Liquid Metallic Hydrogen II. A Critical Assessment of Current and Primordial Helium Levels in the Sun

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Before a solar model becomes viable in astrophysics, one must consider how the elemental constitution of the Sun was ascertained, especially relative to its principle components: hydrogen and helium. Liquid metallic hydrogen has been proposed as a solar structural material for models based on condensed matter (e.g. Robitaille P.-M. Liquid Metallic Hydrogen: A Building Block for the Liquid Sun. *Progr. Phys.*, 2011, v. 3, 60–74). There can be little doubt that hydrogen plays a dominant role in the universe and in the stars; the massive abundance of hydrogen in the Sun was established long ago. Today, it can be demonstrated that the near isointense nature of the Sun's Balmer lines provides strong confirmatory evidence for a distinct solar surface. The situation relative to helium remains less conclusive. Still, helium occupies a prominent role in astronomy, both as an element associated with cosmology and as a byproduct of nuclear energy generation, though its abundances within the Sun cannot be reliably estimated using theoretical approaches. With respect to the determination of helium levels, the element remains spectroscopically silent at the level of the photosphere. While helium can be monitored with ease in the chromosphere and the prominences of the corona using spectroscopic methods, these measures are highly variable and responsive to elevated solar activity and nuclear fragmentation. Direct assays of the solar winds are currently viewed as incapable of providing definitive information regarding solar helium abundances. As a result, insight relative to helium remains strictly based on theoretical estimates which couple helioseismological approaches to metrics derived from solar models. Despite their "state of the art" nature, helium estimates based on solar models and helioseismology are suspect on several fronts, including their reliance on solar opacities. The best knowledge can only come from the solar winds which, though highly variable, provide a wealth of data. Evaluations of primordial helium levels based on 1) the spectroscopic study of H-II regions and 2) microwave anisotropy data, remain highly questionable. Current helium levels, both within the stars (Robitaille J. C. and Robitaille P.-M. Liquid Metallic Hydrogen III. Intercalation and Lattice Exclusion versus Gravitational Settling, and Their Consequences Relative to Internal Structure, Surface Activity, and Solar Winds in the Sun. *Progr. Phys.*, 2013, v. 2, in press) and the universe at large, appear to be overstated. A careful consideration of available observational data suggests that helium abundances are considerably lower than currently believed.

> At the age of five Cecilia [Payne] saw a meteor, and thereupon decided to become an Astronomer. She remarked that she must begin quickly, in case there should be no research left when she grew up.
>
> Betty Grierson Leaf, 1923 [1, p. 72–73]

1 Introduction

Knowledge that helium [2, 3] was first observed in the Sun by Pierre Jules César Janssen [4] and Joseph Norman Lockyer [5], before being discovered on Earth by William Ramsay [6], might prompt the belief that the element was abundant on the solar surface. In fact, helium has never been identified in the absorption spectra of the quiet Sun. Janssen and Lockyer's fortunate discovery was restricted to helium lines appearing within the prominences of the corona and within the disturbed chromosphere [4, 5]. While the element was easily detectable in these regions [7], helium has remained relatively spectroscopically silent on the Sun. Conversely, the stars and the Sun display signs of extreme hydrogen abundance, as first observed by Cecilia Payne [8], Albrecht Unsöld [9], and Henry Norris Russell [10]. Few would take issue with the conclusion that the visible universe is primarily comprised of hydrogen. Helium abundances present a more arduous question.

Despite all the difficulties, several lines of reasoning sustain the tremendous attention that solar helium levels have received in astronomy. First, helium is the end product of the nuclear reactions currently believed to fuel many of the stars, either in the pp process or the CNO cycle [11–15]. Second, solar helium levels are inherently linked to the gaseous models of the Sun [16–18] and the application of theoretical findings to the interpretation of helioseismic results [19–23]. Finally, helium is thought to be a key primordial element in

Big Bang cosmology [3, 24–30]. As a result, the evaluation of helium levels in the Sun brings a unified vision of astrophysics, wherein accepted solar values lend credence to our current concept of the formation of the universe. Still, questions remain relative to the accuracy of modern helium determinations.

A flurry of initial studies had suggested that helium abundances in the stars approached 27% by mass (see [3] for a review). The findings provided support for those who proposed primordial formation of helium prior to the existence of the objects which populate the main sequence [3, 24]. However, these ideas were challenged when it was discovered that certain B-type stars, which should have been rich in helium lines, were almost devoid of such features [3]. As a result, in certain stars, helium was said to be gravitationally settling towards the interior [3,31]. The desire to link helium levels in the Sun with those anticipated from the primordial synthesis continues to dominate modern solar theory [18]. Nonetheless, it can be demonstrated that the methods used to estimate primordial helium levels in the universe [24] are either highly suspect or implausible. Given these complexities, it is appropriate to compose a critical review of how helium abundances have been historically obtained and how they are currently determined, both in the Sun and in the universe at large.

2 Assessing elemental abundances in stellar spectra

2.1 The Saha Equations

Reasoning, like Lindemann [32] and Eggert [33] before him, that the fragmentation of an atom into an ion and an electron was analogous to the dissociation of a molecule, Megh Nad Saha [34, 35] formulated the ionization equations [36, 37] in the early 1920s. In so doing, he called upon the Nernst equation [38] and suggested that the free electron could be viewed as an ideal gas. He also relied on thermal equilibrium and the ionization potentials of the elements. Since Saha's equation was inherently related to parameters associated with the ideal gas (i.e. [39, p. 29–36] and [40, p. 107–117]) he demonstrated that the level of ionization could be increased either with elevated temperature or decreased pressure. Saha hypothesized that the pressure of the reversing layer approached 0.1–1 atm [36, p. 481] and was the first to utilize this assumption to account for the appearance of spectral lines across stellar classes as simple functions of temperature [36, 37]. He was concerned with the marginal appearance of spectral lines [36,37], that point at which these features first appeared on a photographic plate. Cecilia Payne [1, 41] would soon estimate the abundance of the elements in the universe using the same criterion [8].

In his initial work, Saha would comment on the impossibility of solar temperatures increasing as one moves from the photosphere to the upper chromosphere: "*Lockyer's theory... [that elements become more ionized as higher elevations are reached within the chromosphere] ... would lead us to the hypothesis that the outer chromosphere is at a substantially higher temperature than the photosphere, and the lower chromosphere; and that the temperature of the sun increases as we pass radially outwards. This hypothesis is, however, quite untenable and is in flagrant contradiction to all accepted theories of physics*" [36, p. 473]. Saha had not suspected that 20th century solar theorists would maintain such a position. Lockyer's analysis was correct: ionization increased with elevation in the chromosphere. This was an important lesson relative to thermal equilibrium. In any case, Saha did observe that hydrogen was not fully ionized in the chromosphere, since the lines from H_α and H_β were evident at this level. He also recognized that hydrogen should be essentially ionized in O class stars and that the lines coincident with the Balmer series in these stars had originated from ionized helium. At the same time, he outlined that the same spectral lines for classes later than B2A were completely due to hydrogen [37, p. 151].

Subrahmanyan Chandrasekhar's (Nobel Prize, 1983 [42]) thesis advisor, Sir Ralph H. Fowler [43], had provided significant insight and criticisms into Saha's second manuscript [37, p. 153] and the resulting text was masterful. In 1927, Megh Nad Saha was elected a Fellow of the Royal Society [34].

In the meantime, Fowler [43] and Edward Arthur Milne [44] would collaborate and construct a wonderful extension [45,46] of Saha's seminal papers [36,37]. They improved the treatment of ionization to consider not only principle lines arising from atoms in their lowest energy states, but also the subordinate lines produced by excited atoms and ions [45,46]. For his part, Saha had concentrated on the excitation and ionization of the neutral atom [36, 37]. Fowler and Milne understood that the marginal appearance of a spectral line could be used in determining relative concentrations and provided some indication of the minimum number of atoms necessary for appearance [45, 46]. They emphasized the idea that: "*the intensity of a given absorption line in a stellar spectrum is proportional to the concentration of atoms in the stellar atmosphere capable of absorbing the line*" [45, p. 404]. Their first paper also highlighted the value of the maximum of a spectral line in assessing the temperature and pressure of the reversing layer and outlined that this problem was not affected by the relative abundance of the element studied [45]. Using stellar data from the lines of Ca, Mg, Sr, and Ba they determined that the electron pressure of the reversing layer was on the order of 10^{-4} atm [45]. Fowler and Milne understood that electron pressure, P_e, of the reversing layer was not determined by a single ionization process, but by the ionization of many elements: "*In thus regarding P_e as fundamental we are in effect assuming that, due to the presence of more easily ionised atoms, there are so many electrons present that the partial electron pressure is practically independent of the degree of ionization of the element under discussion*" [45, p. 409]. They expressed concern that their results led to the assumption that absorbing species had very large absorption coefficients [45]. Milne had already determined that the absorption coefficients should be very large [47] and would later devote another theoretical paper to their determination [48]. In their work together, Fowler and Milne explicitly assumed that the reversing layer could be treated as existing under conditions of thermal equilibrium, as Saha's treatment required [36]. The validity of such assumptions is not simple to ascertain.

At Cambridge, Milne met Cecilia Payne [1, p. 121], a student at Newnham College [1, p. 112] and learned of her impending access to the vast collection of photographic plates used to generate the Henry Draper Catalogue at the Harvard Observatory [1, p. 144–153]. Prior to the advent of the modern MKK classification [49], the Henry Draper Catalogue was the largest stellar library collection, with over 200,000 classified stars [1, p. 144–153]. Milne suggested that "*if he had... [Payne's] ... opportunity, he would go after the observations that would test and verify the Saha theory*" [1, p. 155]. Cecila Payne soon left Cambridge and sailed to America.

2.2 Cecilia Payne: What is the universe made of?

> "I remember when, as a student at Cambridge, I decided I wanted to be an astronomer and asked the advice of Colonel Stratton, he replied, "You can't expect to be anything but an amateur". I should have been discouraged, but I wasn't, so I asked Eddington the same question. He (as was his way) thought it over a very long time and finally said: "I can see no insuperable obstacle" [50, xv].

Nineteenth century scientists had little on which to base their understanding of the composition of the universe. Their clues could only come from the Earth itself and from the meteorites which occasionally tumbled onto its surface. Consequently, it was not unreasonable to expect that the universe's composition matched the terrestrial setting. However, stellar spectra, already stored on photographic plates throughout Europe and especially in the vast Henry Draper Collection, were hiding a drastically altered viewpoint. With the arrival of yet another woman at the Harvard Observatory [51–60], the stars could not much longer conceal their story. Surrounded by Pickering's Harem [51–60], Cecilia Payne [1, 41] completed her classic report on the abundance of the elements [8] and became the first to underscore the importance of hydrogen as the constitutive atom of universe. Her thesis had been carefully prepared and presented supportive laboratory evidence, not only of ionization potentials, but of the validity of Saha's treatment [8, p. 105–115].

Stellar spectra signaled hydrogen [61] was so abundant that several scientists, including Henry Norris Russell, could not fully accept the conclusion. Payne had written an early manuscript detailing the tremendous presence of hydrogen [1, p. 19]. Her thesis advisor, Harlow Shapley, forwarded the work to Russell who commented: "*It is clearly impossible that hydrogen should be a million times more abundant than the metals*" [1, p. 19]. That early manuscript was never published and has since been lost [1, p. 20]. Tempered by Russell and Shapley, Cecilia Payne finally produced her famous PhD dissertation: *Stellar Atmospheres: A Contribution to the Observational Study of High Temperature in the Reversing Layers of Stars* [8]. She would comment on hydrogen in this manner: "*Although hydrogen and helium are manifestly very abundant in stellar atmospheres, the actual values derived from the estimates of marginal appearance are regarded as spurious*" [8, p. 186]. A little later she would add: "*The outstanding discrepancies between the astrophysical and terrestrial abundances are displayed for hydrogen and helium. The enormous abundance derived for these elements in the stellar atmospheres is almost certainly not real*" [8, p. 188] and "*The lines of both atoms appear to be far more persistent, at high and low temperatures, than those of any other element*" [8, p. 189].

For her part, Payne privately maintained that hydrogen was tremendously abundant in the stars: "*When I returned to visit Cambridge after I finished this first essay in astrophysics, I went to see Eddington. In a burst of youthful enthusiasm, I told him that I believed that there was far more hydrogen in the stars than any other atom. 'You don't mean in the stars, you mean on the stars', was his comment. In this case, indeed, I was in the right, and in later years he was to recognize it too*" [1, p. 165].

Payne's work also highlighted the importance of helium in the O and B class stars [8]. For the first time, hydrogen and helium became the focus of scrutiny for their role as potential building blocks of the stars and the cosmos [8]. She emphasized that: "*there is no reason to assume a sensible departure from uniform composition for members of the normal sequence*" [8, p. 179] and "*The uniformity of composition of stellar atmospheres is an established fact*" [8, p. 189]. She also held, as Eddington and Zeipel had advanced, that given their gaseous nature: "*an effect of rotation of a star will be to keep the constituents well mixed, so that the outer portions of the sun or of a star are probably fairly representative of the interior*" [8, p. 185]. Still, Payne was cautious relative to extending her results as reflecting the internal composition of the stars: "*The observations on abundances refer merely to the stellar atmosphere, and it is not possible to arrive in this way at conclusions as to internal composition. But marked differences of internal composition from star to star might be expected to affect the atmosphere to a noticeable extent, and it is therefore somewhat unlikely that such differences do occur*" [8, p. 189].

Payne would conclude her thesis with a wonderful exposition of the Henry Draper Classification system [8, p. 190–198]. Otto Struve would come to regard the study as "*the most brilliant Ph.D. thesis ever written in astronomy*" [41]. Edwin Hubble would comment relative to Payne: "*She's the best man at Harvard*" [1, p. 184]. As Milne suggested, the first dissertation of the Harvard College Observatory was founded upon the application of the ionization equations [36,37,45,46] to the detailed analysis of spectral lines across stellar classes. It did not specifically address elemental abundances in the Sun. Nonetheless, Payne's 1925 dissertation heralded the application of quantitative spectral analysis in astronomy [8].

2.3 Albrecht Unsöld, hydrogen abundance, and evidence for a solar surface

Albrecht Unsöld extended Payne's studies with a focus on the solar spectra [9]. Following in her footsteps [8], in 1928 [9], he applied the ionization formula [36, 37] to the chromosphere and estimated the levels of sodium, aluminum, calcium, strontium, and barium. In addition, Unsöld determined that the electron gas pressure in the chromosphere stood at $\sim 10^{-6}$ atm [9]. He also concluded that hydrogen must be about one million times more abundant than any other element in the Sun [9, 62]. William McCrea was soon to echo Unsöld, finding that hydrogen was a million times more abundant than Ca^{+} within the chromosphere [62, 63].

Importantly, Unsöld also documented that the absorbance of the hydrogen β, γ, and δ lines did not decrease across the Balmer series ($H_\alpha = 1$; $H_\beta = 0.73$; $H_\gamma = 0.91$; $H_\delta = 1.0$) as expected from quantum mechanical considerations ($H_\alpha = 1$; $H_\beta = 0.19$; $H_\gamma = 0.07$; $H_\delta = 0.03$) [9]. This was an important finding relative to the nature of the Sun. Recently, the behavior of hydrogen emission lines has been analyzed with non-LTE methods [64]. It has been concluded that the "$n = 3$ *and higher levels are in detailed balance deep in the photosphere, but they develop a non-LTE underpopulation further out. However, the levels with higher n-values stay in detailed balance relative to each other at these atmospheric depths, and they also collisionally couple tightly to the continuum*" [64]. Yet, in the gaseous models of the Sun, the continuum is not composed of condensed matter [65]. It represents an area of profoundly increased solar opacity [65]. Nevertheless, the behavior of the Balmer series in the solar atmosphere strongly supports the idea that the Sun is comprised of condensed matter. Only a physical entity of sufficient density, such as a surface, can permit tight collisional coupling to the continuum, as it is impossible to couple to the opacity changes which characterize the continuum in gaseous models [65]. These findings comprise the sixteenth and seventeenth lines of evidence that the Sun is comprised of condensed matter. The others are outlined by the author in recent publications (e.g. [66]).

2.4 Henry Norris Russell: Inability to estimate Helium from spectral lines

Soon Henry Norris Russell [67] surpassed Unsöld in his analysis of solar spectral lines and provided a detailed compositional analysis of the Sun. Relative to the occupied energy levels within atoms on the Sun, Russell affirmed that: "*It must further be born in mind that even at solar temperatures the great majority of the atoms of any given kind, whether ionized or neutral, will be in the state of lowest energy*" [10, p. 21]. At the same time, Russell realized that this rule was not observed by hydrogen, leading him to the conclusion that the element was extremely abundant in the Sun: "*One non-metal, however, presents a real and glaring exception to the general rule. The hydrogen lines of the Balmer series, and, as Babcock has recently shown, of the Paschen series as well, are very strong in the Sun, though the energy required to put an atom into condition to absorb these series is, respectively, 10.16 and 12.04 volts - higher than for any other solar absorption lines. The obvious explanation — that hydrogen is far more abundant than the other elements — appears to be the only one*" [10, p. 22]. In fact, even the hydrogen Brackett lines can be visualized in the infrared spectrum of the Sun [68]. Russell also highlighted Unsöld's observation [9] that the hydrogen β, γ, and δ lines did not decrease as expected. That the hydrogen lines were extremely broad in the Sun had already been well established. Russell echoed some of his contemporaries and suggested that this might result from a Stark effect [10, p. 50].

Finally, Russell accepted Payne's findings relative to hydrogen and reported her numbers for the elements without comment in his table XVI [10, p. 65]. He stated that: "*The most important previous determination of the abundance of the elements by astrophysical means is that by Miss Payne. . .*" [10, p. 64]. Russell found the correlation between their works to display "*a very gratifying agreement*" [10, p. 65]

Like Payne, Russell had relied on the work of Fowler and Milne [45, 46] to set the composition of the Sun. He implemented their suggestion that electron pressures, P_e, could be gathered by considering the spectra and the ionization potential for elements like Ca, Sc, Ti, Sr and Yt. From these, he deduced a P_e of 3.1×10^{-6} atm, in close agreement with Milne (2.5×10^{-5} atm), and Payne and Hogg (2.54×10^{-6} atm) in class G0 stars [10, p. 54–55]. Along with John Quincy Stewart, Russell had previously considered various means of determining the pressures at the Sun's surface and had determined that the pressure of the reversion layer could not be more than 10^{-4} atm [69]. But Russell reported a factor of at least 10 in discordance in calculating electron pressures based on either the ionization formula or the numbers of metallic atoms and ions [10, p. 70–71]. He would resolve the difficulty at the end of his treatise when setting the final elemental composition for the Sun [10, p. 72].

At the same time, while Payne had understood the importance of local thermal equilibrium (LTE) for the proper application of Saha's equation [8, p. 92–101], she did not attempt to make an explicit correction for the lack of equilibrium. Conversely, Russell placed a correction factor in his work for departure from LTE: "*We have finally to take into consideration the fact that the atmosphere may not be in thermodynamic equilibrium. The comparison of solar and stellar spectra affords evidence that this is the case*" [10, p. 52]. Relative to his final abundances he commented: "*The main source of uncertainty which affects them is the magnitude of the correction for departure from thermodynamic equilibrium*" [10, p. 58] and "*If the correction for departure from thermodynamic equilibrium should be wholly disregarded, the calculated abundance of hydrogen — already very great — would be increased thirty fold*" [10, p. 62]. In the 1920s, of course, there was hesitancy concerning the tremendous levels of hydrogen observed in the solar atmosphere.

For Russell, oxygen appeared as abundant as all other metals combined. He also argued against, although did not fully dismiss, gravitational settling in the Sun for the heaviest metals: "*It does not appear necessary, therefore, to assume that downward diffusion depletes the sun's atmosphere of the heavier elements, though the possibility of such an influence remains*" [10, p. 59]. Importantly, he noted: "*The statement that enhanced lines are found in the sun for those elements which have lines of low excitation potential in the accessible region has therefore few exceptions*" [10, p. 35]. At the same time, he advanced that for those elements "*which fail to show enhancement lines in the sun, the excitation potentials for the accessible lines are high in every case for which they have been determined*" [10, p. 35]. Furthermore Russell hypothesized that: "*It appears, therefore, that the principle factor which is unfavourable to the appearance of a spectral line in the sun is a high excitation potential*" [10, p. 35]. This was precisely the case relative to helium.

With respect to the second element, Russell wrote: "*There is but one element known to exist in the sun for which no estimate of abundance has now been made - and this is He. The intensity of its lines in the chromosphere shows that it must be present in considerable amount, but no quantitative estimate seems possible*" [10, p. 62]. Here was an explicit admission that solar helium abundances could not be ascertained using spectral data.

Helium was abundantly visible in early type stars, as Cecilia Payne had already discovered [8] and Paul Rudnick [70] and Anne Underhill continued to confirm [71–73]. Estimates of the number of hydrogen to helium atoms in O and B type stars varied from values as low as 3.2 to more than 27 [73, p. 156]. A factor of nearly 10 in relative abundances from spectral lines in such stars was hardly reassuring. Nonetheless, Underhill still surmised that the number of helium atoms was at the 4–5% level [73]. Yet for the Sun, data about helium abundance remained wanting.

2.5 Local Thermal Equilibrium

Milne was perhaps the greatest authority relative to local thermal equilibrium (LTE) in astronomy [74–77] and many of the most salient aspects of his arguments have been reviewed [78]. Milne advocated that LTE existed in the center of a star and that his treatment permitted "*us to see in a general way why the state of local thermodynamic equilibrium in the interior of a star breaks down as we approach the surface*" [77, p. 81–83]. In 1928, Milne would express concern relative to the appropriateness of the inferred thermal equilibrium in the reversing layer, as required by the Saha equations [36, 37], although he believed that studies based on the validity of the ionization equations should be pursued: "*The recent work of Adams and Russell brings forward evidence that the reversing layers of stars are not in thermodynamic equilibrium. This suggests a degree of caution in applying the fundamental method and formulae of Saha to stellar spectra. Nevertheless, departure from thermodynamic equilibrium can only be found by pushing to as great a refinement as possible the theory which assumes thermodynamic equilibrium*" [48]. Gerasimovic had already advanced corrections for small deviations from thermal equilibrium [79] and Russell applied corrections directly in his work [10]. By 1925, the Saha equations had been generally confirmed under experimental conditions (e.g. [8, p. 111–112] and [80]), but only in the broadest sense. Over time, the ionization equations continued to be widely studied and the problems considered were extended to include two-temperature plasmas (e.g. [81]), high pressures (e.g. [82]), varying opacities (e.g. [83]), and non-LTE (e.g. [84–88]). The Saha equations eventually became a useful staple in the treatment of plasma physics [89, p. 164] and stellar atmospheres [90–92].

As Auer highlighted relative to solar models [88], under non-LTE, a set of rate equations enters into the problem of determining the abundance of any given electronic state. Furthermore, the radiation field is introduced directly into the equations [88] utilized to calculate both opacities and populations. The problem therefore becomes dependent on "*simultaneous knowledge of the radiation field at all frequencies and all depths*" [88, p. 576].

While ionization appeared tractable given modern computing, the solution became linked to the knowledge of stellar opacities, an area of theory whose weaknesses have already been outlined [78]. Nonetheless, non-LTE approaches have been successful in addressing the spectra of early type stars [93–95]. Today, such methods also account for electronic, atomic, and ionic collision processes [64]. Non-LTE approaches have provided considerable insight into the Balmer and Paschen series associated with the hydrogen spectrum of the Sun [64].

Finally, it appears that the treatment adopted by Cecilia Payne might not have been too far afield [8]. For many of the cooler stars, simple LTE seems sufficient to address ionization problems [94]. Non-LTE methods become most important for the O and A class stars [93–95]. In any case, helium cannot be assessed on the Sun using the ionization equations due to the lack of appropriate spectral lines. As a result, while the LTE and non-LTE settings may be fundamental to the proper treatment of spectral lines, the methods have little bearing on the proper evaluation of helium levels in the Sun.

3 Helium from solar theory

3.1 Henry Norris Russell

Since Russell was not able to extract helium abundances directly from spectral lines, he did so, without further scientific justification, by assuming that the Sun had an mean molecular weight of ~ 2 [10, p. 72–73]. Such a value had also been suggested by Saha [36, p. 476], who had in turn adopted it from Eddington [96, p. 596]. As for Eddington, he had previously examined the radiation equilibrium of the stars using a mean molecular weight of 54 [97]. In 1916, this value had been selected based on the belief that the stars were principally composed of elements such as oxygen, silicon, and iron prior to full ionization [1, viii]. Eddington lowered the mean molecular weight to a value of 2 in 1917 [96, p. 596], based on the idea that the elements would be fully ionized in the stars. In the fully ionized state, hydrogen has a mean molecular weight of 0.5, helium of ~ 1.3, and iron of ~ 2 (see [40, p. 102–104] for a full discussion of mean molecular weights in astrophysics). It was this value which Russell was to adopt in his calculations.

Using a mean molecular weight corresponding to a metal rich star, Russell concluded that helium was 13% as abundant as hydrogen by weight [10, p. 73]. He then computed that the Sun had equal percentages of oxygen and other metals (~ 24% each) and that hydrogen comprised just under half of the constitution (~ 45%) by weight (see table XX in [10, p. 73]. If Russell had selected a mean atomic weight of ~ 0.5, there would be dramatic changes in the calculated helium levels.

3.2 Early abundance calculations

In arbitrarily selecting mean molecular weights [96, 97], Eddington determined the mean central stellar temperatures and pressures along with the acceleration due to gravity at the surface (e.g. [97, p. 22]). In turn, these parameters altered the calculated absorption coefficient, and hence opacity, of stellar interiors [97, p. 22]. Consequently, the setting of mean atomic weight had a profound implication on nearly every aspect of stellar modeling, but opacity would always remain paramount. In 1922, Eddington had derived a relationship between opacity and temperature [98] which would become known as Kramer's law [99].

Soon, Strömgren introduced an interesting twist to Eddington's approach [100, 101]. Rather than assuming a mean atomic weight, Strömgren began his calculations by computing opacity values, and from there, estimating the fractional composition of hydrogen within several stars [100], relying in part on Russell's elemental composition [10]. He concluded that the fractional abundance of hydrogen was ~ 0.3 and maintained that the presence of helium would have little effect on these calculations since "*hydrogen and helium do not contribute to the opacity directly*" [100, p. 139]. Strömgren would write: "*we have neglected the influence of helium. The helium proportion is rather uncertain and the error introduced by neglecting helium altogether small* [100, p. 142]. Modern stellar theory would come to rely greatly on the opacity contributions of the negative hydrogen ion (H^-) [102]. Strömgren's assumptions were premature. Still, he championed the idea of initially computing opacity, and from these values obtaining both solar parameters and elemental abundances [100, 101].

Following the publication of a key modeling paper by Cowling [103], Martin Schwarzschild was to take the next theoretical step [104]. First, he made use of the mass-luminosity relation while expressing mean molecular weight and opacity as a function of elemental composition (X = hydrogen, Y = helium) [104]. Then, reasoning that the energy output in the Sun from the CNO cycle [13] was directly related to elemental composition, he derived a fractional elemental composition for hydrogen, helium, and the metals equal to 0.47, 0.41, and 0.12, respectively [104]. The results were once again critically dependent on estimated opacities, which Schwartzchild, like Strömgren before him [100, 101], assumed to display Eddington's [98] −3.5 power dependence on temperature (see Eq. 9 in [104]). In fact, Schwarzschild utilized an even greater dependence on temperature for energy production, allowing a 17th power in the exponential (see Eq. 11 in [104]). Yugo Iinuma then advanced a broader approach to the stellar composition problem [105]. He was concerned with ranges of reasonable starting points, both for hydrogen concentration and average molecular weight. His treatment remained dependent on opacity computations, though less rigid in its conclusions [105]. Schwarzschild et al. [106] then introduced the effects of inhomogeneity in the solar interior and convective envelopes along with solar age into the abundance problem. They reached the conclusion that the temperatures at the core of the Sun were such that the carbon cycle should start to contribute to the problem. Hydrogen abundances were assumed in order to arrive both at a convection parameter and at helium values [106]. The critical link to opacity remained [106]. Weymann, who like Schwarzschild, was also at the Institute for Advanced Study, built on his findings [107]. Taking account of the carbon cycle, Weymann found that the core of the Sun was not convective [107]. Powers of 4 and 20 for temperature were assumed in the energy generation laws associated with the pp and CNO cycles [107]. The hydrogen fractional composition of the Sun was assumed and ranged from 0.60 to 0.80 (see Table 3 in [107]). This resulted in helium and metallic fractional compositions of 0.19–0.32 and 0.01–0.08, respectively (see Table 3 in [107]).

In 1961, Osterbrock and Rogerson would elegantly summarize the situation relative to estimating helium abundances in the Sun: "*Though helium is observed in the upper chromosphere and in prominences, the physical conditions in these regions are too complicated and imperfectly understood for the abundance ratio to be determined from measurements of* *these emission lines. Hence the only reliable way to find the helium abundance in the Sun is by analysis of its internal structure*” [108]. Yet, given the progress to date, the determination of elemental compositions within the Sun had been a complex adventure involving either assumed values of average molecular weights, hydrogen abundances, energy generation reactions, and opacity. The latter would eventually present the greatest difficulties [78]. Osterbrock and Rogerson would utilize Weymann’s calculation, along with making an assumption by setting the Z/X ratio at 6.4×10^{-2} [108], to estimate interior solar fractional abundances at $X = 0.67$, $Y = 0.29$, and $Z = 0.04$. They were guided in this estimation by the belief that: “*the solar, planetary nebula, and interstellar abundances are all essentially the same*” [108, p. 132]. For the planetary nebula NGC 7027 they set the fractional abundances at $X = 0.64$, $Y = 0.32$, and $Z = 0.04$ [108]. Solar elemental composition became decidedly linked to estimates from remote objects. The stage was set for conclusively linking solar elemental composition to stellar evolution and primordial nucleosynthesis.

3.3 Modern abundance calculation

Eventually, the solar neutrino problem entered theoretical modeling [16, 109]. In his simulations, John Bahcall would utilize fractional abundances of relatively narrow range ($X = 0.715 - 0.80$, $Y = 0.19 - 0.258$ and $Z = 0.01 - 0.027$), setting the central densities and temperatures near 150 g/cm^3 and 15 million Kelvin, respectively [16]. The results, as before, were reliant on the use of solar opacity estimates [78]. By the beginning of the 1970s, fractional abundances for helium and the metals were settling on values near 0.28 and 0.02 [25]. Solar models became increasingly complex, relying on stellar opacity tables [110–118], energy generation equations, neutrino flux, and solar age to arrive at internally consistent results [17, 18]. Complexity was also introduced by considering helium and heavy element diffusion throughout the solar body [17, 18, 119, 120]. It became important to establish not only modern helium content, but also the initial helium abundance in the Sun [17,21,121]. Gough had already suggested that helioseismology could be used to help establish fractional abundances: “*Thus one might anticipate inferring the hydrogen-helium abundance ratio by comparing the measured values with a sequence of model solar envelopes*” [19, p. 21]. Helioseismological results became strongly incorporated into solar modeling [20–23] and “*helioseismic techniques . . . [became] . . . the most accurate way to determine the solar helium abundance*” [20, p. 235]. The techniques remained linked to the equations of state which contained six unknowns including: elemental composition, density, temperature, and pressure [20, p. 224]. Moreover, the problems required an explicit knowledge of opacity [20, p. 224] from its associated tables [110–118].

Relative to solar models, the central problem remains linked to the determination of internal solar opacity. The questions are complex and have been addressed in detail already by the author [78]. In the end, opacity tables [110–118] have no place in the treatment of stellar problems, precisely because they are incapable of reproducing the thermal emission spectrum required [78]. They simply mask ignorance of a fundamental problem in astronomy: the mechanism for the production of a thermal spectrum. Their inability to account for the production of a single photon by graphite on Earth [78], establishes that stellar opacity derived from isolated atoms and ions can play no role in the proper understanding of thermal emissivity in the stars. As a result, helium levels can never be established using theoretical modeling based on the gaseous equations of state and their inherent association with stellar opacity tables [78].

4 Primordial helium abundances

The quest to understand helium levels in the stars has been further complicated by the inferred association of this element with primordial nucleosynthesis in Big Bang cosmology [24–30]. Early on, Alpher, Bethe, and Gamow postulated that the elements had been synthesized in a primordial fireball [122]. This nucleosynthesis was proposed to include the entire periodic table and even unstable elements, with short lifetimes, of greater atomic number [122]. Soon, the idea that the composition of the stars was largely related to primordial conditions was born, especially relative to hydrogen and helium [24, 123]. No other scheme appeared likely to explain the tremendous He levels in stellar atmospheres, which approached 27% by weight [3, 24]: “*It is the purpose of this article to suggest that mild ‘cooking’ [such as found in stars] is not enough and that most, if not all, of the material of our everyday world, of the Sun, of the stars in our Galaxy and probably of the whole local group of galaxies, if not the whole Universe, has been ’cooked’ to a temperature in excess of* $10^{10}K$” [123, p. 1108]. By then, the astrophysical community had already accepted that the heavy elements, which constituted trivial amounts of matter compared to hydrogen and helium, had largely been synthesized in the stars [14]. Only ^{1}H, ^{2}H, ^{3}He, ^{4}He, and ^{7}Li became candidates for synthesis through a primordial process [124, 125].

The postulate that “*helium abundance is universal and was generated in a Big Bang*” [125] eventually came to wide acceptance. The entire theory was hinged on elevated helium abundances: “*We can now say that if the Universe originated in a singular way the He/H ratio cannot be less than about 0.14. This value is of the same order of magnitude as the observed ratios although it is somewhat larger than most of them. However, if it can be established empirically that the ratio is appreciably less than this in any astronomical object in which diffussive seperation is out of the question, we can assert that the Universe did not have a singular origin*” [123, p. 1109]. Elevated helium levels, along with the discovery of the microwave background [126] and the red-shifts of distant galaxies [127, 128] became one of the three great pillars of Big Bang cosmology [24, 129, 130]. This explained why gravitational settling had become critical in discounting low helium abundances of certain B type stars [3, 30, 31]. If empirical helium levels fell into question and a mechanism existed to accept the tremendously decreased helium levels in these special B type stars [3, 31] by preventing gravitational settling [131], Big Bang cosmology could not survive. Stellar and solar helium abundances cannot be allowed to drop in modern cosmology.

Today, the quest to link helium abundances and primordial nucleosynthesis has continued [26–30] using two lines of reasoning: 1) the analysis of anisotropy in the microwave background [132, 133] and 2) the observation of helium and hydrogen lines from low-metallicity extragalactic HII regions [26, 134–137].

Unfortunately, the use of anisotropy data [132, 133] to analyze primordial helium abundances are highly suspect. First, insurmountable problems exist with the WMAP data sets, as already highlighted by the author [138]. WMAP suffers from significant galactic foreground contamination which cannot be properly removed [138]. In addition, the WMAP team cannot distinguish between signal arising from a hypothetically primordial origin from those produced throughout the universe as a result of normal stellar activity [138]. While evident 'point sources' are taken into account, it remains impossible to determine, on a pixel by pixel basis, whether the signal has a primordial origin, or originates from an unidentified non-cosmological object [138]. Furthermore, WMAP raw data has proven to be unstable from year to year in a manner inconsistent with the hypothesized cosmological origins of these signals [138]. The data suffers from poor signal to noise and the ILC coefficients used for generating the final anisotropy maps do not remain constant between data releases [138]. Most troubling, the data sets cannot be combined using a unique combination of spectral channels [138]. As a result, since no unique anisotropy data set can be extracted [138], the data has no scientific value in analyzing helium abundances. Similar problems will occur when data from the Planck satellite finally becomes available [139]. As a result, all helium abundances derived from microwave anisotropy data sets must be viewed with a high degree of suspicion.

On the surface, the extraction of primordial helium abundances from H II regions appears more feasible [26, 134–137]. H II regions are rich in both hydrogen and helium but have low heavy element abundances (~ 1/40 solar) [140]. Unlike H I regions (~ 60K), H II regions exist at temperatures between 7,500 and 13,000 K [141]. In H II regions "*the* ^{4}He *abundance is derived from the recombination lines of singly and doubly ionized* ^{4}He*; neutral* ^{4}He *is unobserved*" [140, p. 50]. Unfortunately, experiments which utilized H II regions to assess primordial helium cannot easily ascertain that the sample has a uniform elemental composition. Furthermore, the use of H II regions for this purpose discounts the idea that helium has been synthesized locally. Such a suggestion should not be easily dismissed, as the temperatures of observation [141] are well above those in equilibrium with the hypothesized residual temperature of the Big Bang (~ 3K) [130]. Only low metallicity supports the idea that these helium concentrations are primordial. Nothing should prevent stellar systems from creating regions of low metallicity outside of a cosmological context. In this regard, the elevated temperatures of H II regions suggest that a process well beyond primordial considerations is now influencing elemental abundances in these regions. As such, it is imprudent to derive primordial helium abundances from H II regions.

We do not know, and will probably never be able to ascertain, primordial helium abundances. In order to observe helium in astronomy, elevated temperatures are required. These immediately imply that the processes observed are no longer in thermal equilibrium with those of interest in cosmology [130].

5 Solar winds: The key to understanding helium

Helium abundances can also be monitored in the solar wind [143–152]. Presumably, the results are so dynamic that they cannot be utilized to establish helium levels in the Sun itself. However, solar winds [143–152] have presented astronomy with a wealth of scientific information, which could be used to profoundly alter our understanding of the Sun [131].

Already in 1971, it was recognized that solar wind helium abundance measurements gave values which were lower than those ascertained from theoretical experiments [143, p. 369]. The study of solar winds became linked to models of the corona. Although the relative abundance and velocities of hydrogen to helium were advanced as profoundly dependent on location [143], it remained evident that solar winds harbored a great deal of reliable information. Early on, it was known that helium to hydrogen density ratios in the solar wind could experience dramatic fluctuations [144], especially in slow winds [147], though values appeared more stable at high solar wind speeds [145]. Extremely low ratios of 0.01, rising to 0.08, with an average of 0.037, were reported [144]. Clearly, such values were in direct conflict with the elevated helium levels expected in the Sun from primordial arguments [123]. As such, solar wind measurements became viewed as unreliable relative to estimating helium abundances in the Sun [148].

Nonetheless, something truly fascinating was present in solar wind data. The Sun appeared to be expelling helium (J. C. Robitaille, personal communication [131]) with increased activity. The helium to hydrogen ratio was observed to increase in association with the onset of geomagnetic storms [144] and was highly responsive to the solar cycle [146, 149, 151]. The helium abundance could rise from average values of less than 2% at the solar minimum to around 4.5% at maximum [149]. After the early 1970s, the variation in solar wind helium abundance became increasingly pronounced. By 1982, helium abundances in the solar wind came to vary from values as low as 0.001 to as elevated as 0.35 [147]. A single value as high as 0.40 was reported [147]. At least half of all elevated helium abundance events were related to a transient interplanetary shock wave disturbance [147], though a significant portion were not associated with such events. Each of these extremes highlighted something phenomenal relative to solar winds. To explain the variability, theoretical models turned to the large scale structure of plasma. It was assumed that elevated helium abundance originated in regions of high magnetic field activity in the corona [131]. It was found that helium abundance "*enhancements often have unusually high ionization temperatures, indicative of an origin in active solar processes... Collectively, these observations suggest that... [helium abundance] ... enhancements in the solar wind signal the arrival of plasma ejected from low in the corona during a disturbance such as a large solar flare or an eruptive prominence*" [147]. While solar winds had a close link to the "*composition of the source material*" it could then "*be modified by the processes which operate in the transition zone and in the inner corona*" [148]. Primordial helium abundances within the Sun could be saved by discounting that solar wind helium abundances had any meaning whatsoever relative to the composition of the Sun itself. The idea that solar activity reflected the expulsion of helium from the Sun (J. C. Robitaille, personal communication [131]) was never advanced. While the scientific community maintained that helium abundances were not reliable, they claimed that it was possible to ascertain the fractional isotopic composition of the elements in the solar wind and relate them directly to the solar convective zone: "*The variability of the elemental abundances in the solar wind on all time scales and the FIP... [first ionization potential] ... effect, and its variability, will make it difficult to derive accurate solar abundances from solar wind measurements, with the exception of isotopic determinations*" [150]. Of course, isotope analysis could never constitute a challenge to the existence of large amounts of primordial helium in the Sun [123]. Solar wind helium abundances had to be simply correlated to the coronal magnetic field, although the correlation coefficient was not powerful ($\sigma \sim 0.3$) [152]. Nonetheless, helium abundance depressions could not be explained under such a scenario [152]. At the same time, it is currently believed that "*solar wind abundances are not a genuine, unbiased sample of solar abundances, but they are fractionated. One such fractionation depends on the first ionization potential (FIP): When comparing solar wind to solar abundances, elements with low FIP (<10 eV) are enriched by a significant factor, the FIP bias, over those with a high FIP ... Another fractionation process affects mainly helium, causing its abundance in the SW to be only about half of the solar abundance... It is most likely due to insufficient Coulomb drag between protons and alpha particles in the accelerating solar wind*" [154, p. 16]. Herein was an explicit admission that the cause of extremely low helium levels in the solar wind could not be adequately understood. Conversely, fractionation models continued to insist that elevated helium abundances were linked to the fractionation of large atoms by collisions with protons [152, 153]. Nothing could be gathered about solar helium abundances from solar winds precisely because theoretical constructs forbade such conclusions.

6 Conclusions

Modern day reports of elemental abundances in the Sun [154–156] maintain that the Sun has a relatively large proportion of helium with Y values typically near 0.248 and primordial values of 0.275. These values come from theoretical modeling, as helium remains spectroscopically silent in the photosphere and solar winds are viewed as unreliable [155, p. 166]. Therefore, claims that helium has "*very high abundance*" [155, p. 166] in the Sun are not supported by observational fact. In the end, mankind understands much less about this central element than a cursory review of the literature might suggest. Careful consideration of solar modeling establishes that all theoretical estimates of helium levels in the Sun cannot be relied upon, given their dependence of solar opacity tables [78]. This also applies to theoretical results which attempt to extract helium levels from helioseismology [156]. For this reason, it is simply not possible to establish elevated helium levels in the Sun from theory. As helium levels cannot be established spectroscopically, we are left with the solar winds for guidance.

Currently, solar winds are viewed as too complex to yield information relative to solar abundances. In large measure, this is because scientists are trying to understand this data in the context of an object whose helium abundance has been largely set in primordial times [24, 123, 155]. The idea that the Sun and the stars are actively working to control their helium levels has never been previously considered [131]. Nevertheless, the association of solar activity and elevated helium levels [146, 149, 151] strongly suggests that the active Sun is expelling helium and excluding it from its hydrogen based lattice (J. C. Robitaille, personal communication [131]). Herein can be found the cause of extremely low helium abundance often obtained in the slow solar wind: the Sun works to keep its helium levels low and solar activity represent a direct manifestation of this fact. In the quiet Sun the slow solar winds can report fractional abundances of less than 2% and these should be viewed as steady state helium removal from the convective zone of the Sun. Such an idea strongly supports the contention that the Sun and the stars are primarily comprised of hydrogen in the liquid metallic state [131, 157].

In advancing that the universe is largely composed of hydrogen and that helium is being excluded from the stars (J. C. Robitaille, personal communication [131]), perhaps it is appropriate to turn once again to Cecilia Payne, as the first astronomer to highlight the tremendous abundance of hydrogen in the universe [8]. As a child, she had been eager to become an astronomer "*in case there should be no research left when she grew up*" [1, p. 72–73]. Yet, her position changed dramatically with age: "*Looking back on my years of research, I don't like to dwell only on my mistakes; I am inclined to count my blessings, and two seem to me to be very especially valuable. The first blessing is that the process of discovery is gradual — if we were confronted with all the facts at once we should be so bewildered that we should not know how to interpret them. The second blessing is that we are not immortal. I say this because, after all, the human mind is not pliable enough to adapt to the continual changes in scientific ideas and techniques. I suspect there are still many astronomers who are working on problems, and with equipment, that are many years out of date. Now that I am old, I see that it is dangerous to be in too much of a hurry, to be too anxious to see the final result oneself. Our research does not belong to us, to our institution, or to our country. It belongs to mankind. And so I say to you, the young generation of astronomers: more power to you. May you continue to expand the picture of the universe, and may you never lose the thrill it gave you when it first broke on you in all its glory*" [Cecilia Payne-Gaposchkin, April 10, 1968 [50, p. xv]].

Dedication

This work is dedicated to my oldest son, Jacob.

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