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

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Invocation of a liquid metallic hydrogen model (Robitaille P.M. Liquid Metallic Hydrogen: A Building Block for the Liquid Sun. *Progr. Phys.*, 2011, v. 3, 60–74; 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) brings with it a set of advantages for understanding solar physics which will always remain unavailable to the gaseous models. Liquids characteristically act as solvents and incorporate solutes within their often fleeting structural matrix. They possess widely varying solubility products and often reject the solute altogether. In that case, the solute becomes immiscible. "Lattice exclusion" can be invoked for atoms which attempt to incorporate themselves into liquid metallic hydrogen. In order to conserve the integrity of its conduction bands, it is anticipated that a graphite-like metallic hydrogen lattice should not permit incorporation of other elements into its in-plane hexagonal hydrogen framework. Based on the physics observed in the intercalation compounds of graphite, non-hydrogen atoms within liquid metallic hydrogen could reside between adjacent hexagonal proton planes. Consequently, the forces associated with solubility products and associated lattice exclusion envisioned in liquid metallic hydrogen for solutes would restrict gravitational settling. The hexagonal metallic hydrogen layered lattice could provide a powerful driving force for excluding heavier elements from the solar body. Herein lies a new exfoliative force to drive both surface activity (flares, coronal mass ejections, prominences) and solar winds with serious consequences relative to the p–p reaction and CNO cycle in the Sun. At the same time, the idea that non-hydrogen atomic nuclei can exist between layers of metallic hydrogen leads to a fascinating array of possibilities with respect to nucleosynthesis. Powerful parallels can be drawn to the intercalation compounds of graphite and their exfoliative forces. In this context, solar winds and activity provide evidence that the lattice of the Sun is not only excluding, but expelling helium and higher elements from the solar body. Finally, exfoliative forces could provide new mechanisms to help understand the creation of planets, satellites, red giants, and even supernova.

> *Science is a living thing, not a dead dogma. It follows that no idea should be suppressed. That I totally disagree with what you say, but will defend to the death your right to say it, must be our underlying principle. And it applies to ideas that look like nonsense. We must not forget that some of the best ideas seemed like nonsense at first. The truth will prevail in the end. Nonsense will fall of its own weight, by a sort of intellectual law of gravitation. If we bat it about, we shall only keep an error in the air a little longer. And a new truth will go into orbit.*
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> *Cecilia Payne-Gaposchkin* [1, p. 233]

1 Introduction

As humanity will always be unable to conduct experiments on the stars, insight into stellar physics can only be gained in four steps: 1) the phase of the solar body must be properly ascertained from observational evidence, 2) the substance of which it is comprised must be identified, 3) stellar data must be acquired, and 4) the properties of earthly materials, whose physics might provide at least some level of understanding relative to astrophysical questions, must be taken into account. While such an approach cannot be assured of definitive conclusions, it can nonetheless provide a framework through which the stars can be "understood". Within this context, solar and stellar observations become paramount, as they alone can offer the necessary clues to build realistic models of the stars. Astrophysical data forms the proper foundation for any mathematical treatment. Devoid of observation, theory lacks guidance and leads to stellar models stripped of physical reality.

The postulate that the solar body exists in a liquid state [2, 3] has substantial implications with respect to internal structure and photospheric activity. To understand how the presence of layered graphite-like liquid metallic hydrogen [2, 3] might alter our insight relative to the Sun, one must turn towards condensed matter physics and the intriguing phenomena associated with both graphite and liquid metallic hydrogen. The consequences are far reaching, touching upon virtually every aspect of astrophysics and provide an elegant setting through which one can begin to understand the most complex observations. Condensed matter offers many advantages not available to gaseous solar models and numerous facts now support a liquid state [4–20].[*] For instance, evidence suggests that the solar body and the photosphere are behaving as condensed matter [2, 3, 10, 14, 15, 20]. It is not simply that the photosphere gives the appearance of a surface as a result of opacity changes: it is acting as one [14]. The same can be said of every structural element on the Sun, including sunspots, faculae, and granules [15, 20]. The solar body is also behaving as a liquid in sustaining the oscillations which currently occupy helioseismologists. Seismology is a science of the condensed state [10]. Thus, there can be little doubt that the body of the Sun is condensed matter.

Though Gustav Kirchhoff had promoted the idea that the photosphere was liquid, the prevailing models of the period already focused on the gaseous state [21]. By 1865, condensed matter merely floated on the gaseous solar body [21]. Fragmented liquid or solid surfaces continued to survive as a strange addition to gaseous stars [21], but the idea that they were fully liquid never truly materialized in modern astronomy [21]. Finally, liquid stars were definitively abandoned in the days of Sir James Jeans, their last major advocate [22]. Jeans had been unable to identify a proper structural material for his models [22].

Then, in 1935, Wigner and Huntington proposed that pressurized hydrogen could assume a low energy configuration with graphite-like lattice order (see Fig. 1) [23]. In doing so, they unknowingly provided Jeans with a candidate for the solar substance [2, 3], though it is likely that he remained unaware of their solution's value. A layered graphite-like structure was critical to proper solar modeling, as this lattice configuration was closely linked with the study of thermal emission on Earth [24, 25]. Carbon-based materials, such as graphite and soot, are the closest naturally occurring examples of blackbodies [24, 25]. Consequently, they have continued to be vital in the production of such cavities in the laboratory [24, 25]. Thus, a hydrogen based lattice which could adopt a graphite-like structure provides an interesting framework for assembling the Sun. Wigner and Huntington [23] had endowed astrophysics with the perfect candidate for solar material.

In this work, we wish to briefly highlight some of the astrophysical benefits which accompany a liquid metallic hydrogen [23] model of the Sun [2, 3]. Through the liquid model, not only are features on the solar surface given a proper structural foundation, but the entire set of solar observations becomes easily understood [2, 3, 10, 14, 15, 20]. Unlike the gaseous models and their reliance on magnetic fields to explain all aspects of solar activity, the liquid model can secure answers without recourse to such phenomena. Magnetic fields become an effect, not an underlying cause. At the same time, there are ramifications associated with condensed solar matter, especially with respect to gravitational settling, solar activity, and nucleosynthesis. These should be addressed both in the context of existing gaseous models and of the new liquid models of the stars [2, 3].

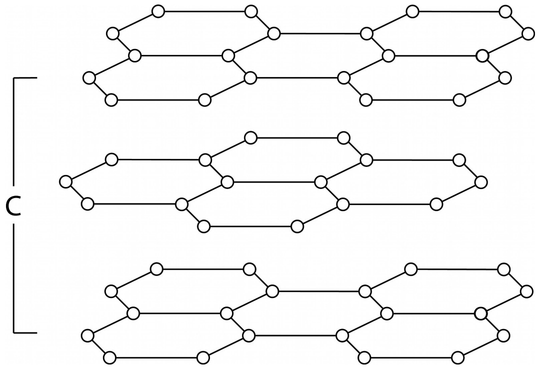

Fig. 1: Schematic representation of the layered hexagonal lattice structure found within graphite and proposed for the liquid metallic hydrogen lattice of the Sun.

2 Solar collapse versus incompressibility

The prevention of solar collapse has always been a central problem with the gaseous models. Theoretical arguments were based on the existence of both gas and radiation pressures in order to balance the masses of the stars against the forces of gravity. In the days of Arthur Stanley Eddington, radiation pressure was believed to play an important role in preventing solar collapse [26]. Over time, this process became generally restricted to supermassive stars [27, p. 180–186]. Solar collapse was prevented by gas pressure [27, p. 132] and radiation thought to contribute only a tiny fraction of the required forces [27, p. 212].

The idea that gas pressure could exist within a star was awkward. On Earth for instance, the atmosphere can be upheld by gas pressure as the planet has a surface through which gas atoms can build positive pressure. Furthermore, the pressure-volume relationship developed using the ideal gas law implied enclosures and rigid surfaces. It was their presence that gave meaning to gas pressure precisely since a rigid compartment defined the volume of interest. But within gaseous stellar models, there are no surfaces. As such, no mechanism exists for speaking of gas pressure.

In his classic text, Donald Clayton would describe the problem as follows: "*The microscopic source of pressure in a perfect gas is particle bombardment.*[1] *The reflection (or*

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[*] The senior author has provided a complete list of his relevant papers to help facilitate the study of this new model.

absorption) of these particles from a real (or imagined) surface in the gas results in a transfer of momentum to that surface. By Newton's second law ($F = dp/dt$)*, that momentum transfer exerts a force on the surface. The average force per unit area is called the pressure. It is the same mechanical quantity appearing in the statement that the quantity of work performed by the infinitesimal expansion of a contained gas is* $dW = PdV$*. In thermal equilibrium in stellar interiors, the angular distribution of particle momenta is isotropic; i.e., particles are moving with equal probabilities in all directions. When reflected from a surface, those moving normal to the surface will transfer larger amounts of momentum than those that glance off at grazing angles*" [28, p. 79]. Clayton's footnote stated: "*In a nonperfect gas strong forces between the particles will represent an additional source or sink of energy for expansions and will therefore contribute to pressure*" [28, p. 79].

There are two problems with Clayton's argument. First, surfaces do not exist within a gaseous Sun. Secondly, by modeling the stars using the ideal gas law, astronomy was requiring elastic collisions between atoms. Yet, if the collisions are elastic, an atom which is moving towards the interior of the Sun could transfer all of its momentum to another atom, without reversing its own direction towards the exterior. In fact, it would simply propel a stationary atom in the interior further inside the Sun. This principle has been well established in the game of billiards. The cue ball can remain completely stationary upon transferring essentially all of its energy to another ball. It is only when a ball hits the banks of the billiard table, or makes use of spin and frictional forces associated with the table surface itself, that it can reverse its momentum. This explains, in the simplest terms, why gas pressure cannot exist within a gaseous Sun devoid of real surfaces and subject to elastic collisions. No net force can be generated with "imaginary surfaces" as the particles have equal probabilities of moving in all directions and transfer their momentum perfectly with no change of direction. A real surface is required to generate a net directional force and such structures cannot exist within a gaseous Sun. Therefore, modern solar models are unable to prevent internal collapse by resorting to gas pressure. In the absence of sufficient radiative forces, gaseous stars collapse.

At the same time, the use of gas models introduced many complications in astronomy. The first was summarized in Eddington's concern regarding internal heating, as stars became increasingly dense: "*I can hardly see how a star which has once got into this compressed condition is ever going to get out of it... Imagine a body continually losing heat but with insufficient energy to grow cold*" [29, p. 172]. Ralph H. Fowler would solve Eddington's dilemma. In 1926 [30], he adapted Fermi-Dirac statistics to stellar problems (e.g. [27, p. 118–128]). Stars could now grow cold. Donald Clayton highlighted the salient aspects of Fowler's solution: "*The physical basis for the resolution of this problem is the thermodynamic peculiarity of a degenerate gas: the temperature no longer corresponds to kinetic energy. The electrons in a zero-temperature degenerate gas must still have large kinetic energy if the density is great*" [28, p. 104]. In fact, Fowler's treatment was so theoretically powerful and the arguments so elegant [30], that gaseous stellar models now dominate astronomy. Nonetheless, no mechanism existed for generating gas pressure within Sun-like stars behaving as ideal gases [27, p. 130–132]. Fowler's solution addressed much later stages of stellar evolution [30].

Conversely, liquids are, by their nature, essentially incompressible. Thus, the problem of solar collapse does not occur within the condensed matter context [2, 3], because the layered graphite-like structure of liquid metallic hydrogen (see Fig. 1) would act to uphold the solar mass. Still, it is anticipated that the hexagonal lattice of metallic hydrogen can become slightly compressed with increasing internal solar pressures. The essentially incompressible nature of liquids implies that, while resisting compression, they remain subject to pressure effects to a small extent. Therefore, it is reasonable to anticipate that liquid metallic hydrogen becomes more metallic farther in the solar interior assuming a Type II lattice [2, 3]. The lower pressures of the photosphere would be conducive to supporting a less dense solar lattice (Type-I) with associated decreased metallicity [2, 3]. Conversely, since the Wilson effect [31] implies that sunspots are depressed relative to the photospheric level, it is reasonable to infer the presence of a Type-II lattice with its increased metallicity in these structures [2,3]. In addition, as facular material is tightly associated with sunspots and may well have been ejected from such regions, it was not unreasonable to extrapolate that their increased metallicity occurs as a result of assuming a Type-II lattice, despite the fact that they appear to float on the photospheric surface [20].

3 Gravitational Settling Versus Restricted Diffusion

Within the context of the gaseous models [32, 33] atoms and ions can diffuse freely within stellar bodies. At the same time, since certain elements are heavier than others, it could be expected that they would slowly move towards the interior of a star through the action of gravitational settling. In fact, such a concept was advanced to explain the lack of helium lines in certain B type stars [34]. Long before, Henry Russell had minimized the idea that heavy elements were gravitationally settling in the Sun: "*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*" [35, p. 59]. Of course, gravitational settling could potentially invalidate all elemental abundances in stellar atmospheres obtained from spectroscopic lines.

Kippenhahn and Weigert discussed both temperature and pressure diffusion (gravitational settling) in their text on "*Stellar Structure and Evolution*" [27, p. 60–61]. They concluded that temperature diffusion was astrophysically irrelevant in the Sun and that diffusion effects were, in general, important only in "special cases" not including the Sun [27, p. 60–61]. Today, the effect of gravitational settling has been included in the calculation of standard solar models [32, 33]. In part, this was because it improved the agreement with the p-mode oscillations from helioseismology: "*One of the principal improvements that has been made in recent years is to include in the calculations the effects of element diffusion. In the absence of an external field, diffusion smooths out variations. However, in the case of the Sun, the stronger pull of gravity on helium and the heavier elements causes them to slowly diffuse downward (towards the solar interior) relative to hydrogen . . . Models that include at least helium diffusion agree with helioseismological determinations of the depth of the convective zone, while neglecting diffusion entirely leads to disagreement with the helioseismological data*" [33]. Gravitational settling was embraced; for gaseous models had no other means of accounting for helioseismological observations.

Within a liquid metallic hydrogen model of the Sun, the free diffusion of the elements becomes highly restricted, as the layered lattice structure of the solar body acts to inhibit the flow of atoms. Rapid diffusion of elements should occur primarily in the layers between the hexagonal liquid metallic hydrogen planes. Such motion may be facilitated by lattice distortions in the hexagonal hydrogen planes in a manner similar to that observed in graphite intercalation compounds.

4 Intercalation and Graphite

Graphite [36–38] can be made to interact with various reagents such that non-carbon atoms occupy lattice points between the hexagonal carbon planes forming intercalation compounds [39–43]. Layered intercalation compounds (see Fig. 2) are created when intraplanar binding forces are much stronger than interplanar forces: "*The most important structural characteristic of graphite intercalation compounds is the occurrence of separate graphite and intercalate layers due to the very strong intraplanar binding and the weak interplanar binding. Thus, the graphite layers retain the basic properties of pristine graphite, and the intercalate layers behave similarly to the parent intercalate material*" [39, p. 36].

In the graphite case, the hexagonal plane excludes non-carbon atoms, the intercalant. In doing so, intercalant atoms can profoundly alter the electrical, thermal, magnetic properties of graphite by acting as electron donors (i.e. Li, K), or acceptors (i.e. $FeCl_3$, HF, BF_3), to the hexagonal plane [39–43]. As a result, graphite intercalation compounds can range from superconductors to insulators [39] with their conductivity often exceeding that of classic metals [43, p. 190]. They consequently occupy an important place in solid state physics. Graphite intercalation compounds can also undergo phase transitions including "*changes in interlayer ordering and changes in intralayer or in-plane ordering, magnetic transitions, and superconductive transition. Structural phase transitions have been induced by variation of the temperature, pressure, and in some cases by variation of the vapour pressure of the intercalant*" [39, p. 55–56]. The presence of intercalated atoms can weaken the interlayer attractive forces within graphite. Since the concentrations of the intercalate can be varied, it is possible to build intercalation compounds wherein many adjacent graphite layers are interrupted by the occasional intercalate layer (see Fig. 3). The stage index, *n*, characterizes the number of graphite layers between intercalation layers (e.g. [39] and [43, p. 88]). In the laboratory, *n* usually ranges from 1 to 10 [39].

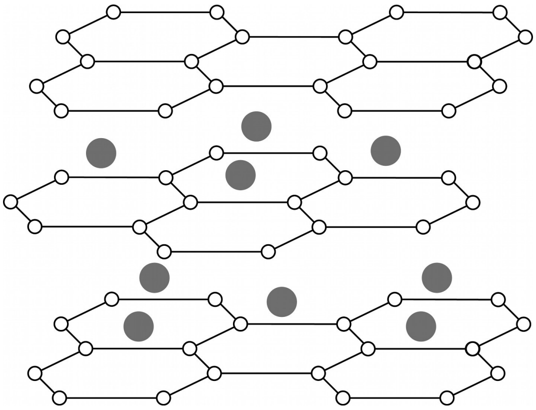

Fig. 2: Schematic representation of an intercalation compound. Non-carbon elements are located between layers of pristine graphite.

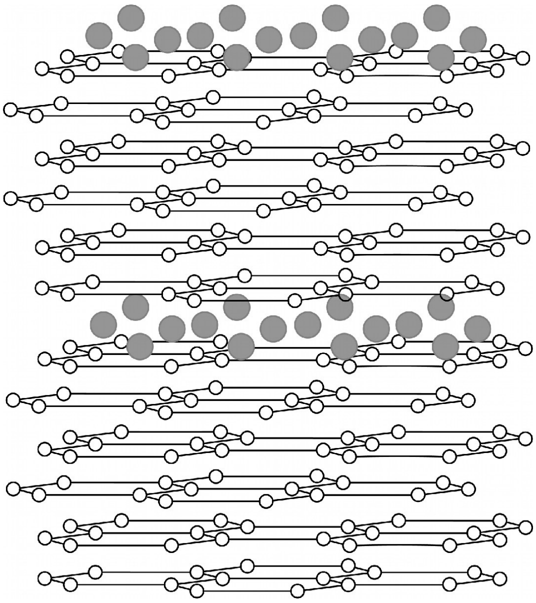

Fig. 3: Schematic representation of the stage index, n, in an intercalate compound, where n = 6.

Graphite intercalation compounds are known to relieve internal strains by undergoing exfoliation [39, p. 9] whereby a great expansion along the c-axis (see Fig. 1) occurs usually due to elevated temperatures [44]. The temperature required for exfoliation is linearly dependent on applied load against the sample [44]. Higher breakaway temperatures, or temperatures of exfoliation, are required under increased pressure. Expansions of the c-axis lattice dimensions of up to a factor of 300 have been reported [44]. These can be violent, even explosive, events wherein layers of material can be torn away from the underlying structure (see e.g. [39, p. 9] and [43, p. 403–413]). They occur as a result of gases being expelled from the graphite intercalated compound. The resultant products are characterized as "*spongy, foamy, low-density, high-surface-area carbon materials*" [43, p. 403].

Martin and Broklehurst [44] performed detailed studies of exfoliation which involved the effect of "*restraining loads on suppressing the onset of exfoliation*" [43, p. 406]. Enoki et al. describe the situation as follows: "*According to [Martin and Broklehurst's] model, the intercalate undergoes a phase change to the vapor phase, forming disk-shaped bubbles of radius* r *and height* I_c *in the interlayer region between graphite planes, with gas pockets accumulating in certain regions where diffusion is facilitated by the presence of defects. Exfoliation then occurs when the gas pressure exceeds the internal stress parallel to the c-axis*" [43, p. 406]. Expressions for the forces involved can be derived, assuming the ideal gas law [44].

Lattice exclusion remains the central lesson of these experiments: the graphite hexagonal planes continue to exclude the intercalate and struggle to remain "*pristine*" even at the cost of exfoliation. Such behavior has strong ramifications when considering the graphite-like liquid metallic hydrogen lattice believed to exist within the Sun [2, 3].

5 Intercalation and Stellar Matter

Graphite's tendency to remain pristine and exclude other elements from its hexagonal plane, even through the process of exfoliation, has important consequences for solar physics. Thermal emission arguments have led Robitaille [2] to postulate that liquid metallic hydrogen in the Sun must adopt a graphite-like layered arrangement. Should this be correct, then liquid metallic hydrogen should be excluding other elements from its hexagonal plane and constantly working to drive them out of the solar body. Such lattice exclusion and the possibility that stars might undergo processes like exfoliation could play a crucial role in at least five separate aspects of solar and stellar dynamics: 1) supplying the driving forces for solar winds, 2) generating the settings for flares, coronal mass ejections, and prominences, 3) accounting for the eleven year solar cycle, 4) providing an alternative explanation for planet and satellite formation, and 5) explaining the existence of red giants and supernovae. Each of these areas could consume many years of study as the liquid metallic hydrogen model of the Sun is adopted. Suffice it, for now, to address these briefly.

5.1 Solar Winds

In modern gaseous models, magnetic fields are thought to be produced by the flow of isolated charged particles within the solar body. In order to prevent collapse, the Sun remains in perfect hydrostatic equilibrium wherein the forces of gravity are balanced by gas and radiation pressure [27, p. 6–7]. However, the preservation of hydrostatic equilibrium severely limits all proposals advanced for the existence of solar winds. An object in equilibrium cannot easily be driving material away from itself.

Conversely, in a condensed model of the Sun, a layered liquid metallic hydrogen lattice exists (see Fig. 1) which is dominated by hexagonal hydrogen planes [2, 3]. Such a lattice restricts the translation of protons within each hexagonal hydrogen layer while permitting electrons to flow in the associated conduction bands [2]. The ability to create conduction bands provides the interatomic binding forces needed to stabilize the hydrogen framework. Proton-proton distances are restricted in order to establish optimal quantum mechanical conditions for these conduction bands. This alone stabilizes the lattice. Since hydrogen atoms possess a single electron and these are restricted to the conduction bands, no conventional bonding can occur. All elements other than hydrogen would be excluded from the hexagonal layer in order to maintain its structural integrity and electronic structure. Protons could be thought of as constantly working to expel elements from the hexagonal planes. This would severely limit the flow of non-hydrogen elements. Each hydrogen layer would act as a barrier to diffusion along the c-axis (see Fig. 1), while providing a channel for rapid elemental diffusion in the region between two hexagonal layers. Herein can be found the driving force for the solar winds and the variable elemental compositions they present due to solar activity [3].

5.2 Flares, Coronal Mass Ejections, and Prominences

In the gaseous models of the Sun, solar flares and coronal mass ejections are considered to be magnetic phenomena [45–48] and are produced by invoking magnetic reconnection [49, 50]. As a gaseous Sun is devoid of a real surface, no other means of generating the required energy is available: "*The magnetic energy stored in the corona is the only plausible source for the energy released during large solar flares. During the last 20 years most theoretical work has concentrated on models which store magnetic energy in the corona in the form of electrical currents, and a major goal of present day research is to understand how these currents are created, and then dissipated during a flare*" [50]. In such a scenario, the corona provides the driving force for expelling atoms from the Sun.

Solar flares are well known to produce helium abundance enhancements (HEA) and have been suggested as the cause of significant ^{3}He HEAs [45]. In an impulsive flare, the ^{3}He/^{4}He ratio can be assumed to approach 1 [51] and thousand-fold enhancements of the ratio have been reported [52] . Solar energetic particle events can result in 100–10,000 fold enhancements of heavy element to oxygen ratios relative to the quiet corona [52]. Solar atmospheric ratios of Mg/O, Si/O, Fe/O and Ne/O can all be substantially elevated with flare activity [51]. In active coronal regions, significant (3–4 fold) elemental enhancements of elements with a first ionization potential (FIP) less than 10 eV can be observed with respect to the quiet photosphere [53, 54]. Within bright active regions, a further twofold elemental enhancement can be detected [55]. The absolute abundance of potassium and calcium are greater in flare plasma than in the photosphere [54].

Magnetic reconnection [49, 50], the physical mechanism invoked to drive solar flares in the gaseous models, cannot easily account for the variable elemental abundances associated with flares and coronal mass ejections [56, 57]. As a parallel, models of quiescent coronal loops result in a 10 fold excess of helium to hydrogen when a 10% helium abundance is assumed for the chromosphere [58]. Such tremendous excesses of helium call for much lower chromospheric helium abundances, but these are incompatible with levels required to account for helium in the solar winds [58]. In addition, in order to explain O and Ne abundances in the fast solar winds, a coronal He abundance of 20–40% is required [59]. The model assumes gravitational settling in the corona [59], which is highly unlikely to take place. As such, the gaseous models are struggling to coherently resolve elemental abundances in the solar winds as a result of the interaction between coronal loops, the chromosphere, and the corona. The situation relative to understanding elemental abundances in flares and coronal mass ejections is equally tenuous.

Long ago, Friedrich Zöllner recognized that solar flares required regions of increased pressure in the solar interior [60]. He placed a liquid layer within his gaseous Sun: "*we must therefore conclude that the layer of division consists of an incandescent liquid*" [60]. The need to generate pressure was justified, but could not easily survive within a fully gaseous solar model.

In the liquid metallic hydrogen model of the Sun, solar flares, coronal mass ejections, and prominences can be explained by the process of intercalation and exfoliation, as described above by Martin and Broklehurst [44]. The pressure anticipated by Zöllner [60] is produced when the intercalate atoms increasingly populate the region between two adjacent hydrogen layers. A rapid increase in temperature in this region, presumably due to localized nuclear reactions (see section 5), generates a gaseous phase whose elevated pressures manifest as solar activity. Therefore, solar flares, coronal mass ejections, and prominences share a common mechanism of formation. Their subtle differences result only from the depth of formation. Magnetic fields are not required to produce these phenomena. They are merely altered by their presence.

5.3 The Eleven Year Solar Cycle

The existence of the eleven year solar cycle remains incompletely understood [61–66]. Nonetheless, increased solar activity is associated with changes in the solar dynamo which characterize the 11 year cycle [61, 64]. Cycle periods as great as 2,400 years have been postulated [66]. Solar inertial motion (SIM), wherein the location of the center of the Sun's mass in the solar system drifts due to interaction with the giant planets [61–66], has been postulated as a possible cause of increased activity. Still, as Cionco and Compgnucci highlight: "*at present there is no clear physical mechanism relating these phenomena*" [64]. How can planetary rotations and the associated *SIM* trigger solar activity? Perhaps the Sun is already predisposed to increased surface turbulence and requires only a simple disturbance to initiate activity. In this regard, insight can be gained from the condensed model of the Sun [2, 3].

In the context of a liquid metallic hydrogen model [2, 3], non-hydrogen elements reside in the layers between hydrogen hexagonal planes forming an intercalate arrangement (see Fig. 2). With solar nuclear activity (see section 5), these interplanar regions become increasingly populated and possible intercalate lattice points occupied. Eventually, localized saturation of a given intercalate layer takes place. The maximal concentration of intercalating atoms has been reached. When this occurs, only slight disturbances, such as found through solar inertial motion, could trigger solar activity and cause the intercalate atoms to be ejected from interior layers. Solar activity then becomes linked to the need to eject saturating levels of non-hydrogen elements from the solar body. As the rate of nuclear activity must remain rather constant over the time frames involved, the Sun is constantly building elements in its interior (see section 5), degassing, and repeating the entire process. The driving force for degassing becomes lattice exclusion, but the trigger to release the instability may, or may not, remain linked to solar inertial motion.

5.4 Planet, Red Giant, and Supernova Formation

The formation of planets around a star presents unique challenges to astronomy. Many ideas have surfaced and are taught in introductory astronomy courses [67, p. 285–290]. With time, Laplace's Nebular Hypothesis [68, 69], initially proposed by Emanuel Swedenborg [70, p. 240–272], evolved into the Solar Nebular Disk Model (*SNDM*) [71]. The latter continues to be the most widely accepted theory for the formation of the solar system [71]. Yet, the problem of planet and satellite formation is far from resolved (e.g. [72–74]). In part, this is because the planets cannot be currently conceived as ejected from a young active gaseous solar mass. The problem is removed when the Sun becomes condensed matter and exfoliative forces can be harnessed to promote planet formation, especially for the solid planets of the inner solar system. The central requirement appears to be that interlayer elemental abundance must be permitted to increase dramatically in one region of the solar interior, followed by ejection from the hydrogen lattice. Over time, the Sun could thus transfer some of its angular momentum to the planets. A similar approach could be utilized to help explain satellite formation around the giant planets, as they are also rich in hydrogen [75–77].

On a tangential note, exfoliation might well account for the very low density and great dimensions of the red giants, as the experiments of Martin and Broklehurst suggest [44]. A red giant would remain condensed matter in that it was formed through a process of exfoliation from a star which had permitted a nearly uniform stage index to develop in its interior. A trigger finally turned the intercalate rapidly into the gaseous phase resulting in a red giant. In the final expanded star the dimensions would be enormous and the density greatly reduced, despite the preservation of condensed matter for the metallic hydrogen framework. Interlayer gas pressure between the layers of the expanded star would help to maintain its structural integrity. Supernova could be envisioned as produced in a similar manner, but with non-uniform staging in the interior. For instance, a band or core of intercalate material in the precursor star rapidly enters the gas phase and explodes its liquid metallic hydrogen envelope, while compressing its hydrogen core. In the end, the advantages of adopting a liquid metallic hydrogen model for the Sun are numerous and its consequences extend much beyond the solar system.

6 Evolution and Nuclear Reactions in Gaseous Stars

With the publication of the *Origin of Species* [78] Charles Darwin would send shock waves not only throughout the biological sciences, but also in areas seemingly as far removed as astronomy. The great American father of solar astronomy, George Ellery Hale, commented as follows in the first line of his text devoted to stellar evolution and experimental astronomy: "*It is not too much to say that the attitude of scientific investigators towards research has undergone a radical change since the publication of the Origin of Species*" [79]. Hale expanded on this concept throughout his first chapter, as he elegantly intertwined biological evolution and astronomy. Hale also highlighted the conflict which Herbert Spencer [21], the prominent evolutionist, had with the astronomers: "*convinced that the principle of evolution must operate universally, and that the stars must have their origin in the still unformed masses of the nebulae, [Spencer] ventured to question the conclusion that the resolution of nebulae into stars was only a question of resolving power. He had not long to wait . . .*" [79, p. 47].

Given Hale's fame as an observer for first reporting the presence of magnetic fields on the Sun [80], his leadership in constructing four record setting telescopes (at Yerkes (1), Mount Wilson (2), and Palomar (1) [81]), and his role in establishing the *Astrophysical Journal* [82], it is not surprising that *The Study of Stellar Evolution* [79] has profoundly affected the course of modern astrophysics. George Ellery Hale's interest in stellar evolution [28, 83–87] was certain to ascend to a preeminent position in modern astronomy. At the same time, since prolonged biological evolution was also associated with increased functional abilities, astronomers quickly adopted the same concepts relative to the stellar evolution. As stars aged their core temperatures increased and gradually acquired the ability to make heavier elements. Astronomers began to see the stars not only as progressing through a life cycle, but also, as endowed with different synthetic abilities. Older stars possessed hotter cores, and hence, could sustain nuclear processes thought to require higher temperatures – the synthesis of heavier and heavier elements. On the surface at least, the theory was elegant with the exception of one very serious consideration: the gaseous Sun was deprived of the ability to directly synthesize the elements.

Early on, the fathers of stellar nucleosynthesis, such as Gamow [88, 89], Bethe [90–92], von Weizsäcker [93], and Hoyle [94, 95] would advance the idea that helium could be built from hydrogen within the stars. From the onset, nucleosynthesis was linked to stellar evolution [88, 89]. Gamow believed that "*different rates of energy liberation must be due to different physical conditions inside the stars and chiefly to differences in their central temperature*" [83, p. 116]. The p–p reaction [90], which assembled helium directly from proton combinations while relying on positron and neutrino emission, was believed to be active only in low weight main sequence stars [83, p. 118]. However, for stars larger than the Sun much of the synthesis of ^{4}He came from the carbon-nitrogen-oxygen (CNO) cycle which had been independently proposed by Bethe and von Weizsäcker [91–93]. Interestingly, while the cycle required three elements of intermediate weight, Hans Bethe insisted that: "*no element heavier than ^{4}He can be built up in ordinary stars*" [92]. He argued, "*The heavier elements found in stars must therefore have existed already when the star was formed*" [92]. With those words, most of the stars were deprived of their ability to make any element beyond helium, despite the fact that mankind would eventually synthesize much heavier elements.

Bethe, of course, based his ideas on the probability of nuclear reactions in the gas phase [92, p. 435]. This was appropriate for gaseous solar models. Reaction energies were derived using accelerators and nucleosynthesis in the stars became strictly dependent on our understanding of reactions in gases. The idea that many particles could be combined simultaneously within a condensed lattice would have greatly lowered the energy required to synthesize the heavier elements. Such a concept was never applied to the Sun. Soon a detailed work by Burbidge et. al [96] organized the entire field into an elaborate theory of nucleosynthesis which covered all of the elements. This work would continue to influence nucleosynthesis in the stars until the present day [97]. Nonetheless, the Sun itself had been crippled. All of the elements in the solar system, other than helium, had been produced by early generation stars which no longer existed.

7 Nucleosynthesis and Condensed Matter

Perhaps the greatest advantage of the liquid metallic hydrogen model of the Sun rests in the fact that atomic positions become restricted to lattice points and subject to the forces associated both with solar pressures and lattice vibrations. Hydrogen is confined to its hexagonal planes and all other elements to the intercalate positions between the hydrogen planes. The synthesis of helium would be driven by the need to relieve the strains of stellar pressures on the underlying lattice. Two protons combine to form a deuteron, with positron and neutrino emission as in the p–p reaction [98]. Upon formation, the deuteron could immediately combine with another in-plane proton resulting in the formation of ^{3}He, which would be ejected from the lattice plane into the intercalate layer. As p–p reactions continue, the population of ^{3}He would expand, and soon continue to react producing ^{4}He, as expected from branch 1 of the p–p chain [98]. With time, the intercalate region would become the birthplace of all the elements. Pressure and lattice vibrations alone can be viewed as controlling the reactions with protons readily available from the hexagonal plane. All stars gain the ability to synthesize every element [19]. Multiple elements could react simultaneously in the intercalate layer because of lattice vibrations. This greatly lowers the energy requirements on a given species for nuclear reaction. Eventually, as elemental concentrations build, the stresses against the hexagonal hydrogen planes would increase. These could then break and the intercalate region expand beyond the confines of strict lattice points. Intercalation now abandoned in this region, thick layers of non-hydrogen elements could arise. These would continue to act as nuclear furnaces. During periods of increased solar activity, localized changes in temperature could vaporize these areas and release newly synthesized elements to the stellar atmosphere beyond the solar surface. During planet formation, such regions could simply be expelled, with (or perhaps without) vaporization, from the interior of the Sun.

8 Conclusions

Much speculation has been offered in this work and the end result was deliberate. In order to consider the condensed models of the Sun, scientists must ponder upon the ability to explain the highest amount of observable phenomena in a manner consistent with known physics. The great solar physicist John Bahcall once commented: "*Science progresses as a result of the clash between theory and experiment, between speculation and measurement*" [99]. In earlier work, considerable focus was placed on establishing what was known about the Sun and the evidence it displayed with respect to its phase and composition [2–20]. Ample proof supports the idea that the Sun exists in the condensed state and Occam's razor would slice in its favor.

Given the elevated levels of hydrogen in the universe [100], a liquid metallic hydrogen framework appears not only reasonable but, in light of its thermal emission, necessary [2, 3]. The unique link between graphite and the layered form of metallic hydrogen, as first proposed by Wigner and Huntington [23], presents enormous potential to refine our concept of the stars. In this regard, graphite intercalation compounds bring a wealth of behavioral and structural information crucial to understanding the heavens [39–44]. The layered nature of liquid metallic hydrogen [23] would not only support the Sun from collapse, but would also severely limit any gravitational settling. Furthermore, exfoliation in graphite intercalate compounds [44] has profound consequences, regarding stellar structure and behavior. Solar winds and solar activity (flares, coronal mass ejections, prominences) become inherently linked to preserving the hydrogen nature of the Sun [3]. The conversion of intercalated atoms from the liquid to the gas phase, as proposed by Martin and Broklehurst [44], has profound implications towards driving solar activity which will forever remain unavailable to gaseous models. The hypothesis that the solar cycle originates from the degassing of non-hydrogen elements and their expulsion from the interior is unique to the liquid metallic hydrogen model. For the first time, a reasonable thesis is being advanced to explain both solar activity and cycles. A mechanism thereby becomes available to those who believe that solar inertial motion might trigger solar activity [61–66]. In addition, the idea that a layered metallic hydrogen lattice will choose to exclude non-hydrogen elements and sequester them within the Sun could add much needed insight relative to the formation of the planets. Exfoliation of a metallic hydrogen lattice of uniform stage might well account for both the size and density of the red giants. Most importantly, this model enables elemental synthesis in the stars. Hexagonal hydrogen planes harbor the p–p reactions, while the interlayers between proton planes become furnaces of more advanced nuclear synthesis.

There is a great deal to be gained by considering a liquid metallic hydrogen model of the Sun. Yet, in this approach, the solar lattice appears to possess long range order on par with solids, despite its liquid state [18]. Given the dimensions involved on the solar surface, even solids might appear to act as liquids. But nonetheless, the model claims the liquid state as more in keeping with observation. In this respect, the authors emphasize that long range lattice order seems to be preserved in the liquid metallic hydrogen framework of the photosphere and solar body. The Sun is fully behaving as condensed matter. As such, this thesis has been built on observation, in keeping with the philosophy of Cecilia Payne:

“The future of a subject is the product of its past, and the hopes of astrophysics should be implicit in what the science has already achieved. Astrophysics is a young science, however, and is still, to some extent, in a position of choosing its route; it is very much to be desired that present effort should be so directed that the chosen path may lead in a permanently productive direction. The direction in which progress lies will depend on the material available, on the development of theory, and on the trend of thought . . . The future progress of theory is a harder subject for prediction, than the future progress of observation. But one thing is certain: observation must make the way for theory, and only if it does can the science have its greatest productivity . . . There is hope that the high promise of astrophysics may be brought to fruition.”

Cecilia Payne-Gaposchkin [1, p. 199–201]

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Dedication

This work is dedicated to Lindsey Marie Robitaille.

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