Opening Session


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Light Elements in the Universe
Proceedings IAU Symposium No. 268, 2009
C. Charbonnel, M. Tosi, F. Primas & C. Chiappini, eds.

doi:10.1017/S1743921310003790

Light elements - one observer's historical perspective

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Abstract. This essay attempts to provide a historical perspective on some of the key questions that engaged the attention of participants at the symposium. In particular, the writer offers and comments on a personal list of milestones in the literature published between 1957 and 1982.

Keywords. nuclear reactions, nucleosynthesis, abundances

1. Introduction

In today's rush to publish new results, one may overlook and even dismiss as unimportant the context in which new observational and theoretical findings should be placed. This essay is an imperfect attempt to provide one individual's perspective on the historical development of the roles played by the light elements in contemporary astrophysics. A warning to the reader: the perspective is biassed towards observations and, perhaps more importantly, is surely incomplete with respect to even the central events. Nonetheless, I hope I achieve my primary goal which is to identify when the seeds were planted that blossomed into the flowers whose scents we are chasing and trying to interpret at this symposium.

Here, this symposium considers the class of light elements to encompass just the first five elements: H, He, Li, Be, and B. In this quintet, the stable nuclides are ^{1}H, ^{2}H, ^{3}He, ^{4}He, ^{6}Li, ^{7}Li, ^{9}Be, ^{10}B, and ^{11}B. Each one of these will feature in talks at this symposium. Certain unstable light nuclides – ^{7}Be, ^{10}Be, and ^{8}B – also play a role in observational astrophysics and deserve a mention. ^{7}Be is important because of its role in the synthesis of ^{7}Li in stars, a topic of several presentations here. Electron capture on ^{7}Be results not only in ^{7}Li but also in a γ-ray and a neutrino. In stable stars, the γ-rays are locally absorbed deep in the interior and so lost to observers; searches for ^{7}Be γ-rays emitted by novae have been attempted but proven unsuccessful. The neutrinos are freed to roam the Universe; ^{7}Be neutrinos account for a fraction of the Sun's neutrino output. ^{10}Be with a half-life of 1.5 Myr is present in cosmic rays where it serves as a clock, a subject notably not aired at this meeting. ^{8}B's notoriety arises from a contribution to the solar neutrino problem with its ultimate resolution ending in the discovery of neutrino oscillations.

A crucial tool from the perspective of an observer is the inventory of spectral lines providing evidence for the light elements. Detection of these lines in absorption or emission is the first step in a determination of the abundance of a light element or of an isotopic ratio. Hydrogen and helium, when detectable, offer several series of lines. On the other hand, Li, Be, and B present - except in very rare circumstances - in trace amounts are detectable almost always only through the resonance lines of neutral atoms or ions. Lithium atoms are detectable in cool gas via the well known resonance doublet at 6707Å and, if Li is abundant, excited lines at 6104Å and 8126Å are also detectable. The He-like Li^+ ion and H-like Li^{++} ions are not providers of detectable lines at the abundances expected for Li. Perhaps, a great disappointment is that Be atoms are not detectable; the Be I resonance line at 2348.6Å has to my knowledge not been detected in a stellar spectrum. Beryllium abundances are based exclusively on the Be II resonance doublet at 3130Å. Higher Be ions of the H-like and He-like isoelectronic sequences are not on an observer's list for detection. With one more electron, the species of boron potentially accessible to the observer are the neutral atom and the ions B^+ and B^{++} with the He-like ion B^{3+} and the H-like ion B^{4+} far beyond accessibility. Indeed, resonance lines of B I at 2496.8Å, B II at 1362.4Å, and B III at 2065.8Å have featured prominently in discussions of the boron abundance in, as appropriate, cool and hot stars and the interstellar medium. In addition to providing estimates of the elemental abundance of a light element, this array of lines for the light elements has under appropriate circumstances provided isotopic abundances for stellar atmospheres, interstellar and extragalactic gas: D/H, $^3He/^4He$, $^6Li/^7Li$, and $^{10}B/^{11}B$.

2. Hydrogen's title role

To stellar spectroscopists, measurements of absorption lines of element X in the spectrum of a normal (i.e. H-rich) star yield the abundance of the element X with respect to H, i.e., the ratio X/H. As shown by years of oral examinations of students, there may not always be a clear understanding of how the ratio X/H is the *natural* outcome of measurements of lines of element X. This lack of clarity reflects, in part, a failure of the student's teachers to explain a fundamental piece of stellar atmospheric physics and, in part, a lack of curiosity by the student who, nonetheless, may be adept at running the appropriate computer programmes. The crucial link between the observation of (say) X I lines and the abundance X/H is, of course, that the strength of the line is set not by the line opacity alone but by both the line and the continuous opacity.

Hydrogen's dominant role was first suggested by Cecilia Payne in her Harvard dissertation published as *Stellar Atmospheres* (Payne 1925). Not only did the dissertation show that similar compositions account for the diverse spectra of stars – spectroscopic variations are primarily due to differences in atmospheric temperature and pressure – but also that hydrogen and helium are the two most abundant elements by far in stellar atmospheres. However, as Longair (2006) reminds us in his majesterial *The Cosmic Century*, Payne qualified her conclusion by writing 'Although hydrogen and helium are manifestly very abundant in stellar atmospheres, the actual values derived from estimates of their marginal appearances are regarded as spurious', Longair adds judiciously 'The conclusion simply reflected the prevailing prejudice' but notes that the dominant role of H was proven a little later by Unsöld (1928) from an analysis of solar absorption lines and by McCrea (1929) from an analysis of the solar chromospheric (flash) spectrum.

Gaseous nebulae to invoke an old term – H II regions, planetary nebulae, for example – are also a major source of information on the abundances of the elements. In the context of the light elements, information is obtainable on H and He and their minor isotopes D and ^3He. Inspection of the optical emission line spectrum of a nebula shows H I, He I, and [O III] (say) lines to be of comparable intensity. Yet, the H and He are much more abundant than O. This seeming paradox is today readily understood as arising from the different excitation mechanisms for the permitted H and He lines and the forbidden O and heavy element lines. An early understanding of the paradox's resolution - perhaps, the first - was provided by Bowen (1935), the identifier of the forbidden lines (Bowen 1927, 1928). In his abstract, Bowen wrote 'A study of nebular line intensities in light of the foregoing processes indicates that H is the most abundant element and He is the second, N, O, Ne, S – and possibly C and A – are present but are very much rarer. The lines of these heavier elements are strong, not because the elements are very abundant but because they are able to make use of large sources of energy that are not available to the predomient [*sic*] H and He lines'. Bowen's attempt to provide quantitative abundance estimates for – say – O/H was frustrated, in part, by his inability to detect recombination lines of oxygen that might be compared simply and directly with the recombination lines of hydrogen. Amusingly, this comparison may now be made and, as I recall, provides an oxygen abundance at odds with that derived from oxygen forbidden lines. The first paper to provide quantitative abundance estimates may be that by Aller & Menzel (1945).

3. Helium's dark role

Every astronomical spectroscopist has surely experienced the frustration over an inability to determine the abundance of a trace element of distinctive astrophysical significance – say, Li, Be or B – but just as frustrating but more rarely expressed must be the inability to determine the He abundance of a cool star. The He abundance of the Sun, for example, is one of the least securely established elemental abundances. This important quantity is not determinable from solar absorption lines but from measurements (e.g., sampling the solar wind) that are impossible to secure on other stars.

Fortunately, all normal Galactic stars are anticipated to have a similar He abundance. The floor is set by the primordial abundance and the likely ceiling by the He abundance of local H II regions and B stars. The error affecting derived elemental abundances resulting from adopting a 'standard' He/H ratio between the floor and the ceiling is almost certainly less than that incurred from the multiplicity of other sources of error, recognized and unrecognized. Yet, there are reasons to wish to ferret out bounds on the atmospheric He/H ratio.

One recalls at once that the dredge-ups experienced by giants on the first ascent and particularly on the asymptotic giant branch are predicted to change the He content of the atmosphere along with the changes to the light elements, C, N, and O as well as the *s*-process in the case of AGB stars. A recent discovery has been that of multiple sequences in the colour-magnitude diagrams of globular clusters. These sequences have generally beeen attributed to differences in He abundance. A lack of spectroscopic confirmation of such differences may be inevitable but is certainly frustrating and, therefore, stands as a challenge for observers.

Helium-rich and hydrogen-poor stars are known, if rare. The prototypes might be said to be (the warm) R Coronae Borealis and (the hot) Popper's star HD124448, the latter discovered at the McDonald Observatory (Popper 1942). These stars are obviously very H-poor because at their effective temperatures the Balmer lines are either absent or very weakly present. At lower temperatures, the H-deficiency may be judged by the weak or absent CH bands.

In light of the impossibility of direct detection of He lines in photospheric spectra of cool stars, one is led to wonder if mildly He-rich cool stars exist, how they might be detected, and how they might arise (diffusion, internal nucleosynthesis and mixing, binary interactions, etc.?).

4. Milestones - a personal selection

Writing the definitive history of the light elements requires talents beyond those at my command. Here, I offer a personal selection of papers that occurred to me as I prepared my talk and which I consider to be milestones marking the road from 1957 to 1982 and, in particular, those that anticipated the hot topics featured at this symposium, and, in particular, the issues and questions providing the four discussion sessions. My selection begins in 1957, a date recognized by all (I hope!) as marking the publication of 'Nucleosynthesis of elements in stars' by Burbidge, Burbidge, Fowler & Hoyle (1957, here B^2FH, of course) and 'Nuclear reactions in stars and nucleogenesis' by Cameron (1957). The final milestone from 1982a is the seminal paper 'Lithium abundance at the formation of the Galaxy' (Spite & Spite 1982) marking the beginning of continuing studies of the Li abundances in halo stars and their relation to the primordial Li yield from the Big Bang.

4.1. *Light elements in 1957*

Hydrogen was considered the basic raw material for all element synthesis by B^2FH and Cameron. The former wrote 'It seems probable that the elements all evolved from hydrogen, since the proton is stable while the neutron is not'. Fair comment but this suppresses the issue of baryogenesis, a subject oddly not raised at this meeting.

Helium was presumed to originate from H-burning in stars. For example, Cameron in his summary table listed He along with C, N, O, Fe, and Ne as products of 'hydrogen and helium thermonuclear reactions in orderly evolution of stellar interiors.

Trace light nuclides of Li, Be, and B (and D) were noted by both B^2FH and Cameron as 'not formed in stellar interiors'. B^2FH were (reluctantly, I conjecture) forced to admit 'We have made some attempt to explain possible modes of production of deuterium, lithium, beryllium, and boron, but at present must conclude that these are little more than qualitative suggestions'. The label x-process was introduced by B^2FH to cover the 'possible modes'. This use of x presumably sprang from the authors' initiation into the symbolic language of algebra in their early schooling in different counties and countries. Cameron's says of D, Li, Be, and B 'possibly made by nuclear reactions in stellar atmospheres after the acceleration of charged particles in changing magnetic fields', a component of B^2FH's x-process.

4.2. *Cosmic He puzzle*

In my tally of milestones, the earliest recognition that He was likely not the product of H-burning in the course of orderly stellar evolution came from Hoyle & Tayler (1964) with observational evidence assembled and theoretical arguments marshalled in a short article in *Nature* with the title 'The mystery of the cosmic helium abundance'. Genesis of this milestone in a lecture course by Hoyle is described by Longair (2006) and in a delightful reminiscence by Faulkner (2009) who recalls lectures, Hoyle the man, and helium the element. Four decades after attending Hoyle's lectures as a first-year research student at Cambridge, Longair would write 'Fred Hoyle gave a course of lectures on the problems of extragalactic research. He would arrive with, at best, a scrap of paper with some notes and expound an area of current research. One week the topic was the problem of the cosmic helium abundance.' The problem and its resolution are succinctly set out in the concluding paragraph of the *Nature* article: 'There has been difficulty in explaining the high helium content of cosmic material in terms of ordinary stellar processes. The mean luminosity of galaxies come out appreciably too high on such a hypothesis. The arguments presented here make it clear, we believe, that the helium was produced in a far more dramatic way. Either the Universe has had at least one high-temperature, high-density phase, or massive objects must play (or have played) a larger part in astrophysical evolution than has hitherto been supposed.' Calculations involving He synthesis in a high-temperature high-density phase were, as Faulkner engagingly retells, very quickly completed by him with the principal result relayed to Hoyle on the Sunday morning following the key lecture. As Longair notes 'the audience had the privilege of being present as a key piece of modern astrophysics was created in real time in a graduate lecture course.'

4.3. *Stellar evolution - dredge-ups*

In the 1960s, papers first appeared describing computer calculations of low mass stars from the main sequence through the first giant branch and then the asymptotic giant branch. Dilution of the surface abundances of the light elements Li, Be, and B (with emphasis sensibly on Li) was noted early in the series of papers. Perhaps, the first paper pointing out how observations might provide quantitative verification of the calculations is Iben's 'The surface ratio of N^{14} to C^{12} during helium burning' (Iben 1964). Iben's purpose was to draw attention to a prediction that 'the ratio of N^{14} to C^{12} at the surface of a star undergoes a significant increase during the rise into the red giant region immediately preceding the phase of helium burning in the core' and to call for spectroscopic verification of this prediction. Of course, N surface enrichment implies reduction of Li, Be, and B surface abundances. Iben was one of the prime movers in this endeavour to model stellar evolution and his reviews 'Stellar evolution: Comparison of theory with observation' and 'Stellar within and off the main sequence' remain valuable reading for the student (Iben 1967a, b). Discovery of the He-shell flashes (thermal pulses) in theoretical models of post-He core burning low mass (i.e., AGB) stars by Schwarzschild & Härm (1965) marked the birth of a vigourous area still of theoretical and observational study. Subsequent and continuing observational and theoretical work on surface abundance changes arising from the first and second dredge-ups in early red giants and the third dredge-up in asymptotic giant branch stars spring from these exploratory calculations.

4.4. *Discovery of the Cosmic Microwave Background*

Discovery of the cosmic microwave background radiation has had fundamental implications for our understanding of the origins of the light elements, as is evidenced here by several papers discussing contemporary strains between prediction and observation. Perhaps, *the* discovery of the CMB was announced by Penzias & Wilson (1965) in a short note with the title 'A measurement of excess antennna temperature at 4080 Mc/s' whose abstract noted the excess temperature was 3.5K higher than expected and 'isotropic, unpolarized, and free from seasonal variations' with a 'possible explanation' being relic radiation from the Big Bang.

This discovery quickly focussed theoretical attention anew on possible observable consequences of the Big Bang, with areas of particular relevance for the light elements being related issues of the primordial nucleosynthesis and the power spectrum of the CMB's very small anisotropy which is fundamental to determining the baryon density, the value of which sets the yields from the nucleosynthesis. First theoretical explorations of the acoustic oscillations in this regard were reported by Zel'dovich & Sunyaev (1969) and Peebles & Yu (1970).

4.5. *Pioneering calculations of Big Bang nucleosynthesis*

Faulkner's calculations inspired by Hoyle's 1964 lecture course were expanded thoroughly by Wagoner, Fowler, & Hoyle (1967) in their paper 'On the synthesis of elements at very high temperatures'. Their study which went beyond the synthesis of He discussed by Faulkner and also by Peebles (1966a,b) provided 'a detailed calculation of element production in the early stages of a homogeneous and isotropic expanding universe as well as within imploding-exploding supermassive stas' with a conclusion 'if the recently measured microwave background radiation is due to primeval photons, then significant quantities of only D, He^3, He^4, and Li^7 can be produced in the universal fireball.' The insertion of 'if' presumably reflected not only natural professional caution about the reality of the microwave radiation background but also possibly tension among the authors over acceptance of a hot Big Bang. Hoyle, of course, never accepted the idea of the Big Bang, a term coined long before by him in a prestigious series of broadcasts on the BBC (Kynaston 2007).

4.6. *Back to the x-process*

Recognition that 'significant quantities' of D and ^{7}Li could be produced in the Big Bang did not address fully the identity of the x-process. What were the origins of ^{6}Li, ^{9}Be, ^{10}B and ^{11}B? This question was very largely answered when the role of Galactic cosmic rays in the spallation of abundant C, N, and O nuclei was appreciated. Reeves (1993) has provided a fascinating account of how this appreciation occurred when he caught Hoyle 'talking in class': 'In 1969, I presented these ideas in a seminar at the former IOTA (Institute of Theoretical Astronomy) in Cambridge (UK). During my seminar, Fred Hoyle kept on talking to Willie Fowler. I could overhear some of his words "I have been repeating that to you for many years. You should have listened to me." Later on, he told me that he had considered this scenario for a long time. We published a paper together on this subject.'

The paper was 'Galactic cosmic ray origins of Li, Be, and B in stars' (Reeves, Hoyle, & Fowler 1970). This and subsequent work with Reeves as an active player showed that spallation by (high energy) Galactic cosmic rays could account satisfactorily for ^{6}Li, ^{9}Be, and ^{10}B as the products of collisions between protons and α particles on the one hand and C, N, and O nuclei on the other hand; the solar system ratios ^{6}Li/^{9}Be and ^{10}B/^{9}Be were well reproduced by the calculations. But the ratios ^{7}Li/^{9}Be and ^{11}B/^{9}Be were greater than could be accounted for by high-energy spallation. ^{9}Be is taken to be a benchmark because no process of stellar Be nucleosynthesis has been identified. Spallation by low energy cosmic rays may account for some of the required extra ^{7}Li and ^{11}B, as first suggested by Meneguzzi, Audouze, & Reeves (1971). In low metallicity gas, collisions between cosmic ray and interstellar He nuclei – α on α collisions – will produce ^{6}Li and ^{7}Li but not Be and B. Neutrino-induced spallation in Type II supernovae may produce ^{7}Li and ^{11}B - the so-called ν-process (Woosley 1977; Woosley *et al.* 1990). Of course, a major contributor to ^{7}Li is the Big Bang.

4.7. *A role for diffusion?*

Discussion of diffusive separation of elements, even isotopes, in a modern form is traceable to Georges Michaud (1970) and the paper 'Diffusion processes in peculiar A stars'. Proposals generally by Michaud and his disciples concerning observable effects of diffusion – principally describing a competition between gravitational settling and radiative levitation – have since 1970 encompassed many kinds on stars across the H-R diagram.

Of relevance here, the principal appearance of diffusion is surely the role attributed by some to it in accounting for the disagreement between the Li abundance of the Spite plateau and the several times higher abundance predicted from Big Bang nucleosynthesis according the baryon density required by the fit to the cosmic microwace background fluctuations.

4.8. *Li synthesis in stars*

Speculations about the x-process included Li (and Be, B) synthesis by spallation on a stellar surface. The stellar interior was known to be highly unfavourable to Li survival;

the very low solar Li abundance (relative to that in chondritic meteorites) was early attributed to convection resulting in Li destruction. Seemingly, the first proposal for Li production in stellar interiors with a consequence for high atmospheric abundances of Li was by Cameron (1955), a proposal further developed by Cameron & Fowler (1971). Today, this idea is widely referred to as the 'Cameron-Fowler mechanism'.

In 1971, the mechanism was presented as an explanation for the high Li abundances seen in a few cool carbon and S stars. The prototype of the group is WZ Cas (McKellar 1940). 'It is tempting to believe that the lithium has been produced by some internal process. However, since the majority of the carbon and S giants do not possess nearly so much lithium, it is necessary to postulate that the production process involves some unusual events' (Cameron & Fowler 1971). The 'unusual events' were suggested by Cameron & Fowler to be the He-burning shell flashes predicted by Schwarzschild & Härm (1965) to occur in stars on the asymptotic giant branch. These flashes had already been suggested by others to be a site for operation of a *s*-process and thus to account for the heavy element enrichment in carbon and S stars and notably the presence of Tc in selected S stars. The paper proposed that the neutron source was the now familiar $^{13}\mathrm{C}(\alpha,n)^{16}\mathrm{O}$ with fresh $^{13}\mathrm{C}$ provided by the mixing of protons into the He-shell.

Lithium synthesis involved the sequence $^{3}\mathrm{He}(\alpha,\gamma)^{7}\mathrm{Be}(e^{-}\nu)^{7}\mathrm{Li}$ (Cameron 1955). To achieve efficient conversion of $^{3}\mathrm{He}$ to $^{7}\mathrm{Li}$, the $^{7}\mathrm{Be}$ must be swept out of the hot layers where it is produced to cooler layers where it and $^{7}\mathrm{Li}$ are immune to destruction by protons. Cameron & Fowler sited initiation of the sequence at the base of the H-rich convective envelope with $^{7}\mathrm{Be}$ and $^{7}\mathrm{Li}$ convected outward to safety. Today, we would refer to the situation as a hot-bottomed convective envelope. In addition to its applicability to AGB stars with such an envelope, the Cameron-Fowler conversion of $^{3}\mathrm{He}$ to $^{7}\mathrm{Li}$ has been applied to account for Li-rich first ascent red giants, stars with internal structures very different from that of an AGB star, as several papers at this symposium discuss.

A star's internal reservoir of $^{3}\mathrm{He}$ is built up from two sources. First, there is the $^{3}\mathrm{He}$ and $^{2}\mathrm{H}$ present at its birth. The $^{2}\mathrm{H}$, surviving Big Bang deuterium, is burnt to $^{3}\mathrm{He}$ in the pre-main sequence phase. The initial $^{3}\mathrm{He}$ is a consequence of Galactic chemical evolution but likely dominated by the Big Bang's $^{3}\mathrm{He}$, and any $^{3}\mathrm{He}$ synthesised by stars during the Galaxy's evolution. A contribution from stellar nucleosynthesis, apart from the D to $^{3}\mathrm{He}$ conversion, is significant only in low mass stars where their long main sequence life allows the initial reaction of the *pp*-chain with its very small cross-section governed by the weak interaction to provide $^{3}\mathrm{He}$ exterior to the energy-energy generating core. A corollary of the last point is that $^{3}\mathrm{He}$ is *not* synthesised by stars once they have evolved off the main sequence. Initiation of the Cameron-Fowler mechanism may begin by increasing the Li abundance in the stellar atmosphere but extended operation will eventually lead to a reduction of the Li abundance as the $^{7}\mathrm{Li}$ is recycled to high temperatures and destroyed and the $^{3}\mathrm{He}$ supply is run to exhaustion.

4.9. *Helium is primarily primordial*

In their 1964 paper, Hoyle & Tayler presented a convicing theoretical argument that the reported He/H ratio of about 0.1 in several Galactic and extragalactic objects could not be accounted for by stellar nucleosynthesis but had been produced 'in a far more dramatic way'. Apart from a measurement of the He/H ratio in a planetary nebula belonging to a globular cluster (O'Dell, Peimbert, & Kinman 1964), observational evidence that He might have a primordial origin with a minor supplement from stellar nucleosynthesis was scant in the extreme. Furthermore, the stellar ejecta comprising a planetary nebula may have been enriched in He in the course of stellar evolution.

Spectroscopy of halo stars (i.e., old and expected to be He-poor if stellar nucleosynthesis is the dominant origin of He) sufficiently hot to show He lines had displayed a tendency to present low He/H ratios but with compositions that 'are quite exotic and hard to accept as being primordial ' (Searle & Sargent 1972). Now, we identify 'exotic' as consequences of diffusion that has distorted the 'true' composition of the stars.

Definitive observational spectroscopic evidence of the primarily primordial origin of He was first provided by Searle & Sargent (1972) in their paper 'Inferences from the composition of two dwarf blue galaxies'. Emission lines in the galaxies I Zw 18 and II Zw 40 showed that O/H and Ne/H were lower than local Galactic values ($[O/H] \simeq -1$ in the case of I Zw 18) but He has a normal abundance. 'These galaxies are the first metal-poor systems of Population I to be discovered: the normal helium abundance is taken as evidence that this abundance is primordial' (Searle & Sargent). I Zw 18 remains one of a handful of O-poor galaxies anchoring the low O/H end of the relation between He/H and O/H that provides our estimates of the Big Bang's He yield (see papers at this symposium).

4.10. *Deuterium as a baryometer*

The realization that the deuterium abundance - D/H - in appropriate locales might serve as a baryometer for the Big Bang was boosted with Reeves *et al.*'s (1973) paper 'On the origin of the light elements'. While the paper offered a comprehensive survey of the origins of all the light nuclides, perhaps its most telling and lasting point were the assertions that 'The deuterium can *only* be produced pregalactically either by the big bang or in some pregalactic event' [emphasis added] and 'the most plausible origin of D is big-bang nucleosynthesis'. Another way to express this result is to say that all modes of stellar nucleosynthesis destroy ('astrate') D and possible production paths involving energetic particles in diverse places (interstellar medium, stellar atmospheres, for example) cannot produce D without overproducing other light elements. The primordial origin of D was amplified by Epstein, Lattimer, & Schramm (1976) with the caveat that 'other, more speculative, sources are not ruled out'. Todate, no such 'other' sources have been ruled in.

Detection of D in the interstellar medium was first reported by Rogerson & York (1973) from *Copernicus* spectra of the hot star β Cen showing Lyman lines of H I and D I - the isotopic wavelength shift of 81 km s^{-1} provided well resolved lines. Measurements of the D/H ratio along several lines of sight followed this pioneering determination for β Cen.

Of course, the D/H measurement might reasonably be taken to be a lower limit to the Big Bang D/H ratio; cycling of gas through stars astrates D. Various attempts were made (and continue to be made) to devise the correction for the cumulative astration. Substantial additions to the library of interstellar D/H measurements, especially from *FUSE* spectra, have added challenges to modelling of GCE of D.

Adams (1976) proposed that the difficulties of correcting the interstellar D/H ratios for astration in order to obtain the pregalactic/primordial ratio could be alleviated, if not avoided, by detecting the Lyman D I lines in absorption from intergalactic clouds along the lines of sight to distant quasars. Such clouds representing almost pristine primordial gas should have essentially their primordial D abundance. The degree to which the clouds have been contaminated by products of stellar nucleosynthesis is assessable from absorption lines of ions of C, O, Si etc. Adams' proposal was ahead of its time. It took 8-meter class telescopes with high-resolution spectrographs to obtain suitable spectra. Even today, as discussed at this symposium, useful D/H ratios have been published for just a handful of quasars; many quasars turn out to have ill-suited spectra; the D I lines of a strong cloud are blended with H I lines of a weaker cloud at a different velocity. A definitive set of D/H determinations continues to elude us.

4.11. *The hyperfine line 8.7 GHz line of* ^{3}*He*$^+$

The ground state of the ion ^{3}He$^+$ with a nuclear spin of 1/2 has a hyperfine line at 8.7 GHz, the analogue of the H atom's 21 cm line. Rood, Wilson, & Steigman (1979) reported on 'The probable detection of interstellar ^{3}He$^+$ and its significance'. The 'tentative detection' referred to a giant H II region. Since 1979, Rood and colleagues have doggedly pursued the 8.7 GHZ line in Galactic H II regions and planetary nebulae, as described by Bania at this symposium. Abundances of ^{3}He$^+$ in these sources have led to what has been dubbed 'the ^{3}He problem' (Galli *et al.* 1997).

The isotope ^{3}He with D and ^{7}Li is a minor product of the standard Big Bang. Additionally, main sequence stars are predicted to synthesise ^{3}He as part of the *pp*-chain and from D-burning (as outlined above in Section 4.8). If one assumes that the synthesised ^{3}He is not subsequently destroyed (astrated) and returned to the interstellar medium, the ^{3}He abundance in the interstellar medium might be expected to increase with time, i.e., the abundance in local H II regions might be higher than the protosolar value, as apparently first pointed out by Rood, Steigman, & Tinsley (1976). This possibility and the lure of pinning down the Big Bang's ^{3}He yield prompted the now 30-year old pursuit of the 8.7 GHz line.

In the 1979 paper, the single probable detection of ^{3}He in an H II region led to the determination of a ^{3}He/H ratio 'comparable to the protosolar number' and the conclusion that there is 'no evidence for the production of ^{3}He predicted for low mass stars'. Knowing the ingenuity of students of Galactic chemical evolution, the conclusion may not necessarily follow from the determination of the similar ^{3}He/H abundances. However, the '^{3}He problem' was starkly evident after the 8.6 GHz line was detected from Galactic planetary nebulae. Balser *et al.* (1997) report the first successful observations of the line with the result that the ^{3}He/H abundances 'are more than an order of magnitude larger than those found in any H II region, the local interstellar medium, or the proto-solar system'. Clearly, 'there is *some* stellar production of ^{3}He' [emphasis in the 1979 abstract]. The ^{3}He problem is the subject of several papers here.

4.12. *The Spite plateau*

My final milestone in this chronological listing is the pair of 1982 papers by Spite & Spite: The *Nature* Letter 'Lithium abundance at the formation of the Galaxy' (Spite & Spite 1982a) and the *A&A* article 'Abundance of lithium in unevolved halo stars and old disk stars: interpretation and consequences' (Spite & Spite 1982b).

The landscape in which this milestone was uncovered may be appreciated by recalling the summary of Li observations assembled by Reeves *et al.* (1973). The local Li abundance was put at $\log \epsilon \simeq 3$ with Li-richer stars (e.g., WZ Cas) attributed to internal Li synthesis and Li-poorer stars (e.g., Sun) attributed to internal Li astration. In their presentation of the possible Galactic evolution of the ^{7}Li abundance (Fig. 6 of Reeves *et al.*), two extremes were presented: (i) the assumption that ^{7}Li was a Big Bang product led to the suggestion of a factor of several *increase* in the Li/H ratio from the present ratio back to the formation of the Galaxy; (ii) an assumption that ^{7}Li came only from enrichment of the interstellar medium by Li-rich gas from red giants led, of course, to Li-poor gas at early times. A third possibility was that the local Li abundance seen in stars with ages spanning at least 5 Gyr represents the pre-Galactic abundance.

Spite & Spite exploiting the spectroscopic capabilities of the (then) new CFHT telescope observed a small sample of halo dwarfs, stars recognized as very old and known to be very metal-poor, i.e., the gas from which these stars had formed should be a fair approximation to pre-Galactic gas. To their (I presume) surprise and delight, the Li abundance of the warmest of these stars was uniform (hence, the Spite plateau) and at $\log \epsilon(\mathrm{Li}) = 2.05$ much lower than the local value. ‘After discussion, it is suggested that the abundance in halo dwarfs is therefore representative of the interstellar matter which formed the stars and also this matter itself retains the lithium abundance of the Big Bang, hardly altered’ (Spite & Spite 1982b).

The existence of a plateau, the Li abundance of the plateau, and the relation between the Li abundance and the abundance provided by the Big Bang have been debated from 1982 to this day, and, indeed, these questions were among the reasons advanced for holding this symposium.

5. Final thoughts

The four discussion sessions at the symposium were intended to focus on the ‘hot’ questions involving light elements in contemporary astrophysics. My contribution sheds light on the historical perspective behind most of these questions. Omissions will be excused, I hope, on the grounds of lack of time and space.

In closing, I offer two rather different historical thoughts: the first on the publication of symposium proceedings and the second on the sophistication of our scientific endeavours.

As a research student, I recall the particular joy I experienced in reading the extended discussions that were reported at length in the two IAU symposia (#12 and #28) on ‘Aerodynamic Phenomena in Stellar Atmospheres’ edited by R.N. Thomas (1960, 1965). These were not meetings I had attended but the discussions almost brought me into the meeting room as an engaged listener, if one too shy and ignorant to participate. Why do organisers of meetings not aspire to emulate these two volumes?

Astronomical spectra are beautiful objects, especially when a striking conclusion may be drawn by inspection. In Geneva, I drew attention once again to Spite & Spite’s (1982b) Figure 1 showing spectra around the Li I 6707Å doublet for four metal-poor dwarfs. Inspection shows Ca I and Fe I lines of differing strength but Li I lines of similar strength in all but the coolest dwarf HD 103095 (alias Groombridge 1830). Thus, the Spite plateau is there in front of ones eyes. (Li is strongly depleted in HD 103095.)

Of course, conversion of spectra to a quantitative abundance estimate cannot be done by visual inspection alone. Tools for the conversion have certainly become more sophisticated and refined over the years spanned by milestones and certainly since 1982. Had I not concentrated on results exclusively, I would have entertained including milestones relating to telescopes, instruments, and analytical tools. Currently, the apex of analytical sophistication surely involves the application of 3D or hydrodynamical model atmospheres with the selective addition of non-LTE considerations in certain cases.

In the area of light elements, 3D atmospheres are being applied in particular to analyses of the Li I 6707Å line in metal-poor dwarf stars to address key questions from cosmology, early Galactic evolution, and stellar physics. If I were to limit the questions to two, my choices would be ‘Is the Li abundance of Spite plateau stars reconcilable with that predicted from the Big Bang with the baryon density set by the CMB fluctuations? and ‘Is there ^{6}Li mixed in with the ^{7}Li in these stars?

To the first question, there appear to be two diametrically different answers to account for the result obtained (even with 3D atmospheres) that the stellar Li abundance is a factor of several less than the Big Bang prediction. One, diffusion is invoked to reduce the atmospheric abundance but to account for the plateau’s observed height and shape over several dex in metallicity turbulent diffusion is introduced without thorough detailed physical understanding. Two, the standard model of the Big Bang is modified by introducing new physics including modifications to the standard model of particle physics. One or two? Or both?

Obviously, observational tests are sought. In the case of one, there is now evidence that diffusion whose effects should be partially undone in evolution off the main sequence has occurred - see the beautiful work reported here on the composition of globular cluster stars. In the case of two, an indicator of some failures of the standard Big Bang model is the presence of ^{6}Li in significant amounts. Measurements of small amounts of ^{6}Li in the presence of ^{7}Li demand a sophistication of line profile analysis rarely required, and possibly not yet achievable.

One looks forward to the next workshop, conference, or symposium on light elements in the Universe. Perhaps, no other set of five elements brings together in such an interlocked fashion matters of cosmology, galaxy formation and evolution, and an array of matters in stellar astrophysics.

In preparing this essay for publication, I took the occasion to explore the literature somewhat more thoroughly than I did prior to the oral presentation in Geneva. This led to some modification of the presentation but, more fundamentally, I was humbled afresh by how much of the history I had forgotten or had never ever appreciated. Thus, I apologise to those whose contributions I have still overlooked or underappreciated. I thank my Austin friends who answered several questions at short notice, especially Volker Bromm and Paul Shapiro. As has been the case for more than 30 years, I are indebted to the Robert A. Welch Foundation of Houston, Texas for grant F-634 which has supported my research into the chemical compositions of stars.

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