The Solar Photosphere: Evidence for Condensed Matter

Pierre-Marie Robitaille

130 Means Hall, 1654 Upham Drive, The Ohio State University, Columbus, Ohio 43210, USA

E-mail: robitaille.1@osu.edu

The stellar equations of state treat the Sun much like an ideal gas, wherein the photosphere is viewed as a sparse gaseous plasma. The temperatures inferred in the solar interior give some credence to these models, especially since it is counterintuitive that an object with internal temperatures in excess of 1 MK could be existing in the liquid state. Nonetheless, extreme temperatures, by themselves, are insufficient evidence for the states of matter. The presence of magnetic fields and gravity also impact the expected phase. In the end, it is the physical expression of a state that is required in establishing the proper phase of an object. The photosphere does not lend itself easily to treatment as a gaseous plasma. The physical evidence can be more simply reconciled with a solar body and a photosphere in the condensed state. A discussion of each physical feature follows: (1) the thermal spectrum, (2) limb darkening, (3) solar collapse, (4) the solar density, (5) seismic activity, (6) mass displacement, (7) the chromosphere and critical opalescence, (8) shape, (9) surface activity, (10) photospheric/coronal flows, (11) photospheric imaging, (12) the solar dynamo, and (13) the presence of Sun spots. The explanation of these findings by the gaseous models often requires an improbable combination of events, such as found in the stellar opacity problem. In sharp contrast, each can be explained with simplicity by the condensed state. This work is an invitation to reconsider the phase of the Sun.

Introduction

The stellar phase has important consequences, not only for modeling the Sun, but indeed, for the proper treatment of nearly every aspect of astrophysics. Recently, the accepted temperature of the photosphere has been questioned [1]. This hinges on the proper understanding of both blackbody radiation [2] and the liquid state [3]. In modern theory, stars can be essentially infinitely compressed without ever becoming liquid. Outside the Earth's oceans, the liquid state appears all but non-existent in the universe. By invoking the gaseous equations of state [i. e. 4] without the possibility of condensation to the liquid and solid state, the accepted models continue to ignore laboratory findings relative to the existence of these transformations. These issues are not simple. However, sufficient evidence exists to bring into question the gaseous models of the Sun.

The physical evidence

1. The thermal spectrum:

It is hard to imagine that, after more than 100 years, our understanding of blackbody radiation could be questioned. If this is the case, it is because of shortcomings in the work of Gustav Kirchhoff [5, 6] which have previously been overlooked [7]. The arguments hinged on whether or not blackbody radiation is in fact universal as initially advanced by Kirchhoff [5, 6], echoed by Planck [2] and theoretically confirmed by Einstein [8]. In order to dissect the problem,

Kirchhoff and Planck are treated together, along with the experimental proof [7]. Einstein's work [8] can then be examined from a conceptual viewpoint [9] without bringing into question any of Einstein's mathematics. Thus, arguments against the universality of blackbody radiation have already been made both on an experimental basis [7] and on a theoretical one [9]. In reality, the entire foundation for the liquid model of the Sun rests on the soundness of these arguments [7, 9]. The belief is that claims of universality are not only overstated, they are incorrect [9]. As such, it is improper to assign any astrophysical temperature based on the existence of a thermal spectrum in the absence of a known isothermal (not adiabatic) and perfectly absorbing enclosure [1, 7, 9].

The Sun possesses a thermal signature as reported early on by Langley [10, 11]. The fact that this spectrum is continuous in nature leads to difficulties for the gaseous models [1]. This is because gases are known to emit radiation only in discrete bands [12]. Consequently, in order to produce the thermal spectrum of the Sun, theoretical astrophysics must currently invoke the summation of numerous spectroscopic processes. Furthermore, this must occur in a slightly shifted manner within each internal layer of the Sun. Many distinct physical processes (bound-bound, bound-free, and free-free) are used to arrive at a single spectrum [i. e. 4]. This constitutes the stellar opacity problem: the summation of many distinct spectroscopic processes to yield a single spectroscopic signature.

In reality, each spectroscopic signature, including the

thermal spectrum, must arise from a single spectroscopic process [1]. Just as an NMR spectrum arises from an NMR process, so must a thermal spectrum arise from a thermal process. Whatever process takes place with graphite on Earth must be taking place on the surface of the Sun. That the gaseous models require many spectroscopic processes along with gradually and systematically changing stellar opacities [i. e. 4] is perhaps their greatest obstacle. Gases simply cannot generate thermal spectra in the absence of a rigid body (condensed matter) enclosure. They are restricted to emission in bands.

In contrast, condensed matter can easily generate continuous spectra [13, 14, 15] as a manifestation of its inherent lattice structure. Thus, relative to the existence of a continuous solar spectrum, a condensed matter model of the Sun has distinct advantages.

2. Limb darkening:

The Sun is also characterized by limb darkening. The solar spectrum becomes less bright when viewing the Sun from the center to the limb. Since a change in the thermal spectrum is involved, the gaseous models must once again invoke the stellar opacity problem. Limb darkening is explained by inferring the sampling of varying optical depths. The Sun must be able to slowly and gradually change its thermal spectrum from one temperature to another based on depth using a perfect combination of bound-bound, bound-free and free-free processes at every location inside the Sun. Gaseous theory therefore places a tremendous constraint on nature relative to limb darkening. As stated above, it is not reasonable to expect that a single spectrum is actually resultant from the infinite sum of many distinct and unrelated spectroscopic processes. If a thermal spectrum is produced by the Sun, it must invoke the same mechanism present in the piece of graphite on Earth. That the gaseous models rely on varying optical depths in order to explain limb darkening might appear elegant, but lacks both clarity and support in experimental physics.

In sharp contrast, angle dependence in thermal emission is extremely well documented for condensed matter [14, 15]. Changes in optical depth are not required. Rather, a subtle change in the angle of observation is sufficient. This is precisely what is observed when we monitor the Sun. For instance, even the oceans of the Earth are known to have angle dependent emission intensities at microwave frequencies [16]. Thus, in the condensed matter scenario, limb darkening is an expression of angle of observation without having to make any arguments based on optical depth.

3. Solar collapse:

One of the key requirements of the gaseous models is the need to prevent solar collapse as a result of gravitational forces. Currently, it is advocated that solar collapse is prevented by electron gas pressure in the solar interior and, for

larger stars, by radiation pressure. However, the existence of gas pressure relies on the presence of a rigid surface [i. e. 4]. The atmosphere of the Earth does not collapse due to the relatively rigid oceanic and continental surfaces. Within the gaseous models of the stars however, there is no mechanism to introduce the rigid surface required to maintain gas pressure. Theoretical arguments are made [i. e. 4] without experimental foundation. The same holds for internal radiation pressure. There is no experimental basis on Earth for radiation pressure internal to a single object [13, 14, 15]. It is well-established that for the gaseous models of the Sun, complete solar collapse would take place in a matter of seconds should electron gas pressure and internal radiation pressure cease [i. e. 4]. In sharp contrast, relative incompressibility is a characteristic of the liquid state. A liquid Sun is by definition essentially incompressible, and experimental evidence for such behavior in liquids is abundant. Stellar collapse is excluded by the very nature of the phase invoked.

4. Solar density:

The Sun has an average density of 1.4 g/cm^3. The gaseous models distribute this density with radial dependence with the core of the Sun typically approaching a density of 150 g/cm^3 and the photosphere 10^{-7} g/cm^3. If the Sun were truly a gaseous plasma, it would have been much more convenient if the average density did not so well approximate the density of the condensed state (> 1 g/cm^3). The gaseous models would be in a much stronger position if the average solar density, for instance, was 10^{-4} g/cm^3. Such a density would clearly not lend itself to the condensed state. In contrast, the known density of the Sun is ideal for a condensed model whose primary constituents are hydrogen and helium. Moreover, for the condensed models [1], the radial dependence of density is not critical to the solution and a uniform distribution of mass may be totally acceptable.

The density of the Sun very closely approaches that of all the Jovian planets. Nonetheless, a great disparity in mass exists between the Sun and these planets. As such, it is probably best not to enter into schemes which involve great changes in internal solar densities. The liquid model maintains simplicity in this area and such a conclusion is viewed as important.

5. Seismology:

The Sun is a laboratory of seismology [17]. Yet, on Earth, seismology is a science of the condensed state. It is interesting to highlight how the gaseous models of the Sun fail to properly fit seismological data. In the work by Bahcall et. al. [18] for instance, experimental and theoretical siesmological findings are compared as a function of Solar radius. Precise fits are obtained for most of the solar sphere. In fact, it is surprising how the interior of the Sun can be so accurately fitted, given that all the data is being acquired

from the solar surface. At the same time, this work is unable to fit the data in the exterior 5% of the Sun [18]. Yet, this is precisely the point from which all the data is being collected. The reason that this region cannot be fitted is that the gaseous models are claiming that the photosphere has a density on the order of 10^{-7} g/cm^3. This is lower than practical vacuums on Earth. Thus, the gaseous models are trying to conduct seismology in a vacuum by insisting on a photospheric density unable to sustain seismic activity. For the condensed models of the Sun, this complication is eliminated.

6. Mass displacement:

On July 9, 1996, the SOHO satellite obtained Doppler images of the solar surface in association with the eruption of a flare [19, 20]. These images reveal the clear propagation of transverse waves on the solar surface. The authors of the scientific paper refer to the mass displacement exactly like the action resulting from a pebble thrown in a pond. This is extremely difficult to explain for the gaseous models, yet trivial for the condensed model. The Doppler images show the presence of transverse waves. This is something unique to the condensed state. Gases propagate energy longitudinally. It can be theoretically argued perhaps that gases can sustain transverse waves. These however would be on the order of a few atomic radii at best. In sharp contrast, the waves seen on the Sun extend over thousands of kilometers. Once again, the condensed state provides a greatly superior alternative to the study of transverse waves on the solar surface.

7. The chromosphere and critical opalescence:

Critical opalescence occurs when a material is placed at the critical point, that combination of temperature, pressure, magnetic field and gravity wherein the gas/liquid interface disappears. At the critical point, a transparent liquid becomes cloudy due to light scattering, hence the term critical opalescence. The gas is regaining order, as it becomes ready to enter the condensed phase. It would appear that the Sun, through the chromosphere, is revealing to us behavior at the solar critical point. Under this scenario, the chromosphere is best viewed as the transition phase between the condensed photosphere and the gaseous corona.

In order to shed light on this problem, consider that in the lower region of the corona, the gaseous material exists at a temperature just beyond the critical temperature. The temperature is sufficiently elevated, that it is impossible for condensation to occur, given the gravity present. However, as one moves towards the Sun, the critical temperature increases as a result of increased gravity. Consequently, a point will eventually be reached where the temperature of the region of interest is in fact below the critical temperature. Condensation can begin to occur. As the surface of the Sun is increasingly approached, the critical temperature increases further. This is a manifestation of increased gravity and

magnetic forces. By the time the photosphere is reached, the region of interest is now well below the critical temperature and the liquid state becomes stable. The surface at this point is visualized.

Therefore, in the liquid model, the chromosphere represents that region where matter projected into the corona is now in the process of re-condensing in order to enter the liquid state of the photosphere. Such an elegant explanation of the chromosphere is lacking for the gaseous models. Indeed, for these models, the understanding of the chromosphere requires much more than elementary chemical principles.

8. Shape:

The Sun is not a perfect sphere. It is oblate. Solar oblateness [21] is a direct manifestation of solar rotation and can best be understood by examining the rotation of liquid masses [22]. The oblateness of the solar disk has recently come under re-evaluation. While exact measurements have differed in the extent of solar oblateness, it appears that the most reliable studies currently place solar oblateness at 8.77×10^{-6} [21]. In order to understand solar oblateness, astrophysics is currently invoking a relative constant solar density as a function of radial position [21]. This is in keeping with our understanding of liquid body rotations [22], but is in direct opposition to the densities calculated using the gaseous equations of state [i. e. 4]. Interestingly, a relatively constant density is precisely what is invoked in the condensed matter model of the Sun [1]. The question becomes even more important when one considers stars like Achanar whose oblateness approaches 1.5 [23]. Such an observation would be difficult to rationalize were the Sun truly gaseous.

9. Surface activity:

The Sun has extensive surface activity and appears to be boiling. Indeed, several undergraduate texts actually refer to the Sun as a boiling gas. In addition to the boiling action, the Sun is characterized by numerous solar eruptions. Both of these phenomena (boiling and solar eruptions) are extremely difficult to rationalized for the gaseous models. Gases do not boil. They are the result of such action. It is an established fact that liquids boil giving rise to gases. There is no evidence on Earth that superheating a gas can give rise to a region of different density capable of erupting from the gaseous mass. These are extremely complex issues for the gaseous models since actions resembling both boiling and superheating must be generated without having recourse to the liquid state.

In contrast, the presence of superheated liquids within the solar interior could easily explain the production of solar eruptions. The existence of boiling action is well documented for the liquid. Nothing further need be added. Phenomena easily explained in the liquid model, become exceedingly difficult for the gaseous equations of state.

10. Photospheric/coronal flow:

It has been well established that the Sun displays pronounced flows at the surface. Matter can be seen rising from, and descending into, the solar interior. However, matter is also traversing the solar surface in a manner perpendicular to established flows in the corona. The photosphere is characterized not simply by a change in opacity as the gaseous models theorize, but by drastically altered directions of material flow relative to the corona. In the liquid model, the interface delineated by flow directions can be explained based on the existence of a phase transition between the photosphere and the corona. In fact, the orthogonality of mass displacement at the solar surface relative to the corona is reminiscent of the orthogonality observed on Earth between the currents in the oceans and the upward and downwards drafts sometimes observed in the overlying air. It is not trivial for the gaseous models to account for the orthogonality of flow between the photosphere and the corona. By contrast, this is a natural extension of current knowledge relative to liquid/gaseous interfaces for the liquid model.

11. Photospheric imaging:

The solar surface has recently been imaged in high resolution using the Swedish Solar Telescope [24, 25]. These images reveal a clear solar surface in 3D with valleys, canyons, and walls. Relative to these findings, the authors insist that a true surface is not being seen. Such statements are prompted by belief in the gaseous models of the Sun. The gaseous models cannot provide an adequate means for generating a real surface. Solar opacity arguments are advanced to caution the reader against interpretation that a real surface is being imaged. Nonetheless, a real surface is required by the liquid model. It appears that a real surface is being seen. Only our theoretical arguments seem to support our disbelief that a surface is present.

12. Dynamo action:

The Sun is characterized by strong magnetic fields. These magnetic fields can undergo complex winding and protrusions. On Earth however, strong magnetic fields are always produced from condensed matter. The study of dynamos relies on the use of molten sodium [26], not gaseous sodium. It is much more realistic to generate powerful magnetic fields in condensed matter than in sparse gaseous plasmas. Consequently, the liquid model and its condensed phase lends itself much more readily to the requirements that the Sun possesses strong magnetic fields.

13. Sun spots:

The presence of Sun spots have long been noted on the solar sphere. Sun spots are often associated with strong magnetic activity. The gaseous models explain the existence of Sun spots with difficulty. The problem lies in the requirement that different types of order (disorder) can coexist in stellar gases, based on the presence of a magnetic field. While there is ample room here for theoretical arguments justifying the existence of Sun spots in a gaseous model, the situation is less complex in the liquid model. Thus, if one considers that the bulk of the solar photosphere exists with hydrogen and helium adhering to a certain lattice structure, all that is required is a concentration of magnetic fields within a region to produce a change in the lattice. The surface of the Sun is changed from a hypothetical "Type I lattice" to a "Type II lattice". The requirement that a strong magnetic field alters the structure of condensed matter in an ordered lattice from one form to another, is much less than would be required to alter the structure of a gaseous plasma (something which has no inherent lattice).

Conclusion

The evidence in favor of a condensed matter model of the Sun is overwhelming. For every avenue explored, the condensed model holds clear advantages in simplicity of understanding. In fact, it remains surprising that the gaseous models have been able to survive for so long. This is partially due to the elegance with which the theoretical framework is established. Moreover, the gaseous equations of state have such profound implications for astrophysics.

Consequently, it is recognized that the acceptance of any condensed matter model will require such dramatic changes in astrophysics that such adoption cannot be swift. In the meantime, it is important to set out the physical evidence for a liquid model both in manuscript [1] and abstract form [27–30]. Eventually, astrophysics may well be forced to abandon the gaseous models and their equations of state. It is likely that this will occur when the field more fully appreciates the lack of universality in blackbody radiation [7, 9, 31]. At this time, gases will no longer be hypothesized as suitable candidates for the emission of thermal radiation. The need for condensed matter will be self-evident.

References

1. Robitaille P. M. L. A high temperature liquid plasma model of the Sun. 2004, arXiv: astro-ph/0410075.

2. Planck M. Ueber das Gesetz der Energieverteilung in Normalspectrum. *Annalen der Physik*, 1901, Bd. 4, 553.

3. March N. H., Tosi M. P. Introduction to liquid state physics. World Scientific, New Jersey, 2002.

4. Kippenhahn R., Weigert A. Stellar structure and evolution. 3rd ed., Springer-Verlag, Berlin, 1994.

5. Kirchhoff G. Ueber den Zusammenhang von Emission und Absorption von Licht und Warme. *Monatsberichte der Akademie der Wissenschaften zu Berlin*, Sessions of Dec. 1859, 1860, 783.

6. Kirchhoff G. Ueber das Verhaltnis zwischen dem Emissions-vermogen und dem Absorptionsvermogen der Korper fur Warme und Litcht. *Annalen der Physik*, 1860, Bd. 109, 275.

7. Robitaille P. M. L. On the validity of Kirchhoff's law of thermal emission. *IEEE Trans. Plasma Science*, 2003, v. 31(6).

8. Einstein A. *Phys. Zs.*, 1917, Bd. 18, 121; English Translation: On the quantum theory of radiation, by D. der Haar, the old quantum theory. Pergamon Press, New York, 1967, 167.

9. Robitaille P. M. L. An analysis of universality in blackbody radiation. 2005, arXiv: physics/0507007.

10. Langley S. P. Experimental determination of wave-lengths in the invisible spectrum. *Mem. Natl. Acad. Sci.*, 1883, v. 2, 147.

11. Langley S. P. On hitherto unrecognized wave-lengths. *Phil. Mag.*, 1886, v. 22, 149.

12. Penner S. S. Quantitative molecular spectroscopy and gas emissivities. Addison-Wesley Publishing Company, Inc., Reading MA, 1959.

13. Knudsen J. G., Hottel H. C., Sarofim A. F., Wankat P. C., Knaebel K. S. Heat transmission. *Perry's Chemical Engineers' Handbook*, 7th ed., R. H. Perry, D. W. Green and J. O. Maloney, Eds. The McGraw-Hill Book Company, New York, 1997, v. 5, 23.

14. Siegel R., Howell J. Thermal radiation heat transfer. 4th ed., Taylor and Francis, New York, 2002,

15. Touloukian Y. S., Ho C. Y. Thermophysical properties of matter. Plenum, New York, 1970, v. 1–8.

16. Ulaby F. T., Moore R. K., Fung A. K. Microwave remote sensing active and passive: radar remote sensing and surface scattering and emission theory. Addison-Wesley Publishing Company, London, 1982, v. 2, 880.

17. Gough D. O. Seismology of the Sun and the distant stars. D. Reidel Publishing Company, Dordrecht, 1986.

18. Bahcall J. N., Pinsonneault M. H., Basu S. Solar models: current epoch and time dependences, neutrinos, and helioseis-mological properties. *Astrophysical J.*, 2001, v. 555, 990.

19. Kosovichev A. G., Zharkova V. V. X-ray flare sparks quake inside the Sun. *Nature*, 1998, v. 393, 28.

20. Fleck B., Brekke P., Haugan S., Duarte L. S., Domingo V., Gurman J. B., Poland A. I. Four years of SOHO discoveries — some highlighs. *ESA Bulletin*, 2000, v. 102, 68.

21. Godier S., Rozelot J. P. The Solar oblateness and its relation-ship with the structure of the tacholine and the Sun's subsur-face. *Astron. Astrophys.*, 2000, v. 355, 365–374.

22. Littleton R. A. The stability of rotating liquid masses. Cambridge University Press, Cambridge, 1953.

23. Domiciana de Souza A., Kervella P., Jankov S., Abe L., Vaki-li F., di Folco E., Paresce F. The spinning-top be star achernar from VLTI-VINCI. *Astron. Astrophys.*, 2003, v. 407, L47–L50.

24. Roberts A. M. Solar faculae stand exposed. *Sky and Telescope*, 2003, v. 106(4), 26.

25. Scharmer G. B., Gudiksen B. V., Kiselman D., Lfdahl M. G., Rouppe van der Voort L. H. M. Dark cores in sunspot pernumbral filaments. *Nature*, 2002, v. 420, 151.

26. Nornberg M. D., Spence E. J., Kendrick R. D., Forest C. B. Measurement of the magnetic field induced by a turbulent flow liquid metal. 2005, arXiv: physics/0510265.

27. Robitaille P. M. L. Evidence for a liquid plasma model of the Sun. APS April 2004, http://www.aps.org/meet/APR04/baps/abs/S280002.html.

28. Robitaille P. M. L. The Sun as a hot liquid plasma: additional evidence. APS Ohio Spring 2004, http://www.aps.org/meet/OSS04/baps/abs/S50002.html.

29. Robitaille P. M. L. The photosphere as condensed matter. APS Ohio Fall 2004, http://meeting.aps.org/meet/OSF04/baps/abs/S60005.html.

30. Robitaille P. M. L. The Sun as a hot liquid plasma: more evidence. APS NE Fall 2004, http://www.aps.org/meet/NEF04/baps/abs/S10004.html.

31. Robitaille P. M. L. Blackbody radiation: Kirchhoff's error propagates beyond Einstein. APS NE Spring 2005, http://meetings.aps.org/Meeting/NES05/Event/31261.

————————