SPECIAL REPORT

A High Temperature Liquid Plasma Model of the Sun*

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In this work, a liquid model of the Sun is presented wherein the entire solar mass is viewed as a high density/high energy plasma. This model challenges our current understanding of the densities associated with the internal layers of the Sun, advocating a relatively constant density, almost independent of radial position. The incompressible nature of liquids is advanced to prevent solar collapse from gravitational forces. The liquid plasma model of the Sun is a non-equilibrium approach, where nuclear reactions occur throughout the solar mass. The primary means of addressing internal heat transfer are convection and conduction. As a result of the convective processes on the solar surface, the liquid model brings into question the established temperature of the solar photosphere by highlighting a violation of Kirchhoff's law of thermal emission. Along these lines, the model also emphasizes that radiative emission is a surface phenomenon. Evidence that the Sun is a high density/high energy plasma is based on our knowledge of Planckian thermal emission and condensed matter, including the existence of pressure ionization and liquid metallic hydrogen at high temperatures and pressures. Prior to introducing the liquid plasma model, the historic and scientific justifications for the gaseous model of the Sun are reviewed and the gaseous equations of state are also discussed.

1 Introduction

1.1 Historical perspective

The modern theory of the Sun [1–5] can be traced back to 1870 when Lane published his discussion of the gaseous nature of this sphere [6]. At the time, of course, one could have had little idea about whether or not the Sun was really a gas. Nonetheless, Eddington [7, 8] would build on these early ideas. He believed that the laws of physics and thermodynamics could be used to deduce the internal structure of the Sun without any experimental verification [7, 8]. In 1926, he would speak hypothetically about being able to live on an isolated planet completely surrounded by clouds. Under these conditions, he still thought he could analyze the Sun without any further knowledge than its mass, its size, and the laws of physics [7, 8]. It was in this spirit that Eddington set out to expand on Lane's model of the Sun.

Eddington, more than any other person, has shaped our current understanding of the Sun. Consequently, it is fitting that a review of the current model be centered on his contributions. Some may argue that we have moved well beyond Eddington in our reasoning. However, Eddington has set a scientific course for the study of the Sun which has remained essentially unchallenged for nearly eighty years. Every new finding has been rationalized within the context of the gaseous model and no alternative starting point exists. Yet, the gaseous model is characterized by inconsistencies and physical interpretations which cannot be easily explained based on laboratory findings.

As such, the hot liquid plasma model is presented herein. The new model provides a scientific alternative in solar analysis. It is based on a reevaluation of the internal processes and structures associated with the gaseous model. The liquid model advocates a much higher photospheric density and temperature, thereby directly invoking the physics associated with high energy/high density plasmas. In addition, it completely eliminates Eddington's radiative zone and brings into question the existence of the current very high density ($150\,\mathrm{g/cm^3}$) core.

1.2 Eddington's polytrope and solar collapse

Eddington began his analysis of the Sun by assuming that Lane's gaseous model was correct [6]. The Sun was treated as a simple polytrope [3], wherein a direct relationship existed between pressure, P, and density, ρ [9]. Eddington's polytrope was of the form $\rho = K_1 P^{1/\gamma}$, where K_1 is a constant and the polytrope exponent, γ, was set to $\frac{4}{3}$. Under these conditions, the central density of the Sun was $\sim$54 times the average density and the central pressure was $1.24\times10^7\mathrm{dyn/cm^2}$ [3]. By having recourse to the ideal gas law and fully radiative heat transfer, Eddington deduced a central core temperature of 1.2×10^7 [3, 7, 8]. Today, this remains the range for

*This work was posted as arXiv: astro-ph/0410075, October 4, 2004. The discussion relative to the internal constitution of the stars in the introduction places a heavy emphasis on the writings of A. S. Eddington. The author wishes to also highlight the work of Nikolai Kozyrev on "Sources of Stellar Energy and the Theory of Internal Constitution of Stars" translated from the original Russian dissertation in Progress in Physics 2005, v. 3, 61–99. Kozyrev's excellent work provides additional important contributions and insight relative to the gaseous models of the stars.

the internal temperature of the Sun $\sim 1.5\times 10^7$ K (e.g., [2–5]).

At the same time, Eddington realized that a gaseous Sun should collapse on itself [7, 8]. Specifically, the great forces of gravity should compress the mass into a much smaller sphere. Like his predecessors, Eddington pondered on why the gaseous Sun did not collapse. He solved the problem by invoking outward radiation pressure originating from the central core. Reasoning that the inside of the Sun was generating light, Eddington thought that these photons could produce the outward pressure sought. Since light quanta clearly possessed momentum, this "light pressure" kept the gaseous Sun from collapsing [7, 8]. Consequently, Eddington postulated that the inner portion of the Sun produced photons. He then deduced that these individual light quanta would sooner or later collide with a gas ion or atom and propel it against the forces of the Sun's gravity. The region of the Sun where this occurs was called the radiative zone. It remains a central portion of solar theory to this day. Importantly, however, this zone exists primarily as a result of Eddington's reasoning. For stars on the order of the solar mass, it is currently held that internal radiation pressure is not as significant as Eddington had advanced. A radiative zone is still present, but the effects of radiation pressure are downplayed. Rather, modern theory holds that the Sun is prevented from collapse due to electron gas pressure [3]. The radiation zone is still present in the Sun, but radiation pressure becomes dominating only for heavy stars on the order of 10 solar masses [3].

The modern theory of the Sun also makes use of a significant convective zone, which extends throughout the outer envelope. Convective zones extend to deeper levels as stellar masses decrease, such that small stars can be viewed as fully convective. Conversely, for stars with masses larger than the Sun, it is the core of the star which is convective [3]. The extent of the convective zone then grows towards the envelope of the star, as mass increases. Eventually, the convective zone extends to 70% of the stellar radius in stars on the order of 50 solar masses. In this case, the envelope is radiative in nature. Supermassive stars, like the smallest stars, finally become fully convective [3].

1.3 Photon shifts and opacity considerations

While Eddington believed that he properly understood a key aspect of solar structure with the creation of the radiative zone, he also wanted to know exactly how many photons the Sun could produce to support this hypothesis. Not sufficiently considering Kirchhoff's work [10], Eddington incorrectly believed that Stefan's law was universal [11]. He then applied this law to estimating the amount of photons produced. Given the dimensions involved, and the temperatures hypothesized for the solar interior, this photon output would have been tremendous. Eddington also recognized that a blackbody at millions of degrees should produce its photons at X-ray frequencies [12].

Thus, Eddington had deduced that the internal portion of the Sun was at 1.2×10^7 K. This resulted in the generation of photons at X-ray frequencies. At the same time, Langley had previously measured the solar spectrum and was setting the temperature of the photosphere at $\sim$6,000 K. In order to resolve this dilemma, Eddington simply stated that when photons are emitted, they are initially produced at X-ray frequencies [7, 8]. However, as these photons are scattered or absorbed in the collisions associated with radiation pressure, they slowly lose some of their energy. In this manner, after millions of years and many collisions, the photons emerge from the Sun's photosphere shifted to the visible region. Only a very small fraction of the total photons in the radiative zone manage to escape at any time. According to Eddington, the radiative zone is acting as a very slowly-leaking "sieve" [7, 8]. The photons traveling through this zone were thought to experience free-free, bound-free, and bound-bound absorptions along with scattering [2, 3]. The entire process would result in producing a certain opacity in the solar interior.

Eddington's model requires that these processes (scattering and free-free, bound-free, and bound-bound transitions) result in a final opacity which becomes Planckian in appearance. This was needed in order to permit the proper absorption and reemission of all photons, at all frequencies, and at all levels of the solar interior. In fact, the "opacity problem" constitutes one of the great weaknesses in a model of an interiorly radiating object. The issue is so complex that Rosseland mean opacities [2, 3], which are frequency independent, are often utilized. Such a procedure completely sidesteps the central issue. It is always possible to build an absorption or opacity profile given enough elements and weighted physical mechanisms (scattering and free-free, bound-free, and bound-bound transitions). However, the requirement that these profiles continually and systematically change throughout the interior of the Sun, while remaining blackbody in nature and yielding the proper frequency dependence, does not appeal either to simplicity or objective reality. In fact, the generation of a Planckian spectrum requires a Planckian process [10]. Such a spectrum can never be generated from the sum of many non-Planckian processes. Once again, the current gaseous model has serious shortcomings in the manner in which solar thermal emission is explained.

Unfortunately, for Langley and Eddington, the situation is even more complex than they initially believed [10]. The Sun is not in thermal equilibrium with an enclosure. In reality, enormous convection currents are present both on the solar surface and within the solar interior. These convection currents can easily act to violate the integrity of Eddington's layers. Therefore, the interior of the Sun represents a significant deviation of the requirements set forth in Kirchhoff's law (equilibrium with a perfectly absorbing enclosure [10]).

The application of the laws of thermal emission [11–13] to the Sun constitutes a violation of thermodynamic principles.

1.4 Coronal heating

Beyond Eddington, the next big step in solar theory came in the 1950's when scientists were beginning to obtain interesting data from the solar corona. It was observed that the corona possessed, within it, highly ionized ions produced at temperatures well in excess of 1.0×10^6 K [14]. The width of Lyman-α lines further demonstrates that temperatures in the corona ranged from 2.6×10^6 to 1.2×10^6 K at 1.5 and 4 solar radii, respectively [14]. These findings of very hot temperatures in the corona presented a problem for solar theory. A temperature within the corona ($>1.0\times10^6$ K) which exceeded that of the photosphere ($\sim$6,000 K) indicated a violation of the 2nd law of thermodynamics. That is, heat could not be coming from inside the Sun to heat the corona, while remaining incapable of heating the photosphere. Thus, if the photosphere was really at $\sim$6,000 K, there must be found an alternative means to heat the corona. It has now been widely accepted that the local heating in the corona occurs as a result of a process involving the flow of ions through the magnetic fields of the Sun [5].

1.5 Helioseismology

Currently, much of the support for the gaseous models of the Sun arises from helioseismology [15] or the study of solar quakes on the surface of the Sun. It is claimed that excellent agreement exists between the theoretical models and the actual seismological data. In large part, this is a direct measure of the gaseous model's ability to permit variations in density, pressure, temperature, composition, depth and opacity values throughout the solar interior. Given enough variables, good agreement with experimental data can be achieved. Nonetheless, it is interesting that despite phenomenal agreement between theory and experiment, the theoretical fits completely break down in the outer 5% of the solar disk [16]. This is not surprising since the solar photosphere currently has a hypothetical density which is lower than that present within the best vacuums achieved on earth. Since acoustic waves cannot propagate in a vacuum, it is not surprising that the theorists are unable to fit the exterior the Sun [16]. Yet, this is precisely that region of the Sun from which all the data is being collected.

1.6 Summary of the gaseous models

Eddington was concerned with the great problems of solar theory: (1) how to prevent the gaseous Sun from collapsing on itself, (2) how to set the internal temperature, and finally, (3) how to shift the frequency of photons produced at X-ray frequencies to the observed visible region. He solved these problems by invoking radiation pressure and the laws of thermal radiation. The creation of the radiative zone resulted in tremendous radiation pressure within the Sun. For Eddington, this radiation pressure exactly balanced with the gravitational forces and resulted in one of the earliest gaseous models of the Sun. The gaseous Sun had been prevented from collapsing and photons were produced appropriately in the visible range. The interior of Eddington's gaseous Sun was at very high temperatures estimated at millions of degrees. Yet, this extremely hot object was surrounded by a very cool photosphere, only $\sim$1,000 kilometers thick and at a temperature of just $\sim$6,000 K.

Regrettably, the idea that photons become the primary means of striving for internal thermal equilibrium in a star is not in accordance with our knowledge of the thermal behavior of objects [17, 18]. Rather, for all other objects, internal thermal equilibrium is achieved through thermal convection and conduction [17, 18]. In contrast, radiative heat transfer enables an object to dissipate heat and reach thermal equilibrium with the outside world (e.g., [17–20]). Astrophysical treatments of thermal radiation [21–23] minimize these arguments and, like all other textbooks, fail to state the underlying cause of the radiation [10].

Under the gaseous model, the internal temperature of the stars continues to rise, despite the fact that photons are being emitted. Stellar compression becomes an uncontrollable process. In order to cool the stars, photons must be injected into their interior. Eddington best summarizes this violation of thermodynamics and the dilemma it creates for all gaseous models [2]: "I do not see how a star which has once got into this compressed condition is ever going to get out of it. So far as we know, the close packing of matter is only possible so long as the temperature is great enough to ionize the material. When a star cools down and regains the normal density ordinarily associated with solids, it must expand and do work against gravity... Imagine a body continually losing heat but with insufficient energy to grow cold!"

Note that the second sentence in this quote is the essence of the problem. Eddington has ignored the consequences of van der Waals' equation and the incompressibility of the liquid state. He constructs a model wherein the known behavior of the condensed states of matter on Earth is discarded. The gaseous model requires production of photons at high frequency (X-ray, gamma) within the core of the Sun, which are then shifted to the visible region [7, 8]. However, the shifting of a blackbody radiation spectrum produced at one Wien's displacement temperature to another is without experimental verification. The current complexity associated with the calculations of stellar opacities hint at the unreasonableness of such conjectures. A Planckian process is required to generate a Planckian spectrum [10]. However, the gaseous stellar models are incapable of yielding a Planckian process, since they "a priori" exclude the existence of condensed matter and of a photospheric lattice.

Since modern stellar theory remains based on gaseous models, the analytical equations of state [24, 25] are founded on the assumption that the Sun can be treated as a compressible gas. The emergence of numerical solutions [24, 25], including such refinements as the addition of partial ionization and Debye-Huckle theory, alters nothing of the underlying framework. Currently, the density of the central core is thought to be $\sim$150 g/cm^3, while that of the lower photosphere is on the order of 10^{-7} g/cm^3 [26]. Neither of the numbers, of course, can be verified by direct experimentation. The modern Sun and all of the main sequence stars remain viewed as compressible gases without lattice structure. Only the details of the local densities, temperatures, composition, opacities, radiative emission, and convection currents, are altered. For stars near the solar mass, it is advanced that electron gas pressure now acts to prevent solar collapse [2, 3]. This is true even though the mathematical analysis of electron gas pressure relies on the use of real or imaginary rigid surfaces [2] which can never exist within the stars. The stars are quite unlike the Earth's atmosphere, since the latter is resting on a distinct surface. As a result, electron gas pressure is unlikely to prevent solar collapse since the gaseous models cannot invoke rigid surfaces while maintaining the integrity of the gaseous state. Irrespective of such arguments, one cannot discount that Eddington's radiative pressure remains extremely important for the gaseous theories, especially in the more massive stars.

2 Liquids and gases

The flow of material on the surface of the Sun (e.g., [2, 3, 5, 27]) makes both the gaseous and liquid states prime candidates for discussing the nature of the photosphere. Unfortunately, the distinction between the gaseous and liquid state is often difficult to establish. Gases and liquids are often viewed simply as fluids with no further distinction, but differences do exists. Liquids are characterized by their relatively high densities and by their surface tensions [28–31]. They also have real internal structure and can be seen as possessing "fleeting lattices" with short range order [28–31]. Gases, on the other hand, fail to display a surface and have no internal structure. Liquids can boil and thereby produce the gaseous state. Gases cannot boil. Liquids, unlike gases, are essentially incompressible [28–31]. In conjunction with solids, liquids correspond to the densest form of matter detected in the laboratory. In this regard, a significant increase in the density of the liquid state would require changes within the atomic nucleus itself, as the atomic number is increased. Large changes in pressure, by themselves, are incapable of significantly altering, by orders of magnitude, the density of the liquid state [28–32]. This is quite unlike the behavior of highly compressible gases, as reflected in the ideal gas law [28, 32].

Although their exact thermal behavior remains extremely poorly documented [20], liquids can also emit continuous radiation by virtue of their continuous physical nature. Mostly liquid metals have been studied [20], and little is known about the thermal properties of nonmetallic liquids. Studies with water at microwave frequencies only add to the complexity of the problem. For instance, it is easy to establish that the oceans are not blackbody in nature. At the Nadir angle (view is normal to the water surface), the sea surface appears with a brightness temperature of less than 100 K at 1.4 GHz [33]. In addition, the brightness temperature of salt water can be relatively independent of actual temperature [33]. When larger observation angles are used, the brightness temperature of sea water rapidly rises [33], although it is always short of the correct value. Since the brightness temperature of salt water is so highly dependent on salinity, it is clear that an understanding of thermal emission processes in liquids is complex [33].

Liquids unlike gases, can support transverse wave propagation as reflected by the presence of weak phonons. The behavior of phonons has been examined in liquid helium [34]. Phonons have also been studied in superionic conductors which are characterized by liquid-like mobility of one of the ionic species [35]. The study of phonons in solids and liquids usually involves neutron scattering experiments (e.g., [34–38]). As for gases, they are unable to support transverse phonons. Neutron scattering experiments, aimed at determining structure in solids and liquids, do not exist as related to gases. Acoustic experiments with gases involve the study of longitudinal waves.

Differences clearly exist between the liquid and gaseous states [28–32]. As such, these two phases are not simply a continuum of one another, as is often assumed. Unlike the ideal gas law, the equations used in the analysis of liquids tend to be complex. Herein lies a major difficulty in advancing a liquid model of the Sun. Nonetheless, in order to discern the relative merits of a gaseous versus a liquid model, solar observations themselves, not mathematical simplicity, must guide the theorist. Thus, solar behavior must be reexamined and the most critical data remains the nature of the solar spectrum.

3 Thermal emission

3.1 Local thermal equilibrium

Modern solar models make extensive use of local thermal equilibrium in order to simplify the analysis of stellar structure [1–3]. Nonetheless, plasmas are well-known to support electronic and ionic temperatures which are not at equilibrium. Recent work [10] highlights that the Sun cannot meet the requirements for a blackbody, as set down by Kirchhoff, for the simple reason that it is not in thermal equilibrium with a perfectly absorbing enclosure [9, 19]. The analysis of the Sun is a non equilibrium problem, as manifested by the presence of convection currents, solar eruptions, solar wind, and emission of light without confinement. All transport processes, including convection, are non equilibrium processes [29]. Planck has previously warned that the presence of convection currents is sufficient to completely destroy local thermal equilibrium arguments [39]. That local thermal equilibrium does not exist is of profound consequence to any theorist, since simplifying assumptions are removed. Despite this complication, the lack of local thermal equilibrium for the interior of the Sun is consistent with observations of non-equilibrium in the solar corona, where significantly different electronic and ionic temperatures have been detected [40]. Nonequilibrium within the corona may well be a manifestation of the state of the entire star. The photosphere is clearly not in thermal equilibrium with an enclosure (e.g., [9, 19]). Furthermore, it possesses convection currents rendering it unsuitable as a candidate in blackbody radiation [10, 39].

As such, it was improper for Langley [41, 42] to set a temperature of the photosphere at $\sim$6,000 K, simply because a thermal emission spectrum was present. The proper assignment of a temperature based on thermal arguments depends on the known presence of a perfectly absorbing enclosure, namely a solid graphite box [10]. Langley's use of Planckian arguments [11–13, 39, 41, 42] to set a temperature for the photosphere constitutes a violation of Kirchhoff's law of thermal emission [10, 43, 44]. The presence of local thermal equilibrium is central to the assignment of any temperature based on thermodynamic arguments [10, 39].

Eddington's need to shift the solar spectrum to lower frequencies requires that gaseous atom or ionic hydrogen or helium be able to both absorb and re-emit a blackbody spectrum. This creates essentially impossible constraints on the opacities needed inside the Sun, especially given that only scattering and free-free, bound-free, and bound-bound transitions can be considered. None of these processes are individually capable of providing the proper Planckian behavior. Only complex summations, involving many discontinuous phenomena, can lead to the required continuous opacities. The problem is so complicated that the entire task is often sidestepped. Rosseland mean opacities, which are frequency independent, are often used to deal with this issue [2, 3]. However, the use of Rosseland mean opacities is unsatisfactory. The requirements set on opacity by Eddington for the radiative zone are contrary to our knowledge of thermal emission spectra in either gases or plasmas (e.g., [45, 46]). As mentioned above, the production of a Planckian spectrum must involve a Planckian process and not the summation of many non-Planckian spectra. The "opacity problem" represents the greatest single warning sign that a gaseous model of the stars cannot be correct.

3.2 Thermal emission in liquids

Like solids, liquids possess a lattice, although this structure is often fleeting (e.g., [29–31]). This is manifested in the presence of Brownian motion within the liquid. Thus, in a liquid, not all of the energy is contained within the vibrational degrees of freedom of the lattice. This directly accounts for the inability to obtain a complete monitoring of the energy distribution within a liquid based only on its thermal emission. Indeed, most of the nonnuclear energy in a liquid may well be contained in the translational and rotational degrees of freedom. The ability of a liquid to store energy in translational degrees of freedom certainly leaves less energy than expected at a given temperature in the vibrational degrees of freedom. This is a problem for a Planckian oscillator model which does not consider translational and rotational energy [13]. As a result, it is hypothesized that the presence of translational and rotation degrees of freedom can cause a liquid to report a much lower temperature than its real temperature, when the laws of thermal emission [11–13] are utilized to monitor its emission spectrum. As mentioned above, the idea that radiation pressure is present within the Sun is not in accordance with the known mechanisms of heat transfer within objects [17]. There is no experimental basis on Earth for invoking that an object can strive for internal thermal equilibrium using thermal radiation. Conduction and convection dominate heat transfer within objects [17]. A liquid model is more apt to deal with heat transfer through these two mechanisms, since it provides increased density, facilitating both more efficient conduction and convection.

4 The liquid model of the Sun

A central tenant of the liquid plasma model is that the density within the solar interior is nearly constant. It has been well established that liquids are essentially incompressible and that their compressibility decreases quite dramatically as pressure is increased [28–31]. Therefore, in the liquid plasma model, the liquid framework is regarded as incompressible and the issue of solar collapse never arises.

There are numerous arguments supporting a liquid plasma model. These include: (1) the continuous nature of the emission spectrum, (2) the average density of the solar mass, (3) the gentle oblateness of the solar sphere, (4) the presence of a distinct solar surface, (5) the presence of surface gravity waves and helioseimology studies, (6) the known existence of hydrogen on Earth in the liquid metallic plasma state at high pressures and temperatures, (7) the existence of solar boiling, and (8) the presence of the corona, transition zone, and chromosphere. In addition, the liquid plasma model provides for the mixing of solar materials, resulting in important evolutionary consequences for the stars. At the same time, the liquid plasma model addresses the issue of coronal heating and helps to resolve the thermodynamic problems in this area.

4.1 Solar emission

The solar spectrum deviates from a blackbody in appearance in that the high frequency region is distorted. This finding urges caution in setting a temperature to the photosphere using Planckian arguments. Based on experimental work in thermal emission, the photosphere cannot be a low density gas or plasma. Gases and plasmas, outside the confines of an enclosure, simply cannot produce a Planckian-shaped thermal emission profile as seen in the visible light of the photosphere. These issues have previously been discussed in detail [10]. The production of a continuous blackbody spectrum is incongruent with an origin from a low density source. Experimental blackbodies are exclusively solids (e.g., [47–51]).

The concept that the photosphere, as an "opaque gas", is able to emit as a blackbody is not supportable. Without exception, the approach to opaque behavior by gases or plasmas is accompanied by an increase in density and pressure. In contrast, the density advanced for the photosphere is on the order of 10^{-7} g/cm^3 [26]. No gas has been demonstrated to approach optically opaque behavior at such densities. Thus, while it is believed that, in the limit of high pressures, some gases can become opaque, it is more likely that they simply become liquids. The idea, that free gases or plasmas can become optically opaque [45, 46] and can follow Kirchhoff's law, ignores the known observation that such behavior cannot be produced outside the confines of a solid enclosure [10]. Studies in which gases or plasmas approach optically opaque behavior are always confined to enclosures at high pressure. For instance, note that the Tokamak reactors used in plasma physics are often lined with graphite [52]. This situation is exactly analogous to the experimental conditions under which Kirchhoff's law was developed [10]. Real blackbodies always involve enclosures which are either made from graphite [49, 50] or lined with soot (graphite) containing paints [47, 48, 51]. As a result, it is not surprising that, in the limit of high pressure within the confines of a Tokamak, the approach to blackbody behavior can be reached [10, 45, 52]. In any case, such a setting is completely unlike the surface of the Sun, wherein a solid enclosure is not present.

Unfortunately, it appears that the exact physical mechanism for producing a blackbody radiation spectrum has not been defined by the scientific community [10]. Nonetheless, thermal radiation must be linked to one of the simplest processes within matter, namely atomic or nuclear vibrations within the confines of a lattice structure [10]. This is reminiscent of Planck and his oscillators [13, 39]. In the final analysis, whatever physical mechanism is invoked for blackbody radiation, it should be independent of nuclear reactions, since all solids are able to emit some form of continuous thermal radiation [20].

If it is true that the frequency and amount of photons released by an object is related only to the amount of energy in the vibrational degrees of freedom of the lattice [10], it is easy to see why Langley believed that the photosphere was at a temperature of only ∼6,000 K. Note the well established convection currents on the surface of the Sun (e.g., [4, 5, 27]). These currents contain translational energy which is not readily available for thermal emission. However, during flares and other eruptions, it is well-known that X-rays can be released from the solar surface. These X-rays reveal brightness temperatures of millions of degrees (e.g., [4, 5, 27]). In this case, the translational energy of the liquid envelope is being converted to thermal photons in a manner revealing a stored energy bath with temperatures well in excess of 6,000 K. Such X-ray findings from the solar surface were not at the disposal of Langley when he set the photospheric temperature in the mid-1800's [41, 42].

It is therefore hypothesized that a liquid can instantaneously lower the total output of photons, at a given temperature, and release them at a frequency significantly lower than what would be predicted from their real energy content and temperature. This is simply an energy partition problem which arises in the presence of convection currents. The sea surface temperature at microwave frequencies discussed above hints to this behavior.

A liquid photosphere with a temperature of $\sim 7.0 \times 10^6$ K could be generating photons not at X-ray frequencies, as expected, but rather in the visible range. This occurs because the photosphere has convection. Since most of the energy of the photosphere is tied up in the translational (or rotational) degrees of freedom and its associated convection, it is simply not available for the generation of thermal photons. However, this energy can become available during a solar eruption which reveals that the real temperatures of the solar photosphere are well in excess of 6,000 K. The liquid phase provides a means of producing a thermal radiation curve for the Sun at a lower apparent temperature than its real temperature. All that is required is to lower the force constant in Planck's oscillators. In this regard, note that an oscillator representing a van der Waals interaction would have a much weaker force constant than one representing covalent bonds.

This hypothesis remedies the problem with Langley's temperature for the photosphere. Setting a real temperature of the photosphere at $\sim 7.0 \times 10^6$ K permits the free flow of heat throughout the outer layers of the Sun. The 2nd law of thermodynamics is no longer violated. Photons do not take millions of years to leave the Sun [7, 8]. Rather, they are solely produced and released at the photosphere using a mechanism common to all condensed objects on Earth. The radiative zone is eliminated and the need to shift high energy photons removed.

4.2 Solar densities

The Sun has an average density ($\sim$1.4 g/cm^3) which can easily support the liquid plasma model. Indeed, the gaseous model applies extremes of density which are not easily justified (150 g/cm^3 for the core and 10^{-7} g/cm^3 for the photosphere [26]). Instead, the liquid plasma model simply requires a very ordinary density throughout the body of the Sun.

The presence of a liquid structure eliminates the need for radiation pressure to prevent the Sun from collapsing on itself. The liquid alone can support the upper layers. For the gaseous models, solar collapse is prevented by having recourse to internal radiation and electron gas pressure both of which are without sound experimental justification. In a liquid model, the problem of solar collapse is simply addressed by invoking the incompressibility of liquids. Interestingly, the Jovian planets all have densities consistent with the liquid state (Jupiter: $\sim$1.33 g/cm^3; Saturn: 0.7 g/cm^3, Uranus: 1.30 g/cm^3, and Neptune 1.76 g/cm^3). For a gaseous model of the Sun, it would have been convenient if at least one of these planets had an average density consistent with the sparse gaseous states (e.g., 10^{-4}–10^{-7} g/cm^3) currently proposed for the convective zone and the photosphere (10^{-7} g/cm^3) [26]. Note that the latter density approaches the value of a reasonably good vacuum in the laboratory. The Jovian planets have high average densities (0.7–1.76 g/cm^3) despite their small size and masses relative to the Sun. As such, the sparse densities currently assigned to the outer layers of the Sun are incongruent with the high average densities of the Jovian planets, especially given that these are also constituted primarily of hydrogen and helium. This leads us to deduce that the Jovian planets are also condensed in nature and that they may have significant liquid components, both on their surface or in their interior.

The densities of materials on Earth is determined primarily by the atomic number and by the packing of the crystal lattice. As far as the existence of a solar core is concerned, there is no experimental evidence for reaching densities of $\sim$150 g/cm^3 using a hydrogen and helium framework. Without exception, high densities involve high atomic numbers. Mathematical arguments to the contrary are based exclusively on the collapse of a gaseous model of the Sun and are without experimental justification in the laboratory. Once again, the Jovian planets do not support the idea of a dense core given that they, like the Sun, possess average densities on the order of 1 g/cm^3. Unlike the gaseous model, which must have a dense core to compensate for its sparse convective zone and photosphere, the liquid model does not necessitate the presence of a dense core. Such a core may or may not be present. However, laboratory observations, with the densities achievable using helium and hydrogen, suggest that it cannot exist.

4.3 The solar surface

The Sun has a reasonably distinct surface. This point has recently been emphasized by images obtained with the Swedish Solar Telescope [53, 54]. These images reveal that the solar surface is not simply composed of clouds hovering about, but has a clear three-dimensional appearance which evolves in a manner reflecting "solar hills, valleys, and canyons" [53, 54]. Solar granulations appear to be "puffy hills billowing upwards" [53, 54]. This represents strong evidence that the solar surface is dense and has surface tension, a clear property of the liquid state.

Gases are not characterized as possessing surfaces. This accounts for the extension of the corona (which is a gaseous plasma) for millions of miles beyond the Sun without a distinct boundary. The hot liquid plasma model of the Sun helps to explain the distinct nature of the solar surface, wherein a transition is observed between the photospheric density and that of the solar atmosphere. The chromosphere is reminiscent of the critical opalescence of a gas in the vicinity of criticality [30], and the existence of such a zone is highly supportive of a liquid model. Furthermore, the surface nature of the Sun is well visualized using imaging methods, including Doppler techniques [40, 53–55]. The surface tension of a liquid provides an elegant explanation for the distinct nature of the solar surface, which is not easily available within the context of a gaseous model.

4.4 The solar oblateness

Solar oblateness, ε is a dimensionless quantity

$$\varepsilon = (R_E - R_P)/R_E$$

obtained by comparing the values of the equatorial (R_E) and the polar radii (R_P). The existence of gentle solar oblateness has been recognized for nearly thirty years. Initial values measured by Dicke and Goldberg [56] were as large as $4.51 \pm 0.34 \times 10^{-5}$. More modern values are slightly less pronounced at 8.77×10^{-6} [57]. While such oblateness appears extremely small and negligible at first glance, it provides a dilemma for the gaseous models.

In order to properly analyze solar oblateness, it is necessary to have recourse to models of rigid body rotation [57]. In this regard, the theory of rotating liquid masses is well developed and extensive discussions can be found in Littleton's classic text [58]. In addressing the oblateness of the Sun [56, 57], the density of this rotating sphere is maintained as essentially constant throughout the solar radius [57]. The model used is described by an analytical form and is able to account both for the rotation of the convective zone and for the differential rotation of the inner Sun [57]. Importantly, the rigid body model [57, 58] is not dependent on the solar density. This is in sharp contrast with the well-known equations of state for stellar structure [2, 3, 24, 25]. The latter, of course, possess a strong interdependence of density and pressure with radial distance.

Beyond the Sun, other stars also possess varying degrees of oblateness. The most significant of these, at present, appears to be the southern star Achernar, a hot B-type star with a mass currently estimated at six times the mass of the Sun. The oblateness of this star is caused by rapid rotation and is a stunning 1.56 ± 0.05 [59]. Achernar's oblateness is so severe that it is completely incompatible with the Roche model, wherein the mass of a star is concentrated near the stellar interior [3, 59]. The oblateness of the Sun and some stars provides significant support for the liquid plasma model of the Sun and a tremendous hurdle for the gaseous models.

4.5 Surface gravity waves and helioseismology

A liquid plasma model of the Sun is also best suited to the study of helioseismology (e.g., [15]). This is because terrestrial observations of this nature are exclusively limited to the oceans and continents, materials with high densities. It would be incongruent to advance such studies for the terrestrial atmosphere. Yet, the density of the terrestrial atmosphere at sea level is $\sim$1,000 times greater than the density proposed by the gaseous models for the solar surface.

A solar seismic wave [55] was produced in association with a flare on the surface of the Sun on 9 July 1996 [40]. Such a Sun quake demonstrates that the solar surface is fully able to sustain a surface gravity (or transverse) wave extending over millions of meters. These are described as "resembling ripples from a pebble thrown on a pond" [40, 55]. The ability to sustain such a wave requires the presence of very dense materials. Indeed, sparse gases are completely unable to sustain surface gravity waves as these require the presence of condensed matter. Such Sun quakes provide powerful evidence that the solar surface is comprised of a material attaining a very high density. While a gaseous model can easily deal with longitudinal acoustic waves within the solar interior, the same cannot be said for its ability to deal with the presence of a surface gravity (or transverse) seismic wave on the surface. Once again, it is clear that the current theoretical fits fail at the solar surface [16].

The ability to conduct helioseismology studies on the Sun (e.g., [15, 40, 55]) is incongruent with a true gaseous nature. While sparse gases and plasmas are able to sustain longitudinal acoustic waves, they are unable to support transverse seismic waves. Terrestrial seismology is limited to the study of the oceans and the continents. The Earth's atmosphere is much too thin to enable such studies. The liquid plasma model of the Sun is better suited to explain the presence of seismologic activity on the surface of the Sun.

4.6 Hydrogen as a liquid metal plasma

At atmospheric temperatures and pressures, hydrogen exists as a diatomic molecular gas. At low temperatures, condensed molecular hydrogen is an insulator with a relatively wide band gap ($Eg = 15$ eV). It is noteworthy that when hydrogen is shock-compressed, and thereby submitted to extreme pressures ($>$140 GPa) and temperatures (3000 K), it is able to under pressure ionization [60]. In so doing, hydrogen assumes a liquid metallic state, as revealed by its greatly increased conductivity [60]. Similar results hold for deuterium, although the insulator to metal transition occurs under less intense conditions [61]. The existence of liquid metallic hydrogen plasmas is of tremendous importance in astrophysics and has direct consequences on the structures of Jupiter and Saturn [30, 60]. However, these findings have not been extended to the Sun, even though the Sun is able to subject hydrogen to higher temperatures and pressures.

In any case, dense liquid metallic plasmas of hydrogen provide very interesting possibilities in stellar structure which should be considered by the plasma physicist. That liquid metallic hydrogen is known to exist, directly implies that the Sun can be treated as a liquid metal plasma. The equations of magnetohydrodynamics [62] become relevant not only in the corona, but also within the entire Sun. This has tremendous consequences for stellar and plasma physics, further implying that the gaseous equations of state must be abandoned. A liquid metal plasma model of the Sun implies (1) high, nearly constant, densities, (2) a rigid body problem, and (3) the use of continuous equations of state and magnetohydrodynamics [45, 62, 63].

Liquid metallic hydrogen may also present interesting lattice characteristics to the theorist. Calculations reveal that metallic hydrogen displays an important dependence of potential energy and interatomic distance [63]. For instance, in liquid sodium, the potential well for interionic bonding has a single minimum. In contrast, for metallic hydrogen, the spatial inhomogeneity of the electron density is so important that higher order perturbations must be considered. This leads to potential functions with groups of minima rather than a single minimum [63]. These potential energy functions have important pressure dependences [63]. As a result, metallic hydrogen should be able to assume a variety of lattice structures, with varying interatomic distances, in a manner which depends primarily on temperature and pressure. It is likely that future extensions of these findings to liquid metallic hydrogen will enable the calculation of various possible structures within the liquid phase itself. This may be important in helping us understand the nature of Sunspots and stellar luminosities, particularly when magnetic field effects are added to the problem.

4.7 The displacement of solar mass

All current gaseous models of the Sun make the assumption that densities are gradually changing between the convection zone, photosphere, chromosphere, transition zone, and corona. In these models, only the opacity changes at the photosphere, in order to create the "illusion" of a surface. Nonetheless, it is clear that a phase transition is occurring between the photosphere and the chromosphere/transition zone/corona.

In the photosphere, both upward and downward radial flows are observed. These are also associated with transverse flows parallel to the surface itself. The motion of Sunspots also reminds us that transverse flows are an important component of mass displacement in the photosphere. In sharp contrast, flows in the corona are clearly radial in nature (ignoring the effects of solar eruptions and flares). The solar wind is a manifestation of these radially pronounced flows. Consequently, the analysis of solar mass displacement, at the surface and in the corona, clearly reveals that we are dealing with an important phase transition at the photosphere. The solar corona is a gaseous plasma. Note that it has all the characteristics of a true sparse state (no surface, no continuous spectrum, not subject to seismological studies, unable to boil). It is proper to think of the corona as representing the vapor surrounding the condensed photosphere. This is typical of every liquid-gas equilibrium observed on Earth. The corona has no distinct boundary, reflecting once again that it is the true gaseous plasma, not the photosphere. As previously noted, the chromosphere is reminiscent of the critical opalescence at the gas/liquid interface near criticality [30]. This is an important observation which should not be dismissed.

4.8 The boiling action of the solar surface

Solar boiling is a well established occurrence. Indeed, it is commonplace to refer to the Sun as a "boiling gas". Gases, however, cannot boil. They are the result of such action. The act of boiling is a property of the liquid state and is directly associated with the presence of a distinct surface. To speak of the Sun as "a boiling gas", as is done in so many astrophysical texts, is an unintended contradiction relative to the current gaseous model of the Sun.

5 Advantages of the liquid plasma model

5.1 Solar mixing and nuclear reaction processes

The presence of a liquid state provides an opportunity for mixing of nuclear species within the solar sphere. The liquid state can maintain the nuclei involved in nuclear reactions in close proximity with constant mixing, thereby providing a significant advantage in achieving efficient nuclear burning. Conversely, within a solid core, the flow of reacting nuclei is greatly hindered. All solar models advocate that the bulk of the nuclear reactions in the Sun occur in the core. As the Sun evolves, it is said that the hydrogen core will slowly burn out [2, 3]. The Sun will then move to helium burning, and later to the burning of the heavier elements. In contrast, in the liquid plasma model, nuclear reactions are free to occur throughout the solar body, as a result of the nearly uniform solar density.

The energy produced in this fashion, within the solar interior, would be brought to the surface by conduction and convection. When nuclear reactions occur on the surface of the Sun, energy could be directly emitted in the form of gamma rays. That nuclear reactions can be distributed throughout the solar interior has dramatic implications for the lifetime of our Sun, since the burning out of a nuclear core would not occur. A liquid model could extend the life of our star more than 10 fold, relative to the current expectancy. This is because only 10% of the hydrogen fuel is hypothesized to be burned, in the core of the present gaseous model, before the Sun is forced to switch to helium [3]. The liquid model elegantly overcomes such limitations, by enabling the continuous free flow of reactants in nuclear processes. As a result, the composition of the photosphere becomes an important indicator of the composition of the entire star, since convection now acts to equilibrate the entire solar interior. The determination of stellar compositions is subject only to the timescale of mixing. Such reevaluations have profound implications for stellar evolution and cosmology.

5.2 Coronal heating

The eruption of solar flares and prominences are associated with the displacement of material from the solar surface. Such events often occur in conjunction with the release of strong X-ray and gamma ray flashes. These flashes point to an underlying thermal potential in the photosphere which is not expressed under normal circumstances. This provides secondary evidence for the hot photospheric liquid plasma model. In this model, the heating of the corona, by complex magnetic field interactions is still permitted, but no longer required. The primary means of internal heat transfer within the Sun once again becomes convection and conduction [17]. Since energy transfer through convection is only proportional to T and not T^4 (as was the case for thermal radiation), it can be expected that regions of non-equilibrium superheated fluid exist within the Sun. A theory based on the release of superheated fluid from the interior could help explain much of the solar activity found on the surface, including flares and prominences.

In order to simultaneously preserve Langley's temperature and respect the 2nd law of thermodynamics, the gaseous model provides two means of generating heat (e.g., [4, 5, 27]). The first of these occurs within the Sun and is thought to be thermonuclear in origin. The second occurs in the corona and is thought to be of magnetic origin. Particles moving at enormous speeds are also involved to ensure this second temperature. Furthermore, something strange must be happening relative to the photosphere. The gaseous model advances that this layer cannot be heated either by the interior of the Sun or by the corona, both of which are at much higher temperatures. This problem is overcome in the liquid plasma model by raising the true temperature of the photosphere itself, based on energy partition in liquids and on the known production of hard X-rays at the solar surface during eruptive events.

At the same time, the liquid model is quite easily extended to include the presence of Alfvén waves in the chromosphere, transition zone, and corona, much in the same way as the current gaseous model (e.g., [4, 5, 27]). In this regard, the increased density of the photosphere in the liquid model may well help to better explain the origin and behavior of the magnetic field lines located at the surface of the Sun.

5.3 The evolution of the stars

It is clear that adopting a liquid plasma model of the Sun constitutes a significant reshaping of astrophysics with important evolutionary and cosmological consequences. These are too broad to discuss in this work. The issue at hand is simply the assignment of the proper state of matter for the Sun.

5.4 The birth of a star

Current stellar evolution theory holds that the stars are initially formed as a result of the free fall gravitational collapse of interstellar clouds [3]. A significant weakness of these models is the need for a disturbance initiating the collapse [3]. It is also difficult to conceive how many stars can form from a single cloud in such models. Nonetheless, as the collapse proceeds, the process rapidly accelerates until a quasi-steady state is reached with the ignition of nuclear reactions [3].

Relative to the formation of a liquid plasma Sun, it may be important to reconsider this question. What if stellar formation is initiated not by gravitational collapse, but rather by the slow condensation and growth of a star? Star formation would be initiated in extremely cold matter, wherein two atoms first make van der Waals contact [28]. Given the low temperatures, if their combined kinetic energy is not sufficient to overcome the force associated with the van der Waals attraction, a two-atom system is created. A third atom would then join the first two and so on, until a larger and larger mass is created.

The latent heat of condensation could be dissipated by radiative emission. Initially, of course, such seeds of stellar formation would be very subject to destruction, because a high energy atom could always come and break up the process. However, a mass could grow large enough that its van der Waals forces, and its energy of cohesion, are sufficient to deal with the kinetic energy of any single noncondensed atom. When this occurs, condensation would increase rapidly. Again, the important interaction is the van der Waals force. Eventually, a large body could be formed and gravitational forces would become important. The stellar mass would continue to grow. Hydrogen would be converted to a liquid metal plasma, when a critical value for the mass and pressure is achieved. This would correspond to a mass on the order of the Jovian planets (since they are currently theorized to be liquid metal plasmas [60]). As the forces of gravity begin to dominate, the mass of the star would grow until the internal pressure and temperatures become high enough to provoke nuclear ignition and the birth of a new star.

A significant advantage of this approach is that stellar formation takes place at low temperatures. Cold hydrogen is permitted to condense and ignition occurs only once a given stellar mass is reached.

6 Conclusions

For over one hundred years now, the gaseous model of the Sun has dominated scientific thought in solar research. Yet, the model is complex and not easily supported by scientific experimentation. Sufficient evidence is presented herein that the Sun is truly a liquid plasma. In contrast, not a single reason can be provided supporting the idea that the Sun is a gas. The argument made in advance textbooks and coursework simply rests on the observation that the Sun is "hot". The assumption then follows that it cannot be a liquid. Such arguments completely ignore the nature of liquids and gases.

Simple extensions of the Clausius-Clapeyron equation, neglect fact that the Sun is not in a closed system. Furthermore, the gaseous model ignores the existence of liquid metallic hydrogen plasmas in the laboratory.

In reality, we have very little understanding of the pressures and temperatures associated with the Sun. As a result, the "proofs of the gaseous model" tend to be mathematical and theoretical, not experimental. That is because of the mathematical simplicity and elegance of the current equations of state [1–3]. However, as Michelson reminds us: "Everything depends on the insight with which ideas are handled before they reach the mathematical stage [32]."

It is not prudent to apply gaseous equations of state to the Sun, without allowing for experimental guidance. Current solutions relative to solar collapse, temperature, density, internal radiative emission, photon shifting, and seismology, are significant issues for which little more that theoretical arguments are advanced. In addition, all the gaseous models ignore that atoms have size. The possibility that the condensed state needs to be considered is being ignored, precisely because van der Waals' contributions to physical phenomena have been dismissed. Real gases are not infinitely compressible. Yet, the Sun is being described as an ideal gas in many solar models, despite the fact that the ideal gas law from the onset violates van der Waals' findings. Furthermore, the gaseous model is counter to many experimental results in the laboratory, relative to the thermal and physical behavior of gases. Unfortunately, no alternative model currently exists as a point of discussion.

In contrast to the gaseous model of the Sun, the hot liquid plasma model is extremely simple; requiring no theoretical arguments beyond those provided by the liquid state itself, even in the area of energy partition. The hot liquid plasma model addresses the problems of solar collapse and seismology with simplicity. It reconciles the violation of the 2nd law of thermodynamics and the heating of the corona, by invoking the simple release of stored energy from the convection currents of the photosphere. It dismisses extreme densities with hydrogen and helium, by having recourse to the incompressibility of the liquid state. The liquid model eliminates radiative heat transfer as a means of striving for internal thermal equilibrium, as contrary to established thermodynamic principles. Internal thermal equilibrium within the Sun must be achieved using convection and conduction, as is the case for every other object.

The liquid plasma model also provides an alternative explanation for "photon shifting". The visible light of the photosphere is simply produced instantly as a direct manifestation of the vibrational energy contained within the liquid lattice of the solar surface. The problem of calculating internal solar opacities, which must be continually adjusted for frequency and temperature, is removed. Rather, it is argued that not a single photon is being produced within the Sun. Radiative emission remains a surface phenomenon for the Sun, as it is for every other object known to man.

As with any new model, it is clear that a great deal of effort will be required to place each solar finding in the context of a liquid framework. The gaseous equations of state had provided a mathematically elegant approach to stellar structure. In the liquid plasma model, the equations associated with magnetohydrodynamics move to the forefront. This implies that, rather than concentrate on pressure and density, we must turn our attention to thermal conductivity and viscosity. This is far from being a simple problem. Pressure and density changes can be relatively easily addressed, in the liquid plasma model, based on known rigid body solutions [58]. However, the determination of solar conductivities and viscosities poses a daunting task for plasma physics. This is especially true since thermal conductivities and viscosities are often viewed as second and fourth-order tensors, respectively.

Nonetheless, the plasma physicist may eventually gain a better understanding of these quantities as related to stellar interiors, particularly as our efforts are focused on the nature and properties of liquid metallic hydrogen.

It is certainly true that the reevaluation of stellar structure will be difficult. As the same time, the introduction of the liquid plasma model brings new and exciting dimensions in our quest to characterize the physics associated with the Sun. Prudence dictates that we consider every possibility, as we continue to explore this still mystical object in our sky.

Dedication: This work is dedicated to the memory of Jacqueline Alice Roy.

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