LETTERS TO PROGRESS IN PHYSICS

The Liquid Metallic Hydrogen Model of the Sun and the Solar Atmosphere IV. On the Nature of the Chromosphere

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The chromosphere is the site of weak emission lines characterizing the flash spectrum observed for a few seconds during a total eclipse. This layer of the solar atmosphere is known to possess an opaque Hα emission and a great number of spicules, which can extend well above the photosphere. A stunning variety of hydrogen emission lines have been observed in this region. The production of these lines has provided the seventeenth line of evidence that the Sun is comprised of condensed matter (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). Contrary to the gaseous solar models, the simplest mechanism for the production of emission lines is the evaporation of excited atoms from condensed surfaces existing within the chromosphere, as found in spicules. This is reminiscent of the chemiluminescence which occurs during the condensation of silver clusters (Konig L., Rabin I., Schultze W., and Ertl G. Chemiluminescence in the Agglomeration of Metal Clusters. *Science*, v. 274, no. 5291, 1353–1355). The process associated with spicule formation is an exothermic one, requiring the transport of energy away from the site of condensation. As atoms leave localized surfaces, their electrons can occupy any energy level and, hence, a wide variety of emission lines are produced. In this regard, it is hypothesized that the presence of hydrides on the Sun can also facilitate hydrogen condensation in the chromosphere. The associated line emission from main group and transition elements constitutes the thirtieth line of evidence that the Sun is condensed matter. Condensation processes also help to explain why spicules manifest an apparently constant temperature over their entire length. Since the corona supports magnetic field lines, the random orientations associated with spicule formation suggests that the hydrogen condensates in the chromosphere are not metallic in nature. Spicules provide a means, not to heat the corona, but rather, for condensed hydrogen to rejoin the photospheric layer of the Sun. Spicular velocities of formation are known to be essentially independent of gravitational effects and highly supportive of the hypothesis that true condensation processes are being observed. The presence of spicules brings into question established chromospheric densities and provides additional support for condensation processes in the chromosphere, the seventh 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]

Nearly 150 years have now passed since Kirchhoff wrote about the Sun [1] and Father Angelo Secchi illustrated chromospheric spicules for the first time [2, p. 32]. Secchi viewed the chromospheric region as clearly defined on one side, like the surface of a liquid layer [2, p. 33]. Though he had concluded that the body of the Sun was gaseous, he believed that condensed matter was "suspended" within the photosphere [3]. Secchi would comment on the appearance of spicules and the outer portion of the chromosphere: *"In general, the chromosphere is poorly terminated and its external surface is garnished with fringes . . . It is almost always covered with little nets terminated in a point and entirely similar to hair"*.* Secchi mentioned the tremendous variability in spicule orientation, their enormous size, and how these structures reminded him of flames present in a field wherein one burns grasses after the harvest . . . *"It often happens, especially in the region of sunspots, that the chromosphere presents an aspect of a very active network whose surface, unequal and rough, seems composed of brilliant clouds analogous to our cumulus; the*

*All translations from French were accomplished by the author.

disposition of which resembles the beads of our rosary; a few of which dilate in order to form little diffuse elevations on the sides" [2, p. 31–36]. He would emphasize that *"there is thus no illusion to worry about, the phenomena that we have just exposed to the reader are not simple optical findings, but objects which really exist, faithfully represented to our eyes using instruments employed to observe them"* [2, p. 35–36].

The chromosphere is a region of intense magnetic activity, but its nature, and in particular that of its mottles and spicules [4–15], remains a mystery [16]. The low chromosphere is dominated by emission lines from neutral atoms and rare earths, but near its upper boundary strong lines from CaII and H are present [16]. Harold Zirin highlights that *"The chromosphere is the least-well understood layer of the Sun's atmosphere... Part of the problem is that it is so dynamic and transient. At this height an ill-defined magnetic field dominates the gas and determines the structure. Since we do not know the physical mechanisms, it is impossible to produce a realistic model. Since most of the models ignored much of the data, they generally contradict the observational data. Typical models ignore other constraints and just match only the XUV data; this is not enough for a unique solution. It reminds one of the discovery of the sunspot cycle. While most of the great 18th century astronomers agreed that the sunspot occurrence was random, only Schwabe, an amateur, took the trouble to track the number of sunspots, thereby discovering the 11-year cycle"* [16].

The struggle to understand the chromosphere is, in large measure, a direct result of the adherence to gaseous models of the Sun and a rejection of condensed matter [17–21]. The chromosphere is hypothesized to be only 2–3,000 km thick [7, p. 232]. Yet, chromospheric emission lines from hydrogen, calcium, and helium can extend up to 10,000 km above the solar surface [6, p. 8]. Zirin comments on the chromosphere as follows: *"Years ago the journals were filled with discussions of 'the height of the chromosphere'. It was clear that the apparent scale height of 1000 km far exceeded that in hydrostatic equilibrium. In modern times, a convenient solution has been found – denial. Although anyone can measure its height with a ruler and find it extending to 5000 km, most publications state that it becomes the corona at 2000 km above the surface. We cannot explain the great height or the erroneous models... While models say 2000 km, the data say 5000"* [16].

Though the chromosphere contains bright floculi in the K line of Ca II, which coincide in position with Hα rosettes [6, p. 85–86], and though it is laced with bright/dark mottles and spicules, gaseous solar models [22–24] have no direct means of accounting for such structures [25].

It remains fascinating that spicule formation velocities appear to be largely independent of gravitational forces [9–15], though some efforts have been made to establish such a relationship [26]. In general, while most velocities of spicules formation seem to move at nearly uniform speeds [4, p. 61], some actually increase with elevation, rise in jerks, or stop suddenly upon reaching their maximum height [6, p. 45–60]. Spicules have been said to *"expand laterally or slit into two or more strands after being ejected"* [26]. Such behavior is strongly suggestive of a condensation process.

Spicules are often associated with magnetic phenomena in the chromosphere [4–15]. They can be represented as lying above photospheric intergranular lanes. In so doing, they seem to be experiencing lateral magnetic pressure from the material trapped within the field lines that originate in the solar surface, as displayed in Fig. 1.

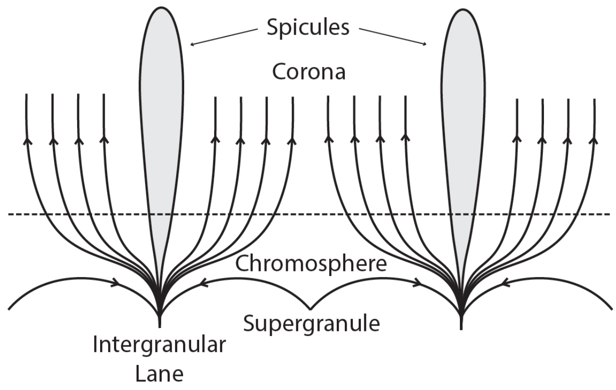

Fig. 1: Schematic representation of spicules overlying the intergranular lane on the outer boundary of a supergranule and surrounded by magnetic field lines emanating from the solar surface. This figure is an adaptation based on Fig. IV–13 in [4, p. 162].

Numerous magnetic field lines escape from the solar interior through the photospheric surface. These fields must traverse the chromospheric material. As a result, most solar observers believe that chromospheric structures are inherently magnetic [4–15]. Spicules are though to be propelling matter upwards into the corona [27] and not gathering matter, through condensation, for rejoining the photosphere.

However, given the appearance of chromospheric structures, such as rosettes and mottles, and the somewhat random orientations of spicules [4–15], it seems unlikely that these objects can be of magnetic origin. What is more probable is that, while non-metallic, chromospheric structures are being confined by charged plasmas, or metallic hydrogen [17–21], flowing in conjunction with the solar magnetic fields lines, much as illustrated in Fig. 1.

Since the gaseous models [22–24] depend on excessive temperatures in order to explain emission lines, spicules have been advanced as partly responsible for heating the corona [27]. Two forms of spicules were postulated from observations. Type I spicules can be viewed as classic spicules with lifetimes on the order of 3–7 minutes [27]. Type II spicules were believed to form rapidly, be short lived (10–150 s) and thin (<200 km), and capable of projecting material into the upper chromosphere at great velocities [27]. Type I spicules were said to move up and down, while Type II spicules faded [27]. Type II spicules were claimed to be potentially important in heating the outer atmosphere [27]. But recently, their existence and role appears to have been soundly refuted [28].

Though chromospheric observers remain intrigued with structure [4–15, 26], they adhere to the gaseous solar models [22–24], even though gases cannot exhibit true condensation. As a result, all chromospheric and coronal structures must be viewed as gasoues plasmas of exceedingly low densities [7]. Since they are not condensed matter in the context of the gaseous models [22–24], the strange properties of spicule formation and the structures of rosettes and mottles, remain an anomaly, rather than indicators of the nature of the chromosphere.

In contrast, this work now advances that chromospheric structures represent solar material in the condensed state [17–21]. Matter in this region fluctuates between gaseous and condensed, as spicules and mottles form and dissipate [9–15, 26]. This is reminiscent of phenomena such as critical opalescence [25]. The chromosphere appears to be a site of hydrogen condensation. The mystery lies only in how this can be achieved.

In order to better understand the chromosphere, one can revisit the classic work of Donald H. Menzel published 1931, *"A Study of the Solar Chromosphere"* [29]. Within this volume, three revelations continue to make their mark. First, there is an amazing prevalence of emission lines from a wide variety of atoms within this layer of the Sun (see Table I [29, p. 18–113]). Second, the chromosphere contains an extensive group of emission lines from hydrogen (see Table 3 [29, p. 128]). Menzel lists more than twenty-three hydrogen emission lines in his Table 3 [29]. Along with Cillié, Menzel soon observed Balmer series emission up to H31, with higher states limited only by resolution [30]. Third, he outlines a hydrogen abundance in the chromosphere which is 100 times more elevated than in the Sun (see Table 20 [29, p. 281]). Menzel's chromospheric hydrogen abundance was nearly 1,000 times more elevated [29, p. 275–281] than that which had been reported by Henry Norris Russell from the Fraunhofer spectrum of the Sun itself just a few years before [31].

While eighty years have passed since *"A Study of the Solar Chromosphere"* was published [29], much remains to be understood relative to this region of the Sun. P. Heinzel writes that *"Moreover, the energy supply into these layers is largely unknown, we only know that the radiation is not the dominant source of heating. The solar chromosphere is probably the least understood part of the Sun, even compared to the solar interior on which helioseismology has focused during last decades"* [8]. Much like other physical processes in the Sun, local heating is being tentatively attributed to magnetic mechanisms. Yet, if the chromosphere remains a mystery, the cause rests on the insistence that the Sun must exist in the gaseous state. Donald Menzel reminds us, *"The province of the scientist is the untangling of mysteries, the rendering of complex things into simple ones"* [29, p. 1].

A condensed solar model provides elegant solutions to the most perplexing questions relative to the chromosphere. This is especially true relative to apparent heating, as best understood through the careful consideration of how chromospheric emission lines are produced.

Within gaseous models, line emission requires either photon absorption, or electron collision, to excite the emitting atom [4, p. 228]. This represents an attempt to explain spectra using random processes. In the condensed model [17–21] spectra are tied to the formation of chromospheric structures. Line emission becomes inherently linked to understanding the very nature of the chromosphere.

The quest for answers begins with the consideration of condensation processes in clusters, the smallest precursors to condensed matter [32–37]. Clusters can be super-stable and act as superatoms [38]. In addition, their most favorable configurations can be linked to highest electron affinity and not to the energy of the ground state [39]. Condensation processes in clusters have been known to be associated with light emission [40, 41] and are exothermic. Thus, the apparent heating of the chromosphere might best be understood by considering these reactions.

In 1996, chemiluminescence was first reported to occur during the agglomeration of silver clusters [40]. By necessity, the reactions involved took place at low temperature (~30K), but the lessons learned directly translate to other conditions. Gerhart Ertl (Nobel Prize, Chemistry, 2007) and his team highlight: *"Exothermic chemical reactions may be accompanied by chemiluminescence. In these reactions, the released energy is not adiabatically damped into the heat bath of the surrounding medium but rather is stored in an excited state of the product; decay from this excited state to the ground state is associated with light emission"* [40].

The reactions presented by Ertl [40], which are of interest relative to the chromosphere, are illustrated by the condensation of two silver fragments, resulting in an activated cluster species: $M_n + M_m \rightarrow M^*_{m+n}$. The activated cluster returns to the ground state by ejecting an excited atom: $M^*_{m+n} \rightarrow M_{m+n-1} + M^*$. Finally, the excited silver atom is able to relax to the ground state by emitting light: $M^* \rightarrow M + h\nu$. Consequently, since condensation processes are exothermic, they are capable of producing excited atoms which result in emission. To extend these concepts to the solar chromosphere, it is useful to consider the types of condensation reactions which might be present in this region of the Sun.

In the chromosphere, it is possible to observe spectroscopic emission lines from atomic hydrogen corresponding to the Lyman ($n_2 > 1 \rightarrow n_1 = 1$ [42]), Balmer ($n_2 > 2 \rightarrow n_1 = 2$ [30]), and Paschen series ($n_2 > 3 \rightarrow n_1 = 3$ [43]).* Lyman emission lines involve relaxation back to the ground state and

*Up to eleven separate Lyman emission lines have been recorded (n_2=7 through n_2=17 [42, p. 47]), Balmer lines at least up to n_2=31 [30], and at least nine Paschen lines (n_2=8 through n_2=16) [43] can directly be deduced to arise from the condensation of hydrogen fragments, $H_n + H_m \rightarrow H^*_{m+n}$, relaxation of the resultant condensation product through the ejection of an excited hydrogen atom, $H^*_{m+n} \rightarrow H_{m+n-1} + H^*$, and finally the return to the ground state of the excited hydrogen atom with light emission, $H^* \rightarrow H + h\nu$.

In reality, it is reasonable to postulate that reactions in the chromosphere primarily involves the combination of molecular hydrogen with much larger condensed hydrogen structures or seeds, CHS, since this region of the Sun displays tangible signs of condensed matter in the form of spicules and mottles [9–15, 26].

In this case, molecular hydrogen, H_2, initially combines with these larger structures, $CHS + H_2 \rightarrow CHS\text{–}H_2^*$, resulting in mass increase, CHS–H, and the subsequent line emission from the ejected hydrogen atom, $H^* \rightarrow H + h\nu$. Given the extensive quantities of hydrogen in the Sun, it would be expected that numerous such reactions could take place simultaneously on any given CHS and result in the rapid appearance of spicules and mottles in the solar atmosphere [9–15, 26]. Since these reactions are *"not adiabatically dumped into the heat bath of the surrounding medium"* [40], condensation processes could result in the emission of Balmer [30] and Paschen lines [43]. In fact, the first line of the Balmer series ($n_2 = 3 \rightarrow n_1 = 2$), known as the H_α line, is responsible for the reddish hue of the chromosphere [7, p. 232].

The aforementioned reactions depend on the presence of molecular hydrogen in the chromosphere. Unfortunately, the concentrations of molecular hydrogen are extremely difficult to estimate in astrophysics, even if this species is widely considered to the most abundant molecule in the universe. The difficulty in establishing molecular hydrogen concentrations stems from the fact that all rotational-vibrational transitions from the ground electronic state of this diatom are forbidden [44]. As a result, astronomers typically use indirect methods to compute molecular hydrogen fractions in the galaxies [44–47] and sunspot umbra where the molecule is thought to be abundant [48].

Nonetheless, molecular hydrogen has been directly observed in sunspots in the extreme ultra-violet, a region of the electromagnetic spectrum were the emission lines are relatively strong [49, 50]. Furthermore, Jordan et al. [49] report a significant enhancement of the molecular hydrogen signal when chromospheric material lies over the sunspot of interest. While these signals are generally weak on the quiet Sun and in the limb [51], the emission from flares [50] and chromospheric plages [52] can be rather strong. Given the difficulty in observing molecular hydrogen in the ground state, these findings are significant and highlight that this species should be available to support condensation reactions in the chromosphere.

Therefore, it is likely that the hydrogen emission lines at the chromospheric level are related to the growth of CHS and the recapture of hydrogen from the outer solar atmosphere. Przybilla and Buttler have already simulated the linewidth of hydrogen emission lines in the chromosphere and reached the conclusion that some of the lines *"couple tightly to the continuum"* [53]. But within the context of the gaseous solar models, it is impossible to *"couple tightly to the continuum"*, as the latter merely represents an opacity change, not a physical structure [54]. It is for this reason that the emission lines of hydrogen have already been ascribed to the seventeenth line of evidence that the Sun is comprised of condensed matter [19]. Line emission can be linked to condensation, as Ertl has already elegantly demonstrated [40, 41]. Moreover, within the condensed models of the Sun, it would be natural that hydrogen emission associated with condensation would *"couple tightly to the continuum"*.

Before closing the discussion of hydrogen, it is important to digress slightly from addressing emission in order to discuss the hydrogen Fraunhofer absorption lines of the Balmer series. These lines are known to be broad and, as first reported by Unsöld [55], their relative intensities do not decrease in the manner predicted from quantum mechanical considerations. This has already been discussed by the author [19]. Therefore, Fraunhofer lines are not directly related to condensation processes. Isolated atoms, unlike diatoms, lack the ability to add protons to condensed structures, while at the same time removing heat. It is unlikely that isolated atoms can condense onto larger structures. It is more probable that they combine with one another to make a molecular species which, in turn, can condense. Hence, the broadening associated with the Balmer Fraunhofer lines can be linked to collisional processes whereby atoms are strongly interacting with the condensed matter which surrounds them, but not condensing. This represents, as previously mentioned, the sixteenth line of evidence that the Sun is comprised of condensed matter [19].

Returning to line emission, in addition to molecular hydrogen, the chromosphere may well possess other species which can facilitate the condensation of hydrogen atoms. Indeed, many hydrides have been identified either on the solar disk itself or within sunspots [56, 57], including CaH, MgH, CH, OH, H_2O, NH, SH, SiH, AlH, CoH, CuH, and NiH. The presence of CaH and MgH in the Sun have been known since the beginning of the 20th century [58]. In the laboratory hydrides from the main group elements (Li, Na, K, Rb, Cs, Be, Mg, Ca, St, Ba, B, Al, Ga, In, Tl, C, Si, Ge, Sn, N, P, As, Sb, Bi, O, S, Se, Te, F, Cl, Br, and I) and many of the transition metals (including amongst others V, Fe, Co, Ni, Cu, Ag, Zn, and Cd) are readily synthesized [59]. Hydrogen appears to have a great disposition to form hydrides of all kinds and this is an important realization relative to understanding the lower solar atmosphere.

Interestingly, the emission lines from CaII and MgII are particularly important in the chromosphere (e.g. [4, p. 361–369]). The second ionization state is singly charged (Ca^+ and Mg^+). But, the inert gas structure of these ions would demand a doubly charged species, i.e. Ca^{+2} and Mg^{+2}. As such, why is it that the most important ions of calcium and magnesium on the Sun are singly charged? The answer is likely to rest with their role in making hydrogen available for condensation.

Consider the reactions for calcium. It should be possible for CaH and a condensed hydrogen structure to create an activated complex, CHS + CaH → CHS–HCa*. This would then be followed by an exothermic step involving the expulsion of an activated CaII ion, CHS–HCa → CHS–H + Ca^{+*}, followed by the line emission from CaII*, $Ca^{+*} \rightarrow Ca^{+}$ + hv.

An identical scenario could be advanced for all the monohydrides, resulting in the observed line emission from their associated cations. Indeed, chromospheric emission lines, involving cations in modest oxidation states, are likely to be generated following a very similar mechanism. Some atoms, like oxygen or iron, may well exist as dihydride or higher complexes of hydrogen. They should participate similarly in condensation reactions, bringing in the process one or more hydrogen atoms to the site of condensation. The metal hydrides thereby would constitute important building blocks in the resynthesis of condensed forms of hydrogen.

When molecular hydrogen delivers a single proton to the condensation reactions, it is also delivering a single electron, if a neutral hydrogen atom subsequently emits. The same can be said for all hydrides wherein neutral atoms are ejected from the condensate to then produce emission lines. Atoms like oxygen have higher ionization potentials that the alkali, alkaline, or transition metals and may well prefer to hold on to their electrons. Emission lines from neutral oxygen are well know to be present during spicule formation [60].

Conversely, a species like CaH is delivering two electrons when generating CaII, as the negative hydrogen ion is being released. This suggests that condensed hydrogen structures, CHS, in the chromosphere might have reasonable electron affinities, though perhaps slightly less than that of oxygen in the lower chromosphere.

Importantly, the delivery of hydrogen to condensed hydrogen structures will involve potentially strong interactions between the carrier atoms (H, Ca, Mg, etc.) and the condensate surface. This would be expected to result in substantial line broadening of the ejected excited species. In support of such an idea, CaII and MgII spicule lines are known to be broad, and the H_α emission lines also display increased linewidths (see e.g. [60–62]). Such findings suggest tight coupling of these atoms to the condensate prior to ejection. Conversely, spicule emission linewidths from the H_β, H_γ, H_ϵ emission line, the D3 line from He, and the line from neutral oxygen are all sharp [60] in spicules, suggesting weaker coupling in those cases.

Contrary to gaseous models of the Sun which have ascribed no reasonable function to the chromosphere, the liquid metallic hydrogen framework [17–21] appears to provide a sound purpose for this layer. A condensed Sun does not permit hydrogen to simply escape, without recovery, into extrasolar space. Rather, molecular hydrogen and hydrides are likely to be participating in the continued recondensation of hydrogen within the chromosphere generating the observed emission lines. The resulting material appears to be nonmetallic since spicules can display orientations which are not coupled to the magnetic field lines of the Sun [9–15]. This material may then rejoin the photosphere and travel into the solar interior, perhaps using intergranular lanes [63]. Once in the interior of the Sun, pressure would facilitate the resynthesis of metallic hydrogen.

In summary, for the first time, it is advanced that complex condensation reactions take place in the chromosphere. These result in line-emission and provides a novel way to explain both spectra and structures on the Sun. The chromosphere appears to be rich in atomic and molecular hydrogen. Furthermore, a wide array of hydride based reactions seem to occur within the chromosphere and these provide a powerful incentive to further the understanding of condensation and hydride chemistry on Earth. In this respect, the presence of metal hydrides [56–58] and the line emission of main group and transition elements in the chromosphere constitutes the thirtieth line of evidence that the Sun is comprised of condensed matter.

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Dedication

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

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