

# Liquid Metallic Hydrogen: A Building Block for the Liquid Sun

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Liquid metallic hydrogen provides a compelling material for constructing a condensed matter model of the Sun and the photosphere. Like diamond, metallic hydrogen might have the potential to be a metastable substance requiring high pressures for formation. Once created, it would remain stable even at lower pressures. The metallic form of hydrogen was initially conceived in 1935 by Eugene Wigner and Hillard B. Huntington who indirectly anticipated its elevated critical temperature for liquefaction (Wigner E. and Huntington H. B. On the possibility of a metallic modification of hydrogen. *J. Chem. Phys.*, 1935, v.3, 764–770). At that time, solid metallic hydrogen was hypothesized to exist as a body centered cubic, although a more energetically accessible layered graphite-like lattice was also envisioned. Relative to solar emission, this structural resemblance between graphite and layered metallic hydrogen should not be easily dismissed. In the laboratory, metallic hydrogen remains an elusive material. However, given the extensive observational evidence for a condensed Sun composed primarily of hydrogen, it is appropriate to consider metallic hydrogen as a solar building block. It is anticipated that solar liquid metallic hydrogen should possess at least some layered order. Since layered liquid metallic hydrogen would be essentially incompressible, its invocation as a solar constituent brings into question much of current stellar physics. The central proof of a liquid state remains the thermal spectrum of the Sun itself. Its proper understanding brings together all the great forces which shaped modern physics. Although other proofs exist for a liquid photosphere, our focus remains solidly on the generation of this light.

## 1 Introduction

Decidedly, the greatest single impetus for a fully gaseous Sun [1, 2] was the elucidation of critical temperatures by Thomas Andrews in 1869 [3, 4]. Since ordinary gases could not be liquefied at the temperatures associated with the Sun, it was inconceivable that the photosphere was made from condensed matter: *“It is, however, scarcely possible to regard as existing in the interior of the Sun, matter in either the solid or in the liquid condition. . . . Since, however, it became apparent from the classic research of Dr. Andrews in 1869, that there exists for every element a critical temperature, above which it is impossible for it under any conditions of pressure to assume the liquid state, it has generally been regarded that a liquid interior to the Sun is next to an impossibility”* [5, p. 36-37]. As a result of such logic, the idea that the Sun was gaseous flourished. Though Father Angello Secchi and Hervé Faye had already proposed a gaseous solar model [1], Andrews’ discovery served to significantly validate their conjectures. Given the logic of the period, the body and photosphere of the Sun could not be liquid [1].

At the same time, scientists of the late 19th and early 20th century remained puzzled with respect to the solar spectrum [1, 2]. Because graphite was the prime source of blackbody radiation on Earth [6], G. Johnstone Stoney placed liquid or solid carbon on the surface of the Sun in 1867 [7]. It would remain there for the next 50 years [2]. Armed with graphite, it

became simple to explain why the solar photosphere emitted a thermal spectrum resembling a blackbody. Over time, the enthusiasm for carbon began to wane. Charles Hastings argued that condensed carbon could not be present on the Sun. The temperatures involved did not permit such a hypothesis. Hastings required an alternative: *“At any rate, we are sure that the substance in question, so far as we know it, has properties similar to those of the carbon group”* [8]. Hastings did not elaborate on these properties, but it was clear that he was searching for a substance with unbelievable refractory characteristics, something with the structure of graphite. A material capable of producing the thermal spectrum of the Sun had to exist in the condensed state at tremendous temperatures.

Eventually, theoretical astrophysics dispensed of the need for condensed matter. In so doing, the stellar opacity problem was created [9]. It was Schuster’s *Radiation through a Foggy Atmosphere* [10] which began to cast condensed matter out of the photosphere [2]. Schuster postulated that all gases, if sufficiently thick, emitted as blackbodies: *“The radiation in this case becomes equal to that of a completely black surface, which agrees with the well-known law that absorption irrespective of scattering tends to make the radiation of all bodies equal to that of a black body when the thickness is increased”* [10, p. 6]. Schuster’s conclusion was not supported by the gaseous nebula. These celestial objects had long been known to emit line spectra [11, p. 87] and, though they were assuredly thick, blackbody lineshapes were not produced. As

previously outlined by the author [2], Schuster's error consisted in resting his derivation upon the premise that Kirchhoff's law of thermal emission was valid [12].

Gustav Kirchhoff insisted that, given thermal equilibrium with an enclosure, a blackbody spectrum could be produced by any object [12]. Yet, if Kirchhoff's law was correct, his contemporaries should not have refused to adopt a fully gaseous Sun throughout the 19th century [1, 2]. They would not have insisted on the need for graphite. If graphite was viewed as less than optimal, they would not have invoked pressure broadening as a means to produce the solar spectrum [1]. Kirchhoff's formulation, after all, was independent of pressure. It would become evident that something was not quite right with Kirchhoff's deductions. The author has outlined why Kirchhoff's law of thermal emission was erroneous [13, 14]. On the simplest level, it constituted a violation of the first law of thermodynamics. In addition, as was outlined relative to the stellar opacity problem, gases remain unable to emit a blackbody spectrum [9]. This was the surest evidence that Kirchhoff's law was invalid.

As a result, if gases could not produce the solar spectrum, astrophysics should have returned to the condensed state. At the beginning of the 20th century, Jeans promoted liquid stars [15] based on stability arguments, only to discard them at the end of his life [2]. If Jeans abandoned liquids, it was likely due to his lack of a proper building block [2]. He conceived of stars as composed of heavy elements such as uranium and radium [2]. When the Sun was shown to contain large amounts of hydrogen [16–18], Jeans was left without a proper structural material. He did not anticipate that metallic hydrogen could exist [19] and that the substance provided the perfect candidate for a fully condensed Sun. In proposing the existence of metallic hydrogen [19], condensed matter physics would unknowingly provide Jeans with a suitable material for liquid stars [2]. Andrews' critical temperature in ordinary gases became inconsequential [20]. More intriguing was the observation that the layered lattice of condensed metallic hydrogen possessed tremendous similarity with graphite [19]. Could the layered form of metallic hydrogen finally replace Stoney's solid carbon on the Sun [2, 7]? Was this the strange material sought by Hastings for generating the solar spectrum [2, 8]?

## 2 Metallic hydrogen

Eugene Wigner (1963 Nobel Prize in Physics [21]) and Hillard B. Huntington [22] were the first to advance the existence of metallic hydrogen in 1935 [19]. They opened their classic paper by stating that "Any lattice in which the hydrogen atoms would be translationally identical (Bravais lattice) would have metallic properties" [19]. Their work focused on the body centered lattice. Recognizing the difficulties in obtaining the pressures required to form this lattice, they proposed that the layered form of metallic hydrogen would be more accessible. According to Wigner and Huntington "it

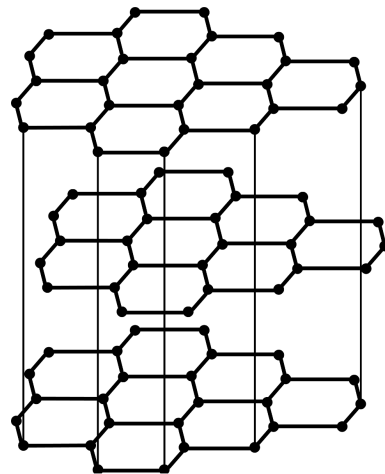


Fig. 1: Schematic representation of the layered lattice of graphite. Wigner and Huntington [19] would propose that most energetically favorable form of metallic hydrogen would assume this crystal structure.

was J. D. Bernal who first put forward the view that all substances go over under very high pressure into metallic or valence lattices" [19]. For the body centered cubic form of metallic hydrogen, they predicted a density of  $0.8 \text{ g/cm}^3$  versus  $0.087 \text{ g/cm}^3$  for molecular hydrogen in solid form [19]. This was nearly a tenfold increase in density. Wigner and Huntington concluded their paper as follows: "The objection comes up naturally that we have calculated the energy of a body-centered metallic lattice only, and that another metallic lattice may be much more stable. We feel that the objection is justified. Of course it is not to be expected that another simple lattice, like the face-centered one, have a much lower energy, — the energy differences between forms are always very small. It is possible, however, that a layer-like lattice has a much greater heat of formation, and is obtainable under high pressure. This is suggested by the fact that in most cases of Table I of allotropic modifications, one of the lattices is layer-like<sup>19</sup>..." [19]. The footnote in the text began: "Diamond is a valence lattice, but graphite is a layer lattice..." [19]. Thus, in the first paper on metallic hydrogen, the layered structure of graphite (see Figure 1), so critical to producing the blackbody spectrum on Earth, was promoted. A solar spectrum explained through dense hydrogen was certain to eventually rise to prominence.

### 2.1 Properties of metallic hydrogen

Initially, Wigner and Huntington estimated that the metallic state of hydrogen, in its most energetically accessible form (layered lattice), could be achieved at pressures in the 250,000 atm range ( $\sim 25 \text{ GPa}$ ) [19]. This value was much too optimistic.

The most astounding property of metallic hydrogen would be its tremendous critical temperature. It was well in excess of anything Thomas Andrews and his contemporaries

could have imagined in 1869 [3,4]. While the complete phase diagram for hydrogen may never be fully known, several attempts have been made to outline its general characteristics, both in condensed matter physics [23–25] and as related to astrophysics [26–28]. Franck [29] listed many of the early contributions to the hydrogen phase diagram, including the work by Alexey A. Abrikosov [30]. Abrikosov eventually won the 2003 Nobel prize in physics while at Argonne National Laboratories.

The critical point of metallic hydrogen has been constantly revised towards ever higher values. Ebeling and Richert [23] provided an overview of these estimates through the 20th century. In 1980, Franck [29] arrived at a critical temperature for metallic hydrogen in the 6,000–9,000 K range. In 1983, Ronik and Kundt [26] gave a critical point at a unprecedented 19,100 K and 24 GPa. A slightly more conservative 16,500 K and 22.5 GPa was soon published [23]. Beyond critical temperatures, the transition pressures in moving from molecular to metallic hydrogen have constantly been revised upwards. At present, the values have moved to the 400–600 GPa range: *“Although quantum chemistry calculations have been developed to a high degree of sophistication, and in general, there is a close correlation between theory and experiment, this is not the case for hydrogen. Phase transition calculations that seek the structure with the lowest lattice energy have difficulty handling the zero-point energy contributions to the total energy and zero-point energy is very important for hydrogen. As a result, the predicted critical transition pressures have an enormous variation, from as low as 0.25 Mbar to over 20 Mbar, while recent predictions are in the 400 to 600 GPa range”* [25].

## 2.2 The theory of metallic hydrogen

Several authors have reviewed the metallic hydrogen literature [31, 32]. In a landmark 1968 publication, Neil Ashcroft hypothesized that metallic hydrogen might be a high temperature superconductor [33]. Ashcroft consequently became one of the most important theoretical physicists with respect to understanding dense hydrogen in its molecular and metallic forms [24, 33–50]. Ashcroft’s prediction relative to high temperature superconductivity was rapidly echoed by Schneider and Stoll [51]. Depending on lattice configurations, they calculated that metallic hydrogen would become superconductive with operational temperatures ranging from 67 to 200 K [51]. Barbee et al. confirmed these calculations, obtaining a temperature of  $230 \pm 85$  K [52]. Metallic hydrogen had the potential to be the highest temperature superconductor known. The point was emphasized in 2001, when Maksimov and Savrasov used *ab initio* calculations to conclude that metallic hydrogen at high pressure might have a superconducting critical temperature of 600 K [53].

Ashcroft also examined the ground state of metallic hydrogen at zero temperature under conditions of changing spatial densities achieved by varying pressures from  $\sim 1$  Mbar

to  $\sim 75$  Mbar [34, 35]. At the highest densities ( $r_s = 0.8, 1.2, 1.36, \text{ and } 1.488$ ), he discovered that crystalline phases were preferred [35]. However, at the lowest lattice density studied ( $r_s = 1.64$ ), he found that metallic hydrogen was metastable between the solid and liquid forms [34, 35]. He postulated that the existence of a liquid ground state could not be excluded, but that it was not established [34]. Ashcroft continued this line of investigation in 1981 and 1982 [36, 37]. He gathered that liquid metallic hydrogen might become essentially devoid of structure and that the protons and electrons would simply act as interpenetrating fluids [36]. The Cornell scientist had theoretically constructed a two-component Fermi-liquid from protons and electrons [36].

Still, there was no direct evidence that metallic hydrogen at absolute zero would ever completely lose all structural integrity. As a theoretical physicist, Ashcroft could not really establish if metallic hydrogen at absolute zero 1) acted as a two component Fermi liquid, 2) behaved much like the unusual theoretical one-component plasma [54, 55], or 3) retained the essential characteristic of a Bravais lattice, an ordered proton field with fully degenerate electrons. Nonetheless, in his 1981 communication, Ashcroft was careful to mention that his conclusions were *“assuming that it [the hypothetical state of liquid metallic hydrogen] is normal”* [36]. He highlighted: *“that in assuming the existence of a liquid phase, the very interesting question still remains of whether or not it exhibits some form of magnetic, momental, or even spatial (e.g. liquid crystal) ordering. . . We do not attempt at this time to resolve the important questions of the existence or properties of possible “ordered” liquid metallic phases of hydrogen”* [36]. In the ninth footnote to his 1982 treatment, Ashcroft repeated the warning: *“The possibility that liquid metallic hydrogen exhibits some kind of momental (e.g. superconductive), magnetic, or even spatial (e.g. liquid crystal) ordering has not been ruled out”* [37]. Only experimental evidence could answer such questions, but none was available, as liquid metallic hydrogen remained an elusive material [25, 31, 32, 56].

Astrophysics was quick to infer that Ashcroft had chosen a path eventually leading to some form of degeneracy of matter [57]. In fact, careful reading of these articles suggested otherwise. Ashcroft’s liquid was a reflection of what theoretical condensed matter physicists were able to calculate at the time. A liquid with spatial order, thoughtfully preserved in the text [36] and in the footnotes [37] of his papers, was well beyond the reach of computational approaches in the absence of laboratory guidance.

Soon after Ashcroft published his groundbreaking papers [34–37], MacDonald and Burgess also wondered about the absence of crystallization in metallic hydrogen [58]. They insisted that, since electronic screening was important in the solid state but negligible in the liquid state, metallic hydrogen would remain fluid at all pressures. Solid metallic hydrogen could not be stable at any pressure [58]. Ashcroft answered

that “*The prospect of a relatively low-density quantum melted phase of hydrogen, over a wide range of densities, is a fascinating one. However, we would like to bring up the following difficulties with concluding too definitely the existence of this phase for all densities*” [38]. Ashcroft then argued that such a state would exist only over limited densities whose range would be difficult to predict, as the solid and liquid phases are both close in energy and widely separated in configuration [38].

When Ashcroft returned to the ground state of metallic hydrogen in 1984, he assumed that the protons occupied the sites of a rigid Bravais lattice [39]. Using the Wigner-Seitz approximation which he regarded as physically appealing, Ashcroft calculated a lower bounds on the density of metallic hydrogen at its transition pressure. This density would be on the order  $0.60 \text{ g/cm}^3$  corresponding to  $r_s = 1.65$  [39]. Metallic hydrogen, if it was stable at all, would have to possess a greater density.

Given the nature of metallic hydrogen, both as a theoretical problem and as a prized material, significant Russian and Ukrainian contributions were made in this area [32,53,59–65], beginning with Alexey Abrikosov [30]. In an important communication, Abrikosov was one of the first to examine the destruction of an atomic lattice under high compression [59]. He noted: “*that at sufficiently small volumes the positive zero-point oscillation energy exceeds the negative Coulomb energy, and this leads to a destruction of the crystal lattice*” [59]. Abrikosov remarked that “*the inter-atomic distances at the transition point are greater than the nuclear dimensions only for the lightest elements, hydrogen and helium. Thus, such a transition can take place only in these two elements*” [59]. It seemed as though elevated pressures might lead to the destruction of the crystal lattice, but Abrikosov never considered that fusion might act to relieve the stresses of compression. Beyond a certain point, perhaps crystals became incompressible. It was unclear if the small volumes required to give prominence to the zero-point oscillations in metallic hydrogen might ever be reached.

After Abrikosov’s classic paper was released [59], Brovman et al. were the first to hypothesize that metallic hydrogen might be a metastable substance [61]. Kagan’s group [32,61] advanced that metallic hydrogen synthesized at elevated pressures might be completely stable even at zero pressure. This behavior would be much like diamond, the metastable form of carbon. Brovman et al. [61] calculated that the most stable lattice of metallic hydrogen would be hexagonal with a triangular string structure [60]. The conjecture would spawn the possibility of industrial and propellant roles for metallic hydrogen [25]. Many years later, Kaim et al. [64] would once again address the metastable nature of metallic hydrogen and essentially confirm Kagan’s findings [61].

However, the most interesting facet of Kagan’s work [61] was the observation that metallic hydrogen displayed liquid tendencies: “*there occurs in metallic hydrogen a unique ten-*

*dency towards the formation of a family of structures with very close energies. . . In a certain sense the picture recalls the situation with graphite, but is apparently even more strongly pronounced. . . the formation of the planar family is evidence of the unique liquid-like tendencies that take place in metallic hydrogen under pressure*” [61]. They continued: “*As a result it is impossible to exclude beforehand, in principle, the possibility that the transition from the molecular phase to the metallic phase is a transition into the state of a liquid metal. (It may turn out that the situation will be different in hydrogen than in deuterium.) The phase diagram could have in this case a very special character. For example, with increasing pressure, the liquid phase could go over into the crystalline phase, but at extremely high densities a liquid would again be produced, but now as a result of the predominant role of the energy of the zero point oscillations (see the paper by Abrikosov<sup>7</sup>). The metastable state could remain crystalline in this case*” [61]. The footnote referred to the work just discussed above by Abrikosov [59]. Relative to the liquid metallic hydrogen model of the Sun, the work by Brovman et al. [61] would remain landmark.

Barbee et al. [52,66] continued the quest to calculate the most stable structure for hydrogen in solid form. The work supported Wigner and Huntington’s [19] contention that a layered Bravais lattice form of metallic hydrogen was the most stable in the  $380 \pm 50$  to  $860 \pm 100$  GPa range [66]. Above such values, the body centered cubic was preferred. Below  $380 \pm 50$  GPa the molecular non-metallic hexagonal-close-packed arrangement was most stable. The authors highlight some of the difficulties faced by theoretical condensed matter physics: “*A metal-insulator phase is expected near 200 GPa, in the m-hcp phase, but this transition pressure is harder to predict because of the shortcomings of local-density theory and the fact that structures with similar enthalpies (e.g. diamond and graphite) may have completely different band structures*” [66].

At about the same time, an interest developed in theoretical physics for examining the mono-, di-, and trilayered forms of atomic hydrogen [67–69]. While it could be argued that such structures were not physically realistic, their study generated additional insight into metallic hydrogen. Significantly, they demonstrated that very small changes in lattice parameters could alter the conductive behavior substantially, creating insulators from metals.

For his part, Neil Ashcroft maintained his interest in the structure of hydrogen. In 1993, he once again examined the metal-insulator transition in this element [40]. At this time, Ashcroft moved increasingly towards the idea that dense hydrogen might lack local structure at the lower densities. It seemed as if the stability of crystal forms was becoming questionable for him, even at the higher densities: “*At sufficiently high densities ( $r_s \leq 1.5$ ), the predicted states of H (eq. 1) certainly include monatomic crystalline arrangements [6], at least where the dynamics of the protons can be ignored*” [40].

Though recognizing the presence of crystalline forms, he emphasized the dynamics of the protons. Observing that the proton pairing in molecular hydrogen was robust, Ashcroft eventually proposed that molecular metallic hydrogen might be energetically preferred [42]. This was a material very different than first proposed by Wigner and Huntington [19]. At low temperatures and at pressures less than 110 GPa, Ashcroft argued that molecular hydrogen existed as a rotational crystal [40,42]. At low densities ( $1.5 < r_s < 2$ ), he envisioned that hydrogen might become a low temperature quantum fluid [45].

Ashcroft moved further towards the idea that, at the proper density, liquid hydrogen was a superfluid [47,48]. In doing so, he revisited the ideas elucidated when first dealing with two component Fermi liquids [36,37] and expanded on his work with Mouloupoulos [41]. Ashcroft appropriately highlighted that experiments up to 300 GPa proved that molecular H-H stretching modes continued to exist at these high pressures [47]. He insisted that both proton-proton and electron-electron pairing could become the dominant interaction, given the proper conditions [41]. The concept that liquid metallic hydrogen was a two gap superconductor was also promoted by Babaev [70]. In such a superfluid, both protons and electrons could flow in the same direction, providing mass transfer without charge transfer. Alternatively, the system could result in a superconducting mode wherein proton and electrons flowed in opposite direction, resulting in the flow of both mass and charge [48]. Ashcroft then emphasized that *“the neutral superfluid mode does not couple to an external magnetic field, while the charged superconducting mode does”* [48]. The work did not address metallic hydrogen in its densest form. Ashcroft mentions that: *“Above any superconducting transition temperature (and above any Bose condensation temperature) liquid metallic hydrogen and deuterium should begin to adopt properties similar to those of conventional liquid metals, at least in the structural characteristics important to electron scattering”* [47].

Ashcroft’s hypothesis that metallic hydrogen might exist as a quantum fluid immediately gained theoretical support [71]. Given increasing compression, Bonev et al. [71] calculated that solid molecular hydrogen [72] would be transformed into a quantum fluid state. Additional pressure would then lead to the monatomic crystal [19,71]. With increasing pressure, it could be computed that hydrogen might undergo a transition from a liquid-molecular state into a non-molecular liquid [71]. This would become known as the liquid-liquid transition [71]. By extending the work of Brovman et al. [61], it was possible to visualize that hydrogen had a zero-temperature structured liquid ground state. With enough pressure, hydrogen could then move from the two component Fermi liquid [36,37,41,46–48,70], to the crystalline solid [19], and finally into a zero-temperature structured liquid state [61]. Alternatively, metallic hydrogen might move from a two component Fermi system directly either into a structured liquid metal [61] or into the solid classical form of

metallic hydrogen [19]. A wide array of theoretical possibilities now existed for the state of hydrogen under dense conditions.

While the theory of liquid metals [73] has remained a fascinating branch of condensed matter physics, hydrogen liquid metals, though they appear simple on the surface, continued to offer unequalled challenges. With only sparse experimental data (see Section 2.4), theoretical condensed matter physics had little guidance from the laboratory. Even so, progress was being made, if only in the realization that metallic hydrogen was a material filled with mystery and promise. Modern condensed matter theory persisted in providing exciting results, often from the most prestigious groups [74–81].

Relative to solar physics, it was clear that the superfluid form of metallic hydrogen [36,37,41,46–48,70], devoid of all structure, could never be found on the surface of the Sun. The material required a very specific critical density along with low temperatures not found on the solar surface. Superfluid metallic hydrogen resembled nothing of the layered structure [19,61] which mimicked graphite and was most likely to generate the solar spectrum. Superfluid metallic hydrogen [36,37,41,46–48,70] might never be found anywhere.

Fillinov et al. [74] studied dense hydrogen states at temperatures ranging from 10,000 to 100,000 K examining plasma phase transitions. Interestingly, at 10,000 K, they noticed droplet formation at certain densities ( $10^{23} \text{ cm}^{-3}$ ). But at the highest densities studied ( $10^{26} \text{ cm}^{-3}$ ), they observed an ordering of protons into a Wigner crystal. These were tremendous densities on the order of  $\sim 150 \text{ g/cm}^3$ . Militzer and Graham extended theoretical calculations to the petapascal range, a full eight orders of magnitude beyond the pressures of the molecular phase [76]. Such computations were appropriate only for the interior of astrophysical objects. Militzer and Graham [76] considered astounding hydrogen densities ( $2100 \text{ g/cm}^3$ ), but, in contrast to Abrikosov classic paper [59], the lattice was not destroyed and the calculations open serious questions as to the nature of the solid state.

Remaining in the realm of physically attainable pressures, Attaccalite and Sorella [77] demonstrated that the molecular liquid phase of hydrogen should be stable at pressures on the order of 300 GPa at  $\sim 400 \text{ K}$ . The melting curves for hydrogen and its phase boundaries have likewise been addressed [78,79] revealing that theoretical approaches have remained difficult and open to new discoveries. Miguel Morales, while working with David Ceperley and Carlo Pierleoni [80], recently addressed the problem of metallic hydrogen by considering a range of temperatures and densities ( $2,000 \leq T \leq 10,000 \text{ K}$ ;  $0.7 \leq \rho \leq 2.4 \text{ g/cm}^{-3}$ ). Such conditions were appropriate for liquid metallic hydrogen devoid of structure, much like the one-component plasma [54,55]. At elevated temperatures and densities, the system was observed to be a fully metallic liquid plasma [80]. However, a combination of lower densities and temperatures resulted in formation of an insulator [80]. Ceperley’s group also con-

sidered electrical conductivity in high pressure liquid metallic hydrogen [81]. The work was noteworthy, as it tried to examine the liquid-semiconductor to liquid metal transition first reported experimentally by Weir et al. [82, 83]. Using either 32 or 54 atom cells, they calculated the transition density to be near  $r_s \sim 1.65$ , a value very close to the experimentally determined number ( $r_s = 1.62$ ) [82, 83]. These calculations assumed that the liquid was devoid of any structure. In addition, David Ceperley examined hydrogen at ultra high pressures,  $P \geq 20$  TPa [84], a value considerably lower than that of Militzer and Graham [76]. Furthermore, the Urbana-Champaign scientist studied the phase diagram for hydrogen in the ground state [85]. However, the theoretical procedure utilized was best suited to tritium and deuterium, as infinitely massive protons were hypothesized to be present. This work presented an excellent literature review and a remarkable array of potentially significant new structures for the ground state of hydrogen as a function of increasing pressure up to 5 TPa [85].

### 2.3 Metallic hydrogen in astrophysics

Soon after Wigner and Huntington [19] published their classic paper, liquid metallic hydrogen entered the realm of astrophysics. Its introduction as a constituent of the giant planets and the white dwarfs far preceded any experimental confirmation. Liquid metallic hydrogen would eventually occupy a peripheral position in astronomy, well removed from the Sun and most stars of the main sequence.

In 1946, Kronig et al. [86] proposed that metallic hydrogen existed at the center of the Earth. Their work was motivated by a recent report postulating that the Earth's center was composed of residual solar matter containing up to 30% hydrogen. Kronig et al. [86] calculated a density for metallic hydrogen of  $0.8 \text{ g/cm}^3$ . The result was apparently independent of Wigner and Huntington [19] as they seemed unaware of this previous communication. Then in 1950, W.H. Ramsey extended the study of metallic hydrogen to the planets and the white dwarfs [87]. According to Ramsey, at the International Astronomical Union meeting in Paris of 1935, H. N. Russell [88] had pointed out: *“that both the planets and the white dwarfs are cold in the sense that the density at any interval point is determined by the pressure at that point. In other words, the influence of temperature is so small that it can be neglected to a good approximation. Thus, in the accepted theory of the white dwarfs it is assumed that the electrons constitute a degenerate Fermi gas at absolute zero temperature”* [87]. The minutes of the meeting highlight how Russell believed that the maximum radius of a cold body was equal to one tenth of the solar radius, or about the diameter of Jupiter [88, p. 260]. It was a crucial statement which linked studies of the giant planets with those of the white dwarfs. At the pressures inside white dwarfs and giant planets, all solids were viewed as metallic [87]. Hydrogen was no exception. In the end, Ramsey deduced that metallic hydrogen could not be

produced inside a small planet like the Earth [87]. Hence, it was primarily because of this work [87] that the quest for liquid metallic hydrogen would be extended simultaneously to the celestial objects with features of mass and density lying to either side of the Sun. In these objects, the study of liquid metallic hydrogen [26–28, 89, 90] progressed quickly to the fully degenerate liquid state (i.e. — states where both protons and electrons were unrestricted by lattice confinements).

Astrophysical bodies are not pure laboratory samples. They are an assembly of mixtures and alloys. As such, once scientists gained interest into the composition of the planets [91–95] and the white dwarfs (see [96] for a short review relative to  $^{22}\text{Ne}$ ), hydrogen/helium mixtures [97, 98] and their alloys [49, 50, 99] were certain to attract attention. Along with Ashcroft, Eva Zurek and her coworkers [50] discovered that lithium had the capability of greatly stabilizing the metallization of hydrogen. Even the phase diagram for carbon under extreme conditions grew in importance, as potentially relevant to understanding Neptune, Uranus, and the white dwarf [100, 101]. A vast number of publications flourished, but they shared one common factor: the paucity of laboratory data. Nellis et al. extended results from the laboratory to interior of Jupiter [94, 95], well before his findings [82] were independently confirmed. Nellis' work on the production of liquid metallic hydrogen (see Section 2.4) at 140 GPa and 3,000 K was supported by conductivity measurements [82], although the merits of these measurements were to remain in doubt. In any case, astrophysics continued to insist that the large planets and white dwarfs were constituted of liquid metallic hydrogen devoid of structure and existing in fully degenerate states. At pressure of  $\sim 500$  GPa (5 Mbar), William Nellis maintained that materials were either semiconductors or fully degenerate metals [102]. Experimental confirmation of a fully degenerate state for liquid metallic hydrogen at such pressures was unproven. In the laboratory, all forms of metallic hydrogen remained ethereal with theoretical predictions far surpassing experimental reality.

### 2.4 Laboratory quests for metallic hydrogen

Throughout the 20th century, the study of extraordinary states of matter has represented one of the most fascinating aspects of physics [102, 103]. The generation of extremes in temperatures, pressures, and densities has always involved complex and sophisticated experimental resources, often attainable only through national or multinational initiatives [103]. Nonetheless, with regards to metallic hydrogen [102], many efforts have been conducted in university level laboratories. Frederic Golden has provided an excellent review of the search for metallic hydrogen which Ho-Kwang Mao dubbed the “Holy Grail” of condensed matter physics [104]. Golden touches on the early Russian and American attempts to synthesize the material, along with a general description of methods [104]. Given the prize [56], experimental progress has been limited.

In June 1989, Ho-Kwang Mao and Russell Hemley, from the Geophysical Laboratory of the Carnegie Institution, reported evidence of metallization for hydrogen at 77 K and 250 GPa in the journal *Science* [105]. The key finding was the near opaqueness of the sample at the highest pressures. Isaac Silvera, working at the Lyman Laboratory of Physics at Harvard, was studying the metallization problem in parallel with Hemley [106–111]. He rapidly contested the validity of Hemley's claims and submitted a letter to *Science* [106] to which Mao and Hemley responded [107]. Silvera argued that visual darkening provided insufficient evidence for metallization and that further tests were needed [106]. Mao and Hemley defended their result, but in the end, conceded that *"The observations and spectroscopic measurements clearly indicate that significant changes in solid hydrogen occur with increasing pressure, but further work is needed to characterize in detail its optical, electrical, and structural properties under these conditions"* [107]. Silvera soon reported that there was no evidence of metallization up to 230 GPa from 77 to 295 K [110]. Metallic hydrogen had slipped away, but Ho-Kwang Mao, Russell Hemley, and Isaac Silvera would come to rank amongst the experimental leaders in the struggle to synthesize the material.

A few years later, Weir, Mitchell, and Nellis reported anew that metallic hydrogen had been produced [82]. Using shock compressed experiments [102, p. 1510–1514], the metallization of fluid molecular hydrogen was thought to have been achieved at 140 GPa and 3,000 K [82]. The communication was supported through conductivity measurements [82] a vital link in establishing metallization. The results were once again contested [112], though Nellis and Weir maintained their position [113]. In arguing against metallization, Besson brought in data with deuterium suggesting that its samples might represent highly degenerate material, something very different from molecular metallization in hydrogen [112]. Beyond this, Besson was concerned that the  $\text{Al}_2\text{O}_3$  windows had affected the experiment [112]. Nellis and Weir countered that *"Our experiment and analysis yield the simple picture of a dense metallic fluid comprised primarily of molecular  $\text{H}_2$  dimers and a relatively low dissociation fraction of ~5% of H monomers"* [115]. The entire sequence of observation was on the order of just a few hundred nanoseconds [102, p. 1512], hardly time to conduct detailed structural analysis, while introducing tremendous difficulties in properly measuring both pressures and conductivities. William Nellis once again addressed his metallization experiments, but this time with Neil Ashcroft as a co-author [114]. During the discussion which followed the paper, Nellis admitted that *"the exact nature of this unusual fluid needs to be determined"* [114, p. 135]. Though Nellis eventually claimed that *"Metallic fluid H is readily produced by dynamic high pressures"* [102, p. 1564], only questionable evidence existed for this state [82]. The shock experiments of metallic hydrogen from this group produced no

additional results and other groups never confirmed the findings. The lack of lattice structure was debatable and mankind was no closer to metallic hydrogen. For his part, William Nellis moved to arguments of degeneracy, without solid experimental grounds [102].

In 1996, a collaboration between the University of Paris and the Geophysical Laboratory at the Carnegie Institution would make the next vital step forward [115]. Loubeyre et al. [115] examined both solid hydrogen and deuterium with X-ray diffraction at pressures just exceeding 100 GPa at 300 K. They discovered that solid hydrogen *"becomes increasingly anisotropic with pressures"* [115]. In like manner, the layered structure of graphite was considered anisotropic. Loubeyre et al. [115] tried to generate the equation of state for hydrogen as a function of temperature and pressure. They concluded that their results differed substantially from ab initio calculations *"indicating that theoretical understanding of the behavior of dense hydrogen remains incomplete"* [115]. Narayana et al. then studied solid hydrogen up to 342 GPa at 300 K [116]. These were pressures similar to those at the center of the Earth [117], but no evidence of metallization was found. The findings confirmed Ramsey's conclusion that the interior of the Earth could not support the metallic state of hydrogen [87]. In 2002, Loubeyre et al. again presented evidence that solid hydrogen became black, this time at 320 GPa and 100 K [118]. These values were not far removed from the 250 GPa used by Mao and Hemley in 1989 [105]. By observing the vibron mode, they maintain that molecular hydrogen in the solid form existed at least until 316 GPa, but Narayana had just reported that solid hydrogen remained transparent up to 342 GPa at 300 K [116]. Two of the world's major groups were again at odds with one another. Perhaps the discrepancies could be explained by difficulties in recording proper pressures at such values [102, p. 1514–1533]. After all, these studies were far from trivial in nature. Loubeyre et al. [118] refrained from stating that metallization had been achieved. Rather, they predicted that the process should occur near 450 GPa [118].

Mankind has remained unable to synthesize metallic hydrogen in the laboratory. However, as pressures rose and experimental settings improved, the characteristics of dense hydrogen did become increasingly established [119–125]. Great attention was placed on constructing phase diagrams for hydrogen (see [119] for a review). Determination of the peak in the melt line of this element has consequently been the subject of intense study (e.g. [121–124]). By this time, the broken symmetry and hydrogen-A phase for dense hydrogen were reasonably established, but neither form was metallic (see [122] for a brief review). Blackbody radiation finally entered such studies, with the goal to properly establish temperatures [122]. Along these lines, statements such as: *"we have shown that the emissivity of platinum is essentially independent of temperature in the temperature region of our study"* [122] would only serve as a reminder that not all was correct

with our understanding of blackbody radiation [13, 14]. For its part, metallic hydrogen continued to be ephemeral.

### 2.5 Commentary on liquid metallic hydrogen

As was seen in Section 2.3, within astrophysics, liquid metallic hydrogen is believed to exist as fully degenerate matter within the interior of white dwarfs and giant planets such as Jupiter or Saturn. Some have suggested that these planets also possessed liquid metallic helium, or a liquid metallic alloy of hydrogen and helium. Solid metallic hydrogen would have no role in astrophysics [27], as every hypothesis was either a molecular or a fully degenerate liquid. The conjecture that condensed matter could become degenerate in the large planets was far from what Chandrasekhar had envisioned when he first promoted degeneracy [57]. As a fully degenerate material, liquid metallic hydrogen could not sustain any useful current or magnetic field. Positive charges in liberal motion along with negative charges do not seem very amicable, either to potential generation or net current flow. At the same time, current flow with mass transfer seemed unreasonable in astrophysical objects. Direct laboratory observations remained much too elusive to reach any confirmation of these theoretical ideas. Some element of structure might always exist in metallic hydrogen independent of temperature. The superfluid form could remain ever theoretical, as Ashcroft had first carefully cautioned in the work with Oliva [36, 37].

The application of fully degenerate matter to the large planets and the white dwarfs was an unusual concept in light of a fully gaseous Sun. If Jupiter contained metallic hydrogen as degenerate matter and the same was true for the white dwarf, then it would not be unreasonable to place at least some condensed hydrogen on the Sun. Solar temperatures would prevent degenerate states and thus layered liquid metallic hydrogen represented a remarkable constitutive element.

When it was first conceived, the most energetically accessible form of metallic hydrogen was the layered lattice arrangement similar to that of graphite. Solid metallic hydrogen was viewed almost as a one component plasma [54, 55], wherein all electrons were degenerate and distributed over a hexagonal Bravais lattice formed from ordered protons [19]. In this sense, solid metallic hydrogen was considered as degenerate only relative to the flow of its electrons. Today, theoretical astrophysics has abandoned early thoughts of solid or liquid metallic hydrogen possessing a Bravais lattice [19], opting instead for fully degenerate materials where both protons and electrons flow freely. Conversely, experimentalists hope to harness metallic hydrogen for processes as varied as earthly fusion and rocket propulsion [25]. Such processes would not be easily approachable with a fully degenerate material. Hence, many experimental physicists are likely to be skeptical of a fully degenerate state for metallic hydrogen.

The progress towards dense hydrogen states has been an intriguing aspect of condensed matter physics. Ashcroft's

two component Fermi liquid has remained a fascinating substance. However, given the combination of low temperatures, exact densities, and atypical conductive properties, it could have little practical role in human advancement. Current flow involving mass displacement was a concept which seemed to oppose structural stability, even though it could sustain magnetic fields. Conversely, when proton and electron displacement occurred in the same direction, there could be no current or the generation of magnetically interesting properties.

Theoretical condensed matter physics promoted hydrogen at extreme densities [76, 84], but hydrogen might not be compressible to such levels. In permitting essentially infinite compression of the lattice, it was debatable whether or not condensed matter physics had adopted a behavior similar to the ideal gas. Moreover, if compression was great enough, the solid might resist further attempts at reducing lattice dimensions. Fusion might relieve the stresses associated with compression.

## 3 Lessons from the Sun

Though the Sun would always remain devoid of the great advantage of our earthly laboratories, it has historically provided us with an amazing insight into nature. When Sir Joseph Lockyer and Pierre Jules César Janssen independently observed the lines of helium within solar spectra acquired in 1868 [126–130], they must have wondered if this unknown element would ever be discovered. Lockyer named this element *Hēlios*, the Greek name for the Sun god and the Sun [126]. Eventually, William Ramsay would isolate helium from cleveite [131–133], and the Sun would be credited for providing the first indication that helium existed. The identification of Coronium would follow a parallel story [134–136]. It took nearly three quarters of a century for Bengt Edlén and Walter Grotrian to finally identify Coronium from transition lines produced by highly oxidized iron, like  $\text{Fe}^{+13}$  and  $\text{Fe}^{+14}$  [136, p. 170]. Hence, a combination of earthly science and celestial observations became critical to the development of astronomy. This spirit of discovery has taught astronomers how to tackle even the most perplexing problems. The understanding of the solar spectrum should not be an exception.

### 3.1 Graphite, metallic hydrogen, and the solar spectrum

If graphite played a critical role, both in the construction of blackbodies [14], and historically in the structure of the Sun itself [2], it was because science has always recognized that graphite possessed a unique ability towards the production of Planck's spectrum [6, 13, 14]. Hastings was searching for a material which would possess many of the properties of graphite [8]. Graphite, the layered form of carbon, differed significantly in optical properties from its cubic counterpart, diamond. Structure was vital to the production of spectra. That materials were condensed was not sufficient, but a distinct lattice arrangement seemed central [9]. As a consequence, it would be expected that the layered form of metallic



hydrogen would resemble graphite itself in its optical properties. In contrast, fully degenerate forms of hydrogen [36, 37, 41, 46–48, 70–72] could never approach such optical behavior. Devoid of a true lattice, such a substance, if it truly existed anywhere, would be completely unable to generate a blackbody spectrum [6]. These are the lessons from our earthly laboratories, after examining thousands of materials over extreme ranges of frequencies and temperatures [13, 14, 137]. The structural lattice of graphite and soot was to remain unique in its thermal properties [13, 14]. It should serve as a guide for the nature of any condensed material placed either on the photosphere or within sunspots. The generation of a thermal spectrum with a blackbody lineshape has been solely a quality of condensed matter, not of gases, degenerate matter, or any other state which physicists might create.

Unlike the giant planets, the Sun possessed a unique feature: the ability to generate tremendous internal pressures and temperatures. Based on the solar spectrum [138–140] and other physical evidence [141], it was therefore reasonable to postulate that liquid metallic hydrogen must constitute the bulk of the solar mass and specifically the photospheric material [20, 142–149]. In considering a solar building block, thermal emission required a distinct lattice [150], as the absence of such structure would lead to the stellar opacity problem [9]. The author has previously made the point: *“As a result, the photosphere must be treated as condensed matter. Unfortunately, it is counterintuitive than an object at extreme temperatures can possess lattice structure. Nonetheless, given the evidence for condensed matter<sup>A</sup>, the solar constitutive element (primarily H) must form a lattice. The presence of powerful solar magnetic fields and gravitational forces make liquid metallic hydrogen a distinct possibility for the condensed state of the photosphere. In this case, the hydrogen nuclei can be viewed as arranged in an array forming an essentially incompressible solar lattice. The hydrogen electrons are contained within the metallic conduction bands. The inter-nuclear distance is being maintained by the need to keep the quantum conditions such that metallic conduction bands can be produced. Hydrogen contains no inner shell electrons. All the electrons are completely delocalized within the metallic conduction bands. As such, hydrogen in this state is not only a liquid metal (reminiscent of liquid sodium) but can also be viewed as a liquid metallic plasma”* [149]. The footnote referred to reference [141] in this work.

In the solar framework, the electrons would translate freely within the confines of conduction bands formed by the Bravais lattice of the protons. Though not a one-component plasma in a theoretical sense [54, 55], liquid metallic hydrogen could be considered as a one-component plasma in the physical sense since the electrons were delocalized. But liquid metallic hydrogen would possess a true Bravais lattice and, perhaps, even liquid crystal behavior [151–153]. In this regard, Ashcroft had left open the possibility that liquid metallic hydrogen was a liquid crystal in 1981 and 1982 [36,

37]. Ashcroft had been unable to exclude the possibility when he advanced the two-component Fermi liquid [36, 37]. Liquid metallic hydrogen could well have an ordered lattice which oscillates between structural forms. The finding by Brovman et al. [61] that metallic hydrogen, much like graphite, could adopt a family of structures with nearly the same energy should be considered in this regard.

In any event, it would be difficult to conceive that conduction bands could truly exist without a lattice and the importance of the Bravais lattice in the formation of metals should not be dismissed. To a large extent, liquid metallic hydrogen should preserve the layered structure of solid metallic hydrogen as anticipated by Wigner and Huntington [19]. But the metallic character might be somewhat reduced in the low pressures of the photosphere. In fact, this could be advantageous for emission, better resembling graphite. Indeed, if the graphitic spectrum was to be produced, the structure and conductive properties of liquid metallic hydrogen should resemble graphite as much as possible. This is because graphite represents the premier laboratory model.

### 3.2 Metallic hydrogen and solar structure

Metallic hydrogen, with its critical temperatures in the thousands of degrees Kelvin [23–26], overcomes all concerns raised regarding a liquid Sun based on Andrews [20] and his findings in ordinary gases [3, 4]. A liquid Sun composed of metallic hydrogen benefits from elevated critical temperatures for liquefaction, permitting hydrogen to adopt a condensed state even within an object like the Sun. Along these lines, it is doubtful that metallic hydrogen could really become infinitely compressed. Such a scenario appears unlikely, as the presence of conduction bands involves quantum restrictions on the lattice. If the internuclear distances are not ideal, quantum mechanical conditions should fail to support conduction. Two boundary conditions should exist. If the interatomic distance becomes too large, the substance should become an insulator. Similarly, if the interatomic distance becomes too small, the crystal should collapse [59] and conduction cease. In this respect, it would be important to note that the Sun has dynamo action and maintains large magnetic fields. Both of these phenomena make destruction of the conducting lattice unlikely [141].

It remains unclear why condensed structures resist compression, but invoking fusion as a means of releasing the strain of compressions should be a viable solution. This is especially the case if compared to the destruction of the crystal [59] and the creation of fully degenerate matter [36, 37, 41, 46–48, 70]. Degeneracy removes all of the forces which lead to fusion. As such, it should be more reasonable to maintain the relative incompressibility of condensed matter. The Sun, after all, has a very ordinary density of  $1.4 \text{ g/cm}^3$  [141] and the same is true for the giant planets. Thus, Jeans' idea that the Sun represents a rotating liquid mass of reasonably constant density should not be dismissed [2]. Condensed mat-

ter and metallic hydrogen provide a framework for ordinary densities, even in light of enormous pressures. The reward of such an approach is threefold leading to: 1) a reasonable framework to generate the solar spectrum, 2) a decent ability to impart structure, and 3) a practical path towards fusion.

A Sun composed of metallic hydrogen provides an interesting model to explain sunspots and other structural elements. The photospheric material in this case might be considered as liquid metallic hydrogen where the lattice dimensions are relaxed at lowered pressures. Perhaps, the material exists much like graphite at the limits of conductive behavior. Conversely, within sunspots, pressures would be more elevated, and liquid metallic hydrogen might assume a more compact lattice, with increased metallic behavior. This would help account for the stronger magnetic fields observed within sunspots. As a result, scientists could be considering the conversion from a Type I lattice in the photosphere to a Type II lattice in the sunspots [141]. Such a scenario has great advantages in terms of simplicity.

Gases have always been an unsustainable building material for an object like the Sun. Gases know no surface and cannot, even momentarily, impart structure. Hence, one cannot be surprised to find that there is no physical evidence which supports a gaseous Sun, while ample evidence [141] has been revealed for its condensed state [20, 142–149]. In order to bring structure to the gas, astrophysics must depend on the action of magnetic fields. However, strong magnetic fields themselves are a property of condensed matter, not gases [141]. In order to maintain a gaseous Sun and impart it with structures, astrophysics must therefore have recourse to phenomena best produced by condensed matter.

A simple illustration of these issues can be focused on the understanding of solar prominences. Such objects appear as sheet-like structures in images captured by NASA's SOHO satellite (see Figure 2). In a Sun built from layered metallic hydrogen, it can be envisioned that a layer of material simply peeled away from the surface to form a prominence. In contrast, within a gaseous body, the creation of such overwhelming structures would remain difficult to explain, even with magnetic fields forming and maintaining these entities. Perhaps it would be more logical to presume that magnetic fields were simply associated with the presence of metallic hydrogen, whether on the surface of the Sun itself or within the prominences.

Moreover, the active photosphere and chromosphere supports structural features [154]. Prominences contain fine structure [155, 156], which would be easier to explain if a condensed solar model was adopted. For more than one century [157, p. 104], prominences have been known to emit continuous spectra in addition to the line spectra which characterize the quiescent state [158–161]. Eilnar Tandberg-Hanssen has long studied prominences and has provided an excellent review of the subject matter [160]. Like other solar physicists, because the Sun was considered as a gas, he viewed promi-

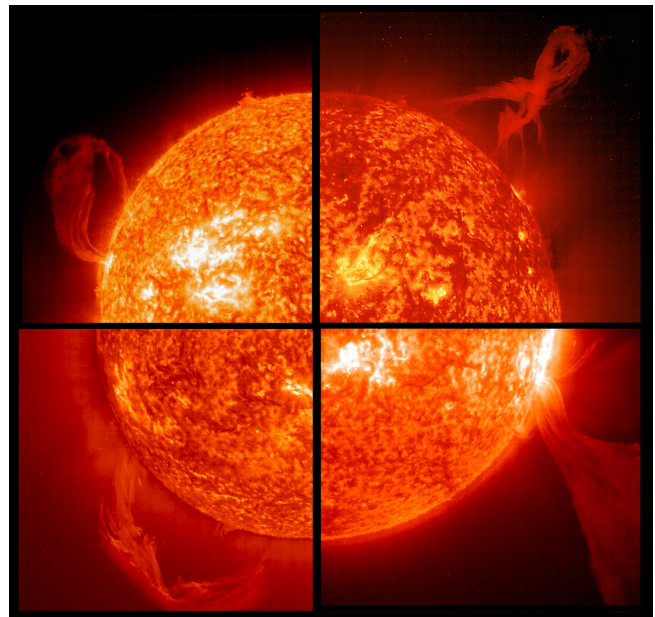


Fig. 2: Sheet like appearance of solar prominences. NASA describes the image as follows: “A collage of prominences, which are huge clouds of relatively cool dense plasma suspended in the Sun’s hot, thin corona. At times, they can erupt, escaping the Sun’s atmosphere. For all four images, emission in this spectral line of EIT 304Å shows the upper chromosphere at a temperature of about 60,000 degrees K. The hottest areas appear almost white, while the darker red areas indicate cooler temperatures. Going clockwise from the upper left, the images are from: 15 May 2001; 28 March 2000; 18 January 2000, and 2 February 2001”. Courtesy of SOHO/[Extreme ultraviolet Imaging Telescope (EIT)] consortium. SOHO is a project of international cooperation between ESA and NASA. <http://sohowww.nascom.nasa.gov/gallery/images/promquad.html> (accessed May 31, 2011).

nences as gaseous in nature [160]. Tandberg-Hanssen maintained that the continuous spectrum associated with some quiescent prominences was being generated by the scattering of light emitted from the photosphere [161]. This was because gaseous prominences could have no means of generating continuous spectra by themselves. They should have produced only line spectra. Conversely, if the Sun was made from condensed metallic hydrogen, the prominences could directly produce the continuous spectrum. No scattering would need to be invoked. If the density of the prominence material in some cases could not sustain a continuous spectrum, then only line spectra would be generated. Thus, as the prominence dissipated with time, it would be expected that the continuous spectrum might weaken or become absent. It is possible to consider that prominences are formed by layered metallic hydrogen separating from the inferior levels of the photosphere. A slight change in density could account for such actions reflecting an abrupt transformation from a more compact lattice to a less dense form. This hypothesis might explain why entire sheets of material appear to be ejected, some-

thing which would be difficult to understand otherwise.

It is possible, one further observation worth pondering involves a figure presented by Fortov in his new text [103]. The figure in question (Figure 7.7 in [103]) consists of a plot of the log of object diameter versus the log of mass. On such a plot, a straight line passes through all astrophysical objects within our solar system, from the smallest cometic dust, to the meteorites, to the comets, to the asteroids, to the satellites of planets, to the planets, and finally to the Sun [103, p. 192]. This plot provides another line of evidence that the Sun should be viewed as condensed matter. Every object on the graph can be considered as condensed. Uranus and Neptune are currently viewed as having metallosilicate cores and mantles of ices [103, p. 193]. Jupiter and Saturn are largely liquid metallic hydrogen or helium in either molecular or atomic form [103, p. 193]. As the only remaining fully gaseous object in the solar system, it may be reasonable to suggest that the Sun should not stand alone on such a graph.

#### 4 Conclusion

Relative to the Sun, a condensed approach brings interesting contrasts and dilemmas versus the gaseous models. The latter are endowed with tremendous mathematical flexibility [1, 2], but their physical relevance appears limited. Gases cannot by themselves impart structure and the solar spectrum is not easily explained in a gaseous framework [9]. The gaseous stars suffer from the stellar opacity problem [9]. Conversely, a liquid metallic hydrogen model imparts a wonderful ability to explain the origin of the solar spectrum relying on the layered structure held in common with graphite [141–149]. Metallic hydrogen possesses a very high critical temperature and can exist as condensed matter even on the solar surface accounting for many features of the Sun best characterized by material endowed with a lattice [141]. Most of the physical attributes of the Sun are more simply explained within the framework of a liquid model [141]. However, a condensed Sun is not as open to theoretical formulations. The advantages of a liquid Sun are now so numerous [20, 141–149] that it is difficult to conceive why the model was not proposed long ago. This speaks to the allure of the gaseous Sun and the mathematical beauty of the associated equations of state.

In closing, it should be highlighted that there is currently an effort to describe the Sun as “liquid-like” (e.g. [162]). In the end, the author believes that such terminology should be avoided. If the Sun is condensed, it should be viewed as liquid, not “liquid-like”. Even gases could be “liquid-like”. Such terms cannot be sufficient, since a real lattice is required for production of the solar thermal spectrum. No compromise can be made on this point for those who have studied thermal emission in real materials. “Liquid-like” might refer to anything from a gas, to a plasma, to fully degenerate matter, to supercritical fluid and none are necessarily endowed with a lattice. The contention of this work remains that the pho-

sphere of the Sun is liquid, with *true lattice structure and ordered interatomic distances*. The adoption of liquid metallic hydrogen as a solar constituent brings with it a wealth of possibilities in describing solar structures and understanding the solar spectrum. Central to this advancement, the lattice must remain the foremost element in all of condensed matter, whether here on Earth, within the Sun, and even, in the firmament of the stars.

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#### Dedication

This work is dedicated to my son, Christophe, and his wife, Lindsey.

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