On Solar Granulations, Limb Darkening, and Sunspots: Brief Insights in Remembrance of Father Angelo Secchi

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Father Angelo Secchi used the existence of solar granulation as a central line of reasoning when he advanced that the Sun was a gaseous body with a photosphere containing incandescent particulate matter (Secchi A. Sulla Struttura della Fotosfera Solare. *Bullettino Meteorologico dell'Osservatorio del Collegio Romano*, 30 November 1864, v.3(11), 1–3). Secchi saw the granules as condensed matter emitting the photospheric spectrum, while the darkened intergranular lanes conveyed the presence of a gaseous solar interior. Secchi also considered the nature of sunspots and limb darkening. In the context of modern solar models, opacity arguments currently account for the emissive properties of the photosphere. Optical depth is thought to explain limb darkening. Both temperature variations and magnetic fields are invoked to justify the weakened emissivities of sunspots, even though the presence of static magnetic fields in materials is not usually associated with modified emissivity. Conversely, within the context of a liquid metallic hydrogen solar model, the appearance of granules, limb darkening, and sunspots can be elegantly understood through the varying directional emissivity of condensed matter. A single explanation is applicable to all three phenomena. Granular contrast can be directly associated with the generation of limb darkening. Depending on size, granules can be analyzed by considering Kolmogoroff's formulations and Bénard convection, respectively, both of which were observed using incompressible liquids, not gases. Granules follow the 2-dimensional space filling laws of Aboav-Weiner and Lewis. Their adherence to these structural laws provides supportive evidence that the granular surface of the Sun represents elements which can only be constructed from condensed matter. A gaseous Sun cannot be confined to a 2-dimensional framework. Mesogranules, supergranules, and giant cells constitute additional entities which further support the idea of a condensed Sun. With respect to sunspots, the decrease in emissivity with increasing magnetic field strength lends powerful observational support to the idea that these structures are comprised of liquid metallic hydrogen. In this model, the inter-atomic lattice dimensions within sunspots are reduced. This increases the density and metallic character relative to photospheric material, while at the same time decreasing emissivity. Metals are well known to have lowered directional emissivities with respect to non-metals. Greater metallicity produces lower emissivity. The idea that density is increased within sunspots is supported by helioseismology. Thus, a liquid metallic hydrogen model brings with it many advantages in understanding both the emissivity of the solar surface and its vast array of structures. These realities reveal that Father Secchi, like Herbert Spencer and Gustav Kirchhoff, was correct in his insistence that condensed matter is present on the photosphere. Secchi and his contemporaries were well aware that gases are unable to impart the observed structure.

1 Introduction

The appearance of sunspots has fascinated mankind for centuries [1–8] and while limb darkening [9–11] has been documented from the days of Galileo [3, p.274], the phenomenon only became well-established in the 1800's [7, 12]. Solar granulations have also long captivated solar science [13, 14]. Although humanity has gazed at the Sun since time immemorial, our understanding of these phenomena remains limited. In a large measure, this reflects the unassailable nature of the Sun. At the same time, our lack of understanding mirrors the incapacity of the gaseous models to properly address questions related to solar structure. Gases will always remain devoid of structural attributes.

Strangely, if Father Angelo Secchi [2] first advanced that the Sun was constituted of a gaseous body surrounded by a photosphere containing particulate matter [16, 17], it was because he was searching to understand photospheric structure. The nature of solar granulations troubled Secchi [2, 17]. He solved the problem by endowing the body of the Sun with a gaseous nature while maintaining a partially condensed photosphere. Secchi's proposed photosphere could not adhere to the full properties of condensed matter. Sixty years later, theoretical physics advocated a completely gaseous solar model.

As a result, it has been nearly impossible to synthesize a realistic and cohesive portrayal of sunspots, granulation, and limb darkening, even though a cursory review of the question suggests otherwise.

2 Granulations and the gaseous models

2.1 Ideas of the 19th century

Secchi built his solar model on two driving forces: 1) Nasmyth's early description of solar granulation [18, 19] and 2) Magnus' demonstration that solid sodium hydroxide increased the luminosity of the gaseous flame [20]. Based on Magnus [20], Secchi advanced [17] that some condensed matter was present within the photosphere, as gases were devoid of the emissive power required to produce the solar spectrum [2]. Secchi considered that the darker appearance of intergranular lanes reflected the inferior radiative ability of the gaseous solar body. He believed that Nasmyth's discovery was noteworthy [18, 19], though remarking that granular features had previously been observed on the solar surface: "*First of all, are these new findings? We believe that, in the end, these are the same granulations that have long since been pointed out by observers, under the name of "lucules" and "pores" and that with the new method they can better be distinguished*" [17]. Secchi's description of granulation was important to the history of astronomy, as the Jesuit scientist was regarded as one of the leading solar observers of his time [2, 21]. His representations of granules depicted in his classic text [21, p.31–34] (reproduced in part within [14, p.4] and [1, p.143–145]) were nothing short of astounding. In 1870, Secchi presented drawings which remain respectable by today's standards and which far surpassed the illustrations which had made James Nasmyth famous only a few years before (see drawings reproduced in [13]).

In the mid-1860s, considerable controversy erupted between James Nasmyth [22] and the Reverend William Rutter Dawes [23] over the appearance of the solar granulation [13]. Nasmyth supported the notion that granules had a consistent structure and resembled regular overlapping "*willow leaves*". For his part, Dawes maintained that they had been discovered long before Nasmyth and that the term "*willow leaves*" was inappropriate as the features displayed an irregular form [13]. The discussion then involved George Airy as the Astronomer Royal, Warren de la Rue, John Herschel, William Huggins, Father Angelo Secchi, and others [13]. Much of the debate would once again transpire in *The Reader* [2]. In 1865, no less than ten letters appeared in the popular magazine and included contributions from Secchi himself [24–33]. Scientists took the controversy beyond conventional journals into the public forum.

With time, Dawes' view [13, 30] rose to prominence and the concept of "*willow leaves*" faded from solar physics. With respect to granulations, Dawes reminded his readers that: "*Their existence was well known to Sir W. Herschel*" [30]. He cited Herschel directly [30]: "*There is all over the Sun a great unevenness in the surface which has the appearance of a mixture of small points of an unequal light*" [34]. Dawes elaborated on his own position: "*I have proposed to term them granules or granulations, as more suitable than any more definite appellation, and therefore unlikely to mislead*" [30]. Nasmyth discovered nothing new [13, 18, 19], but he generated tremendous interest in the nature of solar granules. In turn, this prompted Secchi to put forth his solar model [16, 17]. Dawes did not live to see the resolution of the conflict.

As for Secchi, he observed both the granules and the intergranular lanes. He addressed the appearance of the solar surface as follows: "*The bottom of the solar disc appeared to be formed of a fine black mesh whose links were very thin and full of bright points. It was not so much the shape of the grid that surprised us — for we had seen it also at other times with older methods — as its blackness, which was truly extraordinary. It was such that we suspected some illusion, but in concentrating on certain darker points and finding them of unchanging and precise forms, we no longer remained in doubt about the reality of the aspect. Of this grid-like structure we can give an approximate idea in saying that the Sun looked like a ordinary piece of rough paper seen through a strong microscope; on this paper the prominences are numerous and irregular, and where the light falls rather obliquely, the bottom of the grooves are almost black compared to the more elevated parts, which appear extremely white… The grid-like solar structure seemed to us to offer nothing regular in those parts of the disc that are continuous, and thus the term granular appears very appropriate. The granular structure is more visible near the spots, but it is not recognizable in the faculae; these present themselves like luminous clusters without distinguishable separation, emitting continual light without the interruption of dots or of that black mesh. In the end, we have found the granular structure more notable and easy to distinguish in the middle of the disc than near the limb, and in the zones near the sun's equator, more than in the polar zones*" [17].

It was based on these observations that Secchi advanced his model of a gaseous Sun with a partially condensed photosphere: "*Indeed this appearance suggests to us what is perhaps a bold hypothesis. As in our atmosphere, when it is cooled to a certain point, there exists a fine substance capable of transforming itself in fine powder and of forming clouds in suspension, (water transforming into so-called "vesicular" vapor or into small solid icicles), so in the enflamed solar atmosphere there might be an abundance of matter capable of being transformed to a similar state at the highest temperatures. These corpuscles, in immense supply, would form an almost continuous layer of real clouds, suspended in the transparent atmosphere which envelopes the sun, and being comparable to solid bodies suspended in a gas, they might have a greater radiant force of calorific and luminous rays than the gas in which they are suspended. We may thus ex-*

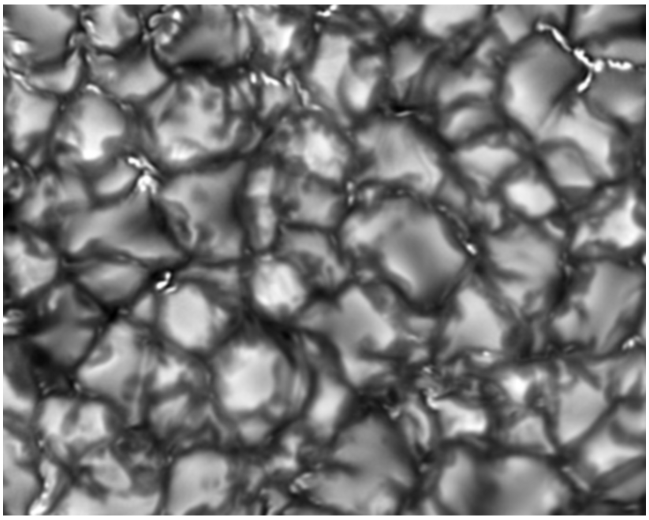

Fig. 1: High resolution image of solar granules acquired by Vasco Henriques on May 23, 2010 using the Swedish 1-m Solar Telescope (SST). "*The SST is operated on the island of La Palma by the Institute for Solar Physics of the Royal Swedish Academy of Sciences in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias*", http://www.solarphysics.kva.se.

plain why the spots (that are places where these clouds are torn) show less light and less heat, even if the temperature is the same. The excellent results obtained by Magnus, who has proved that a solid immersed in an incandescent gas becomes more radiant in heat and light than the same gas, seem to lend support to this hypothesis, which reconciles the rest of the known solar phenomena" [17]. With Secchi's words, others quickly followed suit [2, 25] and the Sun became viewed as having a gaseous body [2]. Such was the authority of Father Angelo Secchi in astronomy.

Objects which appeared as "*rice grains*" or "*willow leaves*" on the Sun's surface offered a rather poor foundation for scientific advancement. Chacornac would distance himself from these concepts: "*As to the form of the objects observed a subject so warmly discussed at the present time — I did not see, with the large instrument of the Paris Observatory, nor have I ever yet seen, that the form is limited to one only, either "willow leaf" or "rice grain". I have always seen the "crystals" of the photospheric atmosphere entangled (enchevêtrés) in a thousand ways, and connected among themselves by one or many points in their peripheries; I have always observed these photospheric clouds affecting forms reminding one of the flocculent mass in an incandescent metal, in suspension in a liquid… I have always in my descriptions compared the "crystals" of the photospheric matter to this silver solder in a state of fusion*" [25]. With these words, Chacornac became one of the first to invoke crystalline structure on the surface of the Sun. In the same letter [25], he echoed Secchi's model published in *Les Mondes* [17] three days prior, without properly referencing Secchi: "*… they constitute one of the essential conditions of the nature of this luminous matter, of which the elements are contained in the exterior atmosphere of the Sun as vapour is contained in our air*" [25]. Chacornac's description of the crystalline structure of granules would be revisited using theoretical analysis, more than 130 years later [35].

Scientists of the 19th century advocated that convection currents were the cause of granular formation. Gaseous material rose from deep within the Sun and then condensed on the photospheric surface before sinking once again in the gaseous atmosphere back towards the interior. The modern gaseous models promote similar hypotheses, but do not permit the condensation of matter. In 1881, Hastings described granules as follows: "*In our theory, then, the granules are those portions of upward currents where precipitation is most active, while the darker portions, between the bodies, are where the cooler products of this change with accompanying vapors are sinking to lower levels*" [36]. The convective nature of the granular field was well recognized, even though solar physicists lacked the mathematical tools required to address such problems.

2.2 Modern concepts of granules

The careful analysis of the solar granulation is important, as such studies reveal that the photosphere possesses objects with defined structures. The presence of such features provides compelling evidence that the Sun is constituted from condensed matter. Today, the study of solar granulation involves sophisticated image acquisition (see Figure 1) and data processing [14, 15, 35, 37–51]. Granules are widely regarded as the result of convective phenomena, wherein subsurface heat is being transported to the solar surface [14, 15, 37, 44, 50]. Convective processes move material upwards within the granule. Following radiative cooling, matter then sinks into the intergranule lanes [43]. The velocities of up and down flows can reach 1200 m/s in granular centers and intergranular lanes [43]. According to the gaseous models of the Sun, once the material reaches the surface layer, radiative heat losses result in greatly lowered opacity and the atmosphere of the Sun becomes transparent [37].

Granules vary in size from ~0.3–4 arcsec with most having a rough diameter of 1–2 arcsec giving a mean of ~1.35 arcsec (~1,000 km) [14, 37, 38]. Del Moro finds that no granule has an area larger than 1 Mm^2 [48]. Other investigators obtain maximal values in the 3-5 Mm^2 range [38, 45]. Small granules are very numerous, but they do not account for much of the solar surface [38]. They tend to be concentrated in downdraft regions, whereas the larger granules are located in areas of strong up currents [45]. The intergranular distance is on the order of 1.76 arcsec [38] and by some measures the darker intergranular lanes account for about 32% of the solar surface [42]. Conversely, Abdussamatov and Zlatopol'skii report that on a mesogranular scale (see below) the intergranular lanes can occupy as much as 55% of the photospheric area [44]. Roudier and Muller provide an excellent review of many key facts relative to granules [38]. The structures tend to be irregular in shape, although they can be properly described as polygons with a slight prevalence of pentagons over hexagons [35].

If the log of the number of granules of a given size is plotted against the log of their area, two distinct lines can be used to fit all granules with a critical diameter of 1.31 arcsec (see Figure 7 in [38]). This suggest that "*granules are self-similar*" [15, 38, 45] which then implies structure. Smaller granules fit the first line and are thought to be produced by turbulent phenomena of a "*Kolmogorov-type*" [38]. Because they are believed to be the result of turbulent eddy motions, Roudier and Muller argue that these small structures should be viewed as "*photospheric turbulent elements*" [38], an idea consistent with their more prevalent occurrence in the downdraft regions [44]. Conversely, they state that only medium and larger structures should be viewed as true "*granules*" as these alone properly transport convective energy [38].

Mean granular lifetimes range from ~5 minutes to 16 minutes with a maximum of approximately 30 minutes [14, 46]. Granules are subject to three evolutionary mechanisms. Most often, they are produced through the fragmentation of larger systems [39, 40, 46, 49]. They often "*die*" through the merger of smaller entities [46]. They seldom appear from, but frequently dissolve into, the background [46]. The larger granules tend to have the largest lifetimes [48]. Granules that are "*long lived*" have a tendency to form clusters [49]. Dark dots often form within granules and these result in violent fragmentation of the structure producing "*exploding granules*" [39, 47, 51]. The formation of these dark dots results in fragmentation within a couple of minutes and the features have no link to magnetic fields [39, 47]. Only very large granules explode [48]. Exploding granules are often very bright, initially suggesting the upward flow of matter followed by great expansion [39]. Their dark dots eventually evolve into intergranular dark regions which are indicative of downward flow even though some have argued, using opacity arguments, that dark dots represent upward material displacement [40].

Mark Rast proposed that exploding granules "*can be better understood if granulation is viewed as downflow-dominated-surface-driven convection rather than as a collection of more deeply driven upflowing thermal plumes*" [51]. Though not mentioned by Rast, such an idea would benefit from the presence of a real solar surface which only a condensed model of the Sun could provide [52].

The smaller the granule, the more likely it is to die without fragmentation or merging [40]. Conversely, if the granule is large, it is likely to merge or fragment [40]. The brightest region and the strongest upflows within large granules tend to be near the intergranular lanes and consequently are not located near the center of the structure [53]. A family of granules shares either fragmentation or merging and can have a lifetime approaching 46 minutes [40].

Granules can be organized into larger assemblies: mesogranulation, supergranulation, and giant cells [41–45]. Such assemblies share common and simultaneous changes in size, temperature, or other parameters [43]. Mesogranulation areas usually tend to be brighter, more dynamically active [42]. They are thought to represent a greater uplifting of matter and can span from 6–9 arcsec [43] and have lifetimes ranging from 30 minutes to 6 hours [48]. They are viewed as connected to common convective origins located at depths of 3,000–8,000 km [43]. Supergranular cells are believed to have their origins at depths of 20,000–30,000 km, while giant cells might stem from convective processes located as deep as 200,000 km below the surface [43]. These hypothetical depths are inherently linked to the gaseous models of the Sun.

Giant cells divide successively into supergranular and mesogranular structures [43]. However, Rast believes that mesogranulation and supergranulations are "*secondary manifestations of granulation itself*" [51]. He provides an excellent review of the solar granulation and these structures [53]. Granules tend to have limited vertical flows on the order of 1 km/s while the mesogranulation with their ~5,000–10,000 km diameters, can have flows approaching 60 km/s [53, 54]. Ikhsanov et al. suggest that the solar surface supports protogranules which are intermediate in size between granules and mesogranules [54]. Supergranulations possess diameters of ~30,000 km, display a 20 hour lifetime, and can manifest horizontal flows on the order of 400 km/s [53]. Such horizontal flows are contrary to a fully gaseous model of the Sun, as highlighted by the author (see §10 in [55]). Recently, Arkhypov et al. have found that Kolmogorov turbulence determines large scale surface activity on the photosphere [56] and claim these indicate that sub-surface convection motion can be detected through photospheric activity of supergiant complexes.

Granules display varying emissivities, but most studies simply report values for the granules and the intergranular lanes (e.g. [44] reports +8±7.5% for granules and −7±5.5% for the intergranular lanes). These descriptions appear to be over simplified as a smooth transition exists between the maximum brightness of a granule and the darkest point of the intergranular lane. As a result, considerable variability can be expected in such values.

Center to limb variations in granular intensities have also been investigated [57, 58]. Initially, Hidalgo et al. reported that granular contrast increased slightly towards the limb up $\mu = 0.6$, followed by a decrease in contrast moving further away from the solar center [57]. It is not clear if this change was due to an increase in brightness. Later, in a wavelength dependent study (0.8 μm and 1.55 μm), Cuberes et al. observed a monotonic decrease in contrast from the center of the solar surface ($\mu = 1$) towards the limb ($\mu = 0.3$) [58]. The change was steeper at the lower wavelength [58]. No peak was observed in contrast variation at either frequency [58]. The contrast at the center of the solar surface was dependent on wavelength, with larger contrast (6.1%) at 0.8 μm, while only 2.9% at 1.55 μm [58].

Title et al. [59, 60] have studied the formation of granules in association with magnetic fields and discovered significant differences relative to size, intensity variation, and lifetime.

Recently, Getling et al. published a series of stunning reports implying that the solar surface possesses a series of ridges and trenches [61–64]. On first inspection, the results appear valid and the authors have gone through considerable lengths to eliminate artifacts [64]. If these findings are genuine, they suggest that the solar surface contains "*quaziregular*" structural systems of great breath and regularity [61–64]. Nonetheless, it is currently unclear if these fascinating results will withstand scrutiny. If so, they would constitute additional support for the condensed nature of the photosphere.

Solar granulations have been the subject of intense theoretical work (e.g. [65]). From the onset [66–68], such studies have been subject to the charge that they can, at times, constitute "*little more than an exercise in parameter fitting*" [67]. Clearly, the gaseous models of state do offer significant flexibility with respect to the number of usable parameters [69]. Given enough variables, fits can almost always be achieved. Nonetheless, this brief review of solar granulation reveals that these elements are filled with structural properties based on size, behavior, and lifetimes. In this regard, it is instructive to consider how solar granulations conform to the laws of convection, turbulence, and structure as obtained in condensed matter (see §3, §4, and §5).

3 Granules and the laboratory

The analysis of granulations as convective processes has always rested on the science of liquids. In 1900, Bénard convection was first observed in the liquid state [70, 71] and the process continues to be a property of condensed matter. Bray et al. re-emphasized that Bénard convection was dominated by surface tension, not buoyancy [14, p.116].

Bénard (or Bénard-Marangoni) convection [72–74] is characterized by hexagonal structures. In fact, such features are properties of both Bénard convection [70–74] and many solar granules [14]. It is difficult to discount the presence of these structural elements on the surface of the Sun as coincidental, even though many solar physicist deny the presence of Bénard convection. Yet, even the laws of Kolmogoroff turbulence are strictly applicable only to an *incompressible* fluid [14, p.14], a framework well-beyond that afforded by the gaseous Sun. Still, since solar physicists currently endorse a gaseous model of the Sun, granular convection has always been viewed as a buoyancy driven phenomenon. Bénard convection cannot occur on the surface of the Sun if a gaseous body is to be preserved. To propose otherwise automatically requires surface tension, an impossibility for gaseous models. Nonetheless, it is particularly troubling that most laboratory experiments used to treat granulation have been performed on incompressible liquids [14, p.116]. To avoid surface tension, experimentalists study incompressible liquids placed between rigid plates [14, p.116]. Such a setting is hardly the equivalent of the hypothetical and illusionary gaseous solar surface.

4 Granulations and crystal structure

Beyond these applications of liquids to the treatment of granular convection, Noever has used the methods of statistical crystallography to analyze the solar surface [35]. He has reported that the granular field displayed a remarkable similarity to crystals [35]. Solar granulation followed both the laws of Aboav-Weaire and of Lewis [75–77] for space filling structures in two dimensions. The agreement with the Aboav-Weaire law had an R value of 0.998, indicating "*a correlation which does not extend beyond the nearest neighbor cells*" [35]. Noever also found that granules followed the perimeter law, suggesting that many sided structures have larger perimeters ($R = 0.987$) [35]. Adherence to the perimeter law implied that "*energy is carried by the cell boundaries*" [35]. Noever stated: "*It is particularly noteworthy that prior to grain fragmentation, a dark region of low luminosity typically appears near this predicted low energy core of each cell. The perimeter law predicts this outcome derived not from any specific fluid parameters but from a statistical picture of lattices alone*" [35]. With these words, Noever accounted for the origin of exploding granules without any recourse to convection, based solely on structural energy considerations. Structure led to behavior and this directly implied that the granulations are condensed matter. Noever further demonstrated that granules obey Lewis' law which relates two dimensional area and cell sidedness ($R = 0.984$) [35]. This places a restriction on granulation based on the need to fill two dimensional space entirely [35]. Gases cannot assume two dimensional space filling forms and cannot follow the laws of structure. Liquids alone can truly account for the convective and structural nature of granules.

Regrettably, Noever's work has been largely neglected [78–81] receiving only one citation relative to solar science [81]. Nonetheless, it represented a critical contribution in the understanding of granulations, precisely because it implied that granules are condensed matter.

5 Emissivity: A common link for solar surface structures

5.1 Metals and sunspots

Non-metals are known to possess directional spectral emissivities which monotonically decrease with increasing angle as illustrated schematically in Fig. 2 [82–84]. Their normal emissivity is typically higher than their directional spectral emissivity. Conversely, metals tend to have lower normal spectral emissivities relative to their directional spectral emissivities. For metals, the directional spectral emissivities usually rise with increasing angle until they fall precipitously as

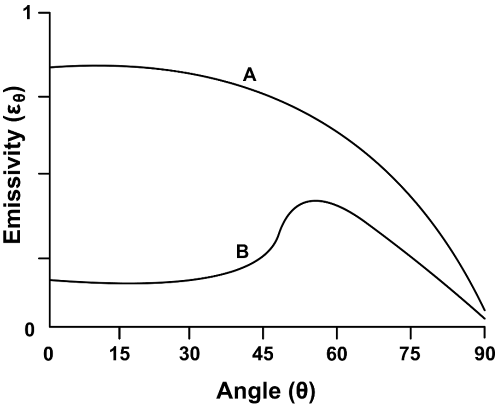

Fig. 2: Schematic representation of directional spectral emissivities for non-conductors (A) and conductors (B). Note that in non-metals, the spectral emissivity decreases monotonically with viewing angle. Conversely, in metals, while the normal emissivity can be substantially reduced, the emissivity can rise with increasing angle before precipitously dropping (adapted from [83]).

orthogonal viewing is approached [82,83]. These simple considerations provide tremendous insight to the structure of the photosphere in the context of a condensed solar model [52].

Consider the liquid metallic hydrogen model of the Sun [52]. When first proposed [85], liquid metallic hydrogen was hypothesized to assume a layered graphite-like structure. This lattice was subsequently adopted for the solar photosphere [52].

Since graphite itself is a great emitter, but only a modest conductor, one can hypothesize that liquid metallic hydrogen on the surface of the Sun is not highly metallic [52]. The inter-atomic distance in the lattice must be such that the photosphere displays little metallic character, but great graphite-like emissivity. This would correspond to the Type-I lattice structure previously discussed by the author [52, 55]. However, within sunspots, the interatomic distance would contract and liquid metallic hydrogen would increase its metallic character while at the same time, lowering its emissivity. In the limit, this would correspond to the Type II lattice [52].

The point can be amplified by examining the emissive behavior of sunspots with respect to magnetic field intensity [86, 87]. Leonard and Choudhary have reported that the emissivity of sunspot umbral regions drops with magnetic field strength suggesting the approach to a saturation limit (see Figure 2 in [86]). They stated: "*Although there is a large scatter, it is tempting to infer that the sunspot umbral intensity attains a maximum value beyond which the magnetic field increases without substantial intensity drop, resulting in a 'saturation effect'*" [86]. While more data of this nature is required, these preliminary findings imply that a limiting structural lattice might be reached within sunspots.

Sunspots are known to have substructure [88] and, as they can be the source of powerful magnetic fields [89], such observations [86] further support the notion that they are metallic in character [52]. The dark nuclei of sunspots clearly have lower emissivities and possess the highest magnetic fields [8, p.80]. Conversely, the light bridges display higher emissivities and lower magnetic fields [8, p.85–86], implying that they are less-metallic in character. The dark cores detected in sunspot penumbral filaments might be a reflection of increased metallicity in these elements [90].

Supportively, helioseismology reveals that sound waves travel much faster through sunspots than through normal photospheric matter [91, 92]. This suggests that the modulus of elasticity is higher within sunspots, in accordance with the hypothesis that the material is both more metallic and slightly denser than photospheric matter.

Consequently, greater attention might be placed on evaluating directional emissivity within sunspots. Measurements from these regions are already giving hints that emissivities may be increasing with angle of visualization. This is reflected in the "*problems of stray light*" into the sunspots [8, p.75–77]. The effect of "*stray light*" acts to increase the observed emissivity of sunspots in precisely the same manner that an increased metallic character would produce (see Eq. 8 in [8, p.75]). As a result, such data may already be affirming the metallic character of sunspots by mimicking the behavior manifested in Fig. 2. "*Stray light*" arguments might have been introduced simply to address a finding which could not be explained otherwise by the gaseous solar models. The observation of large sunspots at high resolution should enable scientists to clearly establish the directional emissivity of sunspots without any "*stray light*" effects and thereby possibly affirm their metallic nature.

It is appropriate to consider that sunspots might represent liquid metallic hydrogen whose lattice density has increased along with a corresponding rise in metallic nature: the stronger the metallic character, the stronger the associated magnetic fields and the weaker the emitted light intensity. This is precisely what one observes in sunspots [86]. Emissivity is strongly dependent on magnetic field intensity. As magnetic field intensity increases, sunspot emissivity progressively falls until a plateau region appears to be reached [86]. This would correspond to the limit of compressibility of the lattice. Beyond this point, liquid metallic hydrogen should become essentially incompressible, the Type II lattice having been reached.

Along these lines, it is interesting to note that liquid graphite displays two lattice forms which differ in spatial dimensions, densities, and metallic character [93]. Liquid graphite [93] appears to provide an interesting parallel with the two structural lattice Types required in a liquid metallic hydrogen model of the Sun [52].

These results can only be explained with difficulty using the gaseous models. After all, the presence of magnetic fields by themselves can have no effect on emissivity. It is well known that a piece of iron does not change its emissivity on becoming magnetized. Emissivity changes demand changes in structure [94] and the gaseous solar models afford none.

5.2 Emissivity, granulation, and limb darkening

Frank Very was the first to monitor the limb darkening of the Sun [12] as a function of frequency. Very examined the photosphere at 7 wavelengths ranging from 0.416 μm to 1.5 μm [12]. He found that limb darkening was much more pronounced at shorter wavelength [12]. Since that time, extensive studies of limb darkening have been performed (e.g. [9–11]). Pierce and his collaborators provided an detailed list of coefficients for polynomial representations of limb darkening spanning a wide range of frequencies [9, 10]. Overall, these functions demonstrated that the photosphere behaves as a non-metal.

Today, limb darkening constitutes a central pillar of the gaseous solar models. The phenomenon remains linked to solar opacity arguments [95]. Nonetheless, when Very first considered the frequency dependence of limb darkening [12], he did not ponder only upon opacity arguments. He questioned whether limb darkening could be explained by the granulated aspect of the solar surface [12].

Solar granules display emissive characteristics which change towards their periphery as the dark intergranule lanes are reached. They also display center to limb variations [57, 58]. In fact, it is likely that the same phenomenon is being observed both locally near the granules and over the expanse of the entire solar surface as the limb is visualized. Granules manifest a brightness which fades in the intergranule lanes in the same manner as darkening manifests itself from the center of the solar body to the limb. As such, higher spatial resolution on granules may soon reveal that they individually exhibit the same features as observed globally in limb darkening. This would be expected if the emissivity of the Sun simply reflected the constitution of its condensed surface. Each individual granule would become a local manifestation of the limb darkening observed over the entire solar disk.

6 Conclusions

From the days of their discovery by William Herschel [34], granules have offered solar science a vast and fascinating array of structural forms which follow specific evolutionary paths and predetermined timelines. By every measure, granules are real entities, not illusions. They obey the laws of two-dimensional structures and manifest themselves as objects which can be analyzed, categorized, and mathematically evaluated. They appear and behave as condensed matter.

Conversely, a gaseous Sun should be devoid of structural elements: sunspots, granules, prominences, and flares which rupture the solar surface. It should be a blob, a haze, a nondescript mass — not a body filled with structure, as Secchi so elegantly described in his classic text [21]. A brief study of granulations and sunspots demonstrates that these are real structures which follow in every manner the behavior of condensed matter. The issues are not only structural, but involve the ability to have variable emissivities and powerful magnetic fields. On the Earth, the generation of strong magnetic fields remains associated with metallic character [55]. Gases can never produce magnetic fields of themselves. They simply respond to such phenomena.

The fact that sunspots possess strong magnetic fields might guide the synthesis of liquid metallic hydrogen on the Earth [52]. If the Sun is really made of liquid metallic hydrogen, then our study of sunspots implies that the material is easily endowed with magnetic properties. Therefore, it is possible that the synthesis of metallic hydrogen on the Earth could benefit by placing the entire experimental setting within a modest magnetic field on the order of 0.5 Tesla. This would correspond to the maximal 5,000–6,000 gauss field observed within sunspots [86, 87]. Large bore human magnetic resonance imaging (MRI) magnets currently operate up to fields of 9.4 Tesla, thereby confirming that suitable magnet technology exists for such studies [96].

At the same time, it is clear that the proper study of granular and sunspot emissivity will require much stronger optical space telescopes devoid of the "*seeing problems*" [1, p.23–25] when visualizing the Sun from the Earth. Resolutions must be increased tremendously such that emissivity can be properly mapped across an individual granule or sunspot umbra. When studying granulations, such maps should be married with Doppler imaging of the solar topology in order to link emissivity to angular changes in the surface. In this manner, solar physicists should be able to directly associate observed darkening with the emissive behavior of the solar surface itself, whether locally on the granular scale, or globally, as observers compare the solar center to the limb. In addition, the study of directional emissivities in sunspots should eventually affirm their metallic nature making investments in powerful space solar telescopes vital to the proper understanding of the solar surface.

As we continue to ponder the nature of the Sun, it is appropriate to close by recalling the brilliance of Father Secchi as an astronomer. Above all, Secchi valued observations. He painstakingly generated drawings of the Sun in an attempt to describe solar structures. Through his writings, he demonstrated that observation must lead theory. Short of data, we know nothing of the Sun. Therefore, should solar physics advance, the tradition of careful observation which Secchi inspired must be imitated. Even 140 years after the publication of *Le Soleil* [21], Secchi continues to astound, as Sobotka highlights [8]: "*In 1870 appeared the first edition of a fundamental work in solar astronomy by P. A. Secchi: Le Soleil. Most of the basic concepts of the sunspots' morphology can be found there. Secchi made his visual observations from 1865 to 1870 with a resolution approaching to* $0''.3$ *in some cases. In his wonderful drawings he presented not only the basic morphological features like multiple umbrae,* *light bridges, and penumbral filamentary structure, but also "knots" in bright penumbral filaments (penumbral grains) and internal structure of light bridges. He also noticed spatial variations in umbral brightness and the darkest regions — "holes" — in the umbra (dark nuclei). In three of his drawings even some umbral dots can be seen, although he did not describe them*". Now, endowed with the gifts of modern technology, solar physicists must be better equipped to properly describe what Secchi himself could only observe in awe using a simple telescope.

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Dedication

Cet ouvrage est dédié à celles qui ont été parmi mes premières enseignantes, les Filles de la Sagesse.

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