LETTERS TO PROGRESS IN PHYSICS

The Liquid Metallic Hydrogen Model of the Sun and the Solar Atmosphere VI. Helium in the Chromosphere

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Molecular hydrogen and hydrides have recently been advanced as vital agents in the generation of emission spectra in the chromosphere. This is a result of the role they play in the formation of condensed hydrogen structures (CHS) within the chromosphere (P.M. Robitaille. The Liquid Metallic Hydrogen Model of the Sun and the Solar Atmosphere IV. On the Nature of the Chromosphere. *Progr. Phys.*, 2013, v. 3, 15–21). Next to hydrogen, helium is perhaps the most intriguing component in this region of the Sun. Much like other elements, which combine with hydrogen to produce hydrides, helium can form the well-known helium hydride molecular ion, HeH^+, and the excited neutral helium hydride molecule, HeH^*. While HeH^+ is hypothesized to be a key cosmological molecule, its possible presence in the Sun, and that of its excited neutral counterpart, has not been considered. Still, these hydrides are likely to play a role in the synthesis of CHS, as the He I and He II emission lines strongly suggest. In this regard, the study of helium emission spectra can provide insight into the condensed nature of the Sun, especially when considering the 10830 Å line associated with the $2^3P \rightarrow 2^3S$ triplet state transition. This line is strong in solar prominences and can be seen clearly on the disk. The excessive population of helium triplet states cannot be adequately explained using the gaseous models, since these states should be depopulated by collisional processes. Conversely, when He-based molecules are used to build CHS in a liquid metallic hydrogen model, an ever increasing population of the 2^3S and 2^3P states might be expected. The overpopulation of these triplet states leads to the conclusion that these emission lines are unlikely to be produced through random collisional or photon excitation, as required by the gaseous models. This provides a significant hurdle for these models. Thus, the strong $2^3P \rightarrow 2^3S$ lines and the overpopulation of the helium triplet states provides the thirty-second line of evidence that the Sun is comprised of condensed matter.

In order to explain the occurrence of the dark lines in the solar spectrum, we must assume that the solar atmosphere incloses a luminous nucleus, producing a continuous spectrum, the brightness of which exceeds a certain limit. The most probable supposition which can be made respecting the Sun's constitution is, that it consists of a solid or liquid nucleus, heated to a temperature of the brightest whiteness, surrounded by an atmosphere of somewhat lower temperature.

Gustav Robert Kirchhoff, 1862 [1]

Estimates of solar helium abundances have varied widely over the years. For instance, *"different methods and different data sets give values ranging from 20% to 40% of the Sun's mass"* [2, p. 381]. 'Primordial' helium levels strongly guide all solar helium abundance determinations, as the amount of helium in the stars is said to be closely correlated with the synthesis of this element soon after the Big Bang [3–6]. Helium abundances currently act as one of the "Great Pillars" of cosmology (see [7] for detailed discussion). As such, any attempt to alter accepted helium levels within the Sun has great implications throughout astrophysics.

Recently, the author has reviewed the determination of solar helium abundances and reached the conclusion that these levels are likely to have been overstated [7]. The most prudent outlook remains that the Sun, like the visible universe, is composed primarily of hydrogen, as first outlined by Cecilia Payne [8]. In this regard, Robitaille and Robitaille have highlighted that the solar body is apt to be excluding helium from its interior [9]. It is well-known that this element can be expelled from the Sun during periods of elevated solar activity with widely varying quantities observed in the associated solar wind [10–14]. As a result, it is unlikely that the Sun is harboring much helium [7, 9]. Significant levels of helium above the photosphere merely represent eons of helium synthesis in a hydrogen based Sun. It can be hypothesized that since helium cannot re-enter the Sun once expelled, it slowly accumulates as a gas within the chromospheric region.

In his classic textbook, *"Astrophysics of the Sun"*, Harold Zirin emphasized that the helium D3 line can be enhanced more than 20 fold, as viewing moves from the center of the solar disk to just beyond the limb, displaying *"a sharp spike"* [15, p. 199–200]. He outlined that this emission *"comes from a low thin layer"* [15, p. 198]. Similarly, Zirin states that the triplet He I transition at 10830 Å is barely visible on the disk, but almost as strong as Hα at the limb [15, p. 199–200]. Moreover, he adds that the λ1640 line is known to increase in intensity at least fifteen times near the limb, while lines from neutral helium are enhanced 50 fold [15, p. 199–200]. Since helium emission peaks at ~1200 km above the photosphere, these findings strongly suggest that the element is floating in a cloud lying several hundred kilometers above the surface, although He remains sparse over coronal holes [15, p. 198].

At the same time, though relatively faint, helium lines are present in the spicules [16]. Since chromospheric structures, like spicules, have been hypothesized to be the site of hydrogen condensation in the solar atmosphere, it is important to understand why helium emission lines are associated with such objects.

Based on the chemiluminescence observed when silver clusters condense [17], the author has recently stated that all emission lines originating in the flash spectrum are a direct consequence of condensation in this region of the Sun [18]. By necessity, these exothermic condensation reactions involve the ejection of an excited atomic species from the condensate which can then relax back to a lower energy level through the emission of a photon. For instance, the Ca II emission, which is so typical of the chromospheric spectrum, has been hypothesized to involve the reaction of CaH and a condensed hydrogen structure, CHS [18], to create an excited complex, CHS + CaH → CHS–HCa*. This step is then followed by the exothermic expulsion of an excited Ca II ion, CHS–HCa → CHS–H + Ca^{+*}, and later by line emission from Ca II*, Ca^{+*} → Ca$^+$ + $h\nu$. Similar reactions have been invoked for all the hydrides present on the Sun [18]. The most significant of these take place using molecular hydrogen, and this explains the prevalence of strong emission lines from this element in the chromosphere. In order to account for the He I and He II emission lines associated with the flash spectrum, a directly analogous scenario must be invoked, which this time requires a helium hydride molecular species.

Many charged molecular ions of helium have been studied. The most famous, helium hydride, HeH$^+$, *is ubiquitous in discharges containing hydrogen and helium.*" [19]. This molecular cation was first discovered experimentally in 1925 by Hogness and Lunn [20]. It has been the focus of extensive spectroscopic studies [21, 22] and also postulated to play a key role in chemical astrophysics [23–25]. Wolfgang Ketterle (Nobel Prize, Physics, 2001) was the first to obtain its spectroscopic lines [26, 27]. The molecule has a bond distance of 0.77Å and a dissociation energy of ~44.6 kcal mol^{-1} [19]. Although it exists only in the gas phase, its Brønsted acidity should be extremely powerful. As a result, the hydrogen hydride cation should have a strong tendency to donate a proton,

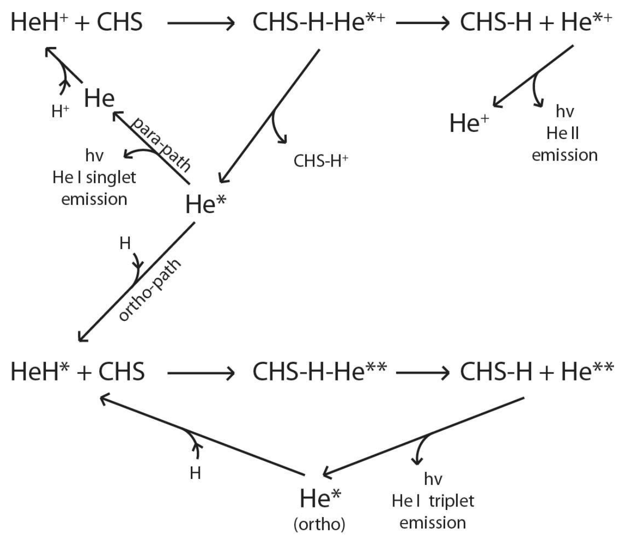

Fig. 1: Schematic representation of possible pathways involved when the helium hydride ion, HeH$^+$, or the excited helium hydride molecule, HeH*, react with condensed hydrogen structures, CHS, in the chromosphere of the Sun. The pathways presented can account for all emission lines observed from He I and He II. Note in this scheme that excited helium, He*, is being produced initially through the interaction of HeH$^+$ with CHS. This excited helium, He*, if it assumes the triplet state (orthohelium — electrons in the same orientation: spin up/up or down/down), will then become trapped in the excited state. This triplet helium can then be used repeatedly, in cyclic fashion, to condense hydrogen atoms onto chromospheric structures, CHS (as shown in the lower half of the figure). Alternatively, if excited helium He* is initially produced in the singlet state (parahelium — electrons in different orientation: spin up/down), emission can immediately occur generating the singlet lines from He I. This scheme accounts for the strong triplet He I transition at 10830 Å observed in the flash spectrum of the chromosphere. Unlike the situation in the gas models, random collisional or photon excitations are not invoked to excite the helium atoms. As a result, de-excitation processes would also be absent, helping to ensure the buildup of triplet state orthohelium in this model.

without the concerted transfer of an electron.

In the chromosphere, the interaction between the helium hydride ion, HeH$^+$, and condensed hydrogen structures, CHS [18], could lead to an array of reactions as outlined in Fig. 1.

The simple combination of HeH$^+$ and CHS could form an activated complex: CHS + HeH$^+$ → CHS–H–He^{+*}. Exothermic expulsion of an excited helium ion, He^{+*}, could follow with full transfer of a proton and an electron to the condensed hydrogen structure: CHS–HHe^{+*} → CHS–H + He^{+*}. The resulting He^{+*} would be able to relax back to a lower energy state through emission, He^{+*} → He$^+$ + $h\nu$, leading to the well known He II lines in the chromosphere (see Fig. 1).

Alternatively, when HeH$^+$ reacts with CHS, it could lead initially to the same condensation adduct, CHS–H–He^{+*}, but this time, exothermic expulsion of an excited helium atom could follow (see Fig. 1). Since HeH^+ should be a strong Brønsted acid, the transfer of a proton to the CHS could occur without electron transfer: $CHS\text{–}HHe^{+*} \rightarrow CHS\text{–}H^+ + He^*$. This leads to several phenomena.

First, the relaxation of an excited helium atom, does not involve the same processes which occur in the helium ion. This is because the He^{+*} possesses only a single electron. As such, the electron in He^{+*} can simply relax back down to any lower energy level, including the ground state, giving the well-known He II lines on the Sun.

Conversely, because an excited helium atom contains two electrons, the possible fate of this species is more complicated. Since one of the electrons has not been excited, it remains in the lowest energy state, with a given spin, either up or down. The excited electron is only allowed by selection rules to return to the ground state, if and only if, its spin is opposed to that of the ground state electron.

If the ground state electron is 'spin down', then the excited electron can make the transition back to the ground state if it is 'spin up'. Helium in this case is known as *parahelium* (or singlet helium), emphasizing that its two electrons have spins with opposite orientation. The singlet He^* would simply relax back to the ground state, given rise to the emission lines from the neutral atom, He I, $He^* \rightarrow He + h\nu$. Likewise, if the ground state electron is 'spin up', the excited electron must be 'spin down' to enable the transition, $He^* \rightarrow He + h\nu$, again producing the identical He I lines from singlet state parahelium.

However, if the two electrons of He^* have the same spin (both up or both down), then the excited electron cannot relax back to the ground state. It remains *trapped* in the excited state. Helium in this case is known as *orthohelium* (or triplet state helium), emphasizing that its two electrons have spins with the same orientation. It is the reactions of orthohelium which are of particular interest in this work, as their existence is elegantly accounted for through the condensation of hydrogen [18], as described below.

Since orthohelium is trapped in the excited triplet state, it has an opportunity to once again react with hydrogen, as displayed in the lower portion of Fig. 1. Wolfgang Ketterle has demonstrated that excited helium hydride also exists [28, 29]. Therefore, given a lack of relaxation, triplet He^* could capture a hydrogen atom, forming neutral excited helium hydride: $He^* + H \rightarrow HeH^*$. This species could once again react with CHS [18], but this time forming a doubly activated complex: $CHS + HeH^* \rightarrow CHS\text{–}H\text{–}He^{**}$. The net transfer of a hydrogen atom in this case leads to release from the CHS of doubly excited helium.* When this occurs, the He^{**} atom is now able to relax, as the excited electron which is now in the 2p or 3s orbital, undergoes a transition down to the 2s orbital. The $2^3P \rightarrow 2^3S$ transition is associated with the strong triplet He I line at 10830 Å observed in the prominences and on the disk of the Sun [30, p. 95]. Alternatively, a $3^3P \rightarrow 2^3S$ transition produces the triplet He I line at 3890 Å [30, p. 95].

As illustrated in Fig. 1, once the doubly excited helium atom has partially relaxed to regenerate orthohelium, it can react once again with atomic hydrogen, leading to the renewed synthesis of excited helium hydride, HeH^*. A cyclic pathway has been created, wherein triplet hydrogen is preserved and continuously working to assist in the resynthesis of condensed hydrogen structures, as the Sun recaptures any atomic hydrogen lost to its atmosphere.

Importantly, the entire process is being 'primed' through the use of a single HeH^+ molecular ion and the intial transfer of a single proton to the CHS. This feature is noteworthy, since true condensation requires the transfer of electrons and protons to the chromospheric structures. In this regard, the generation of Ca II emission lines from analogous condensations of calcium hydride, involves the transfer of two electrons per hydrogen atom [18]. Such parallel reactions could help to ensure that overall charge balance in the building of condensed hydrogen structures can be maintained.

In the end, this approach holds many advantages over the random processes invoked by the gaseous models of the Sun in order to account for line emission in the chromosphere. All line emission in the chromosphere become directly associated with ordered reactions, whose product, CHS, are vital to preserving the solar mass. The Sun does not simply eject hydrogen into its atmosphere, without any hope of regaining these atoms. Rather, in the chromosphere, hydrogen atoms are constantly being recaptured through hydride based reactions. The triplet state of orthohelium, so strongly manifested within prominences and in the chromospheric emission spectrum, becomes not an incidental artifact, but rather, a necessary and direct manifestation that organized chemical reactions are taking place within the chromosphere. As such, the existence of this abundant orthohelium and the strong emission lines which it produces can be said to constitute the thirty-second line of evidence that the Sun is comprised of condensed matter.

*We can assume that the ground state electron remains stationary, but that the initially excited electron has now been transferred to an even higher atomic orbital. Alternatively, both electrons could be excited, but this case will not be considered.

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Dedication

Dedicated to the poor, who sleep, nearly forgotten, under the light of the Southern Cross.

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References

1. Kirchhoff G. The physical constitution of the Sun. In: *Researches on the Solar Spectrum and the Spectra of the Chemical Elements*. Translated by H.E. Roscoe, Macmillan and Co., Cambridge, 1862, p. 23.

2. Bhatnagar A. and Livingston W. Fundamentals of Solar Astronomy (World Scientific Series in Astronomy and Astrophysics – Vol. 6), World Scientific, New Jersey, 2005.
3. Peebles P.J.E. Primordial helium abundance and the primordial fireball. II. *Astrophys. J.*, 1966, v. 146, 542–552.
4. Danzinger I.J. The cosmic abundance of helium. *Ann. Rev. Astron. Astrophys.*, 1970, v. 8, 161–178.
5. Izotov Y.I. and Thuan T.X. The primordial abundance of 4He revisited. *Astrophys. J.*, 1998, v. 500, 188–216.
6. Olive K.A., Steigman G. and Walter T.P. Primordial nucleosynthesis: Theory and observations. *Phys. Rep.*, 2000, v. 333-334, 389–407.
7. Robitaille P.M. Liquid Metallic Hydrogen II: A critical assessment of current and primordial helium levels in Sun. *Progr. Phys.*, 2013, v. 2, 35–47.
8. Payne C.H. The relative abundances of the elements. Stellar Atmospheres. Harvard Observatory Monograph no. 1 (Harlow Shapley, Editor), Harvard University Press, Cambridge, MA, 1925 (reprinted in part in Lang K.R. and Gingerich O. A source book in astronomy and astrophysics, 1900–1975, Harvard University Press, Cambridge, MA, 1979, p. 245–248).
9. 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, 87–97.
10. Robbins D.E., Hundhausen A.J. and Bame S.J. Helium in the solar wind. *J. Geophys. Res.*, 1970, v. 75, no. 7, 1178-1187.
11. Bame S.J., Asbridge J.R., Feldman W.C. and Gosling J.T. Evidence for a structure-free state at high solar wind speeds. *J. Geophys. Res.*, 1977, v. 82, no. 10, 1487–1492.
12. Borrini G., Gosling J.T., Bame S.J. and Feldman W.C. Helium abundance enhancements in the solar wind. *J. Geophys. Res*, 1982, v. 87, no. A9, 7370–7378.
13. Aellig M.R., Lazarus A.J. and Steinberg J.T. The solar wind helium abundance: Variations with wind speed and solar cycle. *Geophys. Res. Let.*, 2001, v. 28, no. 14, 2767–2770.
14. Kasper J.C., Stevens M.L., Lazarus A.J. and Ogilvie K.W. Solar wind and helium abundance as a function of speed and heliographic latitude: Variation through a solar cycle. *Astrophys. J.*, 2007, v. 660, 901–910.
15. Zirin H. Astrophysics of the Sun. Cambridge University Press, Cambridge, U.K., 1988.
16. Zirin H. The mystery of the chromosphere. *Solar Phys.*, 1996, v. 169, 313–326.
17. Konig L., Rabin I, Schultze W. and Ertl G. Chemiluminescence in the agglomeration of metal clusters. *Science*, 1996, v. 274, no. 5291, 1353–1355.
18. Robitaille P.M. The Liquid Metallic Hydrogen Model of the Sun and the Solar Atmosphere IV. On the Nature of the Chromosphere. *Progr. Phys*., 2013, v. 3, L15–L21.
19. Grandinetti F. Helium chemistry: A survey of the role of the ionic species. *Inter. J. Mass Spectrom.*, 2004, v. 237, 243–267.
20. Hogness T.R. and Lunn E.G. The ionization of hydrogen by electron impact as interpreted by positive ray analysis. *Phys. Rev.*, 1925, v. 26, 44–55.
21. Tolliver D.E., Kyrala G.A and Wing W. H. Observation of the infrared spectrum of helium-hydride molecular ion $^4HeH^+$. *Phys. Rev. Let.*, 1979, v. 43, no. 23, 1719–1722.
22. Crofton M.W., Altman R.S., Haese N.N. and Oka T. Infrared spectra of $^4HeH^+$, $^4HeD^+$, $^3HeH^+$, and $^3HeD^+$. *J. Chem. Phys.*, 1989, v. 91, 5882–5886.
23. Roberge W. and Dalgarno A. The formation and destruction of HeH^+ in astrophysical plasmas. *Astrophys. J.*, 1982, v. 255, 489–496.
24. Engel E.A., Doss N., Harris G.J. and Tennyson J. Calculated spectra for HeH^+ and its effect on the opacity of cool metal-poor stars. *Mon. Not. Roy. Astron. Soc.*, 2005, v. 357, 471–477.
25. Galli D. and Palla F. The chemistry of the early universe. *Astron. Astrophys.*, 1998, v. 335, 403–420.
26. Ketterle W., Figger H. and Walther H. Emission spectra of bound helium hydride. *Phys. Rev. Lett.*, 1985, v. 55, no. 27, 2941–2944.
27. www.nobelprize.org/nobel_prizes/physics/laureates/2001/ketterle.html
28. Ketterle W., Figger H. and Walther H. Emission spectra of bound helium hydride. *Phys. Rev. Lett*, 1985, v. 55, 2941–2944.
29. Ketterle W., Dodhy A. and Walther H. Bound-free emission of the helium hydride molecule. *Chem. Phys. Let.*, 1986, v. 129, no. 1, 76–78.
30. Zirin H. The Solar Atmosphere. Blaisdell Publishing Company, Waltham, MA, 1966.