Magnetic Fields and Directional Spectral Emissivity in Sunspots and Faculae: Complimentary Evidence of Metallic Behavior on the Surface of the Sun

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Sunspots and faculae are related phenomena and constitute regions of elevated magnetic field intensity on the surface of the Sun. These structures have been extensively studied in the visible range. In this regard, it has been recognized that the intensity contrast of faculae, relative to the photosphere, increases considerably as the line of observation moves from the center to the limb of the Sun. Such center to limb variation (CLV) suggests that the directional spectral emissivity of the faculae increases at the same time that photospheric directional emissivity decreases. Since the directional spectral emissivity of faculae increases towards the limb, these structures, along with sunspots, provide strong evidence for metallic behavior at the level of the solar surface. This further strengthens claims that the body of the Sun is not gaseous, but rather, comprised of condensed matter.

1 Introduction

In his popular work, *The Birth and Death of the Sun*, George Gamow justified the gaseous nature of the Sun as follows: "*. . . at 6000 degrees all the materials from which a furnace might be constructed, including even such refractory substances as platinum or carbon, will be not only melted but completely evaporated. No material can exist at these high temperatures in a state other than gaseous, and this is exactly what we find on the surface of the Sun, where all elements are present in vapour form*" [1, p. 4–5]. Several prominent members of the astronomy community, by utilizing similar logic, had previously laid the foundation for a gaseous Sun in the mid-1800s [2]. The contention that the Sun was too hot to be anything but gaseous would persist throughout the 20th century [3]. Conversely, experiments had long indicated that the phases of matter did not depend solely on temperature, but on factors such as external pressure, internal atomic composition, and the nature of the lattice adopted in the condensed phase. Yet, using a single justification, the possibility that certain materials might exist in liquid form within the Sun continued to be ignored. Gamow's argument [1, p. 4–5] would discount Wigner and Huntington's 1935 proposal [4] that metallic hydrogen, a material existing in the condensed phase, could be created at elevated temperatures and pressures [5–7].

2 Metallic hydrogen on the Sun

Liquid metallic hydrogen [4] is a particularly alluring substance relative to condensed solar models [5–7], especially given the observation that the Sun appears to be primarily composed of this element [8–11]. Although metallic hydrogen was first proposed nearly eighty years ago [4], it remains an elusive material in the laboratory [5]. Some claims of synthesis have received broad international acclaim [12, 13], often followed, by controversy [14–17] and slow dismissal. Others, such as claims that certain forms of metallic hydrogen can be produced in Rydberg matter, have received less attention [18].

There has recently been a new flurry of activity in the quest to produce metallic hydrogen [4] in the laboratory. In November 2011, Mikhail Eremets and Ivan Troyan published a provocative report in *Nature Materials* [19] which strongly suggested that metallic hydrogen had indeed been synthesized for the first time on the Earth. Nonetheless, given the nature of the quest for metallic hydrogen [5], it seemed crucial that more evidence be acquired [20–22]. Perhaps this time, the synthesis of metallic hydrogen will be affirmed [5].

Beyond metallic hydrogen itself, dense hydrogen could play an important role in the Sun, since the photosphere appears to be less metallic in nature than sunspots [5]. The author has advanced arguments that the photosphere adopts a layered lattice resembling graphite (a Type-1 lattice [5]), while the lattice in sunspots has more metallic character (a Type 2 lattice [5]). This is presumably due to slightly decreased inter-atomic distances within the layered lattice of sunspots. It is noteworthy that a report has recently demonstrated that dense hydrogen could adopt a graphene-like structure at 220 GPa and 300 K [23, 24]. The need for emitting a thermal spectrum provides strong motivation for considering graphite-like layered structures, which can lead to hydrogen in the metallic state, within liquid models of the Sun [5].

3 A liquid Sun

The idea that the Sun could be liquid dates back at least to the days of Gustav Kirchhoff [2] and Sir James Hopwood Jeans was its last major scientific champion [3]. Jeans was a distinguished physicist [25] and Physical Sciences Secretary of the Royal Society from 1919 to 1929 [26]. He was also Sir Arthur Eddington's principle antagonist [3]. For much of his scientific career, Jeans advanced that heavy metals such as uranium comprised the building blocks for a liquid Sun, in opposition to Eddington's gaseous models [3]. When the Sun was determined to be principally composed of hydrogen [9–11], Jeans was left without a structural material. Eddington's gaseous Sun went on to be widely accepted by astronomy. Neither Jeans nor Eddington had anticipated the postulate that metallic hydrogen could be formed at elevated pressures [4]. For his part, Jeans abandoned the liquid model [3], apparently without sufficiently considering that the observational evidence for condensed matter might continue to mount [5–7, 27–29]. At the time, he had elucidated only fragmentary proof for a liquid state (see [3] and references therein).

Today, not a single observational line of evidence supports the idea that the Sun is gaseous, as simple temperature arguments are fallacious. Much of the scientific discussion appears centered on endowing gaseous solar models with the ability to behave as condensed matter (e.g. [30]). By dismissing the facts, the existence of the solar surface has been discounted [3], precisely because the gaseous models have no means of accounting for such a structure [29]. All structural features associated with solar activity (sunspots, faculae, prominences, flares, spicules, etc. . .) tend to be explained using magnetic fields, as the only means to impart structural features to a gaseous entity which, in reality, can support none.

In sharp contrast, observational facts point to a liquid Sun, including more than one dozen proofs for a condensed matter [5–7, 27–29]. Though the most convincing line of evidence for a liquid Sun will always remain the thermal appearance of the photospheric spectrum in the visible range [27], some may not be able to appreciate the power and sufficiency of this proof. In part, this is due to the introduction of local thermal equilibrium reasoning in solar science [30]. Local thermal equilibrium has come to cloud the requirements for producing a thermal spectrum and mask the need for condensed matter [30]. Nonetheless, the arguments which support a liquid Sun based on its thermal emission are definitive [30–33]. Thermal evidence will always remain paramount, because it points to the existence of lattice order on the surface of the Sun [31]. Nothing further is required to demonstrate the presence of condensed matter, as Kirchhoff himself indirectly understood in the mid-1800s [2]. For those who require additional illustrations, sunspots and faculae provide an interesting proving ground.

4 Directional spectral emissivity of sunspots and faculae

As key structural elements on the surface of the Sun, sunspots and faculae provide solar physicists ample opportunity for observation and discussion. In the days of Galileo and Scheiner, even the association of sunspots with the solar body was cause for extensive debate [34]. Since that time, sunspots and faculae have come to reveal much about the Sun, despite the belief that their visual appearance on the photosphere remains an optical illusion in modern solar theory [29].

4.1 Sunspots

As early as 1774, Alexander Wilson [35] noted that sunspots appeared as slight depressions relative to the solar surface. Wilson reached this conclusion based on geometry [35]. Accepted solar models currently account for the visual depression of sunspots, or "Wilson effect", using optical depth arguments (e.g [36, p. 189–190] and [37, p. 46]). Such complexity must be invoked because modern theories are built around a gaseous solar body. Since these models have long deprived the Sun of a true surface [2,29], they cannot rest upon geometrical arguments to account for the Wilson effect [35] and must have recourse to explanations based on optical depth (e.g [36, p. 189–190] and [37, 46]). Conversely, the author has argued in favor of an authentic solar surface, thereby directly challenging accepted models [29]. Hence, the Wilson effect [35], one of the oldest and simplest sunspot observation, has provided a basis for questioning the established gaseous models of the Sun.

Modern astrophysics has advanced an understanding of sunspots which, on cursory examination at least, appears to be complete. In reality, the true physical nature of these structures has remained elusive, despite our arsenal of data. Still, much has been learned about sunspots. The Wilson effect was established at the end of the 18th century [35]. Schwab discovered the eleven year sunspot cycle in 1843 [38]. In the same period, Carrington used sunspot observations and outlined the differential rotation of the Sun in great detail [39].

In 1908, George Ellery Hale discovered that sunspots are regions of powerful magnetic activity [40]. The intensity of magnetic fields at the center of sunspots has been determined to be primarily vertical and known to increase in the dark nuclei of the umbra (e.g. [37, p. 75] and [41, p. 80]). Helioseismic analysis of the Sun has revealed that sound waves travel faster within sunspots relative to the photosphere [42,43]. All of these phenomena are highly suggestive of increased density and metallicity within sunspots and have been utilized to support the idea that the Sun is condensed matter [28]. Strong magnetic fields and the science of seismology are always associated with condensed matter, not the gaseous state of solar models.

Sunspots have also been reported to have directional emissivities that increase with angle of observation, as the observer follows their movement towards the limb of the Sun [41, p. 75–77]. One of the earliest reports of increased sunspot emissivity relative to the photosphere dates back to 1875 and Samuel Langley[*]: "*With larger images and an improved instrument, I found that, in a complete ring of the solar surface, the photosphere, still brilliant, gave near the limb absolutely less heat than the umbra of the spots*" [44, p. 748]. Edwin Frost would soon echo Langley: "*A rather surprising result of these observations was that spots are occasionally*

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[*] Translations from French of Langley's work [44] were executed by the author, P. M. Robitaille.

relatively warmer than the surrounding photosphere" [45, p. 143].

Should the directional emissivity of sunspots truly increase near the limb, such behavior would be highly supportive of metallic character [28]. Non-metals usually display directional spectral emissivities that tend to decrease with increasing angle of observation [46–48]. Metals often possess lower normal emissivities with respect to their directional spectral emissivities. The directional spectral emissivities of metals typically rise with increasing angle, then fall precipitously with orthogonal viewing [46–48]. Thus, a careful analysis of emissivities can provide important clues as to whether sunspots (or faculae) are behaving as metals, potentially generating strong evidence for condensed matter on the surface of the Sun.

Truly gaseous objects should be devoid of emissivities which are directionally dependent. Thus, the increased directional spectral emissivity in sunspots could only be explained with extreme difficulty using gaseous solar models and often attributed to the effect of "stray light" [41, p. 75–77]. Stray light arguments have played an important role in the modern dismissal of increased emissivity in sunspots towards the solar limb. Thus, despite 100 years of study, the exact directional emissivity within these objects remains an unresolved issue in solar physics. The same cannot be said of facular directional spectral emissivity.

4.2 Faculae

The directional spectral emissivity contrast of faculae, with respect to the photosphere, has long been known. George Ellery Hale wrote, relative to the emissivity of the faculae: "*The bright faculae, which rise above the photosphere, are conspicuous when near the edge of the Sun, but practically invisible when they happen to lie near the center of the disk...*" [49, p. 85–86]. Hale later re-emphasized the changing emissivity of the faculae as a function of position on the solar disk: "*Mention has already been made of the faculae, which are simply regions in the photosphere that rise above the ordinary level. Near the edge of the Sun, their summits lie above the lower and denser part of that absorbing atmosphere which so greatly reduced the Sun's light near the limb, and in this region the faculae may be seen visibly. At times they may be traced to considerable distances from the limb, but as a rule they are inconspicuous or wholly invisible towards the central part of the solar disk*" [49, p. 90].

In 1961, Rogerson presented an elegant summary of the increase in facular directional emissivity observed near the solar limb [50]. This work was complemented with theory and a few photographs [50]. Rogerson noted that the contrast variation between the faculae and photosphere increased to a maximum of about 64% near the very limb of the Sun [50]. Today, the center to limb variation (CLV) of facular emissivity is widely accepted and studied [51–54], as has the grouping of faculae with sunspots (e.g. [55, p. 42–43] and [56, p. 248–249]), and the identification of faculae as regions of intense magnetic activity [57–59].

The association of bright faculae with sunspots can be traced at least to the middle of the 19th century. According to de la Rue and his team, in 1865: "*It would thus appear as if the luminous matter being thrown up into a region of greater absolute velocity of rotation fell behind to the left; and we have thus reason to suppose that the faculous matter which accompanies a spot is abstracted from that very portion of the Sun's surface which contains the spot, and which has in this manner been robbed of its luminosity*" [60]. This direct association of sunspot and facular matter has recently been re-emphasized as a result of studying large flares on the solar surface [61].

While faculae display CLV with respect to their spectral emissivity, their emissivity contrast remains highly associated with the magnetogram signal [59]. Facular contrast, after increasing to a maximum near $\mu = 0.2$ (where $\mu = \cos\theta$ and θ is the heliocentric angle between the pixel of interest and direction of the Earth; r, the distance from the disk center, is given by $r = R\sin\theta$, if R represents the solar radius) has been observed to drop rapidly when moving even closer towards the limb [52]. This finding [52] appears to be in agreement with Spruit's "*hot wall*" model of facular emissivity [62, 63].

Spruit's "*hot wall*" model stated that faculae appeared darker when viewed directly from above because very little of the "*hot wall*" was visible. As the faculae moved towards the limb, the "*hot wall*" became increasingly visible and, hence, the structures appeared bright. With increasing distance towards the limb, the "*hot wall*" once again fell out of the line of sight, being obscured by the trailing wall, and the faculae once again appeared darker (see [53] for additional detail). Others have reported that facular contrast continues to increase towards the limb (e.g. [51]). This behavior would be more consistent with the "*hot cloud*" model [50, 64, 65]wherein the faculae are viewed as floating above the photosphere [53]. Today, Spruit's "*hot wall*" model has gained almost universal acceptance, as more in accordance with observation (e.g. [66, 67]).

Alternatively, it is herein proposed that the directional spectral emissivity observed in faculae constitutes one of the most elegant proofs that the Sun is comprised of condensed matter. The reasoning remains that advanced in section 3.1 (see also [28]), with the important distinction that the directional spectral emissivity changes in faculae, unlike sunspots, are uncontested [51–54, 57–59, 66, 67]. Moreover, the observation that directional spectral emissivity contrast in faculae increase towards the limb, before rapidly subsiding at the very edge of the Sun [52], strongly supports metallic behavior in these structures [28, 46–48].

On the Earth, the existence of directional spectral emissivity in condensed matter has been established [46–48, 68]. Materials display emissivities which always manifest their atomic nature and structure, in addition to the temperature of observation [46–48, 68]. Every material possesses a unique signature and this constitutes a powerful lesson from the study of condensed matter [46–48, 68].

The idea that faculae are condensed matter based on directional emissivities also gains support from the realization that these objects, like sunspots, are regions of intense magnetic activity [57–59]. The ideal means of accounting for this activity remains the invocation of conduction bands. A solar body which is comprised of liquid metallic hydrogen and adopts a layered graphite-like lattice presents a wonderful material to account both for the directional spectral emissivities of faculae and the associated high magnetic field [5, 28]. While condensed matter can easily support such fields, there remains no evidence on the Earth that gases, in isolation, can generate powerful magnetic fields. While it is true that gaseous plasmas respond to the presence of magnetic fields, they certainly do not possess the required structure to create such phenomena.

5 Conclusion

Despite the wide acceptance of Spruit's "*hot wall*" model of facular emissivity [62] numerous problems exist with such approaches.

First, modern models of solar emissivity are fundamentally dependent on elemental and ionic opacities within the Sun. However, the solar spectrum cannot be generated using the sum of individual opacities. The author has designated solar opacity as the Achilles' heel of the gaseous solar models [30]. It is not reasonable to account for solar emission with phenomena which cannot explain the simple emissivity found on the Earth within graphite [30].

Second, a discussion of facular emissivity often focuses on local thermal equilibrium (LTE) arguments (e.g. [66]) and such arguments are not applicable to the Sun [30]. The Sun operates well outside the confines of local thermal equilibrium and Milne's argument in support of such a regimen [69–72] leads to conduction, not equilibrium [30].

Third, the assignment of temperatures, based on emissivities on the solar surface, constitutes a direct violation of the principles associated with thermal emission [30–33], as has been highlighted by Max Planck himself [73, §101] and discussed in detail [74].

Finally, the idea that a fully gaseous object can support structure remains contrary to the known principles of physics. Objects such as "*walls*", even when only considering emissivity, require condensed matter. They cannot be mimicked by gases with densities approaching that of the best vacuums achievable on the Earth [27].

In modern solar theory, sunspots are thought to be dark, as the magnetic fields they contain prevent hot gases from rising from the interior of the Sun (e.g. [75]). Conversely, the brightness of faculae are explained when magnetic fields dilute the solar material beneath them and causes the light to escape more easily. These explanations constitute stark contrasts with one another, while at the same time discounting much of what is known on the Earth relative to thermal emissivity. The fact remains that gases are unable to emit photons in a directionally dependent manner. Astrophysical explanations relative to the causes of directional emissivity, as related to photospheric limb darkening, solar granulations, sunspots, and faculae, with their reliance on "optical depth" and "solar opacities", remain at a serious disadvantage, relative to solar models based on condensed matter [27–30].

Irrespective of the mathematical elegance associated with modern solar models, there is no observational support that the body of the Sun is a gas. Given the nature of the solar spectrum, seismic activity, and the presence of structural entities such as sunspots, prominences, and faculae, modern theory must constantly resort to mathematical arguments, or the presence of magnetic fields, in order to endow a gaseous Sun with the properties of condensed matter [8–10]. In reality, while the corona displays features consistent with gaseous plasma, the photosphere, with its sunspots, faculae, and eruptive prominences, strongly manifests the condensed nature of the solar body. The idea that solar temperatures forbid the formation of condensed matter in the Sun ignores the reality that the phases of matter are not solely determined by temperature, but are a manifestation of many factors, including pressure of formation and the internal physical properties of materials [5–7].

Currently, numerous lines of evidence strongly support the condensed nature of the Sun. These include:

1) the continuous nature of the thermal spectrum [6, 27–30],
2) photospheric limb darkening [27, 28],
3) the absence of solar collapse [5, 6, 27],
4) a solar density (1.4 g/cm^3) consistent with a hydrogen lattice [6, 27],
5) the presence of seismic activity [6, 27],
6) the behavior of mass displacement on the solar surface [6, 27],
7) the chromosphere and critical opalescence [27],
8) the existence of solar oblateness [6, 27],
9) the extensive surface activity [6, 27, 28],
10) the orthogonal nature of photospheric/coronal flows [27],
11) the ability to image the solar surface [6, 27–29],
12) the presence of a powerful solar dynamo [27],
13) the nature and behavior of sunspots, including the Wilson effect [27, 28], and
14) the structure and dynamic evolution of solar granulation [28].

Each of these phenomena can be readily incorporated into a condensed model of the Sun. Conversely, gases can neither support nor act as structural entities. A striking example relative to thermal emission and the solar opacity problem in gaseous models has been addressed in detail [30].

In this work, a fifteenth line of evidence for the condensed nature of the Sun is presented:

15) the directional spectral emissivity of faculae. Emissivity fundamentally reflects a "Planckian proof" or a "thermal proof" for condensed matter. Along with 1) the thermal appearence of the solar spectrum, 2) the limb darkening of the photosphere, 3) the directional spectral emissivity of sunspots, and 4) the directional spectral emissivity of granulations [28], the emissivity of faculae constitutes one of the most powerful lines of evidence that the Sun is condensed matter. It therefore represents the fifth thermal proof for condensed matter on the surface of the Sun.

It remains highly likely that the Planckian proofs constitute direct physical evidence for a solar lattice [31]. Through the study of directional spectral emissivity, they argue for metallicity both within sunspots and faculae. Such metallicity represents a manifestation of the lattice and the conduction bands which it supports. The Planckian proofs also remind us of the need to properly address and understand complex emission mechanisms. Driven by a desire to better comprehend the solar spectrum, perhaps someday, the physics community, at last, will link thermal emission to a unique physical process as the author has suggested [31–33]. In so doing, condensed matter and theoretical physicists will finally conclude the work initiated, but left unfinished, by Max Planck [73].

Dedication

The work is dedicated to Professor Manuel Tzagournis, Senior Vice-President for Health Science and Dean of the College of Medicine (Emeritus) at The Ohio State University for the faith he placed in realizing the dreams and hopes of a young assistant professor.

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References

1. Gamow G. The Birth and Death of the Sun. A Mentor Book: The New American Library, New York, N.Y., 1952.
2. Robitaille P.M. A thermodynamic history of the solar constitution — I: The journey to a gaseous sun. *Progr. Phys.*, 2011, v. 3, 3–25.
3. 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.
4. Wigner E. and Huntington H.B. On the possibility of a metallic modification of hydrogen. *J. Chem. Phys.*, 1935, v.3, 764–770.
5. Robitaille P.M. Liquid metallic hydrogen: A building block for the liquid Sun. *Progr. Phys.*, 2011, v. 3, 60–74.
6. 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).
7. Robitaille P.M. The Sun as a high energy/high density liquid metallic hydrogen plasma. *The 33rd IEEE International Conference on Plasma Science*, June 4–8, 2006, Traverse City, Michigan, p. 461, DOI:10.1109/PLASMA.2006.1707334.
8. Payne C.H. The relative abundances of the elements. Stellar Atmospheres. Harvard Observatory Monograph No. 1, Harvard University Press, Cambridge, MA, 1925, Chapter 13 (reprinted in part in Lang K.R. and Gingerich O. A source book in astronomy and astrophysics, 1900–1975, Harvard University Press, Cambridge, MA, 1979, p.245–248).
9. Unsöld A. Über die Struktur der Fraunhofersehen Linien und die quantitative Spektralanalyse der Sonnenatmosphäre. *Zeitschrift für Physik*, 1928, v. 46, 765–781.
10. Russell H.N. On the composition of the Sun's atmosphere. *Astrophys. J.*, 1929, v.70, 11–82.
11. Grevesse N. and Sauval A.J. Standard solar composition. *Space Science Reviews*, 1998, v. 85, 161–174.
12. Weir S.T., Mitchell A.C. and Nellis W.J. Metallization of fluid molecular hydrogen at 140 GPa (1.4 Mbar). *Phys. Rev. Letters*, 1996, v. 76(11), 1860–1863.
13. Mao H.K. and Hemley R.J. Optical studies of hydrogen above 200 Gigapascals: Evidence for metallization by band overlap. *Science*, 1989, v. 244, 1462–1464.
14. Silvera I.F. Evidence for band overlap metallization of hydrogen. *Science*, 1990, v. 247(4944), 863.
15. Mao H.K. and Hemley R.J. Evidence for band overlap metallization of hydrogen — Response. *Science*, 1990, v. 247(4944), 863–864.
16. Eggert J.H., Moshary F., Evans W.J., Lorenzana H.E., Goettel K.A. and Silvera I.F. Absorption and reflectance in hydrogen up to 230 GPa: Implications for metallization. *Phys. Rev. Letters*, 1991, v. 66, 193–196.
17. Besson J.M. Comment on "Metallization of fluid molecular hydrogen at 140 GPa (1.4 Mbar)". *Phys. Rev. Letters*, 1997, v. 78(26), 5026.
18. Holmlid L. Sub-nanometer distances and cluster shapes in dense hydrogen and in higher levels of hydrogen Rydberg matter by phase-delay spectroscopy. *J. Nanopart. Res.*, 2011, v. 13, 5535–5546.
19. Eremets M.I. and Troyan I.A. Conductive dense hydrogen. *Nature Materials*, 2011, v. 10, 927–931.
20. Research Highlights. Hydrogen made metallic. *Nature*, 2011, v. 479, 448.
21. Jephcoat A.P. High-pressure physics: Testing one's metal. *Nature Materials*, 2011, v. 10, 904–905.
22. Cartwright J. Chemists claim metallic hydrogen creation first. *Chemistry World*, November 14, 2011.
23. Howie R.T., Guillaume C.L., Scheler T., Goncharov A.F. and Gregoryanz E. Mixed molecular and atomic phase of dense hydrogen. *Phys. Rev. Letters*, 2012, v. 108(12), 125501 (5 pages).
24. Cartwright J. Hydrogen that mimics graphene. *Chemistry World*, April 2, 2012.
25. Milne E.A. Sir James Jeans — A Biography. Cambridge University Press, Cambridge, 1952.
26. http://royalsociety.org/about-us/governance/officers/ (accessed 10/15/2012)
27. Robitaille P.M. The solar photosphere: Evidence for condensed matter. *Progr. Phys.*, 2006, v. 2, 17–21.
28. Robitaille P.-M. On Solar granulations, limb darkening, and sunspots: Brief insights in remembrance of Father Angelo Secchi. *Progr. Phys.*, 2011, v. 3, 79–88.
29. Robitaille P.-M. On the presence of a distinct Solar surface: A reply to Hervé Faye. *Progr. Phys.*, 2011, v. 3, 75–78.

30. Robitaille P.M. Stellar opacity: The Achilles heel of the gaseous Sun. *Progr. Phys.*, 2011, v. 3, 93–99.
31. Robitaille P.M.L. On the validity of Kirchhoff's law of thermal emission. *IEEE Trans. Plasma Sci.*, 2003, v. 31(6), 1263–1267.
32. Robitaille P.-M. Blackbody radiation and the carbon particle. *Progr. Phys.*, 2008, v. 3, 36–55.
33. Robitaille P.-M. Kirchhoff's law of thermal emission: 150 years. *Progr. Phys.*, 2009, v. 4, 3–13.
34. Galilei G. and Scheiner C. On Sunspots. Translated by E. Reeves and A.V. Helden, University of Chicago Press, Chicago, 2010.
35. Wilson A. Observations on the solar spots. *Phil. Trans. Roy. Soc.*, 1774, v. 64, 1–30.
36. Tandberg-Hanssen E. Solar Activity. Blaisdell Publishing Co., Waltham, M.A., 1967.
37. Thomas J.H. and Weiss N.O. Sunspots and Starspots. Cambridge University Press, Cambridge, U.K., 2008.
38. Schwab H. Sonnenbeobachtungen im Jahre 1843. Von Herrn Hofrath Schwabe in Dessau. *Astronomische Nachrichten*, 1844, v. 21, 233–236.
39. Carrington R.C. Observations on the Spots of the Sun, from November, 9, 1853, to March 24, 1861, Made at Redhill. Williams and Norgate, London, U.K., 1863.
40. Hale G.E. On the probable existence of a magnetic field in Sun-spots. *Astrophys. J.*, 1908, v. 28, 315–343.
41. Sobotka M. Fine structure in sunspots. In: *Motions in the solar atmosphere* (A. Hanslmeier and M. Messerotti, eds.), Astrophysics and Space Science Library, v. 239, Kluwer Academic Publishers, Dordrecht, 1999, p.71–97.
42. Moradi H. and Cally P.S. Time-distance modeling in a simulated sunspot. *Solar Physics*, 2008, v. 251, 309–327.
43. Ilonidis S. and Zhao J. Determining absorption, emissivity reduction, and local suppression coeffcients inside sunspots. *Solar Physics*, 2011, v. 268, 377–388.
44. Langley S. Sur la température des diverses régions du soleil. Les noyaux noirs des taches. *Comptes Rendus*, 1875, v. 80, 746–749.
45. Frost E.B. Observations on the thermal absorption in the solar atmosphere made at Potsdam. *Astronnomische Nachrichten*, 1892, v. 130 (3105–3106), 129–146.
46. Modest M.F. Radiative heat transfer. McGraw-Hill, New York, 1993, p.92–108.
47. Thirumaleshwar M. Fundamentals of Heat and Mass Transfer. Dorling Kindersley, Dehli, 2009, p. 652.
48. Incropera F.P., DeWitt D.P., Bergman T.L., Lavine A.S. Fundamentals of Heat and Mass Transfer, 6th Edition. JohnWiley & Sons, Hoboken, NJ, 2007.
49. Hale G.E. The study of stellar evolution: An account of some recent methods of astrophysical research, The decennial publications of the University of Chicago — Second Series, Vol. X. University of Chicago Press, Chicago, 1908.
50. Rogerson J.B. On photospheric faculae. *Astrophys. J.*, 1961, v. 134, 331–338.
51. Chapman G.A. and Klabunde D.P. Measurements of the limb darkening of faculae near the solar limb. *Astrophys. J.*, 1982, v. 261, 387–395.
52. Libbrecht K.G., Kuhn J.R. On the facular contrast near the solar limb. *Astrophys. J.*, 1985, v. 299, 1047–1050.
53. Lawrence J.K. and Chapman G.A. Photometric observations of facular contrasts near the solar limb. *Astrophys. J.*, 1988, v. 335, 996–1004.
54. Berger T.E., van der Voort L.R., Löfdahl M. Contrast analysis of solar faculae and magnetic bright points. *Astrophys. J.*, 2007, v. 661, 1272–1288.
55. Wilson P.R. Solar and stellar activity cycles. Cambridge University Press, Cambridge, U.K., 1994.
56. Bray R.J. and Loughhead R.E. Sunspots. Chapman and Hall Ltd., London, U.K., 1964.
57. Chapman G.A. Facular line profiles and facular models. *Astrophys. J. Supp. Ser.*, 1977, v. 33, 35–54.
58. Tarbell T.D. and Title A.M. Measurements of magnetic fluxes and field strengths in the photospheric network. *Solar Physics*, 1977, v. 52, 13–25
59. Ortiz A., Solanki S.K., Domingo V., Fligge M. and Sanahuja B. On the intensity contrast of solar photospheric faculae and network elements. *Astron. & Astrophys.*, 2002, v. 388, 1036–1047.
60. de la Rue W., Stewart B. and Loewy B. Researches on solar physics — Series II: On the behaviour of sun-spots with regard to increase and diminution (abstract). *Proc. Roy. Soc. London*, 1865, v. 14, 59–63.
61. Wang H., Deng N. and Liu C. Rapid transition of uncombed penumbrae to faculae during large flares. *Astrophys. J.*, 2012, v. 748(2), 76.
62. Spruit H.C. Pressure equilibrium and energy balance of small photospheric fluxtubes. *Solar Physics*, 1976, v. 50, 269–295.
63. Walton S.R. Flux tube models of solar plages. *Astrophys. J.*, 1987, v. 312, 909–929.
64. Kononovich E.V. A unified interpretation of photospheric and facular granules. *Soviet Astronomy Letters*, 1979, v. 5, 50–52.
65. Schatten K.H., Mayr H.G., Omidvar K., Maier E. A hillock and cloud model for faculae. *Astrophys. J.*, 1986, v. 311, 460-473.
66. Unruh Y.C., Solanki S.K. and Fligge M. The spectral dependence o facular contrast and solar irradiance variations. *Astron. & Astrophys.*, 1999, v. 345, 635–642.
67. Keller C.U., Schüssler M., Vögler A. and Zakharov V. On the origin of solar faculae. *Astrophys. J. Letters*, 2004, v. 607, L59–L62.
68. Touloukian Y.S. and Ho C.Y. Thermophysical Properties of Matter (vols. 1). Plenum, New York, 1970.
69. Milne E.A. Selective radiation-pressure and the structure of a stellar atmosphere. *Mon. Not. Roy. Astron. Soc.*, 1927, v.87, 697–708.
70. Milne E.A. The effect of collisions on monochromatic radiative equilibrium. *Mon. Not. Roy. Astron. Soc.*, 1928, v. 88, 493–502.
71. Milne E.A. Bakerian Lecture: The structure and opacity of a stellar atmosphere. *Phil. Trans. Roy. Soc. London*, 1929, v. 228, 421–461.
72. Milne E.A. Thermodynamics of the stars. *Handbuch der Astrophysik*, 1930, v. 3, Part 1, 65–255.
73. Planck M. The Theory of Heat Radiation. P. Blakiston's Son & Co., Philadelphia, PA, 1914.
74. Robitaille P.M. On the temperature of the photosphere: Energy partition in the Sun. *Progr. Phys.*, 2011, v. 3, 89–92.
75. http://atst.nso.edu/files/press/ATST_book.pdf (accessed on 10/25/2012 — see Page 8).