LETTERS TO PROGRESS IN PHYSICS

The Liquid Metallic Hydrogen Model of the Sun and the Solar Atmosphere VII. Further Insights into the Chromosphere and Corona

Pierre-Marie Robitaille

Department of Radiology, The Ohio State University, 395 W. 12th Ave, Columbus, Ohio 43210, USA.
robitaille.1@osu.edu

In the liquid metallic hydrogen model of the Sun, the chromosphere is responsible for the capture of atomic hydrogen in the solar atmosphere and its eventual re-entry onto the photospheric surface (P.M. Robitaille. The Liquid Metallic Hydrogen Model of the Sun and the Solar Atmosphere IV. On the Nature of the Chromosphere. *Prog. Phys.*, 2013, v. 3, L15–L21). As for the corona, it represents a diffuse region containing both gaseous plasma and condensed matter with elevated electron affinity (P.M. Robitaille. The Liquid Metallic Hydrogen Model of the Sun and the Solar Atmosphere V. On the Nature of the Corona. *Prog. Phys.*, 2013, v. 3, L22–L25). Metallic hydrogen in the corona is thought to enable the continual harvest of electrons from the outer reaches of the Sun, thereby preserving the neutrality of the solar body. The rigid rotation of the corona is offered as the thirty-third line of evidence that the Sun is comprised of condensed matter. Within the context of the gaseous models of the Sun, a 100 km thick transition zone has been hypothesized to exist wherein temperatures increase dramatically from 10^4–10^6 K. Such extreme transitional temperatures are not reasonable given the trivial physical scale of the proposed transition zone, a region adopted to account for the ultra-violet emission lines of ions such as C IV, O IV, and Si IV. In this work, it will be argued that the transition zone does not exist. Rather, the intermediate ionization states observed in the solar atmosphere should be viewed as the result of the simultaneous transfer of protons and electrons onto condensed hydrogen structures, CHS. Line emissions from ions such as C IV, O IV, and Si IV are likely to be the result of condensation reactions, manifesting the involvement of species such as CH_4, SiH_4, H_3O^+ in the synthesis of CHS in the chromosphere. In addition, given the presence of a true solar surface at the level of the photosphere in the liquid metallic hydrogen model, it follows that the great physical extent of the chromosphere is supported by gas pressure, much like the atmosphere of the Earth. This constitutes the thirty-fourth 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]

1 Introduction

If our current understanding of the solar atmosphere appears strained, it is because the gaseous models of the Sun offer no means, other than elevated temperatures, to account for the presence of highly ionized ions in the corona [2]. As a consequence, temperature values ranging from 10^7–10^{11} K have been inferred to exist in the solar atmosphere [3, p. 172]. Such extreme temperatures should have suggested long ago that the methods utilized to infer coronal temperatures could not be valid, given that the core of the Sun is believed to sustain temperatures of only $\sim 1.6\times10^7$ K [4, p. 9]. The claim that temperatures in localized regions of the corona can be 1 000 times higher than within the solar core, challenges reason.

Furthermore, by accepting elevated coronal temperatures, proponents of the gaseous models must discount the continuous emission of the K-corona as illusionary and produced by the photosphere (see [2] for a completed discussion). The continuous spectrum of the K-corona, devoid of Fraunhofer lines, does closely replicate the emission of the photosphere itself, but the spectrum reddens with elevation [2]. If this spectrum was considered as generated by the corona, then the apparent temperature of the outer solar atmosphere would be no higher than that observed on the surface of the Sun.[*]

---

[*] Note that the apparent temperature of the photosphere ($\sim$6 000 K), does not manifest the true energy content of this region. Rather, the author has claimed that it reflects that amount of energy which is contained within the

Should it be true that coronal apparent temperatures are no greater than photospheric values, then it is impossible, within the context of a gaseous Sun, to account for the presence of highly ionized ions (e.g. CaXVII and FeXXIV [6, p. 19]) in the corona. Devoid of condensed matter, the only possible means of generating such ions must rest on temperature. As a result, despite the realization that the spectrum of the K-corona implies that the corona is self-luminous and displays an apparent temperature no higher than that of the photosphere [2], advocates of the gaseous models of the Sun have no choice but to postulate that coronal apparent temperatures far exceed those of the solar surface.

Two problems come to the forefront relative to using elevated temperatures to explain the presence of highly ionized species within the corona. First, extreme temperatures (10^7–10^{11} K [3, p. 172]) must be assumed. Second, the continuous spectrum of the K-corona must be discounted as a byproduct of photospheric light which has been scattered in the solar atmosphere by relativistic electrons (see [2] for a complete discussion).

Moreover, in order to account for the emission lines from ions such as C IV, O IV, and Si IV, gaseous models must incorporate an extremely thin transition zone, whereby apparent temperatures rapidly rise from chromospheric to coronal values over the span of 100 km or less, as illustrated in Fig. 1.

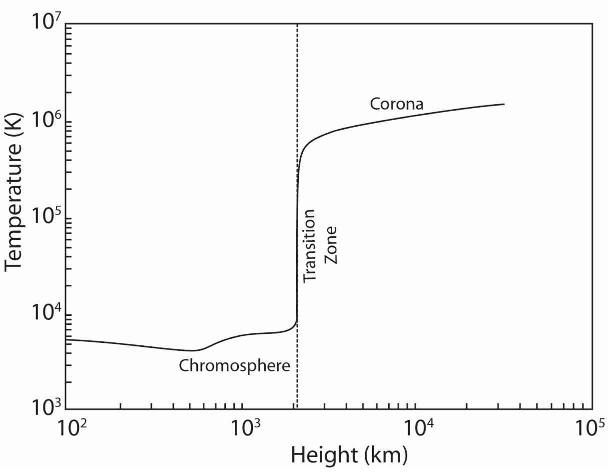

Fig. 1: Schematic representation of the temperature stratification in the solar atmosphere displaying the pronounced increase in the transition zone located at an elevation of ~2 000 km (dashed line). This figure is based on a discussion presented by Phillips, Feldman, and Landi [6] and is an adaptation of their Fig. 1.1.

2 Temperature Stratification

In his chapter on the chromosphere and corona, P. Ulmschneider states, *"While the corona extends to many solar radii the chromosphere is a layer of only 2 or 3 thousand km thickness which becomes visible near the start and end of a total eclipse. The chromosphere got its name from the prominent red emission of the Hα line of neutral hydrogen at 6563Å. The chromosphere is a layer where the temperature rises from photospheric values of between 4 000 and 6 000 K to about 20 000 K and where neutral hydrogen is still present. In the region of a few 100 km thickness between the chromosphere and corona, called transition layer, hydrogen becomes ionized and the temperature increases from 20 000 to millions of K"* [7, p. 232–233].

A. Bhatnagar outlines that *"Between the upper layer of the chromosphere and corona (although the demarcation is not sharp) lies the 'transition layer', where the temperature rises very steeply, from about 25 000 to 500 000 K in height difference of just 1 000 km"* expanding the extent of the transition region by a factor of 10 [8, p. 32]. Conversely, Phillips, Felman, and Landi emphasize *"Model calculations indeed suggest that the transition zone is extremely thin, less than 100 km"* [6, p. 220].

Such dimensions on the Sun are essentially beyond the limit of reliable detection with current instrumentation. Thus, it is interesting to highlight that *"A growing corpus of observations, particularly those starting with the Skylab mission, showed that the transition zone has a much larger extent than was indicated in the earlier models, leading to a revision of our ideas of its nature..."* [6, p. 210].

Harold Zirin, in candid fashion, reminds his readers that anyone with a ruler can establish that the chromosphere can attain elevations of at least 5 000 km from Hα emissions [9]. He reports that, when viewed in Hα, macrospicules can be seen to extend to 20 000 km [9]. How can neutral hydrogen be found at these heights, if the corona already reaches temperatures of 10^6 K just after the transition zone? If the corona was at millions of degrees, neutral hydrogen should not be found at 20 000 km, a region well within the coronal domain.

The situation is aggravated by the realization that H_{Lym} lines have been known to exist in the corona beyond $1.5R_\odot$ for more than fourty years [10]. This region extends beyond the entire vertical range displayed in Fig. 1. Furthermore, Dermendjiev et al. report, from direct photographic visualization in Hα, that faint lines from neutral hydrogen can be observed far into the corona, causing the authors to postulate how the corona could be 'cooled' to allow for the presence of such a line [11]. Yet, models of the solar atmosphere predict that neutral hydrogen should be absent at elevations beyond 2 000 km, where temperatures approaching 10 000 K already result in the complete ionization of this element (see e.g. Table 4.6 in [12, p. 146–147]).

At the same time, highly ionized Fe lines (FeX–FeXIV) have been used to image the solar corona in great detail and indicate that these species can be found at elevations well inferior to the known locations of neutral hydrogen emission lines [13–16]. Clearly, it is not possible for emission lines

---

vibrational degrees of freedom found in the photospheric lattice [5].

which, according to the gaseous models of the Sun, require millions of degrees for formation (FeX–FeXIV) to be juxtaposed with Hα lines which are unable to withstand such temperatures. The only solution rests in recognizing that the formation of highly ionized emission lines in the corona stems not from extreme temperatures, but from electron affinity [2]. It should not be inferred that the outer atmosphere of the Sun maintains a temperature stratification which *increases* with increased distance away from the solar body.

3 On The Validity of Temperature Measurements

In order to support the gaseous models, coronal temperatures have been estimated using four key methods [17, p. 178–185]: 1) doppler broadening of emission lines, 2) density gradients in the corona, 3) radio brightness, and 4) ionization equilibrium. All of these methods provide slightly differing answers [3, p. 165–166], but they share a common overarching result: coronal temperatures are thought to be extremely high. In the end, careful analysis reveals that each of these methods is problematic.

3.1 Doppler Broadening of Emission Lines

Doppler broadening of emission lines (e.g. [6, p. 41–43], [17, p. 178–180], [18, p. 90–94]) has been used extensively to set coronal temperatures. The broadening of an emission line, in this case, is assumed to be thermal in nature. The problems of assigning temperatures with such methods are numerous. Zirin [17, p. 178-180] outlines how separate elements can easily produce differing line widths and associated temperatures. Nonetheless, he concludes that valid coronal temperatures can be derived from such methods.

More than fifty years ago, Jefferies and Orrall addressed the problem of obtaining prominence temperatures by employing spectral line widths stating, *"If the broadening is supposed due to thermal motions of the emitting atoms, then, to the extent that the profiles are Gaussian, the hydrogen line widths imply temperatures of over a hundred thousand degrees and the metals of over five million degrees"* [19]. However, it is not possible to have neutral hydrogen present at a temperature of over a hundred thousand degrees, given that the element has been modeled as fully ionized at ~10 000 K (see e.g. Table 4.6 in [12, p. 146–147]).

Jefferies and Orrall continue, *"To avoid the necessity of considering such unacceptably high and discordant temperatures, the hypothesis is frequently made that the line broadening is due both to thermal motions of atoms and to mass motions of small prominence elements having a Maxwellian distribution of velocities. One may, on this basis, compare the widths of lines from two ions of very different atomic weights to find a hypothetical "temperature,"* T_H *and "mean velocity,"* ξ_H*. If the hypothesis is wrong,* T_H *and* ξ_H *will, in general, bear no obvious relationship to the kinetic temperature or mean random-velocity fields which they are intended to describe. While the truth of the hypothesis has come more and more to be taken for granted, it seems to us that the evidence in its favor is rather slight and certainly insufficient to allow its uncritical acceptance. We have already . . . suggested that the hypothesis may be invalid for analyzing widths of hydrogen and helium lines in quiescent prominences; in this paper we present evidence for its possible failure in active flare-type events"* [19].

Though the discussion by Jefferies and Orrall cannot be cited in its entirety, the authors go on to make the point that the use of line width analysis could, in fact, lead to *negative* temperatures. Furthermore, they clearly discount the existence of temperatures in the 500 000–1 000 000 K range [19].

Despite Jefferies and Orrall [19], today it is commonplace to infer temperatures from line widths and ascribe any *excessive line shape distortion* to velocity. That is, if the line shape is distorted, either in the low (red) or high (blue) frequency range, net velocities will be added (e.g. see Eq. 2.30 in [6]) which can help account for the distortion. Examples can be found throughout the astrophysical literature (e.g. [20]).

The situation is complicated by the realization that, in addition to thermal effects, the line widths of atoms can be altered by pressure, Stark, and electron broadening mechanisms [21, p. 202-233]. However, the derivation of temperatures from line widths in the solar atmosphere is much more precarious than these considerations or the discussions from Jefferies and Orrall [19] might suggest.

Collisional line broadening with condensed matter could greatly impact the line widths under observation. Such line broadening will be affected by the abundances of condensed material and gaseous atoms in the corona and, most importantly, by the extent of the interaction between any given element and such objects. Furthermore, tight coupling between gaseous atoms and condensed matter could dramatically alter line shapes outside the effects of velocity. In light of the evidence for the presence of condensed matter in the corona [2], all temperature measurements from line widths should be reconsidered.

3.2 Density Gradients

Density gradient approaches rely on the use of the white-light continuous spectrum observed in the corona [17, p. 178–180] or chromosphere [22, p. 170–228]. Modern theory assumes that this spectrum has been produced by scattering photospheric light through the action of relativistic electrons, thereby enabling a temperature for the corona to be inferred [17, p. 111–121]. The difficulty with such an approach lies in the assumption that the corona is not self-luminous and that its spectrum arises from photospheric light which must be scattered. However, if the corona is indeed self-luminous and cool [2], as implied by the presence of neutral hydrogen even up to 1.5$R_\odot$ [10], then this entire line of reasoning must be re-evaluated.

3.3 Radio Measurements

Of the four methods for determining coronal temperatures, the final two are perhaps the weakest [17, p. 178–180]. In the end, radio measurements [18, p. 242–247] should be considered with great caution, even though Professor Zirin has stated that they are *"the most dependable data we have"* [9]. Radio data are highly dependent on the input variables (i.e. electron and ion density) which must be modeled in order to obtain brightness temperatures (e.g. see Table I in [9], [12, p. 133–141], and [23]). All determinations of solar brightness temperatures are inherently linked to *a priori* knowledge of electron densities [22, p. 265] which can only be estimated using modeling, *"…it is evident that the quantities* $N_e(h)$ *and* $T_e(h)$ *are too inextricably mixed to be seperately derivable from radio observations alone"* [12, p. 137]. Since radio models cannot disentangle electron density from brightness temperatures, they are often guided by results obtained using optical density gradient methods [22, p. 266]. Direct measurements of electron density remain unavailable and theoretical values may not be accurate.

Radio measurements of brightness temperatures are also highly dependent on wavelength and scattering processes (see e.g. [12, p. 133–141], [22, p. 261–271], and [23]). Widely conflicting data can be obtained (e.g. temperatures of only 300 000 at $1.6R_\odot$ [23]). In fact, radio observations appear to be the source of the most extreme temperature values 10^8–10^{10} K [17, p. 128], while scientists remain confronted with addressing values as low as 10^4 K obtained with such methods (see e.g. [12, p. 133–141] and [23]). As a result, it would be imprudent to place an emphasis on coronal or chromospheric temperatures obtained from radio measurements.

3.4 Ionization Equilibrium

It has already been established that ionization calculations result in models of the solar atmosphere which greatly underestimates the presence of neutral hydrogen in the corona. Consequently, it is evident that temperatures derived from ionization equilibrium must be regarded with caution.

As a rule, coronal temperatures derived from ionization equilibrium tend to be too low to accomodate the gaseous models of the Sun [17, p. 181]: *"We must admit, however, that the ionization theory not only gives the wrong temperature, but fails to account for the many stages of ionization observed in the corona. It is possible that temperature variations explain that fact; we can only wait for better observations of the line profiles of intermediate ions to confirm the existence of temperature differences. It is more likely that there is something erroneous in our basic concept of how ionization takes place; but so far, we do not know what this is"* [17, p. 183]. Immediately after writing these lines, Professor Zirin offers what he believes to be the answer: recombination, a process whereby a single electron is captured by an ion leaving it in double excited state, could be much more important in the corona, resulting in a calculated temperature near 2 MK [17, p.184].

In 1966, Zirin had hoped that more UV data would soon be available to lift the cloud of mystery which surrounded ionization equilibrium calculations [17, p. 181–185]. In fact, the new data only added further confusion. Thirty years later, he would write, *"One would think that observations of the solar ultraviolet would solve many of the problems. However, the intensity of these lines was very much lower than expected and to this day images with adequate resolution have not been obtained. While the UV mimics the radio images, brightening in the network, it is impossible to tell if it comes from the spicules or the magnetic regions at their base. The lines show a deep minimum in intermediate ionization stages of C, N, and O … and the brightness temperature in the extreme ultraviolet scarcely exceeds 4 000 degrees. This gives a remarkable contradiction. Lines are observed of high ionization stages such as carbon 4, neon 5, oxygen 5, which are only formed at temperatures of 100 000 degrees or more but with brightness temperatures 20 times less"* [9]. Nearly forty years after Professor Zirin produced his classic text [17], coronal temperatures from ionization equilibrium are still viewed as too low [3, p. 165–166].

The proper discussion of ionization equilibrium is best reserved for a full treatment. However, suffice to state that methods which depend on the ionization equations are complex (see [24] for a partial review), involving knowledge of whether or not the region of interest can be considered to be in local thermal equilibrium (LTE). E.A. Milne highlighted that the exterior regions of the Sun cannot be considered to adhere to LTE conditions [25, p. 81–83]. Even chromospheric ionization processes depend on non-equilibrium treatments [18, p. 194–198], even if LTE methods continue to be used (see [26] for a brief discussion). Unfortunately, the fluxes associated with such processes remain largely unknown and numerous assumptions will be involved in extracting temperatures with such methods.

In the end, none of the methods utilized to extract coronal temperatures are reliable. Rather, any perceived agreement between approaches is likely to be the result of the desire to *set a reasonable temperature for the corona*. Each method contains enough latitude to permit conformity by altering the value of those input parameters which can only be obtained from theory.

4 The Corona Revisited

Professor Harold Zirin had suspected that *"…there is something erroneous in our basic concept of how ionization takes place"* [17, p. 183]. However, given the belief that the Sun was a gas, no other plausible mechanism of formation could be advanced. Today, the situation has changed dramatically, as a great deal of evidence is building that the Sun is condensed matter (see [2, 24, 27–30] and references therein).

For instance, it is now understood that the corona possesses *"... a radially rigid rotation of 27.5 days synodic period from 2.5 $R_\odot$ to >15$R_\odot$"* [3, p. 116]. This finding by Lewis et al. [31] provides the thirty-third line of evidence that the Sun is comprised of condensed matter. The rigid rotation of the corona is highly suggestive that it possesses condensed matter whose associated magnetic field lines are anchored at the level of the photosphere. Such a structure, if endowed with a elevated electron affinity [2], would provide an elegant network for channeling electrons from the outer reaches of the solar atmosphere onto the photospheric surface. Thus, the corona should be viewed as being in direct contact with the photosphere.

In order to understand ionization states it is important to recognize that condensed matter controls the behavior of the Sun. As previously stated [2], within the solar atmosphere, atoms and ions are being stripped of their electrons by metallic hydrogen present in the corona. Such a process can help ensure that the solar body remains electrically neutral, as electrons are continually conducted back onto the solar surface from the far reaches of the corona. It is known that the electrical conductivity of the corona is extremely high [3, p. 174]. This is in accord with a condensed solar state, which extends into the corona, even if gases are also present in this region.

5 The Chromosphere Revisited

The author has already addressed the chromosphere in detail, as a region of hydrogen re-condensation, superimposed on the corona in the lower portion of the solar atmosphere [28, 29]. He has suggested, that unlike the corona, the chromosphere is not composed of hydrogen in the metallic state. Rather, in the chromosphere, atomic and ionic hydrogen is interacting with other atoms to form hydrides [28, 29] which can be used to build condensed hydrogen structures (CHS). CHS can then bring the harvested hydrogen back onto the solar surface, perhaps using intergrannular lanes [28]. As such, the chromosphere overlaps with the corona. The two regions contain different types of material: metallic in the corona [2] and non-metallic in the chromosphere [28, 29]. Chromospheric material will regain metallic properties once it enters the solar interior, where increased pressures can be used to re-synthesize metallic hydrogen [30].

The tremendous height, 5 000 to 10 000 km, of the chromosphere has posed a longstanding problem for the gaseous models of the Sun [3, p, 140-142]. Early chromospheric models inferred a density scale height of only 150 km [3, p. 140-142]. McCrea [32] attempted to build additional scale height by suggesting that turbulent motions might provide additional support for the chromosphere [3, p. 140-142]. Modern models have extended the theoretical treatment of the scale height problem (see [26] for a brief discussion). But, still today, it remains difficult for the gaseous models of the Sun to account for the presence and extent of the chromosphere. Zirin highlights, *"It was clear that the apparent scale height of 1 000 km far exceeded that in hydrostatic equilibrium. In modern times a convenient solution has been found – denial ... We cannot explain the great height or the erroneous models ... While models place this at 2 000 km, the data say 5 000"* [9]. If it is impossible for the gaseous models to properly account for the great height of the chromosphere, the cause is simple to understand. It is not possible for a gas to support itself. But relative to structural support, gas pressure has been utilized in modern solar theory to explain why a gaseous Sun does not collapse on itself. However, such arguments have been discounted, precisely because a gaseous object cannot possess true surfaces [33]. Without a support mechanism, a gaseous Sun cannot exist [33].

Conversely, within the context of a condensed solar body [33], the Sun does not collapse upon itself because liquids and solids are essentially incompressible. Furthermore, unlike the case with the gaseous Sun, the chromosphere can now be easily supported using gas pressure. This same mechanism is responsible for the support of the Earth's atmosphere (see [33] for a larger discussion). When a gaseous atom encounters a real surface, it reverses its course creating a net upward force. Such a mechanism provides a genuine means of supporting the chromosphere and thereby constitutes the thirty-fourth line of evidence that the Sun is condensed matter (see [2, 24, 27–30, 33] and references therein for the others).

6 The Transition Zone Revisited

Within the gaseous models of the Sun, a transition zone has been conceived in order to account for the existence of ions with *intermediate* levels of ionization. Species such as C IV, O IV, and Si IV come to mind in this regard. Since the intensity of all transition zone lines are low, modern models simply create an extremely narrow region of the solar atmosphere to account for this lack of signal, as illustrated in Fig. 1. Nonetheless, C IV, O IV, and Si IV remain interesting, as they could be created by stripping hydrides such as CH_4, H_3O^+, and SiH_4 of their hydrogen [28]. The vibrational signatures of these molecules (the C-H, O-H, and Si-H stretches) have been observed on the Sun [34]. The author has already suggested that the chromosphere is a region of hydrogen re-condensation where hydrides play an important role [28, 29]. It remains reasonable to conclude that the transition zone does not exist. Rather, the ions which are currently associated with this region of the solar atmosphere are simply involved in the transfer of multiple protons and electrons onto the condensed hydrogen structures, CHS, which constitute the chromosphere. This region of the solar atmosphere therefore plays a vital role in preserving the mass of the Sun and ensuring that metallic hydrogen can eventually be re-synthesized within its interior.

7 Conclusion

Through a recent series of publications (most notably [2, 28, 29]), the author has endeavored to alter our understanding of the solar atmosphere. Rather than a chaotic assembly of gaseous plasma, the chromosphere and corona become the site of both structure and function in the Sun. Such structure is dismissed by the gaseous models, whose advocates prefer to speak of visualizing *"force balance"* [26], rather than real objects. At the same time, the history observational solar physics is replete with scientists, like Father Angelo Secchi, who believed that they were seeing real structures on the Sun [35, 36]. In a parallel line of reasoning, the gaseous models provide no true function, either for the chromosphere or the corona. Conversely, in the liquid metallic model, the corona harnesses electrons [2], the chromosphere condenses hydrogen atoms [28, 29]. In the corona, highly ionized ions are produced when their parent atoms, or ions, come into contact with metallic hydrogen which possesses an elevated electron affinity. They are thereby stripped of their electrons [2]. The metallic hydrogen which is present in the corona has been projected into the solar atmosphere from its site of formation below the surface of the Sun [2]. Since condensed matter appears likely to exist in the corona, it is not tremendously hot, but maintains an apparent temperature which decreases with elevation from the solar body. In the chromosphere, where non-metallic condensed hydrogen structures are formed, the ionization states reveallled from emission lines are linked to key hydride based chemical processes [28, 29]. The transition zone does not exist. It serves a purpose only in the context of the gaseous solar models. Much has been advanced recently relative to the condensed nature of the Sun [2, 24, 27–30, 33] and much remains to be considered. In the end, given the ever mounting evidence for condensed matter (see [2, 24, 27–30, 33] and references therein), eventually the elegance and simplicity of these models will surely come to be recognized.

Acknowledgment

Luc Robitaille is acknowledged for figure preparation.

Dedication

This work is dedicated to the memory of Captain Corona [37], Professor Harold Zirin, whose books [17,18] and articles (e.g. [9]) were both illuminating in their discourse and refreshing in their candor.

Submitted on: May 30, 2013 / Accepted on: May 30, 2013
First published online on: May 31, 2013

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. Robitaille P.M. The Liquid Metallic Hydrogen Model of the Sun and the Solar Atmosphere V. On the nature of the corona. *Progr. Phys.*, 2013, v. 3, L22-L25.
3. Bhatnagar A. and Livingston W. Fundamentals of Solar Astronomy (World Scientific Series in Astronomy and Astrophysics - Vol. 6), World Scientific, New Jersey, 2005.
4. Kippenhahn R. and Weigert A. Stellar structure and evolution. Springer-Verlag, Berlin, 1990.
5. Robitaille P.M. On the temperature of the photosphere: Energy partition in the Sun. *Progr. Phys.*, 2011, v. 3, 89–92.
6. Phillips K.J.H., Feldman U. and Landi E. Ultraviolet and X-ray Spectroscopy of the Solar Atmosphere. Cambridge University Press, Cambridge, 2008.
7. Ulmschneider P. The physics of the chromospheres and coronae. In: *Lectures on Solar Physics* (H.M. Antia, A. Bhatnagar and R. Ulmschneider, Eds.), Springer, Berlin, 2003, p. 232–280.
8. Bhatnagar A. Instrumentation and observational techniques in solar astronomy. In: *Lectures on Solar Physics* (H.M. Antia, A. Bhatnagar and R. Ulmschneider, Eds.), Springer, Berlin, 2003, p. 27–79.
9. Zirin H. The mystery of the chromosphere. *Solar Phys.*, 1996, v. 169, 313–326.
10. Gabriel A.H., Garton W.R.S., Goldberg L., Jones T.J.L., Jordan C., Morgan F.J., Nicholls R.W., Parkinson W.J., Paxton H.J.B., Reeves E.M., Shenton C.B., Speer R.J. and Wilson R. Rocket observations of the ultraviolet solar spectrum during the total eclipse of 1970 March 7. *Astrophys. J.*, 1971, v. 169, 595–614.
11. Dermendjiev V.N, Mouradian Z., Duchlev P. and Leroy J.L. Faint H alpha emission in the solar corona: Morphological, situational and hydromagnetic analysis. *Solar Phys.*, 1994, v. 149, no. 2, 267–277.
12. Bray R.J. and Loughhead R.E. The Solar Chromosphere (The International Astrophysics Series), Chapman and Hall, London, U.K., 1974.
13. Wood B.E., Karovska M., Cook J.W., Brueckner G.E., Howard R.A., Korendyke C.M. and Socker D.G. Search for brightness variations in FeXIV coronagraph observations of the quiescent solar corona. *Astrophys. J.*, 1998, v. 505, 432–442.
14. Habbal S.R., Druckmüller M., Morgan H., Daw A., Johnson J., Ding A., Arndt M., Esser R., Rušin V. and Scholl I. Mapping the distribution of electron temperature and Fe charge states in the corona with total solar eclipse observations. *Astrophys. J.*, 2010, v. 708, 1650–1662.
15. Habbal S.R., Druckmüller M., Morgan H., Scholl I., Rušin V., Daw A., Johnson J. and Arndt M. Total solar eclipse observations of hot prominence shrouds. *Astrophys. J.*, 2010, v. 719, 1362–1369.
16. Habbal S.R., Morgan H. and Druckmüller M. A new view of coronal structures: Implications for the source and acceleration of the solar wind – First Asia-Pacific Solar Physics Meeting. *ASI Conf. Ser.*, 2011, v. 2, 259–269.
17. Zirin H. The Solar Atmosphere. Blaisdell Publishing Company, Waltham, M.A., 1966.
18. Zirin H. Astrophysics of the Sun. Cambridge University Press, Cambridge, U.K., 1988.
19. Jefferies J.T and Orrall F.Q. On the interpretation of prominence spectra. II. The line and continuous spectrum of the spray-type limb event of March 7, 1959. *Astrophys. J.*, 1961, v. 133, 946–962.
20. Fleck B., Brekke P., Haugan S., Sanchez Duarter L., Domingo V., Gurman J.B. and Poland A.I. Four years of SOHO discoveries – Some highlights. *ESA Bulletin 102*, May 2000. (Available online sohowww.nascom.nasa.gov/publications/ESA_Bull102.pdf).
21. Gray D.F. The observation and analysis of stellar photospheres (Cambridge Astrophysics Series), 2nd Edition, Cambridge University Press, Cambridge, U.K., 1995.
22. Thomas R.N. and Athay R.G. Physics of the Solar Chromosphere. Interscience Publishers, New York, N.Y., 1961.

23. Thejappa G. and MacDowall R.J. Effects of scattering on radio emission from the quiet Sun at low frequencies. *Astrophys. J*, 2008, v. 676, no. 2, 1338–1345.
24. Robitaille P.M. Liquid metallic hydrogen II. A critical assessment of current and primordial helium levels in the Sun. *Progr. Phys.*, 2013, v. 2, 35–47.
25. Milne E.A. Thermodynamics of the stars. *Handbuch der Astrophysik*, 1930, v. 3, Part 1, 65–255 (also in Menzel D.H. Selected Papers on the Transfer of Radiation: 6 papers by Arthur Schuster, K. Schwarzschild, A.S. Eddington, S. Rosseland, E.A. Milne. Dover Publications, Inc., New York, 1966, 77–269).
26. Judge P. Observations of the solar chromosphere (Solar MHD Theory and Observations: A High Spatial Resolution Perspective). *ASP Conf. Series*, 2006, v. 354, 259–275.
27. Robitaille P.M. The liquid metallic hydrogen model of the Sun and the solar atmosphere III. Importance of continuous emission spectra in flares, coronal mass ejections, prominences, and other coronal structures. *Progr. Phys.*, 2013, v. 3, L11–L14.
28. 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.
29. Robitaille P.M. The liquid metallic hydrogen model of the Sun and the solar atmosphere VI. Helium in the chromosphere. *Progr. Phys.*, 2013, v. 3, L26–L28.
30. Robitaille P.M. Liquid metallic hydrogen: A building block for a liquid Sun. *Progr. Phys.*, 2011, v. 3, 60–74.
31. Lewis D.J., Simnett G.M., Brueckner G.E., Howard R.A., Lamy P.L. and Schwenn R. LASCO observations of the coronal rotation. *Solar Phys.*, 1999, v. 184, no. 2, 297–315.
32. McCrea W.H. The hydrogen chromosphere. *Mon. Not. Roy. Astron. Soc.*, 1929, v. 29, 483–497.
33. 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.
34. Sinha K. Molecules in the Sun. *Proc. Astron. Soc. Australia*, 1991, v. 9, 32–36.
35. Robitaille P.M. A thermodynamic history of the solar constitution – I: The journey to a gaseous Sun. *Progr. Phys.*, 2011, v. 3, 3–25.
36. Robitaille P.M. A thermodynamic history of the solar constitution - II: The theory of a gaseous Sun and Jeans' failed liquid alternative. *Progr. Phys.*, 2011, v. 3, 41–59.
37. Caltech News 1/12/2012, Harold Zirin, 82 (http://www.caltech.edu/article/295 Accessed online on 5/23/2013).