# Stellar Opacity: The Achilles' Heel of the Gaseous 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

The standard gaseous model of the Sun is grounded on the concept of local thermal equilibrium. Given this condition, Arthur Milne postulated that Kirchhoff's law could be applied within the deep solar interior and that a blackbody spectrum could be generated in this region, based solely on equilibrium arguments. Varying internal solar opacity then ensured that a blackbody spectrum could be emitted at the photosphere. In this work, it is demonstrated that local thermal equilibrium and solar opacity arguments provide a weak framework to account for the production of the thermal spectrum. The problems are numerous, including: 1) the validity of Kirchhoff's formulation, 2) the soundness of local thermal equilibrium arguments, 3) the requirements for understanding the elemental composition of the Sun, and 4) the computation of solar opacities. The OPAL calculations and the Opacity Project will be briefly introduced. These represent modern approaches to the thermal emission of stars. As a whole, this treatment emphasizes the dramatic steps undertaken to explain the origins of the continuous solar spectrum in the context of a gaseous Sun.

## 1 Introduction

The mechanism by which the solar spectrum is produced has long preoccupied astrophysics [1–4]. Though Langley established that the photosphere's emission [5–7] generally conformed to a blackbody lineshape [8,9], two lines of reasoning initially prevailed as to its formation. It was hypothesized that the photosphere contained condensed carbon [1, 2], as graphite was the premier blackbody source on Earth [3, 4]. Alternatively, it was believed that the pressure broadening of hydrogen could account for the spectrum [1, 2]. Although Kirchhoff had formulated his law of thermal emission in 1859 [10], observational astronomers appeared dissatisfied with the idea that Langley's spectrum [5–7] could be produced by assuming thermodynamic equilibrium and enclosure [9, p.1–45]. They insisted on placing carbon particles on the Sun for sixty years [1,2] and essentially dismissed any notion that Kirchhoff's law afforded a sufficient framework to generate the solar spectrum.

It would take the work of men [11] like Schuster [12], Schwarzschild [13], Eddington [14–17], Rosseland [18, 19] and Milne [20–23] to finally remove graphite from the Sun [2]. These communications [12–23] formed the foundation of radiation transfer within stars. They consequently came to represent the heart of modern stellar physics. As a group, these authors used elegant approaches, but without exception [12–23], their mathematical treatments relied on thermal equilibrium and the validity of Kirchhoff's law [10]. In addition, since the standard model of the Sun was deprived of condensed matter, astronomers would have to account for the production of the solar spectrum with physical atoms, ions, and electrons. Graphite was gone, but the theoretical alternative, solar opacity arguments, provided a questionable replacement.

## 2 Kirchhoff's law and local thermal equilibrium

Arthur Milne [2] was perhaps the first to advocate that the interior of the Sun could be regarded as existing in a state of local thermal equilibrium [20–23]. Milne's definition became central to astrophysical thought and will, therefore, be largely recalled: "*It is convenient to have a phrase to describe the circumstances under which the relation $j_\nu = k_\nu B_\nu(T)$ holds exactly. When a small portion of matter has a definite temperature $T$, and is behaving, i.e. emitting, as if it formed a part of an equilibrium enclosure at temperature $T$, we shall say that it is in "local thermodynamic equilibrium" at temperature $T$. We shall examine later in particular cases the conditions under which material is in local thermodynamic equilibrium. It is not necessary that the temperature shall be uniform. In an non-isothermal state, we may still have local thermodynamic equilibrium everywhere. The temperature may vary from point to point, but each point may be characterized by a definite temperature $T$ and the element of matter at each point may be behaving as if in thermodynamic equilibrium at temperature $T$*" [23, p.81]. Milne's treatment was centered on Kirchhoff's law: $j_\nu = k_\nu B_\nu(T)$ [10]. Nonetheless, there was a risk that Milne's setting was so broad that virtually any non-equilibrium process, no matter how violent, could be considered in local thermal equilibrium, provided that sufficiently small volumes of matter were being considered. No restriction was placed on confirming the validity of these arguments.

Much like Milne, Chandrasekhar described local thermal equilibrium as follows: "*. . . we often encounter physical systems which, though they cannot be described as being in rigorous thermodynamical equilibrium, may yet permit the introduction of a temperature $T$ to describe the local properties of the system to a very high degree of accuracy. The interior* *of a star, if in a steady and static state, is a case in point. For, even if the temperature at the center of the Sun, for instance, were* $10^8$ *degree, the mean temperature gradient would correspond to a change of only 6 degrees in the temperature over a distance of* $10^4$ *cm. This fact, coupled with a probably high value for the stellar absorption coefficient, enables us to ascribe a temperature T at each point P such that the properties of an element of mass in the neighborhood of P are the same as if it were adiabatically inclosed in an inclosure at a temperature T*" [24, p.205]. Similar points were raised in Clayton's classic text [25, p.175]. These discussions were focused strongly on assumptions which pertain to a gaseous model.

On the surface, it would seem that Chandrasekhar's temperature gradient of only 6 degrees across 100 meters could be considered quite small [24, p.205]. Yet, the oceans of the Earth sustain convection currents based on much smaller temperature gradients. In fact, oceanographers might reject equilibrium arguments globally for the oceans, even though these temperature gradients are on the order of just a few degrees over spans of thousands of kilometers. The oceans contain convection currents as a direct manifestation of their lack of thermal equilibrium. Convection precludes the existence of equilibrium. As a result, a temperature variation of 6 degrees over a span of 100 meters should be treated as an enormous temperature gradient, not a condition approaching thermal equilibrium. The oceans demonstrate that Chandrasekhar's conditions, even if relaxed 1,000 fold, would still constitute powerful driving forces for convection, thereby eliminating all possibility of viewing the solar interior as existing in a state of thermal equilibrium.

Well before the days of Chandrasekhar, Milne elaborated further on local thermal equilibrium in the gaseous framework: "*The interior of a star is in a state of local thermodynamic equilibrium of this character. As we approach the boundary from the inside, the state of local thermodynamic equilibrium gives place to an entirely different state, in which the influence of external radiation on an element is paramount. It will be shown that when an element at temperature T is subjected to radiation, which is not black radiation of temperature T, the extent to which it behalves as if in thermodynamic equilibrium locally depends on the relative importance of collisions as a cause of atomic absorptions and emissions. If the atoms are sufficiently battered about by colliding with one another, they assume a state (distribution of stationary states) characteristic of thermodynamic equilibrium at temperature T; if they are not sufficiently battered about, their "temperature" becomes irrelevant and they emit and absorb at a rate which is determined by the incident radiation. It is clear that collisions will be the more numerous, and therefore likely to be more effective, the higher the density. This permits us to see in a general way why the state of local thermodynamic equilibrium in the interior of a star breaks down as we approach the surface...This assumption will certainly be satisfied in the far interior, since in the limit at great distances the conditions are those of an enclosure... It follows that the intensity of radiation at* $d\sigma$ *in the direction* $\theta$ *is* $B_\nu(T)$*, the intensity of black radiation for temperature T*" [23, p.81–83].

The argument advanced by Milne was framed in the context of the laws of gases. Milne saw the rapid collisions occurring at the center of the Sun as sufficient to establish equilibrium, but the requirements set forth by Kirchhoff [10] and Planck [8, 9] required something more significant. They demanded that the walls of the enclosure be rigid [9].

If a gas is highly compressed, the collisions with neighboring particles will enable the flow of heat through conduction. Gold has a density of 19.3 g/cm$^3$ [26, p.12–205] and many solids [26, p.12–80] have densities which are just slightly more than one order of magnitude (about a factor of 30) below the 150 g/cm$^3$ currently hypothesized for the center of the Sun [27, p.10]. When heat enters solids, it can travel through conduction, either thermally through its vibrational lattice or electronically through its conduction bands. Clearly, gases cannot sustain conduction bands, but they are subject to thermal conductive processes, especially at these densities. As such, when an atom in the gaseous model vibrates at the center of the Sun, it can transfer its energy to its "*non-rigid*" neighbor. Milne cannot assume that the atoms at the center of the Sun are devoid of collisional energy exchange, precisely because the atoms are not rigid. The center of the Sun cannot meet the requirements for a rigid enclosure as set forth by Kirchhoff and Planck [8–10]. The arguments of enclosure and "*local thermal equilibrium*" are invalid based on these considerations.

At the same time, Planck required that the source of blackbody radiation was found in material particles. Planck's entire *Heat Radiation* [9] was based on the analysis of a material oscillator not present at the center of the gaseous Sun: "*For among all conceivable distributions of energy the normal one, that is, the one peculiar to black radiation, is characterized by the fact that in it the rays of all frequencies have the same temperature. But the temperature of a radiation cannot be determined unless it be brought into thermodynamic equilibrium with a systems of molecules or oscillators, the temperature of which is known from other sources. For if we did not consider any emitting and absorbing matter there would be no possibility of defining the entropy and temperature of the radiation, and the simple propagation of free radiation would be a reversible process, in which the entropy and temperature of separate pencils would not undergo any change. Now we have deduced in the preceding section all the characteristic properties of the thermodynamic equilibrium of a system of ideal oscillators. Hence, if we succeed in indicating a state of radiation which is in thermodynamic equilibrium with the system of oscillators, the temperature of the radiation can be no other than that of the oscillators, and therewith the problem is solved*" [9, §144].

Max Planck required that a perfect absorber be present in order to produce blackbody radiation. Milne neglected this important line from *Heat Radiation*: "*Hence in a vacuum bounded by totally reflecting walls any state of radiation may persist*" [9, §51]. Planck then argued that, if an arbitrarily small quantity of matter was introduced, the radiation in the enclosure will change to a new state. However, it will not be a blackbody state unless the substance is not transparent for any frequency. Planck chose a piece of carbon to ensure blackbody radiation [9, §51]. The desired radiation does not simply appear [9, §51], as Milne and his contemporaries surmised. The presence of an enclosure, by itself, could never satisfy the requirements for the production of blackbody radiation. Planck insisted throughout *Heat Radiation* on the need for a physical oscillator and he reminded his readers that only "*material particles*" can be involved in emission [9, §4] and absorption [9, §12]. A physical oscillator which acted as a perfect absorber must be present. Milne has not advanced such a species at the center of the Sun.

Instead, Milne, like Schuster [12], Schwarzschild [13], and Eddington [14–17] before him, automatically presumed that the invocation of Kirchhoff's law provided sufficient proof that the interior of the Sun harbored black radiation, despite the absence of the rigid enclosure required by Kirchhoff [10]. Blackbody radiation was inserted at the center of the Sun without any requirement on the material generating the needed photons. All that was required was enclosure (even if not strictly rigid) and a newly hypothesized "*local thermodynamic equilibrium*". For Milne, the presence of an enclosure was insured by the hypothesis that the density at the center of the Sun was sufficiently elevated to restrict photonic and atomic diffusion [20–23].

In reality, Milne's idea fell far short of the requirements to produce blackbody radiation. He was considering a setting where conduction, not radiation, could dominate heat exchange. Consequently, his arguments relative to radiative heat transfer were without strong scientific justification. Milne had neglected the observation that the collision of adjacent atoms constituted the universally accepted exchange mechanism for thermal conduction, not equilibrium. It was for this reason that Planck insisted on a rigid enclosure.

A careful review of blackbody radiation has revealed that the production of such a spectrum always requires the presence of a perfect absorber [3]. Planck himself constantly brought forth the carbon particle as inherently linked to the validity of his arguments [3]. Kirchhoff's reasoning that an adiabatic enclosure could contain black radiation has been exposed as flawed and his law of thermal emission as erroneous [3, 4, 28–30]. The universality of blackbody radiation simply does not exist [3, 4, 28–30]. Yet, even if Kirchhoff's law was valid, Milne's argument was fallacious, as he lacked both the rigid enclosure and the materially perfect oscillator required by Max Planck to ensure that a blackbody spectrum could be produced at the center of the Sun.

## 3 Solar and stellar opacity

Solar opacity [22, 31, 32, 34–39] plays a vital role in all modern gaseous models of the Sun [24, 25, 40–46] and is currently at the center of our understanding of the stars. Therefore, the study of solar opacity has far reaching implications throughout modern astronomy.

Opacity, $\kappa$, refers to the ability of a material to absorb incoming radiation. Monochromatic opacity, $\kappa_\nu$, is associated with a single frequency. The extinction coefficient, $\alpha$ (cm$^{-1}$), is equal to the opacity, $\kappa$ (cm$^2$/g) multiplied by the density of the material, $\rho$ (g/cm$^3$).

To calculate opacity within the solar interior, solar physicists first accept that the Sun can radiate internally. By itself, this constitutes a notable departure from the rest of Earthly physics. For all objects on Earth, internal heat transfer occurs through conductive and convective paths, not internal radiation. Radiation allows objects to achieve thermal equilibrium with one another, not within themselves. As a result, the idea that the Sun transfers internal energy through radiation directly implies that astrophysics treats the solar interior as the sum of its individual atomic, ionic, and electronic species. The Sun as a single object does not exist in the gaseous models. Only in such a scenario would internal radiation permit the transfer of energy between the constituent objects which make up the Sun. Still, Milne required that, within the center of the Sun, atoms, ions, and electrons were packed such that collisions occur. This scenario rendered conduction probable, greatly impacting any radiative field.

In gaseous solar models, thermal photons at X-ray frequencies, with a characteristic blackbody appearance, are believed to be produced at the center of the Sun. Over the course of thousands of years, Eddington stated that these thermal photons slowly leaked out of the solar body [16]. As they traversed increasingly elevated layers of the solar mass, photons gradually lost some of their energy. The entire solar spectrum was shifting from the X-ray to the visible range, while preserving a blackbody appearance [16].

### 3.1 Opacity mechanisms

Stellar opacity involves the removal of energy from a beam of photons originating in the core of the Sun through four mechanisms: 1) bound-bound, 2) bound-free, 3) free-free, and 4) scattering processes (see [41, p.137–141] for an excellent description). Bound-bound processes rely on spectroscopic line absorption, either within an atom or an ion. Bound-free mechanisms result in the dissociation of a previously bound electron by an incoming photon. The electron becomes completely free of the atom or ion. Free-free processes are inverse Bremsstrahlung mechanisms, whereby a free electron and an ion interact during which time the combined species is able to absorb a photon [41, p.138]. In scattering mechanisms, the momentum of the photon is being transferred to a scattering electron. Theoretical astrophysics calculates opacities for the Sun by taking the summation of these processes, for all atoms, ions, and electrons at all temperatures within the solar interior.

The negative hydrogen ion was advanced as a significant determinant of solar opacity by Wildt [47]. The concept immediately received the support of Chandrasekhar who calculated that the negative hydrogen atom within the context of a gaseous solar model would contribute greatly to solar opacity in the 4,000–24,000 Å range [48–51]. Of course, the negative hydrogen ion spectrum extended over much of the photospheric emission (~2,500–25,000 Å).

Nonetheless, the negative hydrogen ion could never, by itself, generate the continuous solar spectrum with its characteristic thermal appearance. For gaseous models, the production of the thermal spectrum involves the slow conversion of a hypothetically X-ray blackbody spectrum produced in the solar interior to the visible spectrum observed at the photosphere. Thus, if a blackbody spectrum did exist at the center of the Sun, it would be characterized by a Wien displacement temperature of ~15,000,000 K. Such a spectrum would be centered in the X-ray region. It would then have to be gradually shifted, while always maintaining its thermal appearance, to much lower frequencies.

Consequently, astrophysics is requiring that a perfect mixture of atoms, ions, and electrons exists at all layers within the Sun. In each layer, these mixtures could then produce the desired local blackbody spectrum. Within each solar layer, a new perfect mixture must exist in order that its absorptive characteristics enable the production of a new shifted thermal spectrum.

Therefore, despite Chandrasekhar's findings [48–51], the computation of solar opacity has remained a tremendously complex undertaking. For example, the American astrophysics community has invested heavily in calculating the opacity contributions from neutral and ionized gases. In a project involving international collaboration, the Los Alamos National Laboratory led Opacity Project [33, 34] provided an absolutely phenomenal treatment of nearly every possible atomic species inside the stars, in widely varying states of oxidation. Similar findings have been obtained at the Lawrence Livermore National Laboratories. These studies have resulted in the OPAL opacity values [35–39], but none of the opacity mechanisms considered by these methods can be used to explain the origin of the blackbody spectrum in graphite. This suggests that these mechanisms are not truly related to the production of the solar spectrum.

### 3.2 Rosseland mean opacities

The determination of internal solar opacity values must be performed at each individual frequency of interest, since the production of a blackbody spectrum always remains frequency dependent. The problem becomes so overwhelming that astrophysics has chosen to adopt Rosseland mean opacities [18, 19]. Through Rosseland's approach, a single frequency independent value of opacity can be obtained for each solar level.

On the surface, it could be argued that Rosseland mean opacities merely reduce an otherwise intractable problem. They lower computational requirements and greatly simplify the presentation of opacity data. Rosseland mean opacities enable solar physics to sidestep the reality that, at each level of the solar interior, it is impossible to generate a purely blackbody spectrum with strict adherence to Planckian behavior at all frequencies. It is not feasible to build a blackbody spectrum from the sum of non-blackbody processes. For instance, during the computation stage, a single bound-bound transition will introduce a "*spike-like*" contribution in the calculated spectrum. Each "*spike*" being associated with line absorption. Such a "*spike*" must then be compensated by using the sums of processes (other bound-bound processes, or bound-free, free-free and scattering mechanisms) whose existence will always remain in doubt at the levels required to incorporate the initial "*spike*" into the final solution for the blackbody lineshape. The entire process becomes an exercise in parameter fitting, devoid of confirmatory physical evidence.

Still, Rosseland mean opacities remain at the heart of modern solar models [24, 25, 40–46]. Within each layer in the Sun, a mean opacity can be inferred based on expected atomic, ionic, and electronic species. However, the sum of the processes (bound-bound, bound-free, free-free, scattering) utilized in Rosseland mean opacity computations cannot be infinite. Thus, rather than analyze mean opacities, scientists can convince themselves of the futility of these approaches by taking the mean opacity solutions and using the same species and concentrations to calculate the associated *frequency dependent spectra*. Such solutions will not correspond to black body spectra. As a result, Rosseland mean opacities form a weak foundation for the gaseous solar models. The summation of numerous spectral processes which are individually unrelated to thermal radiation can never give rise to a truly black spectrum.

### 3.3 Elemental compositions

To further complicate matters, the computation of solar opacity, as a function of depth, requires that the elemental composition of the Sun [52] remains independent of spatial position. Such, a requirement can never be justified. Our current understanding of the solar composition rests, and will always rest, on that which can be evaluated at the level of the photosphere. All extensions of the solar composition to the solar interior and all claims of constant elemental constitution with depth should be regarded as scientific conjecture.

## 4 Conclusion

Through opacity considerations, solar physicists believe that an X-ray based blackbody spectrum, produced at the center of the Sun, can be emitted at the solar surface in the visible range. However, from the moment that the Sun was hypothesized to exist in the gaseous state in the mid-1800s, objections were raised as to the ability of gases to emit a blackbody spectrum [1]. The interior of a gaseous Sun was thought to be essentially transparent to radiation. This was the position advocated by Herbert Spencer when he complained that, if sunspots were openings in the photosphere, one should be able to see through them to the other side [1]. In fact, the same "*famous objection*" was voiced by Kirchhoff himself [1]. According to Kirchhoff, the interior of the Sun could only sustain blackbody radiation if it was surrounded by a condensed photosphere [1]. Kirchhoff well understood that no gas, in isolation, ever produced a blackbody spectrum. The presence of condensed matter was always required.

In support of Kirchhoff's liquid photosphere [1], there are numerous lines of evidence that the photosphere is condensed matter [53]. Granules, sunspots, and limb darkening provide additional evidence [56]. Sunspot emissivities are highly suggestive of metallic character [56] strengthening the case for condensed matter. All of these factors should be considered when advancing the proper phase of the photosphere and the mechanism associated with solar thermal emission.

Nonetheless, despite clear violations with regards to enclosure, thermal equilibrium, and the presence of a perfect absorber as required by Max Planck [9], solar physics has tried to account for the generation of the Planckian spectrum. Yet, none of the mechanisms advanced can be used to explained the simple thermal spectrum of graphite itself. In fact, although physics advocates an understanding of internal thermal radiation within the Sun, it has produced no mechanism by which the simplest earthly spectrum can be explained. This constitutes a powerful reminder that tremendous difficulties remain relative to the science of blackbody radiation [3, 4]. In the end, stellar opacity calculations represent a myriad of physical impossibilities. None of the suggested opacity mechanisms (bound-bound, bound-free, free-free, and scattering) are related to the emission of a single photon by graphite.

As such, beyond an inability to support structure, the shortcomings of any gaseous solar model rests on opacity. Even though Milne and his predecessors were incorrect in inferring that a blackbody spectrum could be produced at the center of the Sun, the gaseous models contain numerous other stumbling blocks on their way to generating a continuous spectrum at the solar surface. A truly remarkable thesis has been advanced to explain the photospheric spectrum within the gaseous model. In the end, astrophysics has championed a solution for obtaining the solar spectrum which cannot survive the careful scrutiny of the spectroscopic scientific community.

Each spectroscopic signature in nature is linked to a unique physical process. For instance, a Lyman or a Balmer series can only be produced by electronic transitions within the hydrogen atom. Similarly, atomic line spectra are unique to each individual elemental or ionic species. Nuclear magnetic resonance (NMR) spectra are obtained from particular spin transitions within a well defined physical and experimental context. Physics does not search for the Lyman series in NMR spectra. One process is electronic, the other nuclear. Within the gaseous Sun, modern astrophysics currently believes that it can produce the graphitic spectrum using processes which do not exist in graphite. It is improper to advance that a blackbody spectrum can be produced in the Sun using physical mechanism which are not present on Earth within all the blackbodies currently studied in our laboratories [3, 4]. The use of a nearly infinite sum of atomic, ionic, and electronic processes which can alter their absorption and emission precisely in a manner which preserves the blackbody appearance of the solar spectrum at all depths within the Sun represents a non-scientific exercise based solely on the desire to salvage the gaseous equations of state. It is well-known that thermal emissivity in gases can drop with increasing temperature. Neither pressure broadened gases nor any of the atomic, ionic, and electronic processes advocated in the interior of the Sun have a fourth power of temperature behavior. Furthermore, the gaseous models depend on knowledge of the internal constitution of the stars based on the solar elemental constituents. Mankind will always lack such information.

As a result, this work constitutes an invitation to reconsider the phase of the Sun [53–55]. The gaseous models suffer from two insurmountable weaknesses: 1) the inability to account for photospheric structures [56], and 2) the lack of a proper mechanism to generate the solar spectrum. Observational astrophysics has long documented the existence of features of the solar surface which demand the presence of condensed matter [56]. The belief that opacity arguments can account for the illusionary nature of the solar surface and all associated structures, discounts the realization that the photosphere also *behaves* as condensed matter [56, 57]. Helioseismology demonstrates that the Sun acts as a resonant cavity [53]. On Earth, resonant cavities are manufactured from condensed matter [4]. It is not reasonable to expect that a gaseous Sun can create an illusionary surface in the visible range using negative hydrogen ion opacity, while at the same time and in the same layer, produce a surface which is nearly perfectly reflecting for wavelengths which extend over many thousands of meters. Such are the requirements, if the Sun really acts as a resonant cavity [58, p.60]. Perfect resonators sustain standing waves which are never absorbed [4]. Accordingly, the photosphere of the gaseous Sun must be strongly opaque in the visible region while powerfully reflecting in the sub-audio. In addition, the gaseous models must account for the presence of transverse waves on the surface of the Sun when gases are known to sustain only longitudinal waves [53, 57]. It remains the case that seismology is a science of condensed matter [53]. To account for seismological behavior in a gaseous Sun using opacity arguments constitutes a significant departure from accepted Earthly physics.

Given the problems which surround solar opacity, it remains difficult to understand how the gaseous models of the Sun have survived over much of the twentieth century. Local thermal equilibrium does not exist at the center of the Sun. Both Kirchhoff and Planck require rigid enclosure which is not found in the Sun [9, 10]. Planck has also warned that the Sun fails to meet the requirements for being treated as a blackbody [59]. Milne's rapid collisional regime constitutes a path to conduction, not equilibrium [20–23]. Milne and his contemporaries cannot infer that a blackbody spectrum exists at the center of the Sun based on Kirchhhoff's law [10], even if the law was valid [60]. Unfortunately, not only does the Sun fail to meet the requirements for enclosure and local thermal equilibrium, but Kirchhoff's law itself is erroneous [3,4]. The production of a blackbody spectrum requires the presence of a perfect absorber. Max Planck appeared well-aware of this reality [3,59]. Gaseous opacity arguments will always fall far short of what was required. In the end, the mechanism used to generate the solar spectrum should be shared with graphite itself. The most likely physical cause remains the vibration of atomic nuclei within the confines of a layered graphite-like lattice [28, 55].

### Dedication

This work is dedicated to my sister, Lydia, and to her children, Fabienne and Louis.

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