On the Temperature of the Photosphere: Energy Partition in the Sun

Pierre-Marie Robitaille

Department of Radiology, The Ohio State University, 395 W. 12th Ave, Columbus, Ohio 43210, USA
E-mail: robitaille.1@osu.edu

In this note, energy partition within the Sun is briefly addressed. It is argued that the laws of thermal emission cannot be directly applied to the Sun, as the continuous solar spectrum ($T_{app} \sim 6,000$ K) reveals but a small fraction of the true solar energy profile. Without considering the energy linked to fusion itself, it is hypothesized that most of the photospheric energy remains trapped in the Sun's translational degrees of freedom and associated convection currents. The Sun is known to support both convective granules and differential rotation on its surface. The emission of X-rays in association with eruptive flares and the elevated temperatures of the corona might provide some measure of these energies. At the same time, it is expected that a fraction of the solar energy remains tied to the filling of conduction bands by electrons especially within sunspots. This constitutes a degree of freedom whose importance cannot be easily assessed. The discussion highlights how little is truly understood about energy partition in the Sun.

The discussion of energy partition in materials may be considered to be so complex at times that, perhaps, the most prudent course of action rests in avoiding the entire subject. In the laboratory, the evaluation of energy partition demands years of study involving many hurdles for meager rewards. Nonetheless, before progress can be made in any field, the issues at hand must be identified. It is worthwhile to highlight some general ideas relative to energy partition in the Sun which would eventually afford a detailed mathematical approach to the question. Relative to solar physics, energy partition is complicated by the presence of both conduction and convection on the solar surface.

The interior of the Sun is currently hypothesized to approach temperatures of ~15,600,000K, while the corona manifests values on the order of 2,000,000–3,000,000 K [1, p.10]. Solar physicists maintain that the solar photosphere exists at a temperature of ~5,780K [1, p.10] in an apparent violation of the second law of thermodynamics [2–4]. This surface temperature is based on the application of the laws of thermal emission [5–7] to the solar spectrum [1, p.3–9] as first recorded in its entirety by Langley [8–10]. Still, the assignment of a temperature to the photosphere has not been without controversy.

Throughout the 19th century, great variations existed with respect to the temperature of the photosphere (see [11, p.268–279] and [12, p.48–52] for reviews). In 1898, Scheiner brought apparent unification to the problem when he applied Stefan's law [6] to data acquired by Pouillet, Secchi, Violle, Soret, Langley, Wilson, Gray, Paschen, and Rosetti [13]. Scheiner demonstrated that these previously discordant studies (see [14] for many of the original values) resulted in calculated solar temperatures of 5,000 to 6,200 K, with only one observation standing at 10,000 K [13]. Scheiner believed in a gaseous model and insisted that, even though the Sun's layers supported differing temperatures, it might be viewed as a blackbody. However, such an object did not meet the equilibrium conditions required by Kirchhoff [15, 16]. This immediately brought into question any temperature derived from such methods.

Scheiner was not alone in advocating that the laws of thermal radiation could be applied to the Sun. Two years earlier, in order to justify the extraction of the photospheric temperature from the laws of thermal radiation, Ebert stated that: "*With respect to electromagnetic radiation, the principal mass of the Sun acts like a black body*" [17]. In 1895, most scientists believed that Secchi's model of the Sun [18, 19] was valid. Ebert considered this framework when he initially expressed doubt about the blackbody nature of the Sun: "*There remains only the question, whether we can regard the incandescent particles of the Sun, which yield the continuous spectrum, as comparable to a black body with respect to their total radiating capacity*" [17]. Frank Very [20] was more adamant in questioning the applications of the laws of emission to solar data when, in 1908, he stated in *Science*: "*It is doubtful whether radiation formulae obtained from measures through a limited range of temperature for solid bodies, composed of complex molecules, are applicable to solar conditions at the photospheric level, where it is improbable that any molecules remain undissociated. Extrapolations from Stefan's law of the proportionality of total radiation from a black body to the fourth power of the absolute temperature, are therefore not certainly applicable to the problem, even though the law has been verified through a range of some hundreds of degrees*" [20]. Nonetheless, Very immediately applied Stefan's law to the Sun [20].

The sternest warning against applying the laws of radiation to the Sun would come from Max Planck [21]. The father of modern physics removed all doubt relative to his position when he wrote: "*Now the apparent temperature of the Sun is obviously nothing but the temperature of the solar rays, de-*

pending entirely on the nature of the rays, and hence a property of the rays and not a property of the Sun itself. Therefore it would be not only more convenient, but also more correct, to apply this notation directly, instead of speaking of a fictitious temperature of the Sun, which can be made to have meaning only by the introduction of an assumption that does not hold in reality" [22, §101]. If Planck was so forceful in his comment, he rested his case on solid grounds: "*It is only in the case of stable thermodynamic equilibrium that there is but one temperature, which then is common to the medium itself and to all rays whatever color crossing it in different directions*" [22, §101]. Planck recognized with these words that the Sun was not in thermal equilibrium and hence he refused to accept the concept of "*apparent*" or "*effective*" solar temperatures [22, §101].

Perhaps more than anyone, Max Planck recognized that the laws of thermal emission had been obtained in settings involving complete thermal equilibrium. Kirchhoff's formulation was restricted to radiation within a rigid enclosure [15, 16, 22] sustaining full thermal equilibrium. There could be no net conduction or convection processes present. Based on his objection, Planck recognized that the Sun supported convection currents. Carrington's differential solar rotation had been well known for over fifty years [18] and the convective nature of granular field was also firmly established [23]. In view of Planck's warning, a more considered approach should be adopted relative to applying the laws of thermal emission to the Sun.

Max Planck specifically excluded conduction when treating radiation, on the grounds that it's presence violated thermal equilibrium: "*Now the condition of thermodynamic equilibrium requires that the temperature shall be everywhere the same and shall not vary with time. Therefore in any given arbitrary time just as much radiant heat must be absorbed as is emitted in each volume-element of the medium. For the heat of the body depends only on the heat radiation, since, on account of the uniformity in temperature, no conduction of heat can take place*" [22, §25]. Like conduction, convection reduces emissivity. It is known that the emissivity of gases can fall with temperature in clear violation of Stefan's law [24]. These two realities, the presence of conduction and convection on the photosphere, are likely to explain Planck's hesitation to state anything about the Sun, based solely on the acquisition of its spectrum. Nonetheless, perhaps it is possible to extract something of value from the solar spectrum with respect to energy distribution within the Sun.

Relative to thermal radiation, the availability of electrically conductive paths can alter emissivity. In metals, normal emissivity can be substantially reduced [25–27]. Silver is an excellent conductor, but a poor emitter [28]. In fact, polished silver has one of the highest coefficients of reflection. It can be concluded that electronic conduction reduces emissivity.

When energy enters or escapes from an object, it does so by filling or vacating available degrees of freedom [24]. Without considering nuclear processes, the degrees of freedom are either translational, vibrational, rotational, or electronic [24]. As a rule, electronic degrees of freedom become particularly important at elevated temperatures. Within a gaseous Sun, constituent atoms are viewed as existing in a dissociated state. Such monoatomic species can have recourse only to translational and electronic degrees of freedom. Vibrational and rotational degrees of freedom are restricted to species which are at least diatomic.

In a solid, such as graphite at room temperature, the dominant degrees of freedom are likely to be vibrational [24]. Graphite displays a reasonable thermal conductivity in the hexagonal plane (390 W/m×K for *ab* direction) [29, p.44–57]. This compares well with the thermal conductivity of silver (420 W/m×K) [29, p.57]. Conversely, the thermal conductivity of graphite drops substantially between layers (~2 W/m×K) [29, p.57]. In graphite, thermal conductivity is linked to the vibrations of the lattice and these degrees of freedom [29, p.56].

Relative to electrical conductivity, graphite is a "semimetal" [29, p.57]. Its resistivity is $\sim 3{\times}10^{-3}$ ohm×m between layers making it is good insulator [29, p.61]. However, in the hexagonal plane, graphite has a resistivity of approximately 2.5–$5{\times}10^{-6}$ ohm×m [29, p.61] making it reasonably metallic, but still well below silver which has an electrical resistivity of $\sim 1.59{\times}10^{-8}$ at 293 K [30, p.12–40]. Even in its favored plane, graphite is a significantly inferior conductor relative to silver. Consequently, the electrical conductivity of silver must be responsible for its weak emissivity, since its thermal conductivity is similar to graphite at least in one plane. This leads to the conclusion that the vibrational degrees of freedom are responsible for the excellent emissivity of graphite. Assuming that the object is at rest, the graphitic lattice does not permit translations or rotations, while the electronic degrees of freedom are unlikely to be significantly populated. As a result, when emissivity is properly coupled to temperature, it appears that the vibrational state of the sample primarily dominates [24].

In the gaseous models of the Sun, hydrogen and helium must exist as isolated atoms, many of which are devoid of electrons. Since the gaseous Sun has no lattice, it cannot support either thermal conduction through such a structure or energy transfer through electronic conduction bands. It cannot have recourse to lattice vibrations as a degree of freedom. Consequently, a gaseous Sun must rely almost exclusively on translational and electronic degrees of freedom as receptacles for energy. Yet, laboratory experience dictates that these degrees of freedom cannot support thermal emission of a Planckian nature [7]. Such is the great flaw of gaseous models which solar opacity approaches cannot reconcile [31]. To explain solar thermal emission, a mechanism similar to that which exists in graphite must be invoked. The dominant degrees of freedom in graphite are vibrational and linked to the existence of the lattice itself. In contrast, a gaseous Sun has no lattice and therefore cannot produce a thermal spectrum. Opacity arguments do not suffice to rectify these problems in a gaseous solar model [31].

Conversely, within a liquid metallic hydrogen model of the Sun [32], a lattice exists. In fact, from the days when it was first proposed by Wigner and Huntington [33], metallic hydrogen has been hypothesized to be able to assume a layered lattice similar to graphite. Such a lattice configuration will possess vibrational degrees of freedom which mimic those found in graphite, as required to properly account for the production of the solar spectrum. Accordingly, the thermal spectrum itself should be regarded as one of the strongest proof that the Sun is condensed matter, as its generation requires a lattice which dictates the interatomic spacing of condensed matter.

It appears that the solar spectrum is reporting only a small fraction of the true energy content of the photosphere, providing information which is limited to the vibrational state of the solar lattice. Much more substantial energy is stored in the translational degrees of freedom. This is manifested by the convection currents of the granules [23] and the differential solar rotation observed by Carrington [18]. Moreover, there is strong evidence to suggest that sunspots are metallic [23] and, therefore, maintain electronic conduction bands with their own associated energy.

These realities explain why the temperature of the solar photosphere does not constitute a violation of the second law of thermodynamics. The 5,780 K [1, p.10] measured is linked only to the vibrational degrees of freedom of the photospheric lattice. However, the true energy of the photosphere is dominated by its translational degrees of freedom. This helps to account for the production of X-rays in association with solar flares rupturing the photospheric surface [34]. When this occurs, we are likely to be monitoring some measure of the translational energy associated with the photosphere, as matter moves horizontally across the surface and collides orthogonally with the flare's vertical displacement of material. In a sense, the flare is providing resistance to the horizontal flow of matter on the photosphere. As surface matter collides with the flare, its energy is revealed and X-ray emissions are obtained [34]. Similarly, the temperatures of the corona in the 2,000,000–3,000,000 K range [35, p.3–10] reflect a coupling of these atoms to the translational degrees of freedom on the photosphere. No violation of the second law exists. The energy content of the photosphere is likely to correspond to temperatures of ~7,000,000 K, when properly accounting for all of these phenomena as the author has previously stated [36]. In that case, the photospheric spectrum may be considered as reporting an apparent temperature, with little relevance to the real temperature of the surface [36]. Alternatively, it is also possible to reconcile the emission spectrum to the real temperature of the photosphere. The approach would be similar to that adopted when dealing with the microwave background problem [37] and, unfortunately, involves a reconsideration of Boltzmann's constant [38].

The consideration of energy partition in the Sun opens new avenues of discovery in physics. Most notably, it brings into question the universality of blackbody radiation, as first advocated by Gustav Kirchhoff [15, 16]. *A priori*, the gaseous Sun fails to meet Kirchhoff's requirement for thermal equilibrium with an enclosure, as Max Planck recognized [22, §101]. Regrettably, Kirchhoff's law itself is unsound [39, 40], destroying any perceived ability of gases to emit blackbody spectra. The issue is critical to the survival of the gaseous solar models. If local thermal equilibrium and its extension of Kirchhoff's formulation fails to guarantee that a blackbody spectrum is produced at the center of the Sun, then the gaseous models have no mechanism to generate its continuous emission. In part, this forms the basis of the solar opacity problem [31].

Dedication

This work is dedicated to the memory of Professor David G. Cornwell (10/8/1927–3/23/2011).

Submitted on July 2, 2011 / Accepted on July 9, 2011
First published online on July 16, 2011

References

1. Lang K.R. The Cambridge encyclopedia of the Sun. Cambridge University Press, Cambridge, 2001.
2. Clausius R. Über die bewegende Kraft der Wärme — Part I and Part II. *Poggendorfs Annalen der Physik und Chemie*, 1850, v.79, 368–397 and 500–524 (also in English: On the moving force of heat, and the laws regarding the nature of heat itself which are deducible therefrom. *Phil. Mag.*, 1851, v.2, 1–21 and 102–119).
3. Clausius R. The Mechanical Theory of Heat — with Its Applications to the Steam Engine and to Physical Properties of Bodies. John van Voorst, London. 1865.
4. Thomson W. On the dynamical theory of heat; with numerical results deduced from Mr. Joule's equivalent of a thermal unit and M. Regnault's observations on steam. *Math. and Phys. Papers*, 1851, v.1, 17583.
5. Wien W. Über die Energieverteilung in Emissionspektrum eines schwarzen Körpers. *Annalen der Physik*, 1896, v.58, 662–669.
6. Stefan J. Über die Beziehung zwischen der Warmestrahlung und der Temperature. *Sitzungsberichte der mathematischnaturwissenschaftlichen Classe der kaiserlichen Akademie der Wissenschaften*, Wien 1879, v.79, 391–428.
7. Planck M. Über das Gesetz der Energieverteilung im Normalspektrum. *Annalen der Physik*, 1901, v.4, 553–563. (English translation by ter Haar D.: Planck M. On the theory of the energy distribution law in the normal spectrum. The old quantum theory. Pergamon Press, 1967, 82–90; also Planck's December 14, 1900 lecture Zur Theorie des Gesetzes der Energieverteilung in Normalspectrum, which stems from this paper, can be found in either German, or English, in: Kangro H. Classic papers in physics: Planck's original papers in quantum physics. Taylor & Francis, London, 1972, 6–14 or 38–45).
8. Langley S.P. Experimental determination of wave-lengths in the invisible spectrum. *Mem. Natl. Acad. Sci.*, 1883, v.2, 14762.
9. Langley S.P. On hitherto unrecognized wave-lengths. *Phil. Mag.*, 1886, v.22, 14973.
10. Langley S.P. The invisible solar and lunar spectrum. *Am. J. Science*, 1888, v.36(216), 39710.

11. Clerke A.M. A popular history of astronomy during the nineteenth century. Adam & Charles Black, London, 1893.
12. Meadows A.J. Early solar physics. Pergamon Press, Oxford, 1970.
13. Scheiner J. The temperature of the Sun. I. *Astron. Soc. Pac.*, 1898, v.9(64), 167–179.
14. Rogovsky E. On the temperature and composition of the atmosphere of the planets and the Sun. *Astrophys. J.*, 1901, v.14, 234–260.
15. Kirchhoff G. Über den Zusammenhang zwischen Emission und Absorption von Licht und. Wärme. *Monatsberichte der Akademie der Wissenschaften zu Berlin*, sessions of Dec. 1859, 1860, 783–787.
16. Kirchhoff G. Über das Verhältnis zwischen dem Emissionsvermögen und dem Absorptionsvermögen. der Körper für Wärme und Licht. *Poggendorff's Annalen der Physik und Chemie*, 1860, v.109, 275–301. (English translation by F. Guthrie: Kirchhoff G. On the relation between the radiating and the absorbing powers of different bodies for light and heat. *Phil. Mag.*, 1860, ser. 4, v.20, 1–21).
17. Ebert H. On the electromagnetic nature of the solar radiation and on a new determination of the temperature of the Sun. *Astrophys. J.*, 1895, v.2, 55–57.
18. Robitaille P.M. A thermodynamic history of the solar constitution — I: The journey to a gaseous Sun. *Progr. Phys.*, 2011, v.3, 3–25 — A paper published in this Special Issue.
19. Robitaille P.M. A thermodynamic history of the solar constitution — II: The theory of a gaseous Sun and Jeans' failed liquid alternative. *Progr. Phys.*, 2011, v.3, 41–59 — A paper published in this Special Issue.
20. Very F.W. The temperature of the Sun. *Science*, 1908, v.27(685), 267–269.
21. Robitaille P.M. Max Karl Ernst Ludwig Planck (1858–1947). *Progr. Phys.*, 2007, v.4, 117–120.
22. Planck M. The Theory of Heat Radiation. P. Blakiston's Son & Co., Philadelphia, PA, 1914.
23. Robitaille P.M. On Solar Granulations, Limb Darkening, and Sunspots: Brief Insights in Remembrance of Father Angelo Secchi. *Progr. Phys.*, 2011, v.3, in press — A paper published in this Special Issue.
24. Robitaille P.M. The little heat engine: Heat transfer in solids, liquids, and gases. *Progr. Phys.*, 2007, v.4, 25–33.
25. Modest M.F. Radiative Heat Transfer. McGraw-Hill, New York, 1993, p.92–108.
26. Thirumaleshwar M. Fundamentals of Heat and Mass Transfer. Dorling Kindersley, Dehli, 2009, p.652.
27. Incropera F.P., DeWitt D.P., Bergman T.L., Lavine A.S. Fundamentals of Heat and Mass Transfer. 6th Edition, John Wiley & Sons, Hoboken, NJ, 2007.
28. Touloukian Y.S. and Ho C.Y. Thermophysical Properties of Matter (vols. 1). Plenum, New York, 1970.
29. Pierson H.O. Handbook of Carbon, Graphite, Diamond and Fullerenes. Noyes Publications, Park Ridge, NJ, 1993.
30. Haynes W.M. CRC Handbook of Chemistry and Physics. 91st Edition, CRC Press, Boca Raton, Fl, 2010–2011.
31. Robitaille P.M. Stellar opacity: The Achilles heel of the gaseous Sun. *Progr. Phys.*, 2011, v.3 — A paper published in this Special Issue.
32. Robitaille P.M. Liquid metallic hydrogen: A building block for the liquid Sun. *Progr. Phys.*, 2011, v.3, 60–74 — A paper published in this Special Issue.
33. Wigner E. and Huntington H.B. On the possibility of a metallic modification of hydrogen. *J. Chem. Phys.*, 1935, v.3, 764–770.
34. Kosovichev A. G., Zharkova V.V. X-ray flare sparks quake inside the Sun. *Nature*, 1998, v.393, 317–318.
35. Livingston W. and Koutchmy S. Eclipse Science Results: Past and Present. *ASP Conference Series*, v.205, 2000.
36. Robitaille P.-M. L. The collapse of the Big Bang and the gaseous Sun. *New York Times*, March 17, 2002 (available online: http://www.thermalphysics.org/pdf/times.pdf).
37. Penzias A. A. and Wilson R.W. A measurement of excess antenna temperature at 4080 Mc/s. *Astrophys. J.*, 1965, v.1, 419–421.
38. Robitaille P.M. Blackbody Radiation and the Loss of Universality: Implications for Planck's Formulation and Boltzman's Constant. *Progr. Phys.*, 2009, v.4, 14–16.
39. Robitaille P. M. Blackbody radiation and the carbon particle. *Progr. Phys.*, 2008, v.3, 36–55.
40. Robitaille P. M. Kirchhoff's law of thermal emission: 150 years. *Progr. Phys.*, 2009, v.4, 3–13.