LETTERS TO PROGRESS IN PHYSICS

The Liquid Metallic Hydrogen Model of the Sun and the Solar Atmosphere I. Continuous Emission and Condensed Matter Within the Chromosphere

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The continuous spectrum of the solar photosphere stands as the paramount observation with regard to the condensed nature of the solar body. Studies relative to Kirchhoff's law of thermal emission (e.g. Robitaille P.-M. Kirchhoff's law of thermal emission: 150 years. *Progr. Phys.*, 2009, v. 4, 3–13.) and a detailed analysis of the stellar opacity problem (Robitaille P.M. Stellar opacity: The Achilles' heel of the gaseous Sun. *Progr. Phys.*, 2011, v. 3, 93–99) have revealed that gaseous models remain unable to properly account for the generation of this spectrum. Therefore, it can be stated with certainty that the photosphere is comprised of condensed matter. Beyond the solar surface, the chromospheric layer of the Sun also generates a weak continuous spectrum in the visible region. This emission exposes the presence of material in the condensed state. As a result, above the level of the photosphere, matter exists in both gaseous and condensed forms, much like within the atmosphere of the Earth. The continuous visible spectrum associated with the chromosphere provides the twenty-sixth line of evidence that the Sun is condensed matter.

> *In order to explain the occurrence of the dark lines in the solar spectrum, we must assume that the solar atmosphere incloses a luminous nucleus, producing a continuous spectrum, the brightness of which exceeds a certain limit. The most probable supposition which can be made respecting the Sun's constitution is, that it consists of a solid or liquid nucleus, heated to a temperature of the brightest whiteness, surrounded by an atmosphere of somewhat lower temperature.*
>
> Gustav Robert Kirchhoff, 1862 [1]

When Gustav Kirchhoff was contemplating the origin of the solar spectrum [1], he was probably unaware that structures beyond the photosphere also had the ability to emit continuous spectra. Still, he understood that continuous thermal emission was a property of the condensed state [1]. Gases emit in bands [2] and even compressed gases cannot produce the required thermal spectrum, outside the confines of an enclosure and in the absence of a perfect absorber [3, 4].

Despite these physical realities, over the course of the past 150 years, scientists have moved away from Kirchhoff's realization that the solar surface must be comprised of condensed matter. Instead, gaseous solar models were adopted (e.g. [5, 6]). Sadly, Kirchhoff himself enabled this misstep through his erroneous formulation of the law of thermal emission (see [3,4] and references therein). Discounting problems with the law of emission [3, 4], it can be said that the gaseous models have been based on a false premise: that the thermal spectrum of the Sun could be generated using a vast combination of non-thermal processes [7]. The solar opacity problem [7] reflects the fact that the gaseous models can never properly account for the thermal spectrum. The generation of a continuous solar spectrum has become an insurmountable hurdle for these models [7]. Though gaseous opacity calculations have been used in an attempt to account for the Sun's emission, such calculations are of no value in mirroring the simple graphitic spectrum on Earth, which the solar spectrum strongly emulates. Therefore, gaseous opacity calculations cannot have any lasting merit in generating the continuous spectrum of the Sun [7]. The emission of a thermal spectrum requires an underlying thermal mechanism, not a large sum of non-thermal processes [7]. Condensed matter is required, as illustrated by earthly black bodies (see [3,4] and references therein). In fact, the continuous spectrum of the Sun acts as the most important line of evidence that the Sun is condensed matter (see [8–14] and references therein). This was recognized long ago by Gustav Kirchhoff: gases cannot properly account for the solar spectrum [1].

The presence of continuous thermal emission by the photosphere is complemented in the outer atmosphere of the Sun. The chromosphere also supports weak continuous emission. Hence, an additional line of evidence that the Sun is comprised of condensed matter can be harvested by extending Kirchhoff's insight to the solar atmosphere, above the photospheric surface.

The weak continuous spectrum of the chromosphere [15–18] has drawn the attention of solar observers for over 100 years [19–22]. The great astronomer, Donald Howard Menzel [23], commented as follows on its nature: "*. . . we assumed that the distribution in the continuous chromospheric spectrum is the same as that of a black body at 5700^o, and* *that the continuous spectrum from the extreme edge is that of a black body at 4700^o. There is evidence in favor of a lower temperature at the extreme limb in the observations by Abbot, Fowle, and Aldrich of the darkening towards the limb of the Sun"* [22]. From early days, the continuous chromospheric spectrum was known to vary in temperature with height [24–27]. Consequently, solar observers rapidly introduced temperature variations with increasing height into their atmospheric models (e.g. [17, p. 187-213]; [18, p. 271–352]; [24–31]).

At the same time, problems remained surrounding the formation of the weak continuous chromospheric spectrum. This layer of the Sun, in the context of the modern gaseous models, had an average density of only $\sim 10^{-12}$ g/cm^3 [32, p. 32]. In fact, as one proceeds out from the photosphere to the top of the chromosphere, the density was hypothesized to be changing from $\sim 10^{-7}$ g/cm^3 to $\sim 10^{-15}$ g/cm^3, respectively [33]. It was known that in the chromosphere *"…the intensity of the emitted radiation is several tens of thousand times less than that of the photosphere"* [32, p. 32]. As a result, since the gas models were reducing photospheric densities to the levels of laboratory vacuums, the chromospheric densities had to be even lower.

In order to explain the continuous chromospheric spectrum, theoretical approaches (e.g. [16, 25–27]) exactly paralleled the methods applied for treating the emission from the photosphere (see [7] for a complete discussion). In early contributions, attention focused on neutral H, H$^-$, Rayleigh scattering, and electron scattering (see [17, p. 151–157] and [26, 27]). This was precisely because, devoid of condensed matter, no other mechanism could be invoked. A continuous spectrum, from which Menzel had extracted black body temperatures [22], was being explained using processes unrelated to any experimental production of a thermal spectrum on Earth [7]. Such approaches remain in use, but have already been dismissed relative to explaining the occurrence of continuous spectra [7].

Conversely, the position is now adopted that the presence of a continuous spectrum in the visible range within the chromosphere [15–18] represents a direct manifestation of condensed matter in this region of the solar atmosphere. The proper means of explaining continuous emission in the visible region of the electromagnetic spectrum, especially when it can be hypothesized to hold a thermal lineshape [22], will always remain linked to the presence of condensed matter [7].

The chromosphere corresponds to a region of the Sun where hydrogen atoms are re-entering the condensed state, prior to their recombination with photospheric material.

However, unlike the liquid metallic hydrogen advanced to be present in the solar body [8–14], chromospheric condensed matter appears to lack metallic properties. Chromospheric material, though in the condensed state, might therefore be substantially different than photospheric material. Nonetheless, though the continuous spectrum of the chromosphere remains weak, it demonstrates the presence of condensed matter within a gaseous matrix, much like drops of water can exist within the gaseous atmosphere of the Earth. In this regard, the intensity of the chromospheric emission spectrum can provide some sense of material densities in this layer. The presence of a continuous visible thermal spectrum in the chromosphere thereby constitutes the twenty-sixth line of evidence (and the sixth Planckian proof [34]) that the Sun is comprised of condensed matter (see [8–14] and references therein for the others).

Dedication

This work is dedicated to Marge Marrone, for her friendship and example in leading a joyous life.

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References

1. Kirchhoff G. The physical constitution of the Sun. In: *Researches on the Solar Spectrum and the Spectra of the Chemical Elements*. Translated by H.E. Roscoe, Macmillan and Co., Cambridge, 1862, p. 23.
2. Robitaille P.M. The little heat engine: Heat transfer in solids, liquids, and gases. *Progr. Phys.*, 2007, v. 4, 25–33.
3. Robitaille P.M. Blackbody radiation and the carbon particle. *Progr. Phys.*, 2008, v. 3, 36–55.
4. Robitaille P.M. Kirchhoff's law of thermal emission: 150 years. *Progr. Phys.*, 2009, v. 4, 3–13.
5. Bahcall J.N. and Pinsonneault M.H. Standard solar models, with and without helium diffusion, and the solar neutrino problem. *Rev. Mod. Phys.*, 1992, v. 64, no.4, 885–926.
6. Bachall J.N., Pinsonneault M.H. and Wasserburg G.J. Solar models with helium and heavy-element diffusion. *Rev. Mod. Phys.*, 1995, v. 67, no. 4, 781–808.
7. Robitaille P.M. Stellar opacity: The Achilles heel of the gaseous Sun. *Progr. Phys.*, 2011, v. 3, 93–99.
8. Robitaille P.M. A high temperature liquid plasma model of the Sun. *Progr. Phys.*, 2007, v. 1, 70–81 (also in arXiv: astro-ph/0410075).
9. Robitaille P.M. Liquid metallic hydrogen: A building block for the liquid Sun. *Progr. Phys.*, 2011, v. 3, 60–74.
10. Robitaille P.M. Liquid metallic hydrogen II: A critical assessment of current and primordial helium levels in Sun. *Progr. Phys.*, 2013, v. 2, 35–47.
11. Robitaille J.C. and Robitaille P.M. Liquid metallic hydrogen III. Intercalation and lattice exclusion versus gravitational settling and their consequences relative to internal structure, surface activity, and solar winds in the Sun. *Progr. Phys.*, 2013, v. 2, 87–97.
12. Robitaille P.M. Commentary on the liquid metallic hydrogen model of the Sun: Insight relative to coronal holes, sunspots, and solar activity. *Progr. Phys.*, 2013, v. 2, L7–L9.
13. Robitaille P.M. Commentary on the liquid metallic hydrogen model of the Sun II. Insight relative to coronal rain and splashdown events. *Progr. Phys.*, 2013, v. 2, L10–L11.
14. Robitaille P.M. Commentary on the liquid metallic hydrogen model of the Sun III. Insight into solar lithium abundances. *Progr. Phys.*, 2013, v. 2, L12–L13.
15. Menzel D.H. A Study of the Solar Chromosphere. *Publications of the Lick Observatory*, University of California Press, Berkeley, CA, v. 17, 1931.

16. Thomas R.N. and Athay R.G. Physics of the Solar Chromosphere. Interscience Publishers, New York, N.Y., 1961.
17. Bray R.J. and Loughhead R.E. The Solar Chromosphere, Chapman and Hall, London, U.K., 1974.
18. Athay R.G. The Solar Chromosphere and Corona: Quiet Sun – Astrophysics and Space Science Library – v. 53. D. Reidel Publishing Company, Dordrecht, Holland, 1976.
19. Evershed J. Wave-length determinations and general results obtained from a detailed examination of spectra photographed at the solar eclipse of January 22, 1898. *Phil. Trans. Roy. Soc. London*, 1901, v. 197, 381–413.
20. Evershed J. Preliminary report of the expedition to the south limit of totality to obtain photographs of the flash spectrum in high solar latitudes. *Proc. Roy. Soc. London*, 1900, v. 67, 370–385.
21. Grotian W. Über die intensitätsverteilung des kontinuierlichen spektrums der inneren korona. *Zeitschrift fur Astrophysik*, 1931, v. 3, 199–226.
22. Menzel D.H. and Cillié G.G. Hydrogen emission in the chromosphere. *Astrophys. J.*, 1937, v. 85, 88–106.
23. Goldberg L. and Aller L.H. Donald Howard Menzel 1901–1976. In: *Biographical Memoires*, The National Academy of Sciences USA, 1991 (accessed online on 2/11/2013).
24. Athay R.G., Billings D.E., Evans J.W. and Roberts W.O. Emission in hydrogen Balmer lines and continuum in flash spectrum of 1952 total solar eclipse at Karthoum, Sudan. *Astrophys. J.*, 1954, v. 120, 94–111.
25. Athay R.G., Menzel D.H., Pecker J.C., and Thomas R.N. The thermodynamic state of the outer solar atmosphere V. A model of the chromosphere from the continuous emission. *Astrophys. J. Suppl. Ser.*, 1955, v. 1, 505–519.
26. Hiei E. Continuous spectrum in the chromosphere. *Publ. Astron. Soc. Japan*, 1963, v. 15, 277–300.
27. Weart S.R. and Faller J.E. Photoelectric eclipse observation of the continuum at the extreme solar limb. *Astrophys. J.*, 1969, v. 157, 887–901.
28. Gingerich O. and de Jager C. The Bilderberg model of the photosphere and low chromosphere. *Solar Phys.*, 1968, v. 3, 5–25.
29. Gingerich O., Noyes R.W., Kalkofen W. and Cuny Y. The Harvard-Smithsonian reference atmosphere. *Solar Phys.*, 1971, v. 18, 347–365.
30. Athay R.G. Boundary conditions on model solar chromospheres. *Solar Phys.*, 1969, v. 9, 51-55.
31. Fontenla J.M., Balasubramaniam K.S. and Harder J. Semiemperical models of the solar atmosphere II. The quiet-Sun low chromosphere at moderate resolution. *Astrophys. J.*, 2007, v. 667, 1243–1257.
32. Bhatnagar A. Instrumentation and observational techniques in solar astronomy. In: *Lectures on Solar Physics* (H.M. Antia, A. Bhatnagar and R. Ulmschneider, Eds.), Springer, Berlin, 2003, p. 27–79.
33. Ulmschneider P. The physics of the chromospheres and coronae. In: *Lectures on Solar Physics* (H.M. Antia, A. Bhatnagar and R. Ulmschneider, Eds.), Springer, Berlin, 2003, p. 232–280.
34. Robitaille P. Magnetic fields and directional spectral emissivity in sunspots and faculae: Complimentary evidence of metallic behavior on the surface of the Sun. *Progr. Phys.*, 2013, v. 1, 19–24.