abundances depend upon effective temperatures; however, this alone cannot explain the large variations.

The nuclear reactions that produce red giant branch (RGB) stars provide another explanation for lower Li abundances in stellar photospheres. Without going into all the details, deep convective mixing transports ^{14}N and ^{13}C upward to the observable surface of red giant branch stars (the "first dredge up"). The dredge up also dilutes the surface of RGB stars with Li-poor material from H- burning shell and explains the observed decline in Li contents in red giant branch stars.

The answer to the cosmological Li problem may come from advances in models of stellar structure that include gravitational settling and diffusion of Li from the observable upper atmospheres. Richard et al. (2005) and Korn et al. (2006) presented models that by introducing some turbulent mixing at the base of the outer convection zone can keep the Spite plateau thin and flat. Korn et al. (2006 and subsequent papers in their series) showed that diffusion systematically changes the surface abundances of unevolved stars in globular clusters and once Li abundances are corrected for diffusion effects, the original stellar abundances are around A(Li) = 2.6; much closer to the BBN predictions. Recent models by Fu et al. (2018) consider several additional mechanisms affecting the Li abundance in stars, including pre-mainsequence destruction.

Finally, a few words about production estimates for ^6Li and ^7Li by Big-Bang nucleosynthesis. In principle spectroscopic studies of very metal-poor stars ([Fe/H] < -2) could also constrain the isotopic composition of BBN-produced lithium. However, the most recent and modern analyses of absorption spectra for atomic line shapes caused by isotope-shifts give only upper limits for ^6Li abundances in halo stars. The inadequacy of model atmospheres, consideration of non-local thermodynamic equilibrium, and effects of convective Doppler-shift broadening on the Li line profiles hamper severely all attempts for deriving $^6Li/^7Li$ ratios in the halo stars (Steffen et al. 2012, Lind et al. 2013). Overall, models considering all plausible sources cannot explain satisfactorily the meteoritic (solar system) lithium isotopic composition.

LITHIUM FROM SPALLATION REACTIONS

Galactic Cosmic Ray (GCR) spallation of heavier elements (C, N, and O) made a large fraction of Li, Be and B. Supernovae accelerate the highly energetic GCR, which are mostly protons and helium nuclei. The GCR break-up heavier nuclei while traversing the interstellar medium. Cosmogenic production of Li, Be and B nuclides is also observed in meteorites. The spallation reactions are the same as those occurring when GCR interact with the Earth's atmosphere to produce Li, Be, and B. The ^{10}Be nuclide is the most prominent product and is well known as a tracer in the Earth Sciences.

The principal source of ^{6}Li is spallation. The PAMELA and AMS instruments observed ^{7}Li/^{6}Li = 0.89–0.92 in GCR (Aguilar et al. 2011, Menn et al. 2018); Voyager found 1.2±0.1 (Webber et al. 2002). These ratios are lower than the typical values of 12.2±0.1 found in terrestrial and lunar rocks and meteorites (Seitz et al. 2007) and variations in terrestrial, lunar and meteorites usually deviate at per-mil levels from this value. Cosmogenic production drives the lithium isotope ratio towards expected equilibrium values of ^{7}Li/^{6}Li = 1.2–2.0 (Webber et al. 2002).

Rock grains on the lunar surface contain implanted solar wind. In a clever experiment, Chaussidon & Robert (1999) measured the ^{7}Li/^{6}Li ratio as a function of depth in such grains. Within the first ~10 nm upper surface layers, they found increases in ^{7}Li/^{6}Li up to 22.8 from which they derived ^{7}Li/^{6}Li = 31±4 for the trapped solar wind by mass balance. At around 10–30 nm depths the ^{7}Li/^{6}Li was as low as 6.8 (cf. the average lunar value of 12.1), indicative of in-situ spallation reactions in the lunar grains. Chaussidon & Robert (1999) derived ^{7}Li/^{6}Li > 150 for the base of the solar convective envelope from their ^{7}Li/^{6}Li ratio in the solar wind and elemental abundances of Li and Be. Solar lithium should be almost pure ^{7}Li (^{7}Li/^{6}Li ~10^6) because nuclear reactions at shallower depths in the outer solar convective zone destroy ^{6}Li at temperatures >2×10^6 K (2 MK) whereas ^{7}Li needs > 2.5 MK for fusion with protons. However, solar flares may create some ^{6}Li and ^{7}Li through break-up of C and O by protons in the solar wind. The production of ^{6}Li is also possible though reactions of flare-accelerated ^{3}He and stellar ^{4}He such as ^{4}He(^{3}He,p)^{6}Li. Thus, "solar cosmic rays" can decrease substantially the ^{7}Li/^{6}Li ratio of the solar convection zone value as the solar wind emerges.

However, GCR spallation alone cannot supply the high Li content of meteorites and of recently formed stars. Their high lithium abundances require another source of lithium.

LITHIUM FROM STARS

A few very Li-rich stars are known among evolved red giant branch and asymptotic giant branch stars. Indeed, Li production in giant stars and release into the interstellar medium is required to account for the higher content seen in very young stars. Some of these giant stars show C and Li-enrichments relative to normal stars because Li production is related to the convective mixing that brings C, a product of He-shell burning in AGB stars, to their observable surfaces. One potential problem in the Li assessment is the overlap of Li and Ce absorption lines because cerium is made by the s-process in very evolved AGB stars (Reyniers et al. 2002)

After dwarf stars convert their central hydrogen into helium cores, hydrogen burning via the CNO cycle occurs in a shell around the He-cores. This process turns main-sequence stars into red giants. In stars of 3-8 solar masses, helium core burning occurs next. Subsequently He-shell burning alternates with H-shell burning leading to thermally pulsing asymptotic giant branch stars (AGB stars). Under the right conditions, nuclear reactions in the shells of AGB stars produce ^{7}Li and convection brings it into their observable surfaces from where stellar winds release ^{7}Li and other stellar nucleosynthetic products into the interstellar medium. The production of ^{7}Li starts with ^{3}He(α,γ)^{7}Be (Cameron and Fowler 1971). The ionization of ^{7}Be in stellar interiors prolongs its half-life up to 100 years so it can mix to cooler layers where it decays: ^{7}Be(e^-,ν_e)^{7}Li. Thus, rapid mixing in the large outer convective envelopes prevents ^{7}Be and ^{7}Li destruction by proton capture. However, only about a handful of AGB stars show large Li abundances (Li/H up to 1×10^{-7}) and their stellar winds may not contribute significant Li to the interstellar medium.

Initially, astronomers thought the Cameron-Fowler process occurred only in more evolved AGB stars (where He shell burning takes place) but not in RGB stars or He-core burning (horizontal branch) stars, which both experience H-shell burning. However, this concept was complicated by later observations. Astronomers found some red giant branch stars with far higher lithium contents than seen in old main sequence stars. Several extremely Li-rich stars are now known at the end of the main sequence among metal-poor stars (Kirby et al. 2016, Li et al. 2018). Li et al. (2018) pointed out the problem: How can such unevolved stars become so Li rich? The Cameron-Fowler mechanism explains the high Li content in AGB stars, but not in Li-rich stars on the end of the main sequence or on the early RG branch. The unusually high Li content in several red giants has stimulated several ideas. The high lithium could be "pollution" from planets or substellar companions that a red giant consumed during its expansion, or from mass-transfer from a close binary, or from some production mechanism in the star itself.

But all these explanations have difficulties. Planet engulfment has the problem that even large planets could not supply enough Li to the large outer stellar envelopes. Mass transfer from an evolved stellar companion that already went through the AGB phase and was Li rich implies that the now Li-rich stars should have white dwarf companions – but there are usually none. The binary transfer would supply Li and s-process elements, produced in AGB stars, but observations usually do not show the expected s-process enrichments. Thus, there might be another production mechanism for lithium that awaits discovery.

OUTLOOK

Lithium is ubiquitous in the universe, and great observational progress has been made just in the past decades. Models are inspired and constrained by its occurrence and abundances, but then, the messages that Li left in many astronomical environs have been challenging to figure out since day one.

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