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Review

The Hearth of the World: The Sun before Astrophysics

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Abstract: This paper presents a historical overview of conceptions about the Sun in Western astronomical and cosmological traditions before the advent of spectroscopy and astrophysics. Rather than studying general cultural ideas, we focus on the concepts developed by astronomers or by natural philosophers impacting astronomy. The ideas we investigate, from the works of Plato and Aristotle to William Herschel and his contemporaries, do not line up into a continuous and integrated narrative, since the nature of the Sun was not a genuine scientific topic before the nineteenth century. However, the question recurringly arose as embedded in cosmological and physical contexts. By outlining this heterogeneous story that spreads from transcendence to materiality, from metaphysics to physics, from divinity to solar inhabitants, we receive insight into some major themes and trends both in the general development of astronomical and cosmological thought and in the prehistory of modern solar science.

Keywords: history of astronomy; sun; sunspots; Johannes Kepler; Galileo Galilei; William Herschel

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1. Introduction

For all cultures and in all ages, the Sun has been a subject of distinguished interest. Being the primary source of light and heat in our world and regulating essential natural rhythms such as the diurnal and annual cycles, it is one of the most evident and most fundamental entities in nature. In old times, it was worshipped as a deity, often associated with life, nourishment and prosperity. Ancient natural philosophers pondered on its nature and cosmic role, while astronomers speculated about its motion, size and distance. Some of their views became highly influential, shaping scientific and cultural notions over centuries and even millennia. However, before the emergence of solar science in the 19th century, the corresponding views did not constitute an autonomous tradition: the Sun remained a boundary object [1], lingering at the intersection of various practices including astronomy, natural philosophy, cosmology, astrology, religion and the arts. Given this amalgam of heterogeneous approaches, consensual ideas only seldom prevailed. Due to its inaccessibility, as well as its uniqueness among natural entities, the Sun remained an elusive object surrounded by speculations.

This paper offers a historical overview of these conceptions about the Sun, concentrating on Western astronomical and cosmological traditions before the advent of spectroscopy and astrophysics. Quite surprisingly, such a story has yet to be told in detail. Professional historians of science have long abandoned "grand narratives" in favour of detailed micro-perspectives. Astronomers, on the other hand, are chiefly interested either in the history of modern solar physics, e.g., [2,3] (the latter work being a partial exception by providing a brief summary of the preceding period), or in the history of solar observations [4], usually for the sake of reconstructing solar activity from records [5]—see also the voluminous list of references in this latter work. Further historical accounts, focusing mainly on the modern era, are found in general works, e.g., [6].

While the present journal paper cannot hope to provide a comprehensive exposition of its extensive subject, it nevertheless attempts to lay the groundwork by outlining the main chapters. It focuses on concepts developed by astronomers, or by natural philosophers impacting astronomy, to see how our understanding of the Sun has evolved since the dawn of Western scientific tradition, leading up to the emergence of physical methods developed in the 19th century. Due to spatial limitations, and for the sake of focus and coherence, several related aspects will be ignored or mentioned in passing. Non-Western cultures fall outside the scope of this study. Observations of eclipses, planetary transits, sunspots and other solar phenomena are considered only in so far as they were relevant to the understanding of the nature of the Sun. Similarly, mathematical models of solar motion, as well as parallax and distance measurements, are considered purely in this context. The same goes for religious and mythological approaches. Popular conceptions outside science, such as those appearing in literary fiction, are completely ignored. In addition, most dates, e.g., the births and deaths of prominent scientist, are omitted since they can easily be looked up elsewhere, but for the principal authors these dates are indicated in the summarizing tables of the concluding section.

The intended audience consists primarily of researchers who are interested in the history of astronomy and the prehistory of modern astrophysics and would benefit from a general overview instead of having to survey either the primary literature written by historical actors or the multitude of detailed secondary literature offered by science historians on various local aspects of the topic. Nevertheless, there is a relatively high number of references in this paper, both to (the translations of) the original works and to some of the most useful secondary sources, for two reasons. First, since a broad range of topics is covered in a concise form, references are useful for orienting readers who might want to go after any point in more detail. Second, a lot of misconceptions are in circulation regarding some of the popular subjects addressed here, and the best way to avoid them is being transparent in our reliance on the original works and their professional analyses. If any errors remain in this summary, which is perhaps inevitable for a study of such a wide scope, those are the author's responsibility.

2. Antiquity: The Fundaments

We have very little knowledge of the earliest views. In the Presocratic era of the 6th and 5th centuries BCE, a multitude of cosmological ideas were advocated by various philosophical schools and individuals, often involving notions about the nature of the Sun. In the absence of extant original works, however, we can only rely on fragmented and often incoherent information provided by later Greek authors. These were collected, e.g., in [7] (see the page numbers in the following paragraph).

Initially, it was widely believed, perhaps under Egyptian influence, that during the day the Sun sails across the sky as a golden bowl filled with fire, and at night it circumnavigates the world on Okeanos, the water surrounding the flat earth (pp. 14–15). This view is also attributed in part to Heracleitus (p. 203) and Anaximenes (p. 156), while the latter also said that the flat, leaf-shaped Sun is supported by air (pp. 154–155). In contrast, Anaximander held that all celestial "bodies" are actually holes in the solid rings condensed from primordial fire, and the original fire shines through them from the periphery of the cosmos—except when they are temporarily blocked by mist during eclipses (pp. 133–136). According to Xenophanes, the Sun is a collection of clouds ignited each day anew (pp. 172–175). Empedocles proposed that the Sun is a reflection of fire (pp. 333–334). Anaxagoras claimed that the Sun is a hot glowing stone or metal, larger than the Peloponnese in size (pp. 391–392). For demoting the Sun from being a deity (Helios for the Greeks, also associated with Apollon, see Figure 1) and treating it as a profane natural phenomenon, Anaxagoras is reported to have been charged with impiety and exiled from Athens, possibly with a death sentence in his absence (pp. 362–365).

After the trial of Anaxagoras, philosophical investigations about the nature of the heavens fell out of favour for a century. Plato, one of the most influential philosophers of antiquity and the earliest to write an extensive corpus still extant today, discusses such questions in only one of his dialogues, the *Timaeus*, embedded in a mystical story of cosmogony (38c–40a) [8]. We learn that the seven celestial bodies were created by a single artisan of the cosmos, the demiurge, to establish the rhythms of time, and so they were placed in circular orbits. The Sun is on the second circle, above the Moon but below the planets, and was given a great fire in order to illuminate the entire sky as the only proper light source among them. Heavenly bodies were made mostly out of fire, and they were given the perfect shape of a sphere. These brief remarks made a lasting impact on astronomical and cosmological thinking, cementing not only the idea of the sphericity of celestial objects but also the notion of uniform circular motions, strictly adhered to for two subsequent millennia, even by Copernicus [9].

Figure 1. The chariot of Helios depicted on a krater from around 430 BCE (now in the British Museum, London). (Source: Wikimedia Commons).

In addition, the symbolic function attributed to the Sun in Plato's philosophy was also highly influential. In book VI of *The Republic* (507b–509c) [10], he drew an analogy between the Sun, the source of light, illuminating all perceptible things and making them visible, and the idea (or form) of the "Good", the source of truth, making intellectual things intelligible. Thus, the Sun is elevated above all sensible objects to be a precondition of their sensibility, as well as their growth and nourishment: it is not only an epistemological source of knowledge but also an ontological source of being. Similar concepts were described in his famous allegory of the cave (book VII, 514a–520a) [10] (pp. 118–141), where the final stage of learning the truth is likened to a glimpse of the Sun, the origin of all light. As we shall see, these analogies came to play a central role in the Neoplatonic tradition, e.g., in Plotinus, Proclus and Ficino, eventually motivating the heliocentric arguments of Copernicus and Kepler.

Another fundamental ancient authority was Plato's pupil, Aristotle. He ventured to deal with natural philosophy extensively, including the nature of the celestial realm, especially in his treatise *On the Heavens* [11] (see the chapters and page numbers in this paragraph). He saw the celestial realm as essentially different from the terrestrial domain, made out of an entirely separate kind of matter (chs. I/2–3, pp. 3–7) which is incapable of coming to be and passing away, i.e., it is eternal and immutable (chs. I/10–12, pp. 23–33). The spherical Earth is situated at the centre of the cosmos and is stationary by nature of its material (ch. II/14, pp. 58–61), while the surrounding celestial spheres are also spherical and capable of nothing but uniform circular motion (chs. II/4–6, pp. 39–44)—a higher realm of existence, both literally and figuratively. The globes of celestial bodies are attached to, and carried by, these spheres (ch. II/8, pp. 45–47), and contrary to Plato, they were not made of fire, which is one of the four terrestrial elements, but of the fifth and unchangeable form of matter (ch. II/7, p. 44). Consequently, heat and light do not come from these bodies themselves but from the air below which is inflamed by their rapid motion (ch. II/7, p. 44).

This latter claim is expanded in chapter I/3 of his *Meteorologica* [12]. We learn that the Sun has the capacity to produce so much heat (and light) compared to other heavenly bodies owing to the optimal combination of its speed and position: it is faster than the Moon (i.e., the Moon lags behind the daily rotation of the sky to a greater extent than the Sun) but closer to us than the (still faster) stars. Note that in order for the Sun to have this capacity, it should be near the top layers of the atmosphere, in spite of its sphere being thought to be above that of the Moon—but other than that, Aristotle (just like Plato) placed the Sun below the planets [11] (pp. 49–50) and the outmost sphere of the fixed stars which are "far further away" than the Sun [11] (p. 61). The latter passage also claims that the Sun is greater than the Earth. However, according to the majority of subsequent geocentric astronomical tradition, the Sun is actually on the fourth sphere from the Earth, above the Moon, Mercury and Venus (see, e.g., in Ptolemy [13,14]). This is mostly based on Aristotle's argument that the order of the spheres is determined by their speed: the faster the motion, the higher the sphere [11] (pp. 48–49). Notably, this principle does not distinguish between the Sun, Mercury and Venus, all exhibiting the same annual revolution relative to the stars (i.e., Mercury and Venus accompany the Sun on their course, disregarding their periodic elongations from it)—see the ensuing flexibility recounted in [15].

3. Antiquity: Variations

While the views of Plato and Aristotle had the greatest impact on later concepts, Greco-Roman antiquity witnessed alternative approaches as well. Aristarchus of Samos proposed that the stationary Sun is at the centre of the cosmos, and the Earth orbits around it annually. Unfortunately, the details of this proposition are lost to time, and it is known only from brief references made by other authors, collected in [16]. Whereas this idea is often celebrated as an early formulation of the Copernican theory (see the title of the previously cited book), there are good reasons to doubt this equivalence, based on the absence of any surviving mention of the planets [17]. Moreover, in his only extant work on *The Sizes and Distances [of the Sun and the Moon]*, Aristarchus derived from his astronomical measurements that the Sun is about 20 times further away than the Moon (which amounts to roughly 380 Earth radii in his system [18]) and that it is around seven times larger in diameter than the Earth [16] (pp. 376–381 and 402–407). This size difference is regularly speculated to be a major factor behind Aristarchus's heliocentric commitment (for a possible source of this view, see [16] (p. 310)); nevertheless, most authors did not find it problematic to simultaneously maintain that the Earth is at the centre and that the Sun is much greater [19]—see, e.g., Ptolemy, a pivotal figure in the geocentric tradition, claiming that the size of the Sun is 5.5 times that of the Earth [14] (p. 257).

A notable exception to this general consent was the Epicurean school. Epicurus of the 4th and 3rd centuries BCE, in his *Letter to Pythocles*, asserted that "[t]he size of sun (and moon) and the other stars is for us what it appears to be" [20] (p. 61), and this claim was repeated, e.g., by the Roman poet Lucretius, in book V of his deeply influential poem *On the Nature of Things* [21]. While the exact intention of this proposition is debated today [22], in antiquity it was usually interpreted literally, often as meaning "1 foot in diameter" for the Sun, and this invoked a series of vehement criticisms and denials (see, e.g., a detailed refutation offered by Cleomedes [23]). In addition, the Epicureans adhered to a form of atomism, claiming that all corporeal bodies are composed of tiny particles embedded in an infinite void and sticking temporality together according to the material principles of nature, without divine intervention. Unfortunately, if these ideas were applied at all to the specific composition of the celestial realm, the details of such a conception are now lost.

A rival school to the Epicureans were the Stoics, who accepted the general image of the Aristotelian cosmos, with the central Earth surrounded by the spherical layers of elementary regions [24]. However, they denied the existence of a fifth element in the celestial realm and maintained that the heavenly bodies are made of a pure and rarified form of fire (often called ether). Just like terrestrial fires which must be fuelled, celestial fires are nourished by exhalations arising from the waters of the Earth. Moreover, their cosmos was a living entity, animated by an active and divine corporeal power called pneuma ("breath") that pervades all bodies and binds them together [25]. The universe is governed by an intelligent command-principle (*hegemonikon*), and while many Stoics associated this with the purest form of ethereal fire, at least Cleanthes and Cicero identified it with the Sun, regulating and nourishing all aspects of nature [26]. Cleomedes, in a late Stoic astronomical textbook, discussed the many effects of the Sun on the terrestrial realm [23] (pp. 119–121), in line with the Stoics' general fondness for astral divination [27].

Such a belief in the effective influence of the heavens, and especially of the Sun, on terrestrial regions was widespread in late antiquity. Already Aristotle mentioned in passing, in his work *On Generation and Corruption* (ch. II/10), that the primary changes in all terrestrial things, i.e., their creation and destruction, depended eventually on the Sun, making it a fundamental entity of nature [28]. In an extensive encyclopaedic work, the *Natural History* (book II), Pliny the Elder takes celestial influences for granted, and here the Sun is described as the "the soul, or more precisely the mind, of the whole world, the supreme ruling principle and divinity of nature" [29] (p. 179). Similar concepts about the Sun as the "mind of the universe" are later revisited by the medieval Macrobius, in chapter I/20 of his impactful *Commentary on the dream of Scipio* [30]. Ptolemy's *Tetrabiblos* (ch. I/4), the chief pioneering work of the Western astrological tradition, attributes a heating faculty to the Sun, a humidifying faculty to the Moon and a mixture of these two faculties (borrowed from these primary bodies) to the rest of the planets [31]. These claims would become essential constituents of subsequent notions concerning the specific role of heavenly bodies in natural processes. High appraisal of the Sun was also connected to the Egyptian cultural impact unfolding in the Hellenistic era. For similar late-antique views and authors on celestial affluences, either less impactful or less pronounced with respect to the Sun's role (e.g., Galen and Plutarch), see [32].

Up to the 17th century, mathematical astronomy and natural philosophy were rigidly separated: the former provided geometrical hypotheses describing celestial motions, while the latter investigated the nature of the material world often including, like in the examples above, the heavenly region. Ptolemy's *Almagest*, the quintessential work of the mathematical tradition, modelled the motion of each celestial body independently, among them being solar motion in book III, supplemented with estimations of the Sun's parallax (distance) and size near the end of book V [14] (pp. 131–172 and 251–274). These inquiries never touched upon questions pertaining to natural philosophy, e.g., about what the Sun is, and the disciplinary separation was reinforced in the opening chapter of book I.

However, even within technical astronomy the Sun seemed a special object: Ptolemy's entire treatise is witness to a curious circumstance. For each planet as well as the Moon, one component of their motion, the so-called second anomaly, is tied to the period and mean position of the Sun. This component is represented by the famous epicycle for the higher planets and by the motion along the deferent circle for the lower ones (see books IX–XII). In the case of the Moon, this anomaly, likely discovered by Ptolemy himself, would become referred to as "eviction" in modern astronomy (chs. IV/5, V/2–3). Ptolemy did not stop to ponder about this inexplicable universal linkage to the Sun, but his exceedingly successful mathematical models revealed another aspect of solar prominence in the cosmos. In the Renaissance reception of Ptolemy's astronomy preceding Copernicus's revolution, recognition of this puzzling connection would become widespread [33]. Similarly, it had to be accounted for in geocentric models developed after Copernicus, such as that of Giovanni Battista Riccioli in the middle of the 17th century [34].

4. From Late Antiquity to the Renaissance

Given these historical foundations, it is not surprising that, from late antiquity to the early modern era, the Sun was typically perceived as more than just a physical body. It was often seen as a divine entity, endowed with a mind, even a personality (Figure 2), with a profound symbolic and regulating function in the order of the universe. One philosophical school to highlight the Sun were the Neoplatonists, who reconciled Platonist metaphysics with early Christianism. As a central concept, they expanded on Plato's allegory of the Sun and turned it into a theory of emanation. Just like light diffuses from the Sun to illuminate all things without depleting or even weakening its source, so do the fundamental modes of existence, like Good, Unity and Order, proceed from their source, the one God [35]—see *The Enneads* of Plotinus for an early formulation of this theory [36], summarized, e.g., by [37].

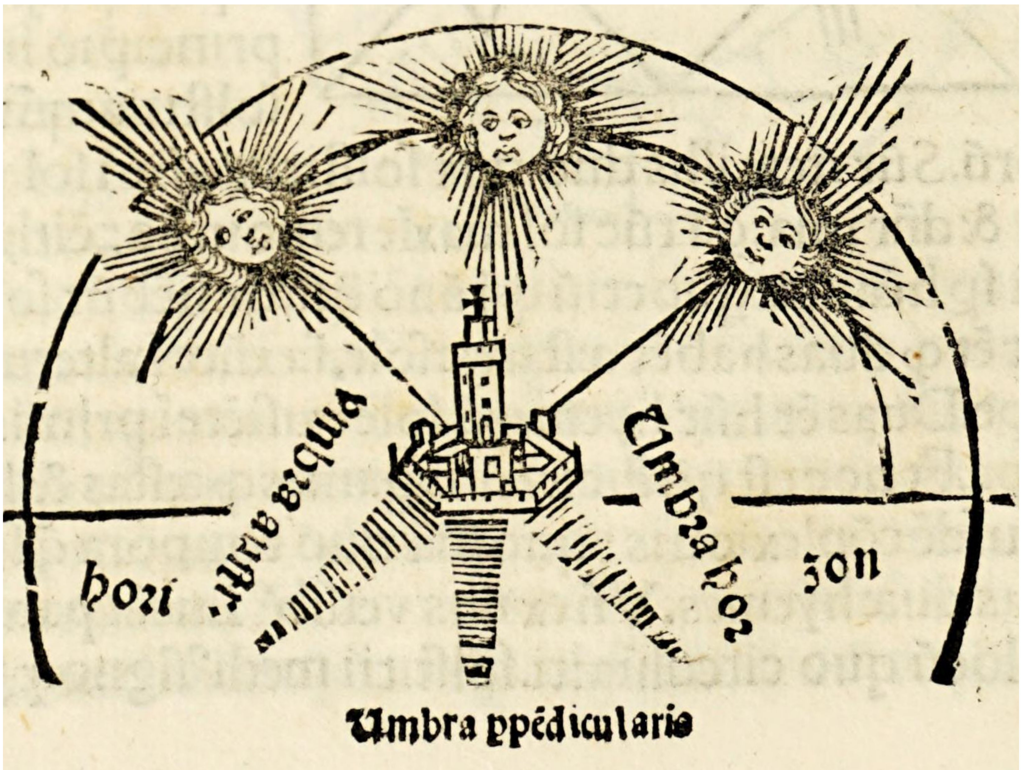

Figure 2. Medieval and renaissance solar imagery often personified the Sun, as seen in, e.g., Johannes Sacrobosco's *De sphaera mundi* [38].

Proclus, a Neoplatonist in the 5th century CE, contemplated on the physical constitution of the celestial realm [39,40]. While the spheres are not corporeal bodies but only regions in which their corresponding celestial bodies move (by themselves), they are nevertheless filled with matter. As he also denied the existence of the fifth element, he maintained that the heavenly region, like everything else, is a mixture of the four classical elements but is made predominantly of fire, the highest element in its purest form. The space between celestial bodies contains traces of air and water (on top of fire) but not earth and therefore is transparent; however, the bodies contain earth as well and thus are both visible (resisting sight) and pellucid (capable of occulting each other). According to him, celestial objects also possess souls in addition to their material body and are eternal and divine: they are somewhere between the purely intelligible forms and the mundane sensible reality. From this immaterial perspective, the Sun is the noblest of them all and, accordingly, it emits the largest amount of light, which is the essential form of fire; but with respect to material composition, it is not explicitly distinguished from the rest of the heavenly bodies.

In the intellectually flourishing period of Scholasticism surrounding late mediaeval European universities, Aristotle's cosmology provided the fundamental framework in which a multitude of positions were developed. With regards to cosmology, these positions are described and disentangled with great erudition in [41] (see the page numbers in this paragraph and the next one). Heavenly spheres are incorruptible and perfect (pp. 189–243), and celestial bodies are condensed regions of their corresponding aethereal spheres, usually understood to be composed of a substance that is material in nature (pp. 244–270), either solid or fluid (pp. 324–370). While the majority of authors held that only the Sun is originally luminous, and the rest of the bodies merely transmit its light (albeit not via simple reflection), others proposed that all stars and planets (perhaps with the exception of the Moon) emit their own light (pp. 390–421). The question whether celestial bodies are alive was debated by proponents of diverse positions (pp. 469–487), but it was ubiquitously agreed that they exert influences on the earthly region by various means (569–617).

Whereas almost no independent analyses were written in this period specifically about the Sun, it was often discussed in the cosmological contexts described above (pp. 451–454). It was seen as the largest celestial body, situated on the fourth sphere. This "central" position in the heavens distinguished it from the other bodies: although it was not the most perfect of them in terms of its location (not the highest) nor its motion (not the simplest), it was nevertheless the most important one as being the chief source of light in the universe, illuminating all from a position in the middle. Also, it vitally contributes to a wide range of natural processes. The metaphors of the "king" and of the "heart" were used to portray its role, and these were often alluded to in later times as well, e.g., in Georg Joachim Rheticus's *First account* of the Copernican hypothesis published in 1540 [42], before the printing of his teacher's seminal work *On the revolutions*.

The allegorical prominence of the Sun, already significant in the solar symbolism of Christianity [43], became even more highlighted in the 15th century when Neoplatonism was restored, primarily by the Florentian Marsilio Ficino, in its original Plotinian form. Obviously, the Sun played a fundamental role in this approach: it signified God himself, and it expressed invisible actions and angelic spirits in the divine realm [44]. Its powers regulated both the heavens and the Earth, by natural as well as occult means. Ficino's philosophy, partly rooted in a metaphysics of light, inspired many scholars in the 16th century [35] (23–29).

5. The Heliocentric Turn

A decisive transformation in how the Sun was viewed was prompted by the Copernican turn. Nicolaus Copernicus practiced mathematical astronomy and, just like his main predecessor Ptolemy, had basically nothing to say about the nature of the Sun. In placing the Sun at (or near) the centre of the universe, he was primarily motivated by the above-mentioned second anomalies of celestial objects, i.e., the presence of the mean solar position in geocentric planetary hypotheses. By reducing these apparent periods to the actual revolution of the Earth, he was able to offer an integrated and explanatory account of the totality of celestial motions. Nevertheless, in an era when Neoplatonism was a popular alternative to scholastic Aristotelianism, he was undoubtedly influenced by the philosophical Sun worship of the Renaissance. In chapter I/10 of his work *On the revolutions*, he broke his dry and technical vernacular in a frequently quoted paragraph where he cited elevated descriptions of the Sun: it is called "the lantern of the universe, its mind by others, and its ruler by still others", "a visible god" by Hermes Trismegistus and "the all-seeing" by Sophocles's Electra, and he adds that it is "seated on a royal throne" governing his family, the planets [9] (p. 22). While it is debated whether Copernicus himself can be labelled as a Neoplatonist [45], the stationary position and central cosmic role he attributed to the chief natural symbol of truth and divinity was certainly consonant with the atmosphere of humanistic culture [46] (Figure 3).

Figure 3. Raphael's fresco the *Disputation of the Holy Sacrament* (Apostolic Palace, Vatican, 1509–1510). The central axis, representing the Holy Spirit, is laden with solar symbolism. (Source: Wikimedia Commons).

One consequence of the Copernican turn, not yet realized by Copernicus, was the dissolution of the unnecessary (since stationary) sphere of the fixed stars. This resulted in a conception of stars distributed in a potentially endless space [47], possibly surrounded by inhabited planetary systems [48]. Accordingly, the Sun was increasingly seen not as a singular entity but as a specimen of a highly populous kind. The most important post-Copernican pioneer of this idea was the Italian friar Giordano Bruno, who maintained that the infinite universe contains an infinite number of worlds, i.e., stars with planetary companions [49]. Suns are made (primarily) of fire, a hot and luminous substance, whereas earths are made (mainly) of water, a cold and reflecting substance—this duality substitutes the traditional doctrine of the four (or five) elements. Suns may move relative to one another, and earths may host inhabitants [50]. Note that however progressive these claims may seem in hindsight, Bruno's cosmological vision was supported less by astronomical observations, let alone calculations, and more by theological considerations and mysticism [51]. Nevertheless, while his works would become only infrequently cited because of his condemnation (and execution) as a heretic in 1601, his ideas are clearly echoed in some of the most influential cosmologies of the 17th century, like those of Descartes and Newton.

Another consequence of heliocentrism was a physical interpretation of the Sun's role in planetary motions, developed most notably by Johannes Kepler [52]. Already in his first published work, *The Secret of the Universe* (ch. 20), he firmly believed that the Sun is not only the centre but also the cause of motions, and he introduced a "moving spirit" or "moving force" originating in the Sun that moves the planets along their orbits [53]. This concept was largely expanded in his later works *New Astronomy* (chs. 33–36, 57) and *Epitome of Copernican Astronomy* (chs. IV/II/2–IV/III/4) [54,55], where he proposed that this force is immaterial but corporeal, i.e., it has no body but acts on bodies, like a magnetic force. Indeed, it is literally in magnetic interaction with the bodies of the planets, thus causing not only their orbiting motion but also their deviation from circular paths (i.e., changing their solar distance along the elliptical orbits—see Figure 4) and their latitudinal elongations from the plane of the ecliptic. In order for the Sun to produce this effect, it needs to be a magnet on the one hand, having magnetic "fibres" both linear (perpendicular to the ecliptic) and circular (parallel to its equator), and on the other hand, it needs to turn on its axis so that its emitted force can also rotate and propel the planets around. Hence the idea of a rotating Sun, proposed on theoretical grounds shortly before the telescopic discovery of rotating sunspots (but already suggested briefly by Bruno: [49] (p. 181)). While this elaborate physical theory is mostly wrong in hindsight, it inspired approaches allowing for, and relying on, unseen immaterial forces acting in material nature, up to the era of Newton [56,57].

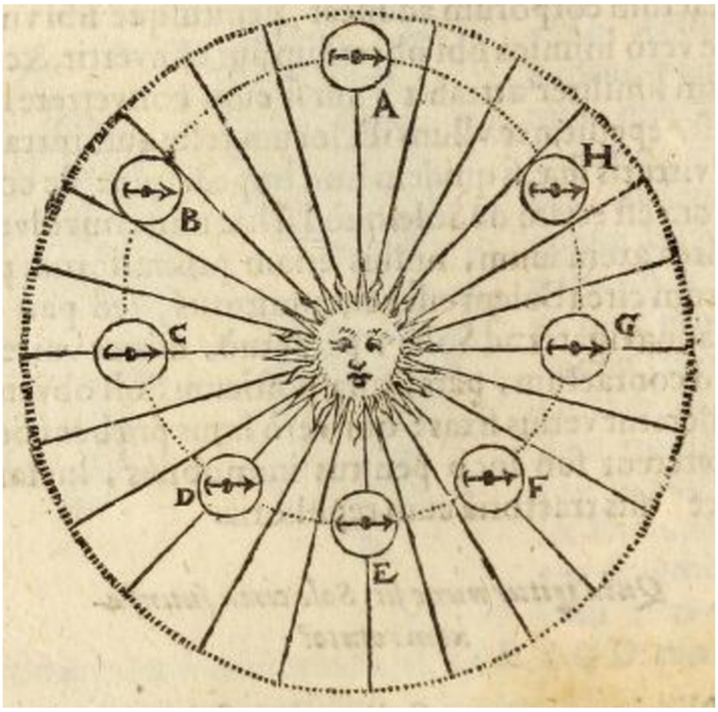

Figure 4. Johannes Kepler's depiction of the immaterial force emitted by the Sun and magnetically shaping planetary orbit [58]. Capital letters designate different positions of the Earth along its orbit, and the arrows indicate the Earth's purported "magnetic axis" (which, for Kepler, is different from the actual magnetic axis going through the magnetic poles and is parallel with the orbital plane).

For Kepler, however, this physical approach was only complementary to an archetypical perspective: his universe was created according to a rational design expressed in the general construction of the cosmos and its geometrical and arithmetical harmonies [59,60]. The Sun was not only a central physical body but also a divine entity. Kepler assumed a correspondence between the stationary parts of the world and the Holy Trinity: the Sun corresponds to God, the motionless starry sphere (which Kepler still accepted) to the Son and the stationary space between them to the Holy Spirit [53] (p. 63), [55] (pp. 13–14). This symbolism is linked to a Neoplatonic emanation theory and, accordingly, solar radiation giving out both light and motive power is described as an endless but instantaneous communication of the Sun's surface image (*species*) to the bodies in the world [54] (pp. 381–384), [61]. In addition, the Sun is "the fireplace [hearth, *focus*] of the world" [55] (p. 15), by whose fire the planets warm themselves, and since the universe is animated with souls, the Sun is also the "source of the world's life" [54] (p. 379). As a transitional figure in the so-called Scientific Revolution, Kepler created a fascinating synthesis between the fading image of the divine and mindful heavens (also expressed in his enthusiasm for astrology) and the emerging picture of a purely material and mechanical cosmos [62].

Moreover, in the "Conjectural Epilogue on the Sun" at the end of his *Harmony of the World* [63], Kepler contemplated about the question of solar inhabitants. As a natural extension to heliocentric cosmology, he often assumed that other planets, just like the Earth being one of them, are inhabited [64]. Here, he raised the question why the Creator would exclude the largest body from the dwellings of potential intelligences, especially since the cosmic harmonies (established throughout his book) can be perceived in their most perfect form only from the centre. He drew an analogy between terrestrial clouds and rain on the one hand and the recently discovered sunspots and faculae on the other and then asked: “Do not the very senses themselves cry out that fiery bodies inhabit [the Sun], which have the capacity for simple minds” [63] (p. 497)? Note that historical belief in solar inhabitants was certainly not widespread, but neither was it exceptional [65], as seen below.

6. The 17th Century: Telescopes and Vortices

Shortly after the invention of the telescope in 1608, reports of novel celestial phenomena upset the already unstable astronomical world engaged in a cosmological crisis, torn between the geocentric heritage, the Copernican theory and its geo-heliocentric alternatives offered, e.g., by Tycho Brahe. While the first telescopic observations of sunspots were probably obtained by Thomas Harriot [66], it was Galileo Galilei who capitalized most successfully on their implications. These observations showed that the Sun, just like the Moon, is not a perfect body, implicitly questioning its divinity, and also that it is subject to temporal changes, contrary to the Aristotelian doctrine of celestial immutability, as argued, e.g., by Galileo in his *Dialogues* [67]. In addition, the axial rotation of the Sun was demonstrated. However, the nature of the phenomenon remained open to interpretation, as illustrated by his polemic with the Jesuit Christoph Scheiner [68] (see the page numbers in the paragraphs below).

While both of these diligent observers agreed on the reality and the visible properties of the phenomena (Figure 5), Scheiner proposed that sunspots are probably numerous dark satellites very close to the solar surface, partly for the sake of preserving the immutability of the Sun and partly because he believed the Sun to be a solid globe, unfitting to carry these unstable formations (e.g., p. 199). Interestingly, he argued in passing that sunspots cast doubt on birth horoscope astrology, since they would erratically but significantly affect the alleged influence of the Sun (pp. 229–230). Galileo, on the other hand, maintained that these turbulent formations cannot be solid bodies and that they bear the closest resemblance to clouds—albeit he refrained from claiming that they actually are clouds, either emitted or attracted by the Sun (pp. 99–100). On the basis of perspectival changes in their shapes and relative positions along their transit across the solar disc, he vehemently argued that spots are so close to the surface that no separation is perceptible, implying that they are attached to the solar body (pp. 111–118, 276–278). Moreover, while the instability of the spots indicate that they reside in an “ambient”, liquid substance, the fixity of their relative location implies that the Sun rotates as a solid body (pp. 124–125).

Figure 5. Galileo Galilei’s illustration of illusory telescopic solar images, in contrast with genuine ones (not shown here), provided that the spots were caused by spiders and flies (**A**), undulating sashes (**B**), clouds (**C**), waterdrops (**D**) or different kinds of bubbles (**E**–**G**) [69]. For details, see [68] (pp. 211–216). The image is rotated to fit better.

Scheiner was not convinced by these arguments at first, although the discovery of faculae changed his mind, as brighter spots cannot be transiting satellites (p. 308). He summarized his observations and conclusions in a lengthy treatise entitled *Rosa Ursina*, which remained the quintessential work on sunspots over the next hundred years [70]. He determined the inclination of the solar axis accurately, as opposed to Galileo who (first) claimed it to be perpendicular to the ecliptic, and Scheiner put great emphasis on repeatedly pointing out his rival's error. In turn, Galileo mocked Scheiner in his *Dialogues*, having his claims advocated (but uncredited) by the dumb antagonist Simplicio [67] (p. 101). Another contemporary arguing for the inclined rotation axis was Simon Marius (Mayr), independent discoverer of the Jovian satellites, who came up with an alternative interpretation of sunspots: these are "slags" of ashes produced by burning flames, and they are the origin of comets that the Sun ejects [71].

For a long while, subsequent telescopic observations did not reveal substantially new solar phenomena, nor did they bring astronomers any closer to a better understanding of the nature of the Sun [6] (pp. 64–65). This may be partly due to the Maunder minimum, an extended period of greatly reduced sunspot activity, but on the other hand, the Sun remained an elusive target throughout the century (and beyond) also because of its great brilliance, which occasioned dubious sightings. Otto von Guericke saw violent bubbling and mountain-shaped bulges on the rim of the solar disc, and in comparison, he reported similar sightings by Christoph Scheiner (who also saw lightning flashes indicating thunderstorms), Simon Marius (reminding him of the boiling of molten gold) and Giovanni Riccioli (interpreting it as a tremor in the solar atmosphere) [72]. No wonder that such sightings led several authors toward fanciful speculations. For instance, Athanasius Kircher imagined a turbulent Sun made of a mixture of solid and liquid fires (Figure 6), fuming up its own (atmospheric) comets that we see as sunspots [73]; similarly, Johannes Hevelius envisioned a vivid ocean of a very heterogeneous fiery liquid mingled with solid parts, displaying its currents, vortices, abysses, exhalations and evaporations [74]. Giovanni Domenico Cassini, on the other hand, believed that sunspots are peaks of solar mountains protruding temporarily above the ebbing tides of the luminous atmosphere or, alternatively, volcanoes spitting out fumes at certain intervals [75].

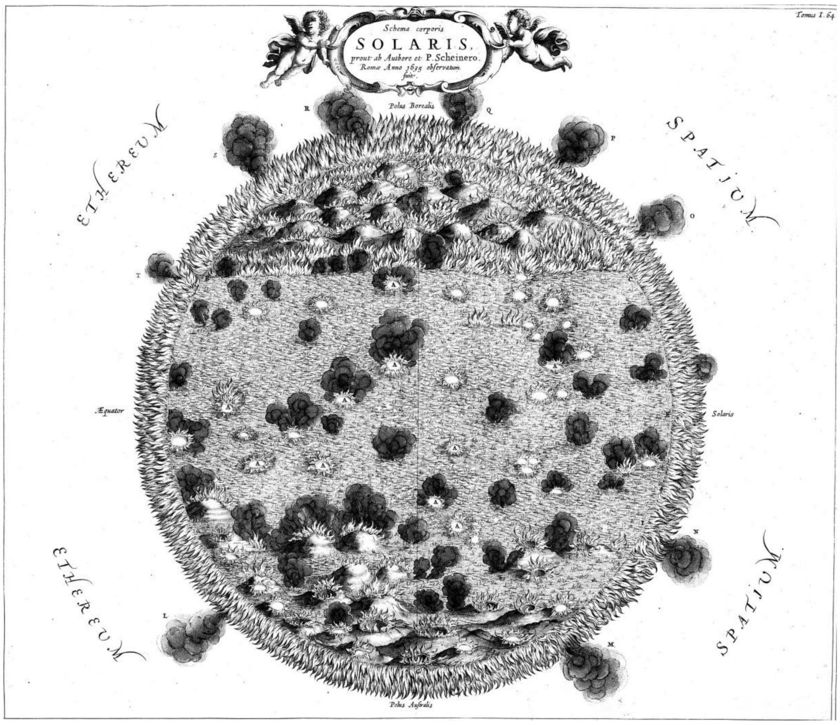

Figure 6. Athanasius Kircher's imaginative drawing of a hectic solar surface, from his *Mundus subterraneus* (1665) [76].

On the theoretical side, transformations in concepts about the material constitution and the physical bases of the world prompted a variety of approaches. One view to emerge as dominant was René Descartes's vortex theory, outlined in two of his works, *The World* and the *Principles of Philosophy* [77,78]. Descartes set out to explain natural phenomena purely on materialistic principles, based on the mechanical interactions of inert bodies according to the rational laws of nature [79]. Material objects are composed of elementary particles of three kinds: the smallest and most agile ones are those of fire, the stuff of stars in the cosmos; the medium ones constitute air that is present between celestial objects; and the largest and most sluggish ones compose earth, the material of planets and comets. Since Descartes rejected the existence of an empty void, he expected the plenum of particles to fill all places. Corpuscles push one another by their motion and, in order to avoid an infinite regress of collisions, their interactions happen in closed causal loops, thus resulting in vortices. The Solar System is such a vortex: fire particles, having the least inertia, tend toward the centre to coalesce as a globe (Sun), and lumps of earth particles (planets) are carried around by the swirl of air particles. Due to convoluted mechanisms, sub-vortices are created around the planets, carrying their satellites and establishing local gravity. Moreover, accepting Bruno's cosmology (without credit), Descartes believed that stars are also suns scattered in an infinite universe, surrounded by their own vortices. Adjacent vortices hold each other together through the perpetual collisions between their corpuscles (Figure 7).

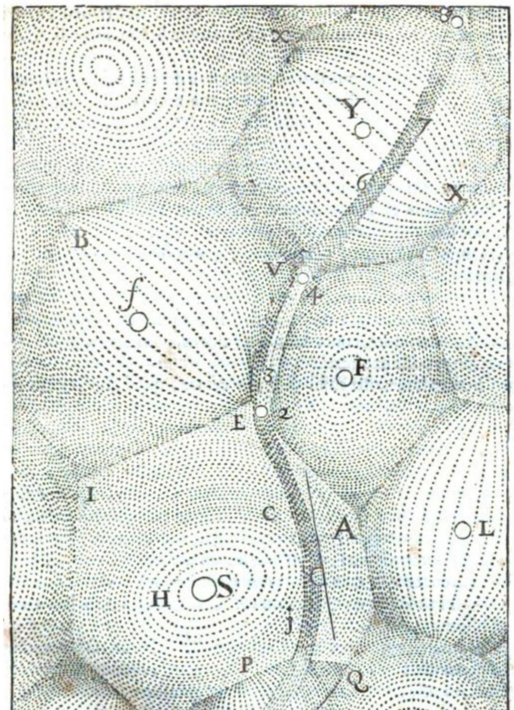

Figure 7. René Descartes's drawing of the Sun (S) among other stars (D, L, F, f, Y), each surrounded by their vortices indicated by the dotted curves [80]. A, E, I, V, B, X are points where adjacent vortices meet. N is a comet, thought to be an interstellar traveller.

In part III of the *Principles of Philosophy* [78], numerous astronomical phenomena are interpreted in this framework, including solar properties. The Sun is built of fire, but it does not need fuel because it is not immediately dissipated by its environment like terrestrial fires (§21–22). It emits light spherically, somehow despite the planar nature of the centrifugal force propelling light particles (§79–81). Sunspots are made of slightly larger and more angular, and therefore less agile, sorts of fire particles (§94), accounting for the spots' distribution, colour, and transient nature (§95–97). The spots may multiply to eventually cover the entire solar or stellar surface, explaining variable stars and novae (§102–114). By mutual interactions, one vortex can swallow another, making its star a planet or a comet (§115–120). Accordingly, Descartes's infinite universe is dynamic: both in that stellar positions are subject to change (note that visible celestial positions are believed to be optical illusions owing to the reflection of light on fluctuating boundary surfaces between vortices) and because stars themselves are mutable and perishable. While his mechanics was soon superseded by the quantitatively accurate physics of Newton, elements of Descartes's cosmology long prevailed as contributing to a phenomenologically successful picture of the universe.

7. Newton and His Legacy

Isaac Newton was perhaps the utmost authority in the newly emerging scientific scene. Book III of his *Principia* portrays solar prominence in a new light [81]: the Sun is the primary cause of the system of motions, and its role can be described in a precise quantitative way. It is a massive body exerting an attractive gravitational force which determines both its shape (spherical) and the geometrical paths of its companions, the secondary bodies such as planets (prop. 13) and comets (prop. 40). In turn, it is slightly moved by the gravitational interactions with other bodies in its system (prop. 12). In addition, it perturbs the orbits of tertiary bodies (satellites) (prop. 25), and it contributes to the tidal phenomena in terrestrial seas (prop. 36), as well as to the axial precession of the Earth (prop. 39). Based on the extent of its influence, it has a measurable quantity of matter (mass) and therefore a specific overall density (prop. 8)—one fourth of the density of the Earth, "rarefied by its great heat" [81] (p. 814).

For Newton, however, the Sun was interesting not only for its fundamental dynamical role but also as an extremely hot and luminous object, as opposed to the rest of the bodies in the solar system but similarly to its spatially distant relatives, the fixed stars. His *Opticks* deals primarily with the experimental properties of solar light, composed of differently refrangible rays, but near the end Newton ventures to outline some uncertain theoretical speculations. In Query 11, he suggests that the solar atmosphere is so vast and dense that it prevents the Sun both from cooling down rapidly (by preserving its heat) and from evaporating and boiling away [82]. The former claim appears also in an unpublished conclusion to the *Principia*: "I suspect that the heat of the Sun may be conserved by its own sulphureous atmosphere" [83] (p. 343). As to the question of how the Sun became hot and luminous in the first place, i.e., why matter condensed into radiant spheres in some places and dark bodies in other places (planets, moons and comets), he admits that he cannot conceive this circumstance as a result of natural causes. Rather, he sees it as an outcome of intelligent design [84], being the first of a series of observations that prove the existence of the Creator, one that is responsible for the grand design of the universe.

In the 18th century, Newton's mechanical theory proved immensely successful in explaining celestial motions, but the material constitution, the luminous property and the heating capacity of the Sun remained an open question. For the state of the art around 1720, see the summary given by Cotton Mather [85], covering, e.g., historical reports on alleged radical reductions in solar luminosity, or a proposal concerning solar light lacking heat (the latter being generated in the atmosphere) or worries about the continuous decrease in the Sun's output due to it losing millions of rays perpetually. William Durham claimed, citing at length a letter from the 17th century William Crabtree in his support, that sunspots are smokes ejected by solar volcanoes [86]. In the middle of the century, John Hill's monumental (and printed but unpublished) encyclopaedia of astronomy, entitled *Urania* [87], dedicated 15 double-column pages to the entry on the Sun, mostly concerning observational phenomena and solar effects on the Earth. Without citing references, it summarized two main alternative conceptions about solar constitution: the Sun is either a solid and opaque body covered by a luminous fluid, the spots being protruding islands or floating volcanic matter, or made of a boiling and turbulent fluid, with floating solid masses on the surface.

At around the same time, the later celebrated German philosopher Immanuel Kant devoted a chapter in his work on natural philosophy, *Universal natural history and theory of the heavens*, to the theory of the Sun [88]. He explained solar luminosity on the grounds of his early conception of matter, rather than divine intervention. Ignoring here the complexities of his soon obsolete theory (see, e.g., [89]), it is worth noting that he believed active solar flaming to be a finite process, eventually terminating when the fuel (trapped inside the solid solar body and breaking out through newly opening chasms) runs out. He also proposed that novae might be dying suns "close to their extinction", giving out their last bursts of flame [88] (p. 277). To note, the problem of the unceasing solar loss through radiation, especially related to a particle conception of light, was repeatedly addressed by contemporary scientists, e.g., Leonhard Euler, Benjamin Franklin and Bryan Higgins [90].

In contrast to philosophical speculations, the first edition of the *Encyclopaedia Britannica* (1771) offered only a laconic claim about the Sun being "an immense globe of fire" [91] (p. 435). Similarly, astronomical journal papers habitually avoided such discussions. The *General Index to the Philosophical Transactions*, indexing the first 70 volumes of the journal up to 1780, provides 126 entries under the label "Sun" [92], but among the many observational publications almost none are concerned with the constitution or nature of this body. Partial exceptions can be found in articles reporting and interpreting sunspot observations, like that of Durham cited above. Another example is Samuel Horsley's brief paper from 1767 in which, assuming that sunspots are floating clouds, the author derives from the alleged duration of their visibility that their height above the surface is 1.4% of the solar radius [93]. Therefore, the Sun's atmosphere is proportionally much thicker than that of the Earth, supporting Newton's speculation concerning the heat-preserving capacity of this vast atmosphere. A further, more extensive and more impactful exception is Alexander Wilson's 1774 paper [94]. Based on what he perceived as perspective effects in his observations, he concluded that sunspots are actually "excavations" or depressions on the solar surface. He then conjectured that the Sun has a dark, solid and cooler body with an irregular surface, surrounded by a luminous liquid (or rather, dense fog) rising from the depths of the solar body and flowing down the sloping sides of sunspots (penumbra), thus exposing the surface (umbra).

Despite the attack by French astronomer Joseph Jérôme Lalande [95], whose ideas featuring protruding solar mountains were closely akin to those of Cassini, Wilson's conjectures gained considerable traction in astronomical circles. Their credibility was supported by the circumstance that two prominent astronomers, Johann Elert Bode and William Herschel, reached very similar conclusions. Bode published his views in 1776, and while his theory is closely reminiscent of that of Wilson, he was unaware of Wilson's paper at the time of writing, as he explains in the endnote attached to his publication [96] (pp. 249–250). Herschel, on the other hand, was inspired both by Wilson and Bode [90] (p. 95), and his improvement on their ideas meant valuable support, him being perhaps the greatest astronomical authority of the subsequent decades.

In his 1795 paper [97], Herschel proposed that the Sun consists of two parts: a dark and solid body and a vast atmosphere composed of elastic fluids, including a lucid component which is probably generated via decompositions. This implies that the Sun may become exhausted, but Herschel conceded that either the process is imperceptibly slow or that it is avoided by yet unknown mechanisms. Spots are devoid of the superior layers' lucid component and therefore are depressions in the atmosphere, while faculae are excessive regions of this decomposed and lighter matter, bulging up higher. The luminous layer is calculated to have a depth between 1843 and 2765 miles (p. 62). Also, some room is left for the theory concerning sunspots as potential mountain tops, "at least five or six hundred miles high" (p. 52).

Based on the analogy with the uneven terrestrial surface, and with the cloudy atmosphere of the Earth, in a frequently quoted passage Herschel concluded that the Sun "appears to be nothing else than a very eminent, large, and lucid planet"; moreover, "it is most probably also inhabited, like the rest of the planets, by beings whose organs are adapted to the peculiar circumstances of that vast globe" [97] (p. 63). In addition, he conjectured that other stars are similar in the former respect, since they are also suns, as seen from their variable luminosity that he attributed to the rotation of their spotted surfaces; thus, he was led to believe that perhaps all cosmic bodies are inhabited [98]. Here, the question arises how solar inhabitants are protected from the great brilliance and heat of the luminous higher atmosphere. In this paper, Herschel proposed that light does not necessarily involve heat but requires a receptive "calorific medium" to develop, so the solar surface does not need to be hot. In a subsequent publication from 1801 [99], relying on numerous observations of solar phenomena interpreted in terms of "openings", "shallows", "ridges", "pores", etc., he distinguished between two atmospheric layers: a superior one that is light and luminous and an inferior or "planetary" one that is dense with clouds (Figure 8). Since "the immense curtain of the planetary solar clouds is every where closely drawn" (p. 299), this inferior layer shields the surface from the brilliance above, while reflecting a sufficient amount of light ("no less than 469 rays out of a thousand", *ibid.*) for the planets to be illuminated. Note that Bode, in the cited essay, had also suggested hypotheses about solar inhabitants clouded in a thick atmosphere which, for him, had a thermal function rather than a shading one [65] (p. 171).

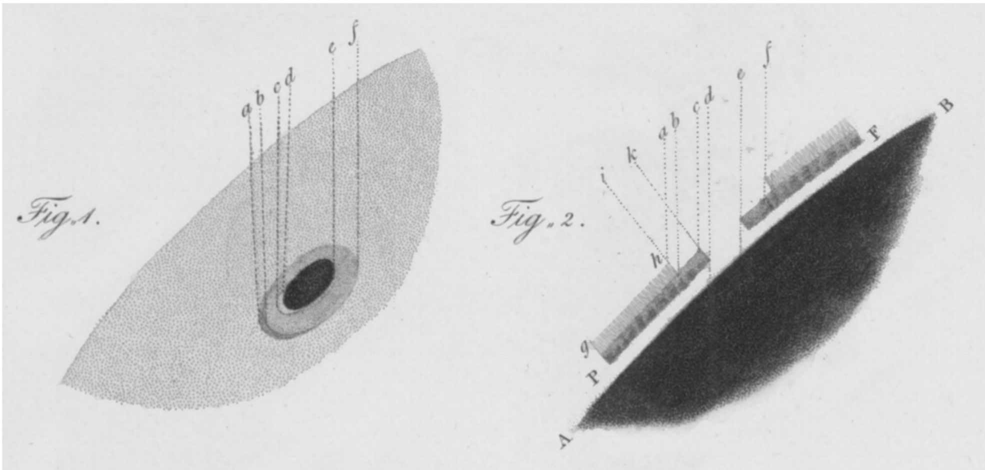

Figure 8. William Herschel's drawings of a sunspot, in [99] (Plate XVIII), interpreted as "an opening in the luminous solar clouds" (p. 318). His "Fig. 1." depicts the optical phenomenon, and "Fig. 2." shows a vertical cross section where AB is the opaque surface, PF is the dense inferior atmosphere, and *gh* is the luminous superior atmosphere. The remaining letters serve to identify parts of the phenomenon (umbra, penumbra) with elements of the structural interpretation on the right.

Herschel's "empyreal" elastic gas originally ascends from the solar body and then decomposes in the upper regions, thus producing light. It must be emitted at an uneven rate, since Herschel found variations in the solar activity, displaying periods of abundant surface features as well as other intervals without any significant visible phenomena. He also proposed that these variations must have an impact on terrestrial climate and, through the corresponding fertility of crops, on the price of wheat [99] (pp. 313–316) (see also his letter to Bode in [100]). In addition to these recognitions, Herschel was the first to successfully determine the proper motion of the Sun in its interstellar environment [101], and he is credited with the discovery that the Sun emits heat-generating invisible light (infrared) [102], although the latter credit is contested [103]. While his theory about the constitution of the Sun was as speculative (and largely wrong) as anyone's guess, his conception of the Sun as a dynamic material body, as well as his struggle to explain solar phenomena on solid observational and physical grounds, was a direct precursor to the emerging solar science in the 19th century.

8. Conclusions

Modern chapters of the story of the Sun can perhaps be summarized in a very straightforward manner, by pointing out how novel observational methods and theoretical developments in physics led to a profound transformation in the understanding of the subject. The emergence of spectroscopy shed light on the material composition and the physical properties of the solar atmosphere, with further details and layers exposed during solar eclipses. The discovery of the solar cycle, and observations on the corresponding variations in terrestrial magnetism and climate (as Herschel predicted), helped to treat the Sun's influence on more tangible physical grounds. And while the internal constitution and the heat-producing mechanism remained a puzzle for a long while [104], 20th century astrophysics gradually pieced together a comprehensive account of this previously elusive subject, based on an increasing apprehension of atomic and nuclear processes, as well as the application of improving observational techniques. This is the story of solar physics in a nutshell.

However, the prehistory of these developments, outlined in this paper and summarized in Tables 1 and 2, looks very different and cannot be recounted in a similarly linear chronicle of triumphant progress. From antiquity to the 18th century, notions concerning the Sun did not converge into a coherent narrative. Various perspectives contributed to this intricate story of cultural and scientific dynamics, with perhaps three dominant approaches. The first one is astronomical, dealing primarily with the motion, position, distance and size of the Sun, determined via observation and geometry. The second approach is physical (or, for a long time, belonging to the realm of natural philosophy), investigating the material nature and constitution of the celestial realm, including heavenly bodies with the Sun among them. And the third one is metaphysical, speculating about the theological, teleological, allegorical and symbolic role of the Sun in the cosmos and the general structure of reality. Eventually, in the 19th century, astronomical and the physical perspectives merged together, while the metaphysical one gradually vanished from science. Before that, however, they all played their pivotal roles in shaping conceptions along the way, contributing to multiplex and messy cultural dynamics within which science evolved.

Table 1. Summary of some principal pre-Copernican authors and schools and their views on various aspects of the Sun.

	Plato −427–347	***Aristotle*** −384–322	***Aristarchus*** c. −310–230	***Epicureans*** −3rd to 3rd c.	***Stoics*** −3rd to 2nd c.	***Ptolemy*** c. 100–170	***Proclus*** 412–485	***Scholastics*** 13th–15th c.
Place	2nd sphere	2nd sphere	Centre		2nd/4th sph.	4th sphere	2nd sphere	4th sphere
Size		>Earth	7 × Earth	Tiny	Large	5.5 × Earth	Large	Largest
Matter	Fire	Ether		Atomistic	Fire	(Ether)	Fire, air, water, earth	Ether
Role	Allegorical origin of truth and knowledge	Prompts all terrestrial changes			Governing the cosmos, regulating terrestrial events	Astrological influences	Metaphysical prominence	Various
Other	Doctrine of uniform circular motions	Heat and light from the ignited atmosphere below				Common solar component in celestial motions		"Middle" position among spheres

Table 2. Summary of some principal post-Copernican authors and their views on various aspects of the Sun.

Nicolaus Copernicus	1473–1543	Geometrically central Sun; allegorical solar prominence
Giordano Bruno	1548–1600	Fixed stars as suns, with orbiting planets and possible inhabitants
Johannes Kepler	1571–1630	Physically central rotating Sun, origin of motions; symbol of God; possible solar inhabitants
Galileo Galilei	1564–1642	Mutable (solid) globe, with cloud-like sunspots
Christoph Scheiner	1573–1650	Perfect solid globe; rotating sunspots as satellites
René Descartes	1596–1650	Collection of fire particles in the middle of a vortex; changing brightness and potential extinction
Isaac Newton	1642–1727	Primary cause of the system of planetary motions; measurable mass; dense insulating atmosphere
William Herschel	1738–1822	Dark and solid core + luminous, composite and hectic atmosphere; possible solar inhabitants; influence on terrestrial climate; proper motion

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