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Empty space or ethereal plenum?

Early ideas from Aristotle to Einstein*

Helge Kragh**

Introduction

Space is not what it used to be, but then it never was. Modern physicists and astronomers are convinced that there is no such thing as a truly empty space, an absolute vacuum corresponding to the metaphysical concept of nothingness. Whatever nothingness is, it is beyond scientific understanding (Sorensen 2003; Rundle 2004). On the contrary, they believe that so-called empty space is a frothing sea of quantum processes that on a cosmic scale manifests itself in the form of the dark energy that causes the universe to accelerate. As pointed out by historian of science Gerald Holton (1998, p. 10), the opposite concepts of vacuum and plenum, and the struggle between them, can be followed through the history of natural philosophy, from the ancient Greeks to the present. They are what he calls a couple of antithetical themata.

The modern vacuum energy is sometimes considered a resurrection or "transmogrification" of the ether that played such a crucial role in late-nineteenth century physics (Sciama 1978). According to Paul Davies (1982, p. 582), physicists at the time "would surely have been gratified to learn that in its modern quantum form, the ether has materialised at last." Likewise, although Einstein enthroned the ether, Nobel laureate Frank Wilczek suggests that presently it – "renamed and only thinly

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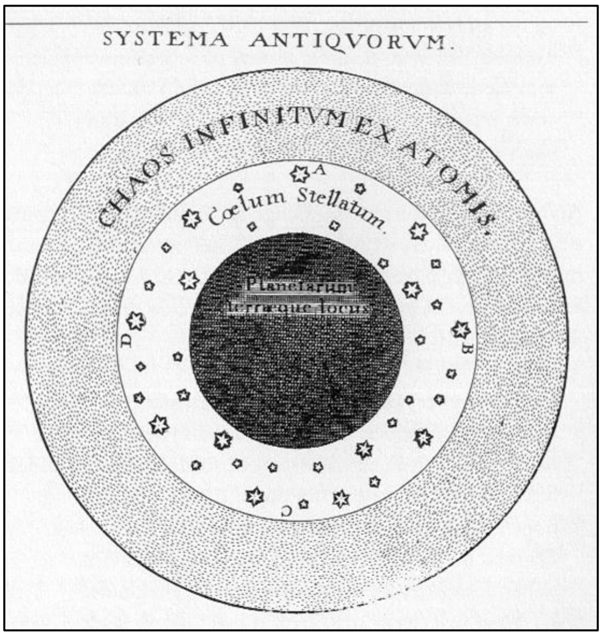
disguised" – plays a most important role in physics (Wilczek 1999). Tempting as it may be to consider the classical ether as an anticipation of modern vacuum energy, it is at most a crude analogy. The historical connection between the two concepts is largely a reconstruction with only slender support in actual history. Analogies to modern physics apart, the idea of empty or not-so-empty space has its own interesting history, which has been charted in several surveys (Genz 1999; Barrow 2001; Close 2009). What follows is a brief account of aspects of this history.

Under the shadow of Aristotle

A summary version of the story of empty space may go like this. For nearly two millennia a true vacuum was thought to be impossible, or at least something which does not exist in nature. Then, in the seventeenth century, the new experimental physics proved that a vacuum can in fact be produced artificially and made a study of inquiry. However, later generations of physicists realized that this vacuum is a far cry from the absolute empty space discussed by the ancients. Their insight resulted in the electromagnetic ether and, later, the quantum vacuum.

To begin with the beginning, according to some Presocratic thinkers, notably the atomistic school associated with Leucippus and Democritus, a vacuum was not only possible but also necessary. The entire natural philosophy of the atomists rested on the postulate that the indivisible elements of matter, called atoms, move in an absolute vacuum. This is all there is, atoms and empty space, and the latter is no less real than the former. According to Simplicius, a Greek commentator from the early sixth century AD, "supposing the substance of the atom to be compact and full, he [Leucippus] said it is 'being' and that it moves in the void, which he called 'non-being' and which he declares is no less than what is" (McKirahan 1994, p. 306). However, this was a view that Aristotle, the most influential thinker ever in the history of science and ideas, would have nothing of.



Democritus' atomistic universe as depicted in a book published in England in 1672. Outside the planetary system (dark) is the stellar sphere, surrounded by a chaos of atoms moving randomly in infinite empty space.

Aristotle's cosmos was a plenum, and his basic concepts of space and place ruled out a vacuum, whether on a small or large scale. In *Physics* and other of his works, he launched an impressive number of objections against void space, which he defined as a place devoid of body, but capable of receiving it. Almost all of his arguments were thought experiments, or of the *reductio ad absurdum* type where the assumption of a vacuum was shown to lead to absurd conclusions. For example, by its very nature empty space is completely homogeneous and for this reason admits no difference. Every part of it is identical to every other part, and so there can be no spatial orientation in a void and no measurement of distance either.

What Aristotle called natural motion was, in so far as it happens on the Earth and not in the heavens, either straight up or straight down. Whereas the elements fire and air naturally move upward, water and earth move downward. But in empty space there is no "up" and "down," and so a stone would not know how to move.

According to ancient thought bodies move because there is a reason for it, but in a vacuum there can be no reason for moving in a particular direction rather than in some other direction. Aristotle (1999, pp. 96-98) phrased his objection as follows:

> There is as little differentiation within the void as there is within nothing, since the void is supposed to be something without being. … [Moreover,] it would be impossible to explain why something which has been set in motion should stop anywhere: why should it stop here rather than there? Either it never moves or it has to go on and on moving for ever, unless something stronger than it impedes it. … As a result of these arguments we are in a position to see that, if there is a void, its consequences contradict the reasons given for its existence by its champions.

Other of Aristotle's arguments rested on the basic presupposition that the speed of a body varies inversely with the resistance of the medium as given by its density. In the case of a freely falling body, he suggested what somewhat anachronistically has been called "Aristotle's law of motion." This law or principle states that the speed v of the body varies as

$$v = k\frac{F}{R},$$

where k is a constant and R the friction between the body and the surrounding medium. F is the motive force, assumed to be proportional to the weight or *gravitas* of the body. Thus, a body falling freely in empty space ($R = 0$) would, irrespective of its weight, size and material, move with infinite velocity. Clearly, instantaneous natural motion must be ruled out as impossible. Even if motion in a void were finite, bodies of different weight would fall with equal velocities, contrary to Aristotle's principles of natural philosophy. Because there is no medium in a void, no reason can be given why one body should move with a greater velocity than another.

At the end of the ancient era, Aristotle's arguments against a void were critically examined by John Philoponus, a Christian philosopher from Alexandria who lived in the sixth century. Denying the assumption of inverse proportionality between speed and resistance, Philoponus concluded that it was quite possible for motion to take place through a void in a finite time (Cohen and Drabkin 1958, pp. 217-220). Not only did he reject Aristotle's terrestrial plenum, he also rejected the extra-terrestrial ethereal element and Aristotle's cosmology in general, including the doctrine that the physics of the heavens differed radically from the one of the Earth.

Aristotle's ether, as he discussed it most fully in his influential work *De caelo et mundo*, was a divine substance or fifth element, known by his medieval successors as *quinta essentia*. It made up everything in the heavens – the part of the universe above the Moon – and was, unlike the matter of the sublunar world, pure, ungenerated, incorruptible, and transparent. While the vast expanse between the celestial bodies appears to be empty, in reality it is filled up with the subtle matter or quintessence. According to some modern commentators, Aristotle's ether is in some ways close in spirit to the dark cosmological energy (Krauss 2000, p. 222; Decaen 2004). However, there is the obvious difference that whereas dark energy is everywhere in space, the ether of the Aristotelians was strictly limited to the celestial regions. And, of course, this is not the only difference.

Whereas Aristotle's space and quintessential ether were essentially passive qualities, other Greek thinkers proposed that all of space was filled with a continuous active principle. The Stoic school of philosophy agreed that there was no empty space, and their space-filling *pneuma* was a means to avoid it. However, pneuma was a vital elastic substance that could change in both time and place. Stoic philosophers conceived the plenum as a mixture of the elements fire and air, the mixture being associated with a dynamical function embracing all natural phenomena. The pneuma filled the whole universe, both the space between bodies and the bodies themselves. According to Chrysippos, a philosopher of the third century BC, "the whole of nature is united by the pneuma which permeates it and by which the world is kept together and is made coherent and interconnected" (Sambursky 1963, p. 135). This universal binding force has been likened to the physical field of later science and also to the kind of ether that emerged at the time of Newton. On the other hand, Aristotle's ether or fifth element was restricted to the heavens, and in this respect it differed from pneuma.

There were similarities as well as dissimilarities between the Aristotelians and the Stoics. The latter followed Aristotle in conceiving the physical cosmos as a finite sphere without any vacuous space whatsoever. They also adopted Aristotle's definition of vacuum as a space than could contain body, but in fact did not. Nonetheless, they supposed the most un-Aristotelian notion of an immense void that was not only extra-cosmic but also infinitely extended. This extra-cosmic void was a three-dimensional container in which the finite spherical cosmos was embedded. They thought that the two parts of the universe at large were strictly separate: the infinite void space had no properties of its own and thus there could be no physical interaction between it and the physical cosmos. Matter could not dissipate into the void, for "the material world preserves itself by an immense force, alternately contracting and expanding into the void following its physical transformations, at one time consumed by fire, at another beginning again the creation of the cosmos" (Sambursky 1963, p. 203). The Stoics' universe was cyclic, which was another non-Aristotelian feature.

In spite of the general rejection of a vacuum in Greek-Roman antiquity, the idea survived in the atomistic philosophy of Epicurus and his followers. In his famous text *De rerum natura*, dating from about 50 BC, the Roman poet Titus Lucretius Carus argued at length for an atomistic world view. All there existed, he said, was atoms and void. In agreement with Epicurus he argued that if there were no empty space, "we must deny motion to all bodies whatsoever." Moreover: "If there were no place, and no space which we call vacant, bodies could not be situated any where, nor could at all move whither in different directions" (Lucretius 1997, pp. 19-21). Thus, while Aristotle considered used the existence of motion a strong argument against empty space, for Epicurus and Lucretius the same phenomenon was proof that empty space existed. *De rerum natura* was largely unknown in the middle ages, but when it became known in the fifteenth century it contributed to the revival of interest in atomism and vacuism.

Medieval interlude

By the mid-thirteenth century Aristotle's entire work had been translated into Latin and enthusiastically received by most medieval scholars. Whereas they, as pious Christians, were bound to deny Aristotle's conclusion of an eternal, uncreated world, there were no serious obstacles to other of the principles of "the philosopher." Thus, in the high middle ages it was generally granted that "nature abhors a vacuum" (Grant 1981). Although the famous doctrine of *horror vacui* was in general agreement with Aristotle's rejection of a vacuum, it cannot be found in the work of the Greek philosopher. It was an original contribution of the middle ages, much discussed but rarely doubted. On the other hand, the consensus was not complete, for some philosophers attempted to undermine Aristotle's arguments against motion in a void by asserting that such motion did not need to be instantaneous. There were even those who treated empty space as if it were a material medium. However, their non-Aristotelian ideas won little acceptance.

The Jewish philosopher Maimonides, who lived in Cordoba and Cairo in the twelfth century, entertained views closer to those of the atomists than the Aristotelians. In his *Guide for the Perplexed*, one of the propositions about the natural world was that all things are composed of atoms. It was followed by the proposition that, "there is a vacuum, i.e., one space, or several spaces which contain nothing, which are not occupied by anything whatsoever, and which are devoid of all substance." His argument was largely the same as the one proposed by the Greek atomists, that motion of atoms is impossible without a void.

The problem discussed by the European natural philosophers was primarily concerned with vacua produced by bodies in motion or existing in the pores of matter, so-called intra-mundane vacua. While it was generally agreed that no such vacua could exist, there was less agreement concerning the possibility of an extra-mundane void. This problem was endlessly discussed, and as much in a theological as in a philosophical context (Grant 1981). It was common for the learned philosophers to relate it to God's omnipotence. Sure, a void does not exist naturally and nor can it be produced artificially, but could God have created an extra-mundane void if he so wished?

The schoolmen at the new universities in Oxford, Paris and elsewhere discussed at length whether or not the corporeal world was surrounded by an immense void space, as assumed by the Stoics. The distinguished Paris philosopher Jean Buridan represented the majority view when he wrote: "An infinite space existing supernaturally beyond the heavens or outside this world ought not to be assumed" (Grant 1994, pp. 170). Yet he qualified his statement by adding that beyond this world God could create whatever space and corporeal substances it pleased him to create. Although medieval philosophers generally followed Aristotle's denial of an extra-cosmic void, several of them considered the idea of an infinite "imaginary space" that in some sense encompassed the physical universe. This space was a kind of vacuum, but very different from the one discussed by the ancients. It was dimensionless and unable to contain matter. In effect, it was a theological construct, God's infinite abode and an abstract expression for his immensity.

Among those who subscribed to such a view was Thomas Bradwardine, an eminent Oxford mathematician and natural philosopher. Although following Aristotle's arguments against a void a long way, Bradwardine maintained that there was an imaginary vacuum outside the world. This extra-cosmic vacuum was void of any body and of everything other than God.

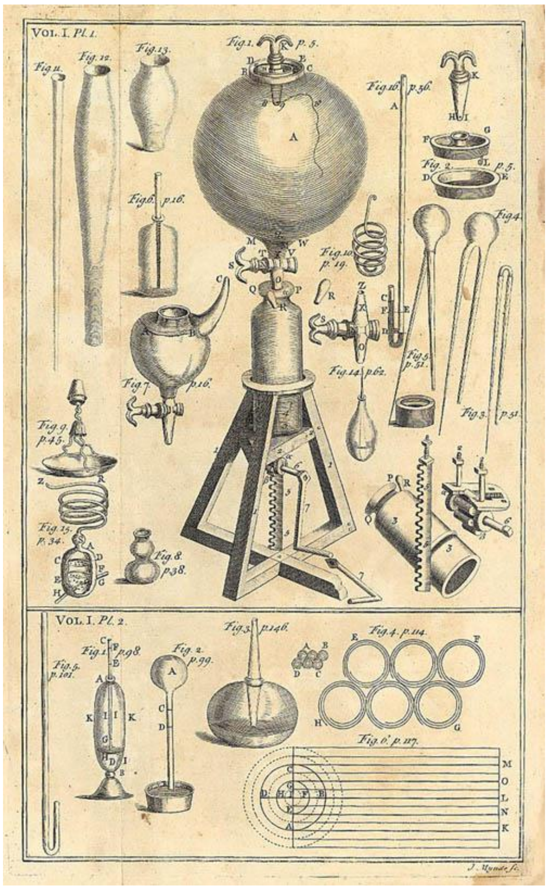
The popularity of Aristotelianism caused some concern among leading theologians who feared that some of the views held by radical philosophers might undermine established church dogmas. As the result of a growing controversy between faith and reason, in 1277 the Bishop of Paris, Etienne Tempier, issued a list of no less than 219 propositions that were declared false and heretical (Grant 1974, pp. 48-50). Among the heresies was, "That God could not move the heavens with rectilinear motion; and the reason is that a vacuum would remain." None of the propositions referred directly to void spaces within our cosmos, but they were sometimes taken to do so indirectly. The point of the Church was that the omnipotent deity was not bound to follow Aristotle's rules. This and other of the condemnations did not silence the philosophers, but it is of interest because it indicates that the Aristotelian *horror vacui* did not enjoy unrestricted ecclesiastical support. Rather on the contrary, for it was now confirmed that God could create a vacuum and consequently it became admissible to discuss various kinds of vacua at least hypothetically. On the other hand, it remained largely undisputed that vacua did not *actually* exist in nature.

The scientific revolution

The consensus view of the middle ages and the renaissance was questioned and eventually refuted during the scientific revolution in the seventeenth century. Galileo argued that although nature in a certain sense abhorred a vacuum, it was not in an absolute sense. A state of vacuum, in the sense of a portion of space devoid of air, might be produced experimentally. Evangelista Torricelli, Galileo's last assistant, greatly developed his master's suggestion and in 1644 succeeded in evacuating the air from the space above a mercury column. This he considered a kind of vacuum, if an incomplete and unnatural one.

When Blaise Pascal in France learned about Torricelli's work, he improved it in a series of brilliant experiments and provided the observed phenomena with a clearer and better argued explanation. He realized that the apparently empty space produced above the mercury column in Torricelli's experiment was actually empty, or at least approximately so. According to Pascal, all the phenomena that traditionally had been ascribed to nature's *horror vacui* were in reality effects of the weight and pressure of the ambient air. "Does nature abhor the vacuum more on the top of a mountain than in the valley, and even more so in wet weather than in sunshine?" Not according to Pascal: "Nature does nothing to avoid the vacuum; rather, the weight of the air masses is the true reason for all these phenomena which we have been ascribing to an imaginary cause" (Genz 1999, p. 121). Pascal even weighed the vacuum, meaning that he showed that it had no measurable weight compared to air.

Not all of the pioneers of the scientific revolution agreed that vacuum belonged to the order of nature. In René Descartes' important *Principia Philosophiae* from 1644, Principle XVI reads: "That it is contrary to reason to say that there is a vacuum of space in which there is absolutely nothing." Descartes identified space with matter. According to him, extension devoid of matter was a contradiction, from which he inferred the impossibility of void space. The Cartesian world was a plenum, like the one of Aristotle, if for reasons entirely different from those of the Greek philosopher. In spite of the popularity of Cartesian natural philosophy, by the 1660s the hypothesis of *horror vacui* was becoming obsolete. New Aristotelian or Cartesian versions of it continued to be proposed, but they were generally considered inferior to the new explanations based on void space and the pressure of air. On the other hand, not all prominent philosophers were vacuists. Apart from



Boyle's air-pump, as shown in his *New Experiments Physico-Chemical* of 1660.

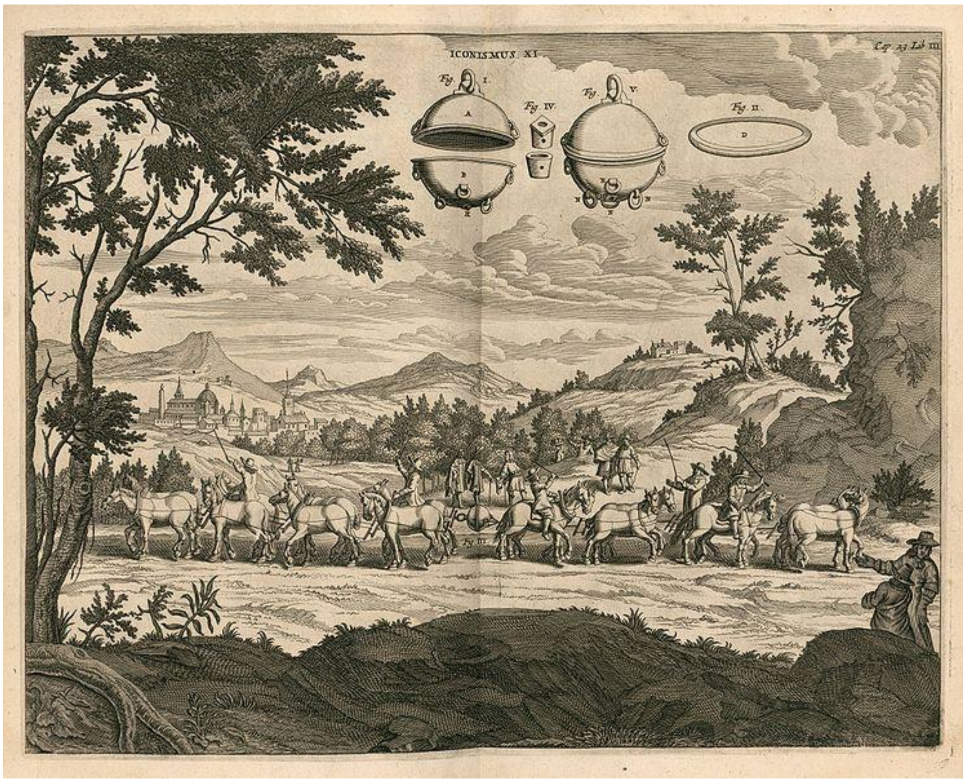
Descartes and his followers, Thomas Hobbes in England and Gottfried Wilhelm Leibniz in Germany were convinced that voids were imaginary.

The first air-pumps, devices to evacuate air from closed containers, followed in the wake of the discoveries of Torricelli and Pascal. At about 1650 Otto von Guericke, the illustrious mayor in Magdeburg, Germany, invented his first version of a pneumatic pump. Some years later it was turned into an improved machine by Robert Boyle in England, although his pumps were actually constructed by his assistant Robert Hooke, an ingenious experimenter and natural philosopher. Incidentally, Hooke did not believe in a true vacuum, but rather that the evacuated space contained an ethereal fluid that filled "the vast Expanse of the World" and through which light propagated at infinite speed (Purrington 2009, pp. 153-155).

Guericke and Boyle not only demonstrated the elasticity of air – or what Boyle called the "spring of air" – they also investigated some of the properties of the produced vacuum. For example, whereas sound could not propagate through a vacuum, it did not hinder the propagation of either magnetism or light. Both of the inventor-philosophers speculated about the nature of the evacuated space, discussing whether it was a true vacuum or not.

As to speculation and imagination, not to mention showmanship, Guericke far outstripped Boyle. In a famous demonstration of 1654, one of the most spectacular stunts in the history of science ever, he joined two hollow hemispheres of copper and evacuated the resulting sphere with a pump constructed for the purpose. The two hemispheres were kept together so forcefully that eight strong horses pulling on either side could not separate them! But if air was allowed to enter the sphere, they could effortlessly be separated. According to Guericke, it was the pressure of atmospheric air that kept the evacuated hemispheres together. This kind of experimentally produced empty space was three-dimensional and included no ethers. But there was another kind of vacuous space, which he thought was infinite, divine and dimensionless. "It has celestial splendor, higher than the stars, brighter than the flash of lightning, and has perfection itself, universally blessed," Guericke wrote. He claimed that everything created had its origin and place in what he called "nothing" and which he conceived as an infinite extra-cosmic void indistinguishable from God. Although this true nothingness had no dimensions, it was real.

Contrary to Boyle, Guericke's vacuum was of deep cosmological significance and part of his argument for an infinite universe populated by an infinity of stellar bodies. In his main work from 1672 with the abbreviated title *Nova Experimenta Magdeburgica* he explained that, far from being absolutely void and physically impotent, the nothing of infinite space was an active and powerful entity. It was real



Engraving of the Magdeburg experiment in Guericke's *Nova Experimenta Magdeburgica*.

and imaginary at the same time. In what has been called an "ode to nothing" he expressed the vacuum-nothingness in lyrical language (Grant 1981, p. 216):

> Nothing contains all things. It is more precious than gold, without beginning and end, more joyous than the perception of bountiful light, more noble than the blood of kings, comparable to the heavens, higher than the stars, more powerful than a stroke of lightning, perfect and blessed in every way. Nothing always inspires. … Nothing is outside the world. Nothing is everywhere.

When it came to the question of whether or not the air-pump produced a true vacuum, Boyle was much more restrained than his fellow-physicist in Magdeburg. He refused to speculate about the relationship between the evacuated space and the traditional meaning of vacuum, which to him was a metaphysical concept. Instead he adopted an operationalist notion of the vacuum, simply identifying it with the space from which all air had been removed. Boyle realized that even the most completely evacuated space might not be absolutely empty, since there was always the possibility of the presence of some undetectable ethereal substance. But for him, as an experimental philosopher, it was a problem that could be safely ignored and left to the metaphysicians.

Ether physics

In spite of the opinion of Boyle, many later natural philosophers assumed the existence of a rare and penetrating "subtle matter" that was present also in a void. One of them was Newton, who in his famous queries 17-23 in the 1706 edition of *Opticks* (1952, pp. 349-353) speculated at length on the nature of the ether:

> Is not the Heat … convey'd through the *Vacuum* by the Vibrations of a much subtiler Medium than Air, which after the Air was drawn out remained in the *Vacuum*? And is not this Medium the same with that Medium by which Light is refracted and reflected, and by whose Vibrations Light communicates Heat to Bodies, and is put into Fits of easy Reflexion and easy Transmission? …And is not this Medium exceedingly more rare and subtile than the Air, and exceedingly more elastic and active? And doth it not readily pervade all Bodies?

Newton also suggested that the ether might be of astronomical significance and even be the cause of the gravitational force: "Is not the Medium much rarer within the dense Bodies of the Sun, Stars, Planets and Comets, than in the empty celestial Spaces between them? And in passing from them to great distances, doth it not grow denser and denser perpetually, and thereby cause the gravity of those great Bodies towards one another?"

Although some physicists accepted the vacuum as a passive nothingness, this was not the generally held view. The period from Newton to Maxwell saw a bewildering variety of ethers which in many cases were introduced for specific purposes, such as explaining electricity, magnetism, light, gravitation, nervous impulses, and chemical action (Cantor and Hodge 1981). In an article on the ether for the *Encyclopaedia Britannica*, Maxwell (1965, vol. 2, p. 763) noted that "To those who maintained the existence of a plenum as a philosophical principle, nature's abhorrence of a vacuum was a sufficient reason for imagining an all-surrounding æther." After all, since the first four of the phenomena were easily transmitted in empty space, it might indicate that their corresponding ethers were parts of even a perfect vacuum. Maxwell continued: "Æthers were invented for the planets to swim in, to constitute electric atmospheres and magnetic effluvia, to convey sensations from one part of our bodies to another, and so on, till a space had been filled three or four times with æthers."

As Maxwell pointed out, the many hypothetical ethers were ad hoc and therefore unsatisfactory from a methodological point of view. And yet he was himself not only a believer in the ether, his field theory of electromagnetism was instrumental in introducing a new and unified kind of ether, one which was electrodynamical rather than mechanical in nature. Since the early decades of the nineteenth century the ether became increasingly associated with optics and seen as the medium in which light propagated. Following the pioneering work of Thomas Young in England and Augustin Fresnel in France, by the 1820s the corpuscular theory of light was abandoned and replaced by a theory of transverse waves. The new "luminiferous" ether pervaded the universe and, according to most physicists, had to behave like an elastic solid that – strangely – did not interact with other matter. Although it had the form of a solid, and was sometimes likened to steel, the planets and comets passed through it without noticing any resistance. Strange indeed! Much ingenuity and mathematical effort was put into the construction of ether theories by theoretical physicists such as George Green, Gabriel Stokes, and James MacCullagh (Schaffner 1972).

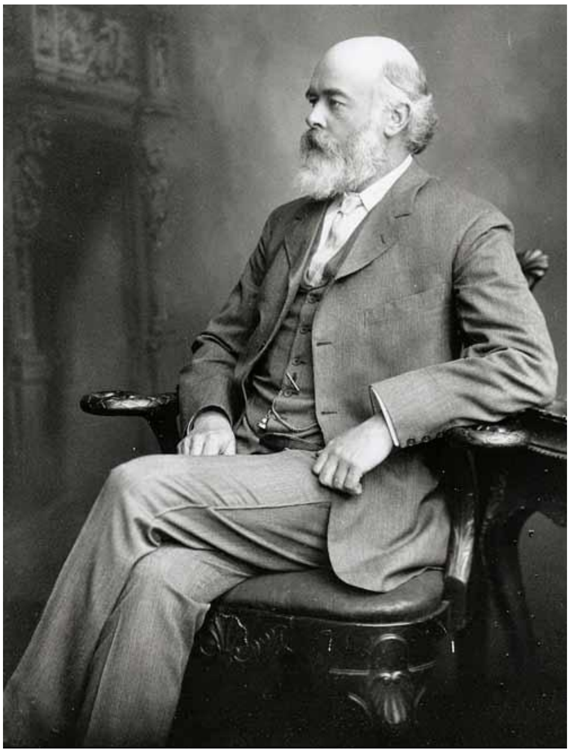
Ethers of the elastic-solid type were developed until the 1880s, often without connection to phenomena of electrodynamics. With the gradual acceptance of Maxwell's electromagnetic theory of light, as fully expounded in his monumental *Treatise on Electricity and Magnetism* from 1873, the ether came to be seen as inextricably associated with electromagnetism. Through the works of Hendrik A. Lorentz, Joseph Larmor, Oliver Heaviside, Max Abraham and many other theorists, Maxwell's field theory was developed into a sophisticated theory of the electromagnetic ether. Characteristically, when the German physicist Paul Drude in 1894 wrote an advanced textbook of Maxwellian electrodynamics, he chose to entitle it *Physik des Aethers* (Drude 1894). Whatever its precise nature, the ether was considered indispensable. Another German physicist and specialist in electrodynamics, August Föppl (1894, p. 308), suggested that space without ether would be a contradiction in terms, like a forest without trees.

Late nineteenth-century physics consisted of the physics of matter and the physics of the electromagnetic ether. To avoid the unwanted dualism, the trend was to identify matter with ether, rather than the other way around. In the early years of the twentieth century it became common to regard the new electron as a concentration of or singularity in the ether; or, what was about the same, electromagnetic fields. This was a basic assumption of the so-called electromagnetic world picture that for a decade or two held a strong position in theoretical physics (Kragh 1999, pp. 105-199). But the views concerning space, ether and vacuum differed. In a lecture of 1909 at Columbia University, Max Planck said: "In place of the so-called free ether there is now substituted the absolute vacuum, … . I believe it follows as a consequence that no physical properties can be consistently ascribed to the absolute vacuum" (Planck 1915, p. 119). He regarded the speed of light not as a property of the vacuum, but a property of its electromagnetic energy: "Where there is no energy there can be no velocity of propagation." Two years later Planck would suggest the notion of zero-point energy and thereby unwittingly initiate a development that led to the modern view of a quantum vacuum endowed with physical properties (Kragh 2012).

A plenum filled with energy

It is possible to trace the concept of dark energy far back in time, say to the days of Newton (Calder and Lahav 2008) or even to the pneuma of the Stoic philosophers. However, if one wants to point to pre-quantum and pre-relativity analogies to dark energy, a more sensible arena might be the ethereal world view of the late nineteenth century. The general idea that cosmic as well as terrestrial space is permeated by an unusual form of hidden energy – a dark energy of some sort – was popular during the Victorian era, where space was often identified with the ether. The generally accepted ethereal medium existed in many forms, some of them assuming the ether to be imponderable while others assumed that it was quasi-material and only differed in degree from ordinary gaseous matter in a highly rarefied state.

The ether – or vacuum – was sometimes thought of as a very tenuous, primordial gas, perhaps consisting of ether atoms of the incredibly small mass 10^{-45} g (Wood 1886). On the other hand, according to the popular vortex theory, which was cultivated by British physicists in particular, the discreteness of matter (atoms) was epiphenomenal, derived from stable dynamic configurations of a perfect fluid. This all-pervading fluid was usually identified with the continuous and frictionless ether. The highly ambitious vortex theory invented by William Thomson, the later Lord Kelvin, was not only a theory of atoms, it was a universal theory of ether, space and matter, indeed of everything (Kragh 2002).



Oliver Lodge (1851-1940).

The point is that by the turn of the nineteenth century few physicists thought of "empty space" as really empty, but rather as filled with an active ethereal medium. The ether was widely seen as "a perfectly continuous, subtle, incompressible substance pervading all space and penetrating between the molecules of all ordinary matter, which are embedded in it" (Lodge 1883, p. 305). H. A. Lorentz and other physicists in the early twentieth century often spoke of the ether as equivalent to a vacuum, but it was a vacuum that was far from nothingness. Although Lorentz was careful to separate ether and matter, his ether was "the seat of an electromagnetic field with its energy and its vibrations, … [and] endowed with a certain degree of substantiality" (Lorentz 1909, p. 230). On the other hand, the popular belief in a dynamically active ether was rarely considered in astronomical or cosmological contexts.

Among the firm believers in the ether as a storehouse of potential energy was the English physicist Oliver Lodge, a devoted follower of Maxwell who has been called a "remote ancestor" of the modern quantum vacuum. Rowlands (1990, p. 285), a biographer of Lodge, comments: "The infinite energy density of the zero-point vacuum field fluctuations is almost indistinguishable from the infinite elasticity of the universal ethereal medium." Lodge was indeed an enthusiastic protagonist of the active Victorian ether, which he considered incompressible and a reservoir of an immense amount of energy. This energy was not directly testable, but it could be calculated. In one such calculation, dating from 1907, he estimated the minimum etherial energy density to be "something like ten-thousand-million times that of platinum," or of the order 10^{12} g/cm^3. In the words of Lodge (1907, p. 493):

> The intrinsic constitutional kinetic energy of the æther, which confers upon it its properties and enables it to transmit waves, is thus comparable with 10^{33} ergs per c. c.; or say 100 foot-lbs. per atomic volume. This is equivalent to saying that 3×10^{17} kilowatt-hours, or the total output of a million-kilowatt power station for thirty million years, exists permanently, and at present inaccessibly, in every cubic millimetre of space.

The energy density of Lodge's ether, if transformed to a mass density by means of Einstein's formula $E = mc^2$, corresponded to about 10,000 tons per cm^3. No wonder that Lodge, in an address to the Royal Institution, characterized the intrinsic energy of the ether as "incredibly and portentously great" (Lodge 1908, p. 733). Although his energy density was extreme, he was not the only British ether physicist to support an ether packed with energy. In his paper of 1907 (p. 501) he referred to George Fitzgerald, who, in an address of 1896, had estimated a value of 10^{22} erg/cm for the ethereal energy.

The energy of the ether had earlier been considered by Maxwell, who in a seminal paper of 1865 contemplated the possibility that gravity might be explained as an effect of the electromagnetic field. However, in that case "every part of this medium [the ether] possesses, when undisturbed, an enormous intrinsic energy" (Maxwell 1965, vol. 1, p. 571). Since he was "unable to understand in what way a medium can possess such properties," he abandoned further speculations on the cause of gravity.

To return to Lodge, in a later paper on the possible granular structure of the ether he repeated the energy estimate 10^{30} to 10^{33} erg cm^{-3}, adding that "the ether may quite well contain a linear dimension of the order 10^{-30} to 10^{-33} centim." (Lodge 1920, p. 171). Although not more than a curiosity, it is worth pointing out that the linear dimension of Lodge's ether happened to be of the same order as the Planck length that in modern physics characterizes the domain of quantum gravity:

$$\sqrt{\frac{Gh}{c^3}} = 4 \times\ 10^{-33}\ \text{cm}$$

A length scale of the same order, about 10^{-32} cm, appears in the modern theory of superstrings.

As another example of a fin-de-siècle scientist devoted to the active ether, consider the French psychologist and amateur physicist Gustave LeBon, the author of the hugely popular *The Evolution of Matter*. In complete agreement with Lodge, he spoke of the ether as "the first source and the ultimate end of things, the substratum of the worlds and of all beings moving on their surface" (LeBon 1905, p. 93). He pictured electrons and other charged particles as intermediates between ordinary matter and the ether. LeBon's cosmic scenario started with "a shapeless cloud of ether" which somehow was organized into the form of energy-rich atomic particles. However, these would be radioactive and slowly release their energy. They were "the last stage but one of the disappearance of matter," the last stage being represented by "the vibrations of the ether." Matter formed by electric particles would eventually radiate away all their stored energy and return to "the primitive ether whence they came … [and which] represents the final nirvana to which all things return after a more or less ephemeral existence” (pp. 313-315).

LeBon was not highly regarded by most physicists, but his ethereal ideas captured the zeitgeist of the period as well as did those of Lodge.

Conclusion

The intertwined concepts of space, ether and void have a rich history, the final chapter of which has not yet been written. Although the ancient belief in a plenum was for a period replaced by the dualistic system of material atoms moving in a void, in the nineteenth century the pendulum swung back, now with the physical ether as the preferred plenum. Then, in the early part of the twentieth century, the classical ether was abandoned as a result of the victory of the theory of relativity. On the other hand, neither relativity nor quantum theory reinstated the classical vacuum. On the contrary, later developments justified a new kind of ether filled with energy. As Robert Laughlin (2005, p. 121), theoretical physicist and Nobel laureate of 1998, comments:

> The word “ether” has extremely negative connotations in theoretical physics because of its past association with opposition to relativity. This is unfortunate because, stripped of these connotations, it rather nicely captures the way most physicists actually think about the vacuum. . . . [Space] is filled with “stuff” that is normally transparent but can be made visible by hitting it sufficiently hard to knock out a part. The modern concept of the vacuum of space, confirmed every day by experiment, is a relativistic ether. But we do not call it this because it is taboo.

The idea of a relativistic ether makes sense, but it should not be seen as belonging to the classical tradition of either Aristotle or Lodge. Although Einstein sometimes spoke of space and ether as were they synonymous terms, he emphasized that his new ether, justified by the general theory of relativity, could not be assigned a state of motion. For example: "Physical space and ether are only different terms for the same thing; fields are physical states of space. If no particular state of motion can be ascribed to the ether, there do not seem to be any grounds for introducing it as an entity of a special sort alongside space" (Einstein 1934, p. 237; Kostro 2000).

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