

Polarized Light from the Sun: Unification of the Corona and Analysis of the Second Solar Spectrum – Further Implications of a Liquid Metallic Hydrogen Solar Model

Pierre-Marie Robitaille¹ and Dmitri Rabounski²

¹Department of Radiology, The Ohio State University, 395 W. 12th Ave, Columbus, Ohio 43210, USA
E-mails: robitaille.1@osu.edu¹, rabounski@ptep-online.com²

In order to account for the slight polarization of the continuum towards the limb, proponents of the Standard Solar Model (SSM) must have recourse to electron or hydrogen-based scattering of light, as no other mechanism is possible in a gaseous Sun. Conversely, acceptance that the solar body is comprised of condensed matter opens up new avenues in the analysis of this problem, even if the photospheric surface itself is viewed as incapable of emitting polarized light. Thus, the increased disk polarization, from the center to the limb, can be explained by invoking the scattering of light by the atmosphere above the photosphere. The former is reminiscent of mechanisms which are known to account for the polarization of sunlight in the atmosphere of the Earth. Within the context of the Liquid Metallic Hydrogen Solar Model (LMHSM), molecules and small particles, not electrons or hydrogen atoms as required by the SSM, would primarily act as scattering agents in regions also partially comprised of condensed hydrogen structures (CHS). In addition, the well-known polarization which characterizes the K-corona would become a sign of emission polarization from an anisotropic source, without the need for scattering. In the LMHSM, the K, F, and T-coronas can be viewed as emissive and reflective manifestations of a single coronal entity adopting a radially anisotropic structure, while slowly cooling with altitude above the photosphere. The presence of “dust particles”, advanced by proponents of the SSM, would no longer be required to explain the F and T-corona, as a single cooling structure would account for the properties of the K, F, and T coronas. At the same time, the polarized “Second Solar Spectrum”, characterized by the dominance of certain elemental or ionic spectral lines and an abundance of molecular lines, could be explained in the LMHSM, by first invoking interface polarization and coordination of these species with condensed matter in the chromosphere. The prevalence of polarized signals from the Rare Earth metals, a chemically unique group of the periodic table, provides powerful evidence, based on the “Second Solar Spectrum”, that chemical reactions and coordination are taking place in the atmosphere of the Sun. This concept is also supported by the polarized signal from lithium, an element previously hypothesized to assist in stabilizing metallic hydrogen structures. The possibility that some atoms are coordinated with CHS implies that the relative abundance of elements cannot be simply ascertained through the analysis of emission or absorption lines in the solar atmosphere.

... it follows that a body, which absorbs more rays from one plane of polarization than from another, sends out in the same ratio more rays from the first plane of polarization than from the second.

Gustav Kirchhoff, 1860 [1]

1 Introduction

Recently, considerable doubt has been raised [2–4] relative to Kirchhoff’s formulation of his law of thermal emission [1]. In this regard, the equivalence between emitted and absorbed radiation under conditions of thermal equilibrium, properly known as Stewart’s law [5], has not been questioned. However, the German scientist’s claim that the radiation within an arbitrary cavity will always be independent of the nature

of the walls, while subject only to the temperature and the frequency of observation, has never been demonstrated experimentally and is unsupported by mathematical derivation [2–4]. Regrettably, even the proof of Kirchhoff’s law of thermal emission, as advanced by Max Planck, has been found to be physically unsound [2].* As such, beyond the restatement of Stewart’s law [5], it would appear that little can be preserved from Kirchhoff’s classic paper [1].

Yet, there is an experimental aspect of Kirchhoff’s work which can never be discounted, namely that a tourmaline plate can absorb radiation more favorably in one plane than in the other [1, § 16]:

*Since mathematics is the language of physics, this is a serious problem for all those who adhere to the validity of Kirchhoff’s claims [2].

“A tourmaline plate, cut parallel to the optic axis, absorbs, at ordinary temperatures, more of the rays which strike it normally, if the plane of polarization of these is parallel to the axis than when it is perpendicular to it. Assuming that the tourmaline plate retains this property when it is at a glowing heat, it must give out rays in a direction normal to it, which are partially polarized in the plane passing through the optic axis and which is the plane perpendicular to that which is called the plane of polarization of tourmaline. I have proved this striking deduction from theory by experiment and it confirmed the same.”

With this observation, Kirchhoff was emphasizing that certain objects, especially when highly anisotropic in their crystal structure, could emit polarized light [6, p. 604]. Kirchhoff's finding, that the light emitted by a heated tourmaline plate was polarized in the same plane as that which preferentially absorbed light, had also been noted by Balfour Stewart [7, § 68]. P.P. Feofilov addressed this aspect of nature in his classic text on *The Physical Basis of Polarized Emission* [8, p. 33–34]:

“... in order that the polarization should appear in the radiation due to a macroscopic system, it is necessary that the mutual orientation of the elementary radiating systems should not be random. A random aggregate of anisotropic elementary radiators, gives, clearly, a completely unpolarized radiation. A regular orientation of the separate elements of a macroscopic system may be due to the properties of the system itself, and this is the case, for example, in anisotropic crystals, or it may be induced from outside by electric and magnetic fields, by mechanical action, or finally, by light incident from outside the system, since a light ray, because of its nature, is always anisotropic... In the case of regular crystals, the orientation of the emitting centers may be complete, and the emitted light may be practically totally polarized...”

In the case of tourmaline, the degree of polarization can approach 40% [9, p. 112].

Beyond crystals, it is not generally known that incandescent metals can often be a source of strongly polarized light [9, p. 110 & 138]. This effect does not occur when observing metals perpendicular to the surface, but polarization can approach 90% when the angle of observation departs substantially from the normal, in studying a clean metal [9, p. 110 & 138]. Thin metal wires exhibit polarized emission [10, 11] and the heat radiation, from small but long cylindrical objects, can also be highly polarized [12]. More recently, polarized light emission has been noted from individual carbon nanotubes, their fibers, bundles, and arrays (see



Fig. 1: An anisotropic tourmaline crystal (National Mining Hall of Fame and Museum — Leadville, CO; 3/18/2015; Photo by PMR).

[13, 14] and references therein). Importantly, within these carbon-based bundles, the light emission maintained a black-body spectral appearance [13].

Still, Kirchhoff's observation relative to tourmaline [1], these others [6–14], and many more, which highlight the importance of anisotropy relative to the emission of polarized light, have been discounted by astronomy. Clearly, since the Standard Solar Model (SSM) advocates that the Sun is gaseous in nature, there is little room in modern astrophysics for condensed matter.* The stars are thought to be devoid of solids and liquids. Rather, most astronomers believe that these objects are composed either of gaseous plasmas or highly degenerate matter, in accordance with the stellar type involved and the dictates of mathematical models. Nonetheless, ample evidence exists that the Sun itself is comprised of condensed matter or, more specifically, of metallic hydrogen [15]. Thus, it is fitting to reconsider the lessons of the tourmaline plate [1] in order to obtain a new perspective with respect to the emission of polarized light by the Sun and the stars.

2 Polarized light in the corona

Knowledge that the solar corona emitted polarized light was first gained at the eclipse of 1868 [16, p. 44]. Schuster provided a mathematical treatment of the problem as early as 1879 [17]. But it was not until R. K. Young analyzed photographic plates of the eclipses of 1901, 1905, and 1908 with a Hartmann microphotometer, that the extent of polarization could be properly quantified [18]. Young discovered that polarization increased gradually, with increasing elevation above the photosphere, to a value of ~37% before slowly starting to decrease. He also noted [18] that the corona was

*With the exception perhaps of some planets, meteors, asteroids, etc.

“...formed from matter which has been projected from the Sun” and that “The distribution of matter in the corona is dependent on high inverse powers of the distance from the Sun’s center, probably the sixth or eighth or a combination of the two.”

Young also believed that the polarization was due to the scattering of photospheric light by small particles. As a consequence of such early studies, it was established that the light arising from the K-corona was radially polarized [18].

With the advent of the Lyot coronagraph in 1930, the study of the solar corona outside of total eclipses became possible [19]. That same year, Minnaert published his work on the nature of the continuous coronal light and its polarization [20]. Minnaert considered the idea that the corona was self-luminous [20]. Sixty years earlier, William Harkness had viewed a total eclipse from Iowa and had also concluded that the corona was *“... a highly rarefied self-luminous atmosphere surrounding the Sun”* [21, p. 199].

However, the concept that the corona could be self-luminous has been largely abandoned by astronomy. In part, this dates back to the days of Schuster and his analysis of the polarization question. The British scientist had treated a luminous sphere surrounded by small particles which could scatter the light, thereby producing the desired polarization [17]. Schuster noted that [17]:

“In reality the polarisation rapidly diminishes and very soon a point is reached at which no polarisation can be observed; the corona must therefore contain some matter which is either self-luminous or too large to polarise the light while scattering it ... The rapid decrease of polarisation with increasing distances from the Sun, as well as the comparatively small amount of observed polarization, shows that a large part of the light is not due to scattering particles. This light may either be produced by incandescence, or by particles which are too large to polarise the light in the act of scattering it.”

Like Schuster, Minnaert also left open the possibility that the corona was capable of both scattering photospheric light and self-emission [20]. For his presentation, Minnaert considered that the scattering, leading to polarization, was taking place through the action of free electrons.

Within the context of the SSM, K-coronal polarization is thought to be produced by relativistic electrons which scatter photospheric light such that most Fraunhofer lines can no longer be observed [16, p. 4-5 & 135].

At the same time, streamers are known to constitute the most polarized portion of the corona, with values ranging from 30-60% [16, p. 136-138]. Such findings, along with Young’s discovery that the degree of polarization could first increase and then decrease with elevation above the photo-

sphere [18], provide strong evidence that the cause of polarization must involve structure and not simply the presence of relativistic free electrons.

In this respect, given the degree of ionized atoms in the E-corona [16, p. 4-5 & 135], it is doubtful that the determinations of electron density from polarization measurements could be accurate [16]. Furthermore, such calculations discount the notion that condensed matter may well be present in this region of the Sun [22]. It has been proposed that the metallic hydrogen which makes up the corona is electron starved and this, in turn, not MK temperatures, leads to the presence of the highly ionized atoms which characterize the E-corona [23, 24]. The Liquid Metallic Hydrogen Solar Model (LMHSM) [15, 22-24] leaves little possibility for the presence of substantial numbers of free electrons, in the upper coronal atmosphere of the Sun. In order that a star can remain stable, it must work to salvage both its hydrogen [25-27] and its electrons [22-24]. Such an idea has only been advanced within the context of the LMHSM [15, 22-27].*

3 Unifying the K-, F-, and T-coronas in the LMHSM

Throughout much of the solar atmosphere, K-coronal polarized light is mixed with F-coronal radiation. The F-corona is characterized by the presence of Fraunhofer lines and, in the SSM, is believed to be produced by dust particles which act to scatter photospheric light without polarization [16, p. 4-5 & 135]. Indeed, polarization has been utilized as a basis of discriminating between the K- and F-coronas, as F-coronal light was initially thought to be unpolarized [32-34]. However, it soon became clear that the polarization of the F-corona beyond $5R_{\odot}$ could not be ignored [35].[†] Using the degree of polarization, attempts to excise a K-coronal signal has been

*One of the authors (PMR) recently became aware that Professor J.E. Hirsch proposed, in 1989, that sunspots might be composed of metallic hydrogen based on the presence of strong magnetic fields in these regions: *“Sunspots are characterized by having a lower temperature than their environment, and very strong magnetic fields. It is natural to conclude that metallic hydrogen develops large spin polarization in these regions”* [28]. Since no lattice structure was specified to account for the emission of sunspots, Professor Hirsch appears to have adopted the accepted view from the SSM that the lower emissivities from these structures are associated with decreased temperatures [28] and not due to changes in emissivity as a result of increased metallic character [15]. Unlike Robitaille, who has promoted the idea that sunspots reflect slightly higher densities relative to the photosphere [15], Professor Hirsch speaks of a lower density inside sunspots [28]. At the same time, Hirsch makes a compelling case for the importance of metallic hydrogen throughout astronomy, as a universal cause of magnetism. On a related question, based on solar densities of $\sim 150\text{g/cm}^3$ associated with the SSM, Professor Setsuo Ichimaru has advanced that the solar core might be comprised of metallic hydrogen [29-31]. Conversely, while Robitaille recognizes the presence of a solar core, he has advocated that the Sun possesses a nearly uniform density of $\sim 1\text{g/cm}^3$ (see [15] and references cited therein). This is because a density of 150g/cm^3 in the core, as proposed by Ichimaru [29-31], would leave little material to build condensed structures on the photosphere. Further, Robitaille’s position is in keeping with the idea that liquids are essentially incompressible.

[†]Coronal polarization has been measured out to an amazing 10 solar radii [36, p. 187].

used to compute electron densities in this region [32–35]. The problem rests in that electron densities calculated in this manner are dictated by the very mechanism proposed for the polarization, without any independent confirmation that polarization was in fact produced by electrons. In addition, it is evident that there should be a strong decrease in free electron density as a function of distance from the Sun (e.g. [36, p. 188]). It is difficult to justify distant polarization with relativistic electrons.

Relative to the nature of the “dust” which is believed to constitute F-coronal matter in the SSM, Mukai et al. [37] advocated, in 1974, that graphite grains were the most likely candidate. They envisioned that the grains would sublime, as the distance to the solar surface was decreased, hence accounting for the known reduction in the F-coronal contribution in this direction [37]. A T-corona has also been hypothesized to exist, in order to account for the increased reddening of coronal light with increasing altitude above the photosphere [16, p. 4–5 & 135]. This reddening had been noted long ago by Allen [38]:

“microphotographs for solar distances varying from $R = 1.2 s$ to $R = 2.6 s$ show that the coronal radiation reddens slightly as the distance from the Sun is increased.”

Pondering on all of these fragmented pieces of information, there is a need to arrive at a unifying principle relative to the corona of the Sun.*

Rather than speak of the K-, F-, and T- coronas as separate entities [16, p. 4–5 & 135], the idea should be entertained that the corona is composed of condensed matter which is manifesting spatially variable emissive, reflective, and structural properties. It is logical to postulate that condensed coronal matter is based on photospheric Type-1 metallic hydrogen which has been ejected from the solar surface [22–24]. Since photospheric matter produces unpolarized radiation, it is reasonable that, in the lower solar atmosphere, coronal material will also lack the ability to significantly polarize light. Nonetheless, it will remain capable of self-emission. With elevation above the solar surface, the ejected photospheric material, which now constitutes the corona, begins to adopt a radially anisotropic structure, as manifested by streamers, for instance. Such structural anisotropy thereby enables the emission of polarized light from incandescent radially aligned coronal material [8]. This explains the presence of the K-coronal signals. No Fraunhofer lines are present, because the coronal matter is self-luminous and positioned above the elevation where intense absorption by free atoms or ions is possible. With increased elevation above the photosphere, coronal

material begins to cool, losing incandescence. In response to decreased temperatures, emissivity decreases and reflectivity increases, much like the iron rod placed in a forge. With increased reflectivity, coronal material becomes less able to emit polarized light in the visible range. Rather, it now increasingly reflects photospheric light. That is why the Fraunhofer lines become visible in the F-coronal spectrum. At the same time, since coronal material is cooling, it begins to emit its light, not in the visible, but in the infrared. Hence, the production of the T-coronal spectrum.

With this new proposal, the K-, F-, and T- coronas simply become manifestations of the same coronal material. A streamer can be viewed as a real structure whose emissive and reflective behavior is characterized by both temperature and structural changes within the *same* entity. A streamer is unlikely to be comprised of an assembly of isolated gaseous ions or atoms, as currently held by the SSM, as the simplest explanation for such structure rests upon condensed matter.

As for the E-corona [39], it is being produced, not by the presence of MK temperatures in the corona, but rather through the removal of atomic and ionic electrons by condensed coronal material [15, 22–24]. With increased elevation above the photosphere, the coronal metallic hydrogen, which acts to channel electrons back onto the solar surface, can be viewed as becoming increasingly electron starved. As a result, any ion or atom which comes into contact with such material will be likely to be stripped of electrons, since the Sun is working to maintain neutrality [22–24]. Electron affinities, not extreme temperatures, govern the production of highly ionized elements in the corona.

4 Polarization at the solar limb

In 1946, Chandrashekhar, through mathematical consideration of Thomson scattering by electrons [40, p. 249], first advanced that the body of the stars could emit a continuous spectrum, characterized by polarization, concluding that [41]

“the degree of polarization must vary from zero at the center of the disk to 11 per cent at the limb”

Using similar approaches, Sobolev confirmed Chandrashekhar’s finding [42] and the problem has been extensively reviewed [43, p. 119–203].

According to Dolginov, Gnedin and Silant’ev [43, p. 120], stellar polarization can be attributed to three major factors:

“a) nonsphericity of stellar shape, b) the eclipses of a hot star within a binary system, c) scattering in a nonspherical circumstellar envelope by gas flux.”

They argue that even a spherical star can have mechanisms for changes in luminosity across its surface, the most important of which might be temperature variations [43, p. 121]. The scattering of light by electrons has continued to play an

*The idea that the F-corona was produced by interplanetary dust particles was initially adopted in accounting for the behavior of the corona, even within the context of the LMHSM [22–24]. However, upon further reflection, it is clear that the SSM explanation for the presence of the F-corona should not be salvaged.

important role, relative to accounting for the production of polarized light in the context of gaseous stars and the SSM.

In the final analysis, the need to account for the production of polarized light in a gaseous object requires a suspension of objective reality. For instance, Chandrasekhar's analysis depends on the generation of polarized light from a gaseous star [41]. Yet, at the same time, the SSM views the Sun and the stars as a nearly ideal blackbody emitters [44–46]. It is well-known that blackbodies are incapable of emitting polarized light, by definition (see [47, p. 450], and [48, §5 & 107]). Hence, it should have been difficult for proponents of the SSM to accept Chandrasekhar's claim that a gaseous star could emit up to 11.7% polarized light at the limb, a number which was actually very large [41]. In order to reconcile Chandrasekhar's findings with the SSM and blackbody behavior, a gaseous Sun must be divided into that opacity region which produces the thermal spectrum and an upper layer responsible for polarization [49,50]. The reality remains that, since the Sun sustains convection currents and conduction, it makes for a very poor example of a blackbody [15], as highlighted by Max Planck himself [48, § 51]. Moreover, because Thomson scattering by an electron is frequency independent [51, p. 69] and the polarization of the continuous solar spectrum is frequency dependent, Rayleigh scattering by neutral hydrogen had to be introduced to reconcile theory [40–43] with solar observations [49, 50].

In order to account for the slight degree of frequency-dependent polarization in the continuous spectrum towards the solar limb, it is more prudent to postulate that the body of the Sun emits unpolarized light. A single photon can be considered which leaves the photosphere at the center of the solar disk. That photon, if it escapes at an angle far from the normal, could then travel in the direction of the limb. Along its path, it will encounter molecules and small particles which could cause scattering in the direction of the Earth. In this manner, photons experiencing a 90° scatter towards the Earth could then be polarized.* It does not depend on the electron and does not necessitate that the body of the Sun itself emit polarized light, as theoreticians have proposed [41–43]. The only requirement rests in acceptance that both polarizing molecules and various forms of condensed matter† exist above the photosphere of the Sun, a concept supported by ample evidence, including both spectroscopy and coronal seismology [15].

5 Polarization and second solar spectrum

Beyond the frequency dependent polarization of the continuous solar spectrum [49, 50], the Sun also emits polarized light from numerous individual spectral lines. In combina-

*The phenomenon parallels that which occurs daily with sunlight in the atmosphere of the Earth [9, 47, 52–54].

†Atomic clusters are known to be polarizable [55, p. 64–85]. Thus, it might be appropriate to consider that small hydrogen based atomic clusters might also be present in the solar chromosphere and corona.

tion, these two findings lead to the “Second Solar Spectrum” [49,50,56–67]. Brief historical accounts of this problem have been presented [58, 61] and the major features of the Second Solar Spectrum are as follows:

1. Relative to the Fraunhofer spectrum, these signals are extremely weak, rarely exceeding a Q/I level of 10^{-3} in the visible range [57, 58].

2. The most important atomic lines in the Second Solar Spectrum are produced from Ti I and Cr I [58]. These two elements possess ground state electronic configurations of $[\text{Ar}]3d^24s^2$ and $[\text{Ar}]3d^54s^1$, respectively.‡

3. The phase of the emission lines relative to the continuum can be highly variable [61]. Therefore, spectroscopic lines are said to either add to (i.e. polarize [61]) or subtract from (i.e. depolarize [62]) the continuum polarization. It is also said that the lines appear, either in emission or absorption, for the same reason [50], but that the strongest lines tend to be depolarizing [57].

4. The strongest polarizing lines include the following: H I, Na I, Mg I, Ca I, Ca II (6.11 eV), Ti I, Ti II (6.83 eV), V I, V II (6.75 eV), Cr I, Mn I, Fe I, Co I, Ni I, Cu I, Sr I, Sr II (5.69 eV), Zr I, Zr II (6.63 eV), Nb II (6.76 eV), Ru I, Pb I, Ba I, and Ba II (5.21 eV) [61].§

5. The spectrum is particularly rich in molecular lines, including, most notably, lines from MgH, C₂, and CN [56, 57, 63–65]. The intensity of this polarization increases towards the solar limb.

6. The spectrum contains an amazing array of lines from the Rare Earth elements: Sc II (6.56 eV), Y I, Y II (6.22 eV), La II (5.58 eV), Ce II (5.54 eV), Nd II (5.53 eV), Sm II (5.64 eV), Eu II (5.67 eV), Gd II (6.15 eV), Dy II (5.94 eV), and Yb I [61].

7. Lithium, Li, is barely detectable in the regular solar spectrum of the photosphere [70], but its doublet at 6708 Å appears at the $\sim 10^{-4}$ level in the polarized spectrum [57, 67]. This constitutes a tremendous increase in relative detectability for this element.

5.1 The second solar spectrum and the standard solar model

Adherence to the SSM brings many difficulties when studying the Second Solar Spectrum. A means must first be found to excite these atoms or molecules, such that they can later emit the required line spectrum. The only reasonable mechanism available, in the context of a gaseous Sun, involves

‡The calculated, or experimentally determined, static electric dipole polarizabilities, α_D , of neutral atoms in their ground state are readily available (see e.g. [68, p. 11] and [69, § 10; 188–189]). However, these values are of limited interest for this problem, as the polarizability of the excited atoms or ions may be more appropriate to consider, but are not easily ascertained.

§The elements followed by a Roman numeral I are neutral and said to be in spectroscopic state I. Elements in the +1 oxidation state are in the second spectroscopic state (i.e. state II). The ionization energy for each element involved in producing its state II ion is provided in brackets [69, § 10; 197–198].

direct excitation through photon absorption and subsequent re-emission. Thus, a random process is invoked. Chemical reactions are never considered, despite the fact that the chemically similar Rare Earth elements produce prominent signals. Furthermore, all ionic strongly polarizing lines present were produced by the removal of a single electron from atoms, requiring ~ 6 eV of energy, as can be ascertained by examining the ionization potentials listed in 4 and 6 above.

In the SSM, a polarization mechanism must also be advanced, namely anisotropic radiation. Thus, in order to polarize the emitting species, proponents of the SSM must also have recourse to anisotropic light as follows [57]:

“The polarization arises because the incident radiation, being anisotropic, induces a net dipole moment in the scattering particle. If the particle does not suffer a collision before it re-radiates, the phase relations between the vector components of the dipole moment . . . are preserved and become imprinted on the scattered radiation.”

Such arguments bring further complications, as a cause for anisotropic radiation in the atmosphere of a fully gaseous Sun must now also be advanced. In the end, the center-to-limb variation (CLV) in solar intensity is adopted, to account for the anisotropic light [49, 50, 57]. However, at the level where these lines are being produced, such a mechanism is unlikely to be valid. Thus, it is also advanced that “*. . . local inhomogeneities on the Sun will produce scattering polarization all over the solar disk . . .*” [57]. But, in the SSM, there can be no local cause of inhomogeneities. The magnetic fields, so often advanced to explain such inhomogeneities, cannot be reasonably generated in the context of a gaseous Sun [15].

Finally, since many of the lines appear to *depolarize* the continuum polarization, some means of accounting for this effect must be brought forward. In this regard, three mechanisms have been hypothesized [61]: 1) Hanle depolarization produced by random magnetic fields [57, 71], 2) collisional depolarizations produced by hydrogen atoms (see [72] and references cited therein) and 3) radiation transfer effects (see [72] and references cited therein). Consequently, magnetic fields must be applied in the SSM, both to produce the anisotropic light required for polarization and as a means of depolarization. At the same time, collisional depolarization using the hydrogen atom contradicts one of the tenets of the gaseous Sun, namely that collisional processes are not significant in the gaseous solar atmosphere associated with the SSM: “*Collisional processes of excitation and de-excitation occur so seldom that they are of no importance*” [73, p. 10]. This is because, within this model, the chromosphere and corona exist as tremendous vacuums, essentially devoid of material and with inferred densities of less than 10^{-12} g/cm³ (see references within [15]). While computations of collisional and radiation transfer effects might be reasonably applied to a few lines, the problem becomes daunting, when

considering an entire spectrum, especially given that “*. . . our knowledge of the collisional rates is still very limited*” and “*. . . there are many physical processes that are involved in the generation and modification of the polarization*” [61].

The dilemmas faced in the context of the SSM relative to accounting for the Second Solar Spectrum has been outlined [61]:

“... probably one of the most important questions concerning the whole Second Solar Spectrum, that still waits for an answer, is why only particular lines, of certain elements, produce strong polarizing signals. For instance, one can wonder why some elements are particularly present with their lines in the Second Solar Spectrum, whereas other elements of comparable abundance are totally absent.”

5.2 The second solar spectrum and the LMHSM

Novel insight can be gained, with respect to the Second Solar Spectrum, if the findings are interpreted within the context of a model wherein condensed matter participates in the generation of spectroscopic lines.

5.2.1 Excitation and relaxation in the LMHSM

Contrary to the SSM which advocates that emitting species must first be excited through the interaction with light, followed by re-emission disconnected from chemical processes, the LMHSM proposes that all emission lines are inherently linked to chemical or electrical processes in the Sun [23–27]. In the corona, the interaction between free atoms or ions with condensed matter results in the production of highly ionized species, like FeXXV [23, 24], since condensed matter has the ability to maintain a higher electron affinity than a free atom. It is this affinity, not the presence of extreme temperatures, which is hypothesized to be responsible for the production of such highly ionized atoms in the corona [23, 24]. In this manner, the body of the Sun can recapture lost electrons, by stripping coronal atoms or ions and channeling the resulting harvest back down to the photosphere. Consequently, the emission lines observed in the corona are associated with the capture of electrons from free atoms or ions by condensed matter. Such processes should be exothermic in nature, hence their association with light emission [23, 24]. Electron capture is thus associated with the activation of a highly ionized species which then emits the well known coronal lines. Unlike the SSM, light need not be invoked to excite these highly ionized species. Collisional relaxation processes are not important in this region of the Sun. Any excited ion achieves the ground state through the emission of light.

As for the chromosphere, it has been viewed as the site of proton and hydrogen recapture [25–27]. The hypothesized condensation reactions take advantage of hydrogen’s tremen-

dous ability to form hydrides. These are then used to deposit hydrogen atoms onto condensed hydrogen structures, CHS [25–27]. Such a model can account for the presence of both He I and He II emission lines in the chromospheric spectrum [27]. In this case, line emission becomes associated with exothermic hydrogen based condensation reactions [25–27]. Collisional processes of excited atoms or ions back to the ground state is not necessary either for further excitation or relaxation back to the ground state.

In combination, the mechanisms advanced in the corona and chromosphere act to reclaim both protons and electrons in the outer solar atmosphere and, thereby, help to maintain mass and charge balance in the LMHSM. Such means of preserving the integrity of the Sun are absent in the SSM.

As mentioned above, in order to account for the behavior of several ions in the Second Solar Spectrum, collisional depolarization mechanisms have been invoked (see [72] and references cited therein). Yet, such random processes are unlikely to be of true significance in governing the behavior of emission lines in this spectrum, as definite lineshapes must depend on repeatable processes, not chance occurrence. Moreover, the densities for the chromosphere proposed in the SSM of 10^{-12} g/cm³ (see references within [15]), leave little room for such processes. Lineshapes are inherently linked to the environment in the vicinity of the emitter itself. It is this microenvironment which must be considered, not the presence of macroscopic phenomena, as will be addressed in the next section.

In the LMHSM, the presence of condensed matter and elevated chromospheric densities, well-beyond the densities of the Earth's atmosphere, are entirely compatible with a condensed solar photosphere. Unlike the setting proposed by the SSM, collisional processes can be invoked in the LMHSM. Such processes do not need to play any role in understanding the emission lines of the chromosphere and corona. But they can provide an important relaxation mechanism for the Fraunhofer lines, as the atoms involved in photon absorption, must relax again prior to repeating the process. It is here that collisional relaxation mechanisms can play an important function, beyond simple scattering, in the context of the LMHSM. This is because, the LMHSM does not insist that the chromosphere of the Sun possesses a density which is vacuum-like and greatly inferior to that in the Earth's atmosphere. This is another important advantage of the LMHSM over the SSM.

5.2.2 Chemical reactions and the second solar spectrum

Rather than speak of polarizing (or emission) and depolarizing (or absorption) signals, it is best to consider all the lines in the Second Solar Spectrum as inherently polarized, but with an emission phase which can either add to or subtract from the polarized continuum. Thus, lineshape becomes a question of phase, as with any other spectroscopic process.

If a species is to have a net phase, then it must be relative to a common framework. In nuclear magnetic resonance (NMR), phase is determined relative to receiver channels placed in quadrature, with respect to one another, as dictated by a master oscillator. In NMR, lineshapes reflect specific nuclear environments and populations at the local level. These same principles can guide lineshape analysis in the Sun, with phase being determined by electronic orbital orientation relative to a polarizing interface. Since emission lines are being observed, then chemical activation of the emitting species can once again be invoked, but this time within the context of coordination of the emitting species.

As noted in introduction to section 5, the Second Solar Spectrum is characterized by many powerful lines from molecules and the Rare Earth elements [74]. Rare Earth metals are actually relatively abundant in the Earth's crust [74] and they are likely to be similarly abundant in the Sun with respect to the other metals, as polarization studies suggest. These elements share a common outer electron configuration often with a single electron in an outer d-shell and two electrons in the immediately inferior s-shell. In this regard, the Lanthanide series is slowly filling the 4f-shell, while maintaining a (6s²5d¹) outer configuration. The latter is similar to the Group IIIB elements of scandium (Sc), Yttrium (Y), and Lanthanum (La), which have outer electronic configurations of 4s²3d¹, 5s²4d¹, and 6s²5d¹, respectively. Generally speaking, atoms with a single unpaired electron are easiest to polarize.

The presence of the Rare Earth elements in the Second Solar Spectrum strongly suggests that *a similar chemical reaction is responsible for all of these lines*. It is likely that these reactions involve the condensation of hydrogen onto CHS, a process which has been inherently tied to the function of the chromosphere in the LMHSM [25–27].

Consequently, Rare Earth metal hydrides could interact with CHS in the chromosphere. Upon release of their hydrogen atom, the resulting activated Rare Earth metal would be interface polarized by the adjacent CHS with which it would remain at least partially interacting. In this way, atomic orbitals always maintain the same orientation, relative to the surface and relative to all other ions or atoms involved in similar interactions with CHS, while maintaining coordination. As a result, the relative phase of all atoms involved in such processes would be dictated by coordination with the charged interface. Upon relaxation through emission, these atoms would then be released in association with the delivery of hydrogen.

The ability to deliver hydrogen and the exact strength and nature of the associated coordination would depend on the atomic species involved. Some atoms, like He for instance, may well participate in condensation reactions [27], but given their noble gas electronic configurations, might be difficult to polarize and might remain uncoordinated during emission. Others, like the noble gases below helium in group VIIIA of

the periodic table, would not be expected to interact at all with hydrogen. Hence, given their inability to participate in condensation reactions, they should be devoid of neutral atom chromospheric emission lines.

Thus, within the context of the LMHSM, it is reasonable to conceive that structures comprised of condensed matter exist in the chromosphere. Such condensed hydrogen structures, CHS, could possess a surface electric charge polarizing any atom brought in its proximity through interface polarization mechanisms. Each atomic species involved in condensation reactions would have a preferred means of being coordinated with the surface, in a manner dependent on their atomic orbitals. In such a way, it is possible to explain why a given line would adopt a consistent and at times complex appearance in the Second Solar Spectrum.

Support for the idea that chemical reactions are involved can be gained by appreciating not only the prevalence of the chemically similar Rare Earth metals, but also from the fact that all of the most polarizing lines from ions arise from elements with a first ionization potential of ~ 6 eV [61]. This cannot be coincidental, but strongly supports the contention that chemistry, and not random processes, are involved.

The same is true for the presence of molecular lines. Note that the three most important molecular species observed, namely CN, MgH, and C₂, all have the potential of delivering hydrogen to CHS structures, through species such as HCN, MgH₂, HC₂, and HCCH.

Note also that, at first glance, none of the elements from Group IVA, VA, VIA, and VIIA (with the exception of Pb at the bottom of group IVA), appear to participate in generating the Second Solar Spectrum. Since these atoms are increasingly electronegative towards the upper right of the periodic table, they may share a lack of ability to enter into condensation reactions that involve the delivery of a hydrogen atom.

Finally, the presence of a doublet signal from Li in the polarized spectrum provides another important clue that chemical processes are involved [57,67]. Signals from this element are weak or non-existent in other spectra (Fraunhofer, chromospheric, or coronal), leading proponents of the SSM to advocate depletion of Li in the Sun and the stars, despite its abundance in meteors [70]. Conversely, within the LMHSM, the paucity of detectable lithium has been linked to the ability of this element to stabilize metallic hydrogen, a proposal first advanced by Zurek et al. [75]. Coordination within the solar interior, not depletion, appears to be a more reasonable answer, especially given meteoric abundances [70]. This idea is also in keeping with the proposal that atoms, which are involved in condensation reactions, can be interface polarized in the excited state prior to emission. This helps to account for the presence of lithium in the Second Solar Spectrum. It also provides powerful evidence that interface polarization, not random processes and anisotropic radiation, is responsible for the production of the Second Solar Spectrum.

6 Conclusion

The study of solar and stellar polarimetry is one of the most fascinating aspects of astronomy, as the associated observations hold a treasure of clues, relative to the structure and functioning of the Sun, the stars, and the galaxies [76, 77]. At every turn, polarization studies also add tremendous support to the concept that the Sun is comprised of condensed matter [15]. In this regard, the LMHSM provides a strong platform to account for the polarization of the K-corona, enabling polarized self-emission from an anisotropic structure. At the same time, the model elegantly unifies the K-, F-, and T-coronas into a single entity, with variable emissivity based on cooling with elevation and increasingly radial anisotropy. The idea that the chromosphere and the corona act to recapture hydrogen and electrons which have escaped from the solar body has no equivalent in the SSM [23–27].

Given the evidence, it is more reasonable to postulate that the Second Solar Spectrum results from interface polarization and associated condensation reactions, rather than calling for anisotropic radiation, Hanle depolarization, and collisional depolarization.

Ample proof exists that the Second Solar Spectrum is inherently tied to chemistry, as the presence of Rare Earth elements, relevant ionization potentials, molecular lines, and phase sensitive lineshapes suggest. In the end, the Second Solar Spectrum is perhaps the most significant of all spectroscopic signals obtained from the Sun, as in its lines, the scientist can find compelling evidence for the presence of chemical reactions within the solar atmosphere.

Dedication

This work is dedicated to our friend, Larissa Borissova.

Submitted on: May 1, 2015 / Accepted on: May 11, 2015
First published online on: May 13, 2015

References

1. Kirchhoff G.R. Über das Verhältnis zwischen dem Emissionsvermögen und dem Absorptionsvermögen. der Körper für Wärme und Licht. *Poggendorfs Annalen der Physik und Chemie*, 1860, v.109, 275–301. (English translation by F. Guthrie: Kirchhoff G. On the relation between the radiating and the absorbing powers of different bodies for light and heat. *Phil. Mag.*, 1860, ser.4, v.20, 1–21; also found in Harper's Scientific Memoirs, edited by J. S. Ames: The Laws of Radiation and Absorption: Memoirs of Prévost, Stewart, Kirchhoff, and Kirchhoff and Bunsen, translated and edited by D. B. Brace, American Book Company, New York, 1901, 74–97, also available online).
2. Robitaille P.-M. and Crothers S.J. "The Theory of Heat Radiation" revisited: A commentary on the validity of Kirchhoff's law of thermal emission and Max Planck's claim of universality. *Progr. Phys.*, 2015, v. 11, no. 2, 120–132.
3. Robitaille P.-M. Blackbody radiation and the carbon particle. *Progr. Phys.*, 2008, v. 3, 36–55.
4. Robitaille P.-M. Kirchhoff's Law of thermal emission: 150 Years. *Progr. Phys.*, 2009, v. 4, 3–13.
5. Stewart B. An account of some experiments on radiant heat, involving an extension of Prévost's theory of exchanges. *Trans. Royal Soc.*

- Edinburgh*, 1858, v. 22, no. 1, 1–20 (also found in Harper's Scientific Memoirs, edited by J. S. Ames: The Laws of Radiation and Absorption: Memoirs of Prévost, Stewart, Kirchhoff, and Kirchhoff and Bunsen, translated and edited by D. B. Brace, American Book Company, New York, 1901, 21–50).
6. Wood R.W. Physical Optics (2nd Edition), The MacMillan Company, New York, N.Y., 1911.
 7. Tait P.G. Sketch of Thermodynamics, Edmonston and Douglas, Edinburgh, 1868.
 8. Feofilov P.P. The Physical Basis of Polarized Emission. Consultants Bureau, New York, N.Y., 1961.
 9. Können G.P. Polarized Light in Nature (Translated by G.A. Beerling), Cambridge University Press, Cambridge, U.K., 1985.
 10. Öhman Y. Polarized thermal emission from narrow tungsten filaments. *Nature*, 1961, v. 192, 254.
 11. Bimonte G., Cappellin L., Carugno G., Ruoso G., Saadeh D. Polarized thermal emission by thin metal wires. *New J. Phys.*, 2009, v. 11, 033014.
 12. Golyk V.A., Krüger M., Kardar M. Heat radiation from long cylindrical objects. *Phys. Rev. E*, 2012, v. 85, 046603.
 13. Li P., Jiang K., Liu M., Li Q., Fan S. and Sun J. Polarized incandescent light emission from carbon nanotubes. *Appl. Phys. Lett.*, 2003, v. 82, 1763.
 14. Singer S.B., Mecklenburg M., White E.R., and Regan B.C. Polarized light emission from individual incandescent carbon nanotubes. *Phys. Rev. B*, 2011, v. 83, 233404.
 15. Robitaille P.-M. Forty lines of evidence for condensed matter – The Sun on trial: Liquid metallic hydrogen as a solar building block. *Progr. Phys.*, 2013, v. 4, 90–142.
 16. Golub L. and Pasachoff J.M. The Solar Corona, Cambridge University Press, Cambridge, U.K., 1997.
 17. Schuster A. On the polarization of the solar corona. *Mon. Not. Roy. Astron. Soc.*, 1879, v. 40, 35–56.
 18. Young R.K. Polarization of the light in the solar corona. *Lick Observatory Bulletin*, 1910–1911, v. 6, no. 205, 166–181; summary in: *Publ. Astron. Soc. Pacific*, 1912, v. 24, no. 141, 123–125.
 19. Lyot B. La couronne solaire étudiée en dehors des éclipses. *Comptes Rendus*, 1930, v. 191, 834–837.
 20. Minnaert M. On the continuous spectrum of the corona and its polarization. *Zeitschrift für Astrophysik*, 1930, v. 1, 209–236.
 21. Dick S. Sky and Ocean Joined: The U.S. Naval Observatory 1830–2000. Cambridge University Press, Cambridge, 2003, p. 196–205.
 22. Robitaille P.M. The Liquid Metallic Hydrogen Model of the Sun and the Solar Atmosphere II. Continuous Emission and Condensed Matter Within the Corona. *Progr. Phys.*, 2013, v. 3, L8–L10.
 23. Robitaille P.M. The Liquid Metallic Hydrogen Model of the Sun and the Solar Atmosphere V. On the Nature of the Corona. *Progr. Phys.*, 2013, v. 3, L22–L25.
 24. Robitaille P.M. The Liquid Metallic Hydrogen Model of the Sun and the Solar Atmosphere VII. Further Insights into the Chromosphere and Corona. *Progr. Phys.*, 2013, v. 3, L30–L36.
 25. Robitaille P.M. The Liquid Metallic Hydrogen Model of the Sun and the Solar Atmosphere I. Continuous Emission and Condensed Matter Within the Chromosphere. *Progr. Phys.*, 2013, v. 3, L5–L7.
 26. Robitaille P.M. The Liquid Metallic Hydrogen Model of the Sun and the Solar Atmosphere IV. On the Nature of the Chromosphere. *Progr. Phys.*, 2013, v. 3, L15–L21.
 27. Robitaille P.M. The Liquid Metallic Hydrogen Model of the Sun and the Solar Atmosphere VI. Helium in the Chromosphere. *Progr. Phys.*, 2013, v. 3, L26–L29.
 28. Hirsch J.E. Ferromagnetism in metallic hydrogen. *Phys. Letters A*, 1989, v. 141, 191–195.
 29. Ichimaru S. Statistical Plasma Physics – Volume II: Condensed Plasmas, Addison-Westly, Redwood, CA, 1991 (reprinted by Westview Press, Boulder, CO, 2004).
 30. Ichimaru S. and Kitamura H. Pycnonuclear reactions in dense astrophysical and fusion plasmas. *Phys. Plasmas*, 1999, v. 6, no. 7, 2649–2671.
 31. Ichimaru S. Radiative proton-capture of high-Z nuclei in the sun and in liquid metallic hydrogen. *Phys. Letters A*, 2000, v. 266, 167–172.
 32. van de Hulst H.C. The electron density of the solar corona. *Bull. Astron. Soc. Netherlands*, 1950, v. 11, no. 410, 135–149.
 33. van de Hulst H.C. On the polar rays of the corona. *Bull. Astron. Soc. Netherlands*, 1950, v. 11, no. 410, 150–159.
 34. Schmidt M. Brightness, polarization and electron density of streamers in the solar corona. *Bull. Astron. Soc. Netherlands*, 1953, v. 12, no. 447, 61–67.
 35. Hayes A.P., Vorlidas A. and Howard R.A. Deriving the electron density of the solar corona from the inversion of total brightness measurements. *Astrophys. J.*, 2001, v. 548, 1081–1086.
 36. Zirin H. The Solar Atmosphere. Blaisdell Publishing Company, Waltham, M.A., 1966.
 37. Mukai T., Yamamoto T., Hasegawa H., Fujiwara A. and Koike C. On circumsolar grain materials. *Publ. Astron. Soc. Japan*, 1974, v. 26, 445–458.
 38. Allen C.W. The spectrum of the corona at the eclipse of 1940 October 1. *Mon. Not. Roy. Astron. Soc.*, 1946, v. 106, 137–150.
 39. Phillips K.J.H., Feldman U. and Landi E. Ultraviolet and X-Ray Spectroscopy of the Solar Atmosphere. Cambridge University Press, Cambridge (U.K.), 2008.
 40. Chandrasekhar S. Radiative Transfer. Dover Publications, Inc., New York, N.Y., 1960.
 41. Chandrasekhar S. On the radiative equilibrium of a stellar atmosphere X. *Astrophys. J.*, 1946, v. 103, 351–370.
 42. Sobolev V.V. A Treatise on Radiative Transfer (Translated by S.I. Gaposchkin), D. Van Nostrand Company, Inc., Princeton, N.J. 1963.
 43. Dolginov A.Z., Gnedin Yu.N., and Silant'ev N.A. Propagation and Polarization of Radiation in Cosmic Media. Gordon and Breach Publishers, Basel, Switzerland, 1995.
 44. Eddington A.S. The Internal Constitution of the Stars. Cambridge University Press, Cambridge, U.K., 1926.
 45. Reddish V.C. The Physics of Stellar Interiors: An Introduction. Edinburgh University Press, Edinburgh, U.K., 1974.
 46. Kippenhahn R. and Weigert A. Stellar Structure and Evolution. Springer-Verlag, Berlin, 1990.
 47. Jenkins F.A. and White H.E. Fundamentals of Optics (4th Edition), McGraw-Hill, Inc, New York, 1976.
 48. Planck M. The theory of heat radiation. P. Blakiston's Son & Co., Philadelphia, PA, 1914, <http://gutenberg.org/ebooks/40030>.
 49. Fluri D.M. and Stenflo J.O. Continuum polarization in the solar spectrum. *Astron. Astrophys.*, 1999, v. 341, 902–911.
 50. Stenflo J.O. Polarization of the Sun's continuous spectrum. *Astron. Astrophys.*, 2005, v. 429, 713–730.
 51. van de Hulst H.C. Light Scattering by Small Particles, Dover Publications, New York, 1957.
 52. Tenquist D.W., Whittle R.M., and Yarwood J. University Optics, Vol. II, Gordon and Breach Science Publishers, New York, 1970, p. 96–97.
 53. Smith G.S. The polarization of skylight: An example from nature. *Am. J. Phys.*, 2007, v. 75, no. 1, 25–35.

54. Liu Y. and Voss K. Polarized radiance distribution measurement of skylight II. Experiment and data. *Applied Optics*, 1997, v. 36, no. 33, 8753–8764.
55. Bonin K.D. and Kresin V.V. Electric-Dipole Polarizabilities of Atoms, Molecules, and Clusters. World Scientific, Singapore, 1997.
56. Stenflo J.O. and Keller C.U. New window for spectroscopy. *Nature*, 1996, v. 382, 588.
57. Stenflo J.O. and Keller C.U. The Second Solar Spectrum: A new window for diagnostics of the Sun. *Astron. Astrophys.*, 1997, v. 321, 927–934.
58. Gandorfer A. A high resolution atlas of the Second Solar Spectrum. *APS Conference Series*, 2001, v. 236, 109–116.
59. Gandorfer A. The Second Solar Spectrum: A High Spectral Resolution Polarimetric Survey of Scattering Polarization at the Solar Limb in Graphical Representation, Vol. I: 4625Å to 6995Å, Hochschulverlag, AG an der ETH Zurich, 2000; Gandorfer A. The Second Solar Spectrum: A High Spectral Resolution Polarimetric Survey of Scattering Polarization at the Solar Limb in Graphical Representation, Vol. II: 3910Å to 4630Å, Hochschulverlag, AG an der ETH Zurich, 2002; Gandorfer A. The Second Solar Spectrum: A High Spectral Resolution Polarimetric Survey of Scattering Polarization at the Solar Limb in Graphical Representation, Vol. III: 3160Å to 3915Å, Hochschulverlag, AG an der ETH Zurich, 2005.
60. Nagendra K.N. and Stenflo J.O. Solar Polarization, Kluwer Academic Publishers, Dordrecht, Germany, 1999.
61. Belluzzi L. and Landi Degl’Innocenti E. A spectroscopic analysis of the most polarizing atomic lines in the Second Solar Spectrum. *Astron. Astrophys.*, 2009, v. 495, 577–586.
62. Fluri D.M. and Stenflo J.O. Depolarizing lines in the Sun’s spectrum. *Astron. Astrophys.*, 2003, v. 398, 763–773.
63. Milić I. and Faurobert M. Modeling scattering polarization in molecular solar lines in spherical geometry. *Astron. Astrophys.*, 2012, v. 539, A10.
64. Landi Degl’Innocenti E. Polarization properties of resonance scattering in molecular bands.: The intermediate (a-b) coupling regime. *Astron. Astrophys.*, 2007, v. 461, 1–10.
65. Ramos A.A. and Bueno J.T. Evidence for collisional depolarization in MgH lines of the Second Solar Spectrum. *Astrophys. J.*, v. 635, L109–L112.
66. Manso Sainz R., Landi Degl’Innocenti E., and Bueno J.T. A qualitative interpretation of the Second Solar Spectrum of Ce II. *Astron. Astrophys.*, 2006, v. 447, 1125–1129.
67. Belluzzi L., Landi Degl’Innocenti E., and Bueno J.T. The physical origin and the diagnostic potential of the scattering polarization in the Li I resonance doublet at 6708Å. *Astrophys. J.*, 2009, v. 705, 218–225.
68. Maroulis G. Atoms, Molecules and Clusters in Electric Fields: Theoretical Approaches to the Calculation of Electric Polarizability. Imperial College Press, London, U.K., 2006.
69. CRC Handbook of Chemistry and Physics, 95th Edition (Internet Edition, W.M. Haynes, T.J. Bruno, D.R. Lide, Eds), Boca Raton, FL, 2014–2015.
70. Robitaille P.M. Commentary on the Liquid Metallic Hydrogen Model of the Sun III. Insight into Solar Lithium Abundances. *Progr. Phys.*, 2013, v. 2, L12–L13.
71. Stenflo J.O. Limitations and Opportunities for diagnostics of solar and stellar magnetic fields in “Magnetic Fields across the Hertzsprung-Russell Diagram” (G. Mathys, S.K. Solanki, and D.T. Wickramasinghe, Eds.), APS Conference Series, 2001, v. 248, 639–650.
72. Derouich M., Sahal-Bréchet S. and Barklem P.S. Collisional depolarization and transfer rates of spectral lines by atomic hydrogen. IV. Application to ionized ions. *Astron. Astrophys.*, 2004, v. 426, 707–715.
73. Athay R.G. Radiation Transport in Spectral Lines. D. Reidel Publishing Company, Dordrecht, Holland, 1972.
74. Barrett S.D. and Dhesi S.S. The Structure of Rare-Earth Metal Surfaces, Imperial College Press, London, 2001.
75. Zurek E., Hoffmann R., Ashcroft N.W., Oganov A.R., Lyakhov A.O. A little bit of lithium does a lot for hydrogen. *Proc. Nat. Acad. Sci. USA*, 2009, v. 106, no. 42, 17640–17643.
76. Clarke D. Stellar Polarimetry. Wiley-VCH Verlag GmbH & Co., Weinheim, Germany, 2010.
77. Dufay J. Galactic Nebulae and Interstellar Matter. Dover Publications, Inc., N.Y., N.Y., 1968.