2011 Isonomia
Rivista online di Filosofia
Università di Urbino

Re-thinking a Scientific Revolution:
An inquiry into late nineteenth-century theoretical physics

Stefano Bordoni
Università degli Studi di Urbino "Carlo Bo"
stefano.bordoni@gmail.com

Abstract

In the early 1890s, before his well-known experiments on cathode rays, J.J. Thomson outlined a discrete model of electromagnetic radiation. In the same years, Larmor was trying to match continuous with discrete models for matter and electricity. Just starting from Faraday's tubes of force, J.J. Thomson put forward a reinterpretation of the electromagnetic field: energy, placed both *in* the tubes of force and in the motion *of* tubes of force, spread and propagated by discrete units, in accordance with a theoretical model quite different from Maxwell and Heaviside's. Larmor developed a different theoretical model, wherein *electrons*, discrete units of matter and electricity, stemmed from the continuous structure of aether. Both of them tried to realise an original integration between two different British traditions: Maxwell's contiguous action applied to electrodynamics, and W. Thomson's kinetic model of matter. Although Larmor and J.J. Thomson's specific theoretical models were formally dismissed after the deep transformations which took place in theoretical physics in the first decades of the twentieth century, I find a persistence of commitments and conceptions. This conceptual link has been overlooked in more recent secondary literature. What appears as a sort of *missing link* in recent historical studies was seriously taken into account by contemporary physicists. Nevertheless, authoritative physicists like Planck and Millikan were led astray by oversimplifications and misinterpretations. In order to appreciate the continuity between late nineteenth-century electromagnetic theories which emerged in the British context, and early twenty-century new physics we should disentangle the different levels of that theoretical physics. We should distinguish first-level specific theoretical models from second-level more general conceptions or *conceptual streams*.

1. Matter and energy in late nineteenth-century theoretical physics

In the 1875 edition of the *Encyclopaedia Britannica*, J.C. Maxwell stated that, although the «small hard body imagined by Lucretius, and adopted by Newton, was invented for the express purpose of accounting for the permanence of the properties of bodies», it failed «to account for the vibrations of a molecule as revealed by the spectroscope». On the contrary, «the vortex ring of Helmholtz, imagined as the true form of atom by Thomson, satisfies more of the conditions than any atom hitherto imagined». He found that the main satisfactory feature of that model was its «permanent» and, at the same time, pliable structure[1].

W. Thomson's kinetic model of matter can be placed alongside a conceptual tradition wherein matter is not a fundamental entity but is derived from some kind of dynamism. M. Hesse identified «a physical picture in which force is more fundamental than matter» with the ideal line connecting, in the chronological order, Leibniz, Boscovich, Kant and Faraday.[2] This can be accepted provided that we acknowledge that this common conceptual stream went through scientific theories and natural philosophies which were quite different from each other. Historians have always found it difficult to give a definite interpretation of Leibniz's concept of mass, because of some changes intervening in the subsequent stages of his philosophical and scientific system. Nevertheless we can say that, in the final stage, mass became a dynamical entity, endowed with an active power.[3] A general conceptual stream, which involved Leibniz and then W. Thomson, found interesting implementations in J. Larmor and J.J. Thomson's theories, and then re-emerged in the twentieth century.

In his 1885 book on matter, P.G. Tait, who held the chair of Natural Philosophy at Edinburgh, introduced a new couple of fundamental entities in physics: «In the physical universe there are but two classes of things, MATTER and ENERGY»[4]. In many passages he emphasised what he considered the keystone of physics: the deep link between matter and energy. More specifically, he stated that «Energy is never found except in association with matter» and probably «energy will ultimately be found [...] to depend upon motion of matter». Nevertheless, this symmetry between matter and energy was broken by two elements: matter consists of «parts which preserve their identity» while energy «cannot be identified»; in addition, matter «is simply passive» or «*inert*» while energy «is perpetually undergoing transformations»[5].

In the same year, J.H. Poynting, then professor of physics at the Mason College of Birmingham, linked the new conception on the transfer of electromagnetic energy to the model of tubes of force.[6] That model, which could seem outdated when compared to Maxwell's more abstract theory, re-emerged with an unexpected heuristic power, because it challenged the intrinsic continuous nature of the electromagnetic field. As I am going to show in the following sections, the re-emergence of lines of force or tubes of force in British electromagnetic theories smoothed the sharp distinction between continuous and discrete representations for matter and energy.

In 1887, when he held the chair of Theoretical Physics at Kiel University, M. Planck wrote a treatise on the conservation of energy. Three elements appeared tightly connected: the interpretation of electromagnetic phenomena, the interpretation of the conservation of energy, and the confrontation between the theoretical models of contiguous action and action at a distance. The former appeared to Planck more suitable in order to explain electromagnetic phenomena. He tried to combine contiguous action with the conservation of energy, and found for this combination the name «infinitesimal theory». That *infinitesimal* approach involved all physics: every action on an infinitesimal volume could be transmitted, in a finite time, through the surface surrounding it.[7] Energy, electromagnetic or not, could be interpreted as something similar to matter. Not only could energy neither be created nor destroyed, but it could not disappear from a given place and instantaneously appear in another distant place. Energy could flow through the boundaries of a volume, just as matter did. The principle of conservation of energy became closely linked to specific ways of transfer of energy. According to this conception or «infinitesimal theory, energy, like matter, can change its place only with continuity through time». The energy of a material system could be represented as a series of units or elements: «every definite element approaches its place and just there can be found».[8] This conception helps us to better understand the conceptual roots of the theoretical researches Planck subsequently undertook on the electromagnetic and thermodynamic properties of radiation[9].

The assumption of a meaningful conceptual link between matter and energy was one of the hallmark of late nineteenth-century theoretical physics. In 1900, H.

Poincaré's represented the electromagnetic energy as something flowing as «a fictitious fluid»; what actually prevented Poincaré from the complete identification with «a real fluid» was the fact that «this fluid is not indestructible»[10].

Following Poynting's theoretical model, J.J. Thomson put forward discrete models of matter and energy long before his 1897 experiments on cathode rays, and, even more important, from a purely theoretical point of view.[11] Larmor had been dealing with both continuous and discrete models of matter and electricity since 1885. Both Larmor and J.J. Thomson tried to realise a deep integration between continuous and discrete models, for both matter and energy. In the 1880s, they had undertaken a theoretical dialogue with Helmholtz and Maxwell's theories. Furthermore, in J.J. Thomson and Larmor's theories we can find an original integration between two different British traditions: Maxwell's contiguous action applied to electro-dynamics, and W. Thomson's kinetic model of matter.

J.J. Thomson and Larmor were strongly involved in the emergence of late nineteenth century theoretical physics: their «different approaches» cannot be identified respectively with the practise of mathematical physics and experimental physics. They were theoretical physicists, and the differences between them were authentically theoretical[12].

The emergence of theoretical physics in the late nineteenth century is a very sensitive issue. Although the emergence of chairs of «theoretical physics» in German speaking countries in the last decades of the nineteenth century must be distinguished from «theoretical physics» as a new practice in physics, the latter emerged as a really new approach.[13] A new alliance between the tradition of mathematical physics and the most speculative side of the tradition of natural philosophy was a specific hallmark of late nineteenth-century theoretical physics. Besides an explicit meta-theoretical and methodological commitment, a new awareness emerged: the mathematical structure and the empirical content could not qualify the whole of a physical theory. There was a third meaningful component, a conceptual one: this component allowed the physicist to appreciate the deep differences among theories which were equivalent from the mathematical and empirical point of view.

J.J. Thomson shared Poynting's belief that the concept of «electric displacement» was misleading, and supported Poynting's attempt to revive Faraday's tubes of force.

Just starting from Faraday's tubes, he put forward a reinterpretation of the equations for the electromagnetic fields *E*, *D*, *H*, *B*, and, early in the 1890s, arrived at a discrete theoretical model for matter, energy and electricity. Energy, placed both *in* the tubes of force and in the motion *of* tubes of force, spread and propagated by discrete units, in accordance with a theoretical model quite different from Maxwell and Heaviside's. In the same years, Larmor developed a different theoretical model, where discrete units of matter and electricity stemmed from the continuous structure of aether and fields. In particular, J.J. Thomson outlined discontinuous structures for the electromagnetic field, and Larmor outlined a subatomic structure of matter, wherein that discrete structure consisted of nothing else but dynamical actions propagating through aether. They represented a vanguard: they offered new landscapes to subsequent researchers in theoretical physics. J.J. Thomson and Larmor's aether theories allowed, for the first time and some years before the turn of the twentieth century, new professionalized and specialised physics to cross both the boundaries between matter and energy, and the boundaries between discrete and continuous models.

In the history of science, when we take into account general and long-term conceptions, we find a competition, or a wide-scope conceptual tension, between discrete and continuous models in the representation of the physical world. At the end of the nineteenth century, J.J. Thomson and J. Larmor, transformed that competition into an integration. The conceptual tension between continuous and discrete aspects of matter and energy transformed into the co-existence of complementary components. That integration was put forward by scientists who belonged to the last generation of natural philosophers and, at the same time, to the first generation of professionalized physicists.

2. Scientists who dared cross the boundaries

In a paper published in 1891, tubes of force allowed J.J. Thomson, then Cavendish Professor of Experimental Physics (the chair previously held by Maxwell), to undertake another conceptual shift. The electric field as a continuous entity transformed into a new «molecular» theory, where electric fields were imagined as a collection or discrete, individual entities, endowed with their own identity. He introduced two levels of investigations, macroscopic and microscopic. In thermodynamics, the macroscopic level of the theory of gases corresponded to the microscopic level of the kinetic molecular theory: in some way, the latter was an *explanation* of the former. The microscopic level corresponded to a higher level of comprehension or to a finer interpretation. In the electromagnetic theory, to a macroscopic level, described in terms of continuous fields, corresponded a microscopic level, described in terms of an invisible, discrete structure: the tubes of electric induction. J.J. Thomson put forward a conceptual shift towards a *kinetic molecular* theory of energy, the same conceptual shift already realized in the case of matter[14].

Another conceptual shift occurred in the representation of matter, from the model of solid dielectrics to the model of electrolytes. Electrolytes were exactly the kind of matter which was not easy to explain in the context of Maxwell's theoretical framework. At the same time, gases seemed to exhibit the same behaviour of electrolytes when electricity passed through them. Liquid electrolytes and ionised gases became the new model of matter «undergoing chemical changes when the electricity passes through them». The theory Maxwell had put forward was essentially a theory based on solid dielectrics and conductors; now liquids and gases were on the stage and Thomson attempted to explain the properties of metals by means of the properties of liquids and gases[15].

In 1893, in the treatise *Recent Researches in Electricity and Magnetism*, J.J. Thomson put forward a discrete structure for matter, electricity and energy, provided that the tubes of force represented a sort of substantialisation of the electromagnetic energy stored in the field. The deep connection among matter, electricity and tubes of force gave rise to a draft of electric theory of matter. Even ordinary matter was embedded in a net of tubes of force connecting atoms to each other, in order to produce those structures which we call molecules. Inside a molecule, Thomson saw short tubes of force keeping atoms close to each other, in order to assure molecular stability: in this case, the length of the tubes were of the same order of molecular dimensions. On the contrary, if the length of the tubes was far greater than molecular dimensions, we would have in front of us atoms «chemically free»[16]. Not only was matter embedded in a net of tubes of force but even aether was. Indeed, tubes of force were not a mere materialisation of electric forces: Thomson imagined a sea of tubes of force spread throughout aether even without any electric force. There was a distribution of tubes corresponding to an unperturbed state. The effect of electric forces was an overbalance in the sea of tubes: electric forces made tubes move towards a specific direction. The drift of the tubes, driven by the electric forces, gave rise to electrodynamic effects, for instance the establishment of a magnetic field[17].

Tubes of force were the *hardware* associated to energetic processes. They underwent a sort of Law of Conservation: they could be neither created nor destroyed. A symmetry between matter and energy was explicitly assumed: in Thomson's theoretical model, the *sea* of tubes of force behaved as a *cloud* of molecules in a gas.[18]

A statistical aspect of Thomson's theory emerged, an aspect which connected electromagnetism to thermodynamics: in both cases, the macroscopic picture was the statistic effect of a great number of microscopic events. Thomson was strongly committed to a meta-theoretical issue, which flowed through the specific features of his theory like an enduring conceptual stream. This issue was the pursuit of the unity of physics. The theoretical model of «molecular» electric tubes of force allowed him to realize at least a certain degree of unification[19].

In a subsequent section, «Electromagnetic Theory of Light», Thomson tried to give a more detailed account of propagation of light in terms of tubes of force. He thought that Faraday's tubes of force could help to «form a mental picture of the processes which on the Electromagnetic theory accompany the propagation of light»[20]. The propagation of a plane wave could be interpreted as «a bundle of Faraday tubes» moving at right angles to themselves and producing a magnetic force oriented at right angles with regard to both the direction of the tubes and the direction of motion[21].

Starting from Maxwell's electromagnetic fields, represented as stresses propagating through a continuous solid medium, Thomson arrived at a representation of fields as a sea of discrete units carrying energy and momentum. The wave theory of light, then a well-established theory, seemed violently shaken by a conception which echoed ancient, outmoded theories[22].

The debate on the nature of light and the clash, continuously renewed, between continuous and discrete models was the vivid background of J.J. Thomson's *Recent Researches*. The conceptual tension between the *discrete* and the *continuous* affected aether, matter, energy and electric charge. This tension led to a unified view, where a new symmetry emerged between matter and energy: both were represented as discrete structure emerging from the background of a continuous medium. Invisible, discrete, microscopic structures explained the properties of apparently continuous, macroscopic phenomena. J.J. Thomson tried to transform Maxwell's theory into a unified picture where atomic models of matter stood beside *atomic* models of fields. Indeed he moved away from Maxwell's specific theoretical models of matter and energy, even though he shared the general framework of Maxwell's electromagnetic theory. One unit of matter corresponded to one unit of electricity, and one unit of tube of force connected units of matter-charge to each other[23].

From 1893 to 1897, Larmor, then fellow of the *Royal Society*, published in the *Philosophical Transactions* three thick papers under the title 'A Dynamical Theory of the Electric and Luminiferous Medium'. The title drew readers' attention to aether, which represented the keystone of the whole project: it was the seat of electrical and optical phenomena, and it was involved in the constitution of matter.

In 1894, Larmor tried to clarify the relationship between electricity and structure of matter. The lines of twist starting from an atom and ending on another atom of the same molecule resembled the short tubes of force connecting the atoms in a molecule as suggested by J.J. Thomson some years before. In that theoretical model, the transfer of electricity as pure propagation of breakdowns of elasticity across the aether appeared not completely satisfactory, because the seat of electricity could also be inside matter. To fill the gap, Larmor took a step forward: the transfer of electricity also consisted of the «convection of atomic charges». Electric charge underwent a conceptual shift from a phenomenon connected to the distribution and transfer of energy to a phenomenon connected to the distribution and transfer of matter. Conversely, matter became a peculiar entity, stemming from dynamical actions taking place in the aether. However, a sort of conceptual continuity was assured, for the transfer of particles, represented as dynamical structures of the aether, was not so different from the transfer of *pure* energy. In other words, in Larmor's general framework, matter and energy, in their intimate nature, were not radically different from each other[24].

His picture was based on a medium which was «a perfect incompressible fluid as regards irrotational motion» but was endowed with rotational elasticity. The medium was «the seat of energy of strain», and «undulations of transverse type» were propagated throughout it. Both matter and electricity were permanent dynamical effects taking place in that kind of aether. The discreteness of matter stemmed from the continuity of the medium and the tension between continuous and discrete representations seemed thus overcome[25].

The motion of a charged particle through aether produced an «elastic effect of convection through the medium», consisting of «a twist round its line of movement». The effect was not so different from the propagation of elastic actions in *displacement* currents: such a twist was just the common feature of every kind of electric current. At the same time Larmor acknowledged that he had not managed to enlighten what he considered the core of every electromagnetic theory: «the detailed relations of aether to matter». Therefore he assumed that the basic dynamic entity was placed at the sub-atomic level: he labelled «electron» that entity.

The new solution, the «electron», confirmed the integration between the continuous *substratum* and the discrete unit, in some way a *particle*, of electric charge. The specific unifying element of the new theory was the convective nature of all kind of electric currents, both macroscopic and microscopic[26].

Independently from their peculiar nature of dynamical singularities in the aether, electrons were electric charges in motion along closed paths, therefore undergoing an accelerate motion. Consistently with Maxwell's electromagnetic theory of radiation, accelerated electric charges would have sent forth electromagnetic waves. That effect was in contrast with Larmor's atomic model, for a swift damping of electronic motion would have followed. To save the model, Larmor introduced (*ad hoc*, indeed) the concept of «steady motion», and the concept of perturbation of a steady motion. Electric waves could stem only from those perturbations[27].

This new condition of «steady motion» broke the symmetry between macroscopic and microscopic level, for the condition of *steadiness* appeared suitable only for the latter. Unfortunately, the tension between *macroscopic* and *microscopic*, which seemed to have been overcome by the attribution of a convective nature even to microscopic currents, re-appeared once again. There was a difference between the intimate nature of matter, concerning microphysics, and its visible features, concerning ordinary physics[28].

The double nature of electrons, as individual building blocks of matter, on the one hand, and as dynamical structures of aether, on the other, affected their behaviour with regard to velocity. As long as their velocity remained far less than the velocity of radiation, their dynamical properties could be expressed 'in terms of the position of the electrons at the instant'. When their velocities approached that of radiation, they had to be «treated by the methods appropriate to a continuum». In other words, low velocity electrons behaved like particles, whilst high velocity electrons behaved like radiation. Electrons could be described either like particles or like radiation, and the choice depended on their energy: the transition from the first description to the second took place in some unspecified way. The old clash between continuous and discrete models faded into a new representation, where *continuous* and *discrete* became complementary aspects of an entity endowed with an intimate double nature[29].

Larmor's electron as a rotational stress in the aether led to a model of electric current not so different from Thomson's, because an electronic flow could be looked upon as a motion of some kind of aethereal perturbation. I find that, beyond some specific, important features, which differentiated Larmor's electrons from Thomson's tubes of force, both entities consisted of dynamical and aethereal structures propagating through aether itself. Moreover, in both cases, we are dealing with the propagation of a series of discrete units, either tubes of force or electrons[30].

The sharp distinction between mechanical and electromagnetic world-views seems not suitable for them. J.J. Thomson and Larmor's theoretical models were based at the same time on mechanical and electromagnetic foundations. Aether and elementary structures *in* aether, or *of* aether, were the common root for both mechanical and electromagnetic entities, in particular matter and fields. Larmor cannot be put into the category of the so-called *electromagnetic* world-view, and J.J. Thomson cannot be put into the category of the so-called *mechanical* world-view.[31] They tried to bridge the gulf between mechanics and electromagnetism. For this reason, I find early 1890s physics more interesting and meaningful than assumed by the received view of the history of physics.

3. From history to philosophy of science

In the late nineteenth century, the scientific debate was explicitly undertaken with the awareness that alongside specific physical hypotheses and mathematical tools, the scientific practice required more general hypotheses, involving the nature of physical science, its methods and its aims. Neither before nor after the late nineteenth century, the boundaries of physics were so wide and transparent. Conceptual components were not sophisticated additions but essential components: physics could neither be practised nor understood by setting them aside. This was a specific feature of late nineteenth-century theoretical physics. In that time, the conceptual tensions between specific models, between long-term conceptual streams, and between meta-theoretical and methodological options, gave rise to a process of trespassing of boundaries between those models, conceptual streams, and methodologies. The boundaries between matter and energy, between mechanics and electromagnetism, between continuous and discrete models, between macroscopic and microscopic descriptions, between contiguous action and action at a distance, and between mathematical physics and theoretical physics were repeatedly crossed. Following those debates allows us to encounter the last generation of physicists who were proud of being natural philosophers; some years later, even the expression *natural philosophy* would have appeared unsuitable and puzzling to the next generation of physicists. In the course of the twentieth century, theoretical physicists have underestimated their primitive link with the more speculative side of that long-lasting tradition.

Although the history of electromagnetic theories from Maxwell to J.J. Thomson and Larmor, through Poynting and Heaviside, could be considered as a theoretical *evolution*, I think that it would be quite hard to depict it as an instance of scientific progress. The concept of progress itself seems to me quite questionable when applied to the history of theoretical physics. From the point of view of present-day standard conceptions on electromagnetism, selected passages from Hertz, echoing some kind of mathematical phenomenology, would appear as a progress when compared to J.J. Thomson's substantialised fields or Larmor's aethereal electrons. It is the result of the *formalistic* drift, which has taken place in the twentieth century, both in the field of research and in the field of teaching. On the other hand, some conceptions emerging from theoretical physics in the last decades of the twentieth century appear in general terms similar to J.J. Thomson and Larmor's conceptions of particles and fields.[32] The concept of theoretical *evolution* could perhaps be associated to a higher level of unification. If we compare Maxwell and W. Thomson's theories, on the one hand, with J.J. Thomson and Larmor's, on the other, we find that the latter actually managed to better integrate a theory of matter with an electromagnetic theory, mechanical models with electromagnetic equations, and discrete with continuous models.

The actual and clearly perceived *scientific* progress, which took place in the late nineteenth century, was a *technological* progress: indeed, electromagnetic devices had their share of success in it. The progress consisted in the spread of electric energy, electric lighting and telegraphy: by the end of the nineteenth century, a hundred thousand miles of telegraph cables connected the most important towns in the world, crossing mountains and oceans.[33] For the first time in the modern age, physics realized dramatic transformations in everyday life. During the so-called *Scientific Revolution* of the seventeenth century, the emerging science influenced and transformed intellectual life but did not manage to affect material standards of life and habits of ordinary people. On the contrary, a widespread material transformation was the specific effect of scientific practice in the late nineteenth century. In some way, there was a *revolution*, namely the occurrence of meaningful events, which deeply transformed both the material and intellectual life. Nevertheless, physicists of the late nineteenth century never claimed that they were doing something revolutionary; only their contemporaries, historians and other observers, acknowledged that a deep transformation was taking place, involving both science and social life. Even nowadays, historians but not physicists look upon that *fin de siècle* as a particularly meaningful stage[34].

It seems to me that L. Boltzmann clearly pointed out the different historical effects of the two aspects of late nineteenth century physics, namely the theoretical debates and technological achievements. In a lecture held in 1904, in St.Louis (USA), at the *Congress of Arts and Science*, he qualified «the development of experimental physics» as «continuously progressive». He saw some permanent achievements: among them, «the various applications of Röntgen rays» or «the utilisation of the Hertz waves in wireless telegraphy». On the contrary, he acknowledged that the «battle which the theories have to fight is, however, an infinitely wearisome one». Theoretical physics dealt with «certain disputed questions which existed from the beginning» and which «will live as long as the science». In other words, theoretical physics deals with conceptions which continuously emerge, then are neglected and subsequently re-emerge. One of the «problems» which he found «as old as the science and still unsolved» concerned the choice between *discrete* and *continuous* in the representation of matter. He found that those queries had their natural seat on the boundary between the history of physics and the history of ideas; in Boltzmann's words, they «form the boundary of philosophy and physics». Moreover, the historical consciousness, which had already emerged in scientists of the last decades of the nineteenth century, found in Boltzmann an advanced interpretation. Physical theories could not be looked upon as «incontrovertibly established truths», for they were based on hypotheses which «require and are capable of continuous development»[35].

I find that, if not a revolution, J.J. Thomson and Larmor realized a deep transformation in physics. In their theoretical models, a deep integration between discrete and continuous representations was achieved. The link between matter and radiation, and the integration between continuity and discreteness, at a fundamental microscopic level, is now acknowledged as a milestone in modern physics and, in general, in modern science.

Planck's 1900 theoretical model of radiation, and Einstein's 1905 theoretical models for matter and radiation were different, sharply different implementations, of the same attempt to integrate complementary conceptions. The connection between J.J. Thomson and Larmor, on the one hand, and Planck and Einstein, on the other hand, is a meaningful connection, underlying the different specific features of their correspondent theories[36].

I find that we can correctly stress changes and innovation introduced by early twentieth century theoretical physics and, at the same time, acknowledge the importance of theoretical researches taking place at the end of the nineteenth century. There was continuity in the attempt to integrate complementary conceptions for matter and energy; there was a revolution in the specific features of Planck and Einstein's theories. Some decades ago, talking on the concept of «Differential History», A. Funkenstein criticised who assumed «continuity and innovation to be disjunctive, mutually exclusive predicates», and I share his criticism.[37] I also agree with Miller's interpretation of the history of physics in the first half of the twentieth century: the concept of scientific revolution «describes only the gross structures of scientific change». When we take into account the fine structure, we find that «change is gradual» and we have the opportunity to appreciate elements of both continuity and discontinuity[38].

There are two issues mutually interwoven, which deserve further analysis: first, the nature of the link between a specific physical theory, and the more general conceptions, or *conceptual streams*, converging on it, and second, the nature of the link between late nineteenth-century and early twentieth-century theoretical physics. I will discuss the former in the following passages, and the latter in the following section.

The specific features of the theories under consideration, namely electrons and elementary tubes of force, can be considered as a *first level*. Those specific features made reference to general models of continuity and discreteness, which can be considered a *second level*. I label *conceptual streams* the most general theoretical models: for instance the continuous or discrete conceptions of matter, and the continuous or discrete conceptions of energy. Furthermore, we can find a meta-theoretical tension between mathematical phenomenology, on the one hand, and British theoretical physics, on the other. If the latter aspired to an intimate representation and explanation of natural phenomena, the former confined itself to a mere description or to a quantitative generalisation. If the latter made use of mental pictures and displayed sophisticated concepts and models, the first pointed to facts and equations.[39] I call *third level* the level corresponding to such a methodological or meta-theoretical commitment. It is worth mentioning that, in J.J. Thomson's writings, that methodological tension transformed into a pedagogical tension between a technical and formal teaching, on the one hand, and a teaching taking care of student's mental representations, on the other.[40]

Larmor's electrons or J.J. Thomson's bundles of tubes of force are specific theoretical models: they are an instance of *first level* options. According to Larmor, elementary masses emerge as dynamic structures in a universal continuous medium, and, according to J.J. Thomson, electromagnetic radiation was endowed with microscopic discrete structure: they are general models, or *second level* options, belonging to a long-term conceptual stream. The stress on specific and general conceptual models as an essential component of physics was an important methodological or meta-theoretical issue: it was a *third level* option.

In the debate which took place in late nineteenth century British electromagnetism, besides the conceptual tension between discrete and continuous models, we encounter other tensions between other couples of issues: macroscopic representations *versus* microscopic representations, contiguous actions *versus* actions at a distance, mathematical generalisations *versus* physical models. Those conceptual tensions concerned different levels of scientific practice: some of them, for instance the tension between discrete and continuous models, were *theoretical*; others, for instance the tension between mathematical physics and theoretical physics, were *meta-theoretical* or methodological.

Among the conceptual streams flowing underneath late nineteenth-century theoretical physics I could single out many general statements: matter has a continuous structure, matter has a discrete structure, energy has a continuous structure, energy has a discrete structure, interactions between bodies are contiguous actions, interactions between bodies are actions at a distance, matter has only passive properties, matter has active properties, light consists of continuous waves, light consists of discrete bundles of tubes, etc.

Those conceptual tensions and the corresponding debates played an important role in late nineteenth century physics, and offered a fruitful background to subsequent theoretical researches. We should acknowledge the existence of a deep continuity, as well as a deep discontinuity, in the transition from late nineteenth century to early twentieth century theoretical physics. In order to correctly appreciate both historical continuity and discontinuity, we have to distinguish the *first level* of specific theoretical models from the *second level* of long-term *conceptual streams*. I find discontinuity at the first level, and continuity at the second level[41].

My *streams* are units of scientific thought, which do not suffer mutual exclusion: in some theories which emerged in the second half of the nineteenth century, we find the convergence of two conceptual streams, for instance continuity of matter and contiguous action. Moreover, we find a convergence and an attempt to integrate two complementary streams, for instance continuity and discreteness of matter. Although the conceptual streams correspond to simple statements, they cannot be looked upon as *logical* statements in accordance with *classic* logic.

I must stress that my *conceptual streams* are simpler, less sophisticated and more easily identifiable than Kuhn's *paradigms*, Lakatos' *research programmes*, or Laudan's *research traditions*. They have something in common with Holton's «themes» or «themata». I will not discuss historiographical theses like those of Kuhn or Lakatos: my specific, historical researches, confined within a narrow range of space and time, do not allow me to draw conclusions on the general structure of science. Laudan's theses deserve to be briefly discussed: some features of his *research traditions* are akin to some features of my *conceptual streams*, even though the two entities are, on the whole, quite different. Laudan, for instance, put the «atomic theory» in the list of his *research traditions* and qualified it as founded «on the assumption that matter is discontinuous»; indeed, it is one of my *conceptual streams*. Nevertheless, he put in the same list an entity like the «quantum theory», which is not a simple conceptual unit but a set of different theories: among them, as Laudan himself explicitly acknowledged, «there are huge conceptual divergences».[42] Other entities qualified as *research traditions*, like «Darwinism», or «the electromagnetic theory of light», or «Cartesian physics», have different natures: if Darwinism and Cartesian physics could be looked upon as theories or sets of theories, the electromagnetic theory of light could be looked upon as a specific issue of a theory. The fact is that Laudan's *research traditions* are entities more complex and more sophisticated than theories; on the contrary, my *conceptual streams* are less complex than theories. A more striking difference emerges when we note that many conceptual streams can converge on a theory; this multiple convergence appears more problematic for research traditions.

If a conceptual stream can carry, in a broad sense, «*metaphysical* […] commitments», as Laudan claimed with regard to his *traditions*, I find that a conceptual stream cannot carry «*methodological* commitments». Moreover Laudan sharply stated that «*research traditions are neither explanatory, nor predictive, nor directly testable*» because of their abstract and complex nature.[43] On the contrary, a conceptual stream maintains more friendly relationships with explanations, predictions and experimental tests. The statement that cathode rays have a discrete structure was actually and repeatedly tested at the end of the nineteenth century, even though in a non-conclusive way. That Larmor's electron was not solid matter in a traditional sense but consisted of a dynamical structure of aether was as predictive as explanatory, even though, at that time, not easily testable.

What Laudan in 1977 called «normative difficulties» and «worldview difficulties» are quite close to the *third-level* issues I have introduced in my analysis of nineteenth century theoretical physics. He acknowledged that «normative conceptual problems» affected «the historical evolution of science», but he looked upon them as tensions between science and «extra-scientific beliefs». In other words, he found that those debates concerned the relationships between science, on the one hand, and «metaphysics, logic, ethics and theology», on the other. In the specific context of the history of theoretical physics in the late nineteenth century, those debates were authentic *scientific* debates and were considered as such by the contemporaries[44].

As already remarked, my historiographical sketch has something in common with Holton's approach: history of science has always been crossed by general conceptions which Holton called *themes* and I call *conceptual streams*, in order to underline their historical evolution. In 1973 the «class of hypotheses», «thematic hypotheses», or «thematic propositions» were looked upon by Holton as «directly neither verifiable nor falsifiable». He imagined the scientific enterprise as endowed with three components: empirical ground, formal language and a «thematic content». The last component represented a specific *dimension* of scientific enterprise, «a dimension that can be conceived as orthogonal to the empirical and analytical content», where the adjective *orthogonal* suggests a sort of mutual independence among them. Furthermore, the thematic component would consist of a couple of «opposing or complementary theme and antitheme»: for instance the thematic couple of «atomism and the continuum» or «discontinuity and the continuum»[45].

I think that the adjectives *unverifiable*, *unconfirmable* and *unfalsifiable*, used by Holton and Hesse, cannot be accepted in an absolute sense.[46] History of science, in particular the period I am dealing with, shows a complex interplay between hypotheses and experimental checks. Physicists in the late nineteenth century, for instance, tried to experimentally check the discrete structure of matter. At the same time, there were theoretical attempts to explain that discrete structure in terms of a hypothetical continuous structure of aether. The fact is that, when Holton introduced his themes, he did not take into account the difference between specific theoretical models, general conceptual models (namely my *conceptual streams*), and meta-theoretical or methodological commitments. In 1982 and 1986, he described some «themata and metaphors» endowed with «immense explanatory energy». He listed specific theoretical models, like lines of force, together with meta-theoretical commitments, like Einstein's commitment to unification, or general theoretical models like «the continuum».[47] Adjectives like *verifiable* or *falsifiable* can be associated to some specific theoretical model or to some general conceptual model, but are unsuitable for meta-theoretical commitments.

I agree with Holton's claim that the presence of themes represents an element of continuity in the history of science, for they «indicate the obverse side of the iconoclastic role of science». Nevertheless, there are themes which have introduced meaningful discontinuities in the history of science. I find that the *conceptual streams* (mainly when they are members of a couple of opposite models) emphasise both the continuity and the discontinuity in scientific enterprise. On the one hand, I see a persistence of general models and general dichotomies; on the other, I see the extreme variability of their specific implementations[48].

With regard to the persistence of themes or conceptual streams it is worth mentioning D'Agostino's criticism: he claimed that, whereas theoretical models have experienced frequent transformations, mathematical structures have survived for a longer time. In other words, mathematical structures are more persistent than conceptual models. I find that the series of subsequent disappearances and re-emergences of a given conceptual stream is a long-term phenomenon, even longer than the persistence of mathematical structures. The short-term phenomenon pointed out by D'Agostino corresponds to the specific implementations of a given *conceptual stream*[49].

I would like to specify that my historiographical sketch cannot be looked upon as an epistemological framework suitable for the whole history of physics or the whole history of science. It is an interpretative framework concerning theoretical physics in the late nineteenth century, and its connections with theoretical physics of the early twentieth century. Although I think that conceptual streams are long-term phenomena, I find that the explicit acknowledgement of their existence, the explicit role they played in scientific practice, and the existence of an explicit debate involving them were specific hallmarks of that historical period. I do not claim that long-term conceptual streams have always affected science in the same way in the course of the whole history of science. In this sense, my interpretative framework is merely *local*: it could be stretched across longer periods of time only after having undertaken further detailed historical investigations[50].

4. A problematic heritage

Although the specific theoretical models of Larmor's aethereal matter and J.J. Thomson's discrete structure of radiation were formally dismissed in the transition between late nineteenth century and early twentieth century theoretical physics, at a deeper level we find a persistence of themes or conceptions. The similarity between matter and energy, in particular between the structure of the electromagnetic field and elementary corpuscles, survived and found new implementations: for instance, Einstein's conceptions on matter and energy. The more general commitment to integrate continuous and discrete representations of the physical world survived as well. I find that the debates on electric charge, matter and energy, which took place in Great Britain in the late nineteenth century, can be considered one of the roots which fed twentieth century theoretical physics.[51] I think that the fruitfulness of those debates can be found in the queries they raised and in the process of integration they triggered off. In the course of the twentieth century, those queries were reinterpreted or, in some cases, overlooked: in any case, the answers subsequently given became alien to the scientists who had formulated them.[52] Indeed, Einstein's theories are quite different from Larmor and J.J. Thomson's theories, both at the level of specific theoretical models (*first level*), and at the level of methodological attitudes towards models and representations (*third level*). The specific theoretical content of Einstein's 1905 papers on the inertia of energy and on quanta of energy can be deemed not comparable (even *incommensurable*) with the electromagnetic theories J.J. Thomson and Larmor outlined early in the 1890s. The last generation of natural philosophers made use of theoretical models which, in the course of the twentieth century, were looked upon by physicists as outmoded if not definitely meaningless. The role of conceptual models changed: the meaning and the actual practice of theoretical physics changed as well[53]. At the same time, at the level of conceptual streams, (*second level*), I find in Einstein the same commitment to integrate discrete and continuous models in the description of matter and energy, as I find in J.J. Thomson and Larmor. If I see meaningful differences at the first and third level, I see meaningful analogies at the second level.

Some decades ago, a historian, Giusti Doran, pointed out a deep conceptual link between Larmor and Einstein; more than a half century before, the 1922 Nobel Prize winner Millikan had claimed the existence of a similar continuity between J.J. Thomson and Einstein. I find that they failed to satisfactorily explain that continuity, because they failed to identify the different levels involved in the comparison. Nevertheless, the connection between J.J. Thomson and Larmor's theories, on the one hand, and Einstein's, on the other hand, is deep and meaningful. The papers the young Einstein wrote in 1905, in particular those on the inertia of energy and on the new «heuristic point of view» on radiation, would appear less astonishing if only we took into account British electromagnetic theories which emerged in the late nineteenth century, besides the better known Continental theories (Lorentz, Poincaré, …)[54].

In this section, I would like to discuss in some detail the nature of that problematic link. First of all, I will focus on the comparison between Larmor's theoretical model of aether and inertia, and the new model of aether which Einstein devised after 1905. Then I will focus on the comparison between J.J. Thomson hypotheses on the nature of electromagnetic radiation and Einstein's 1905 theoretical model of light *quanta*.

A suitable starting point is offered by the short paper Einstein wrote in September 1905 on the connection between the inertia of matter and its content of energy.[55] At the outset, Einstein placed his trust in the «Maxwell-Hertz equations for empty space» and in his own *Relativitätprinzip*. Then he took into account both the electromagnetic radiation sent forth by a body and the remaining energy of the body, when observed from two different inertial reference frames. In the end, he found that when «a body loses an amount L of energy, its mass decreases of L/v^2», where v is the velocity of light. Finally he assumed that, in general, « the mass of a body is a measure of its content of energy »[56].

With regard to the first level, Larmor and Einstein's specific models are quite different. On the one hand, we have an electron, namely a microscopic concentration of rotational energy, corresponding to a concentration of electric energy: when in motion, the electron should experience an electromagnetic inertia. On the other hand, we have a macroscopic body, which, after having sent out electromagnetic radiation, finds its energy shortened by a precise amount. As a consequence, its inertia should decrease in a proportional way. At the first level of specific theoretical models, there are not similarities: microscopic, dynamical structures in the aether, on the one hand, and macroscopic bodies and a macroscopic energy balance, on the other. The analogies can be found at the second level, wherein both Larmor and Einstein realised a process of *substantialisation* of the electromagnetic energy and, conversely, a process of *desubstantialisation* of matter. The two complementary processes led, in both cases, to an equivalence between the inertia of matter and the electromagnetic energy.

After 1894, Larmor went on inquiring into the aethereal concentration of energy which was peculiar to his electron. In 1895, in the first lines of the second paper of the trilogy «A Dynamical Theory of the Electric and Luminiferous Medium», he re-introduced «electrons or permanent strain-centres in the aether, which form a part of, or possibly the whole of, the constitution of the atoms of matter». In the same paper, he described aether «as containing a distribution of electrons, that is of intrinsic centres or nuclei from each of which a configuration of rotational strain spreads out into the surrounding space». Moreover, every electron, when in motion through aether, will «carry its atmosphere of strain along with it, practically without alteration unless the velocity of the electron is so great as to approximate to the velocity of radiation»[57].

These repeated references to aether, which was the keystone of Larmor's theory, appear definitely in contrast with the sharp rejection of aether announced in Einstein's 1905 electrodynamics. Nevertheless, after the accomplishment of his General Relativity, Einstein himself began to take into account a new kind of aether. It is known that, in 1920, he held a lecture at Leiden in honour of Lorentz, wherein he outlined a new, more sophisticated model of aether. In that outline Giusti Doran found an implementation of «the primordial medium of Thomson's vortex-atom and Larmor's strain-center electron». In order to appreciate to what extent Giusti Doran's claim is convincing, and in order to evaluate similarities and differences in Larmor's and Einstein's models of aether, we must analyse both Larmor's subsequent sources and Einstein's Leiden lecture[58].

In 1897, in «A Dynamical Theory of the Electric and Luminiferous Medium – part III: Relations with Material Media», Larmor qualified aether as a «continuous, homogeneous, and incompressible medium, endowed with inertia and with elasticity purely rotational». In that kind of medium, electrons «exist as point-singularities, or centres of intrinsic strain», and «atoms of matter are in whole or in part aggregations of electrons in stable orbital motion». In that long paper of the trilogy, Larmor expressed even meta-theoretical remarks about aether and its functions. Aether was «entirely supersensual», he claimed: we could even «ignore the existence of an aether altogether» and confine ourselves to describing phenomena «in accordance with the system of mathematical equations». Although «in strictness, nothing could be urged against this procedure», he thought that aether offered «so overwhelmingly natural and powerful an analogy» that to assume its existence was useful «for purposes of practical reason». The fact is that, in Larmor's theoretical physics, aether served two different purposes, the first being theoretical and the second meta-theoretical or methodological. It was the universal, primitive substratum, giving rise to matter and fields, but it also was a *mental tool*, which allowed the scientist to go beyond the accumulation of «descriptive schemes of equations». In that sense, aether was «more or less a priori». Larmor thought that, «without the help of simple dynamical working hypotheses», we would be prevented from going «very far below the surface» of phenomena involving matter and fields. Without aether we could not understand «how this interaction between continuous aether and molecular matter takes place».[59] On the third-level *methodological-philosophical* context, the role played by aether was not so different from the role of space or time, namely the role of invisible entities which allow us to represent a wide set of visible phenomena.

In the «Preface» to his 1900 *Aether and matter*, Larmor qualified the «suprasensual aethereal medium» as a conceptual tool, which «may of course be described as leaving reality behind us». According to Larmor, it was indeed a «result of thought», an attempt to interpret physical reality: it was «more than a record or comparison of sensations». Larmor's specific theoretical model involved «a system of discrete or isolated electric charges» embedded in «an elastic aether»; they were as «singular points involving intrinsic strain in the structure of the medium». Matter had the same structure of electricity, consisting of «a permanent nucleus or singularity in and belonging to the aether»[60].

His general model led to «the fundamental consequence that the structure of matter is discrete or atomic» but «the ultimate reality» required a conceptual shift «from sensible matter to a uniform medium which is a *plenum* filling all space». The discrete structure of matter stemmed from a pre-existent continuous medium, so that «all events occur and are propagated in this *plenum*». That discrete structure was kinematical or dynamical in its nature, because «ultimate elements of matter» consisted of «permanently existing vortices or other singularities of motion and strain located in the primordial medium». He specified that those ultimate, elementary elements could «never arise or disappear»[61].

Larmor's model entailed a remarkable, unified view for both electromagnetic fields and matter. On the one hand, electromagnetic actions consisted of «elastic actions across the aether», so that «an electric field must be a field of strain». On the other hand, *protions*, endowed with intrinsic electric charge, «must be surrounded by a field of permanent or intrinsic aethereal strain» and therefore they must be «in whole or in part a nucleus of intrinsic strain in the aether». Propagations of pure fields and propagation of elementary matter yielded the same effects; in other words, Maxwell's *displacement* currents and convective electric currents shared the same intimate nature. He portrayed *protions* or *electrons* as something which «can move or slip freely about through that medium much in the way that a knot slips along a rope»[62].

At this point, we can take into account the lecture Einstein held in Leiden in 1920, *Äther und Relativitätstheorie*. That text shows us an Einstein committed to integrate not only theoretical models of matter with theoretical models of field, but also electromagnetic fields with gravitational fields. He started from the conceptual tension between the electromagnetic equations and their mechanical explanation: «Maxwell's laws [...] were clear and simple, the mechanical interpretations clumsy and contradictory», he stated. Einstein found a dualism between mechanics and electromagnetism and thought that the dualism could be traced back to Hertz's conception of «electric and magnetic force as fundamental concepts side by side with those of mechanics». In other words, Hertz's theory had «the defect of ascribing to matter and ether, on the one hand mechanical states, and on the other hand electrical states, which do not stand in any conceivable relation to each other».[63] He claimed he had managed to realize an important unification in 1905, for «according to the special theory of relativity, both matter and radiation are but special forms of distributed energy». Nevertheless, he acknowledged, «the special theory of relativity does not compel us to deny ether». A new point of view seemed to him «justified by the results of the general theory of relativity». Moreover, in order to make Mach's concept of inertia match with contiguous action, he thought that we should invent a sort of «Mach's ether», an aether which, «not only *conditions* the behaviour of inert masses, but *is also conditioned* in its state by them»[64].

It is worth noticing that, in 1912, on the path towards a *relativistic* theory of gravitation, in a paper on «gravitational induction», Einstein considered «likely» the so-called Mach's hypothesis: «the entire inertia of a massive particle is an effect of the presence of all the other masses». In other words, he thought that inertia was a gravitational effect, «based on a sort of interaction» between the particle itself and the other masses. In 1949, in his «Autobiographical Notes», Einstein remarked that what he had labelled *Mach's Principle*, namely «inertia would have to depend upon the interaction of the masses», did not fit «into a consistent field theory»: it «presupposes implicitly [...] masses and their interactions as the original concepts». Indeed, the so-called Mach's Principle and the subsequent «Mach's ether» stemmed from different conceptual models of physical *space*[65].

In 1920, Einstein looked upon his «ether of the general theory of relativity» as the heir of *Mach's aether*, namely «a medium which is itself devoid of *all* mechanical and kinematical qualities, but helps to determine mechanical (and electromagnetic) events».[66] The new aether had to be intrinsically gravitational, he claimed, because we cannot define space without taking into account gravitation. Nevertheless, that requirement restored the dualism between gravitation and electromagnetism: the two fields, gravitational and electromagnetic, when considered independent from each other, led to a fundamental asymmetry. On the one hand, we have a gravitational field «inseparably bound up with the existence of space»; on the other hand, «a part of space may very well be imagined without an electromagnetic field». In other words, «in contrast with the gravitational field, the electromagnetic field seems to be only secondarily linked to the ether». He assumed that «the elementary particles of matter are also, in their existence, nothing else than condensations of the electromagnetic field». His theoretical model required «two realities which are completely separated from each other conceptually, although connected causally». Matter appeared like the two sides of a coin: on the first side, matter was conceived as a concentration of electromagnetic energy; on the other, it was intrinsically linked to the gravitational field or gravitational aether. The demanding task of «comprehending the gravitational field and the electromagnetic field together as one unified conformation» appeared to Einstein as the greatest achievement of twentieth century «theoretical physics»[67].

If we take earnestly into account Einstein's 1920 lecture, then we must take earnestly into account Giusti Doran's interpretation, which called for the existence of a conceptual stream connecting Larmor's 1894 theory with Einstein's 1920 remarks. To begin with, I do not agree with her interpretation of Einstein's 1920 aether as «the physical medium of electromagnetic propagation», because that new aether had more gravitational than electromagnetic features.[68] Nevertheless, I find in Larmor and Einstein a common commitment to look for a unified theory of matter and radiation. Larmor's aether and Einstein's new aether were different, but in some way complementary: whereas Larmor hoped that even gravitation could be explained by means of his mechanical-electromagnetic proto-aether, Einstein was looking for an electromagnetic integration of his «gravitational aether». For both of them, the tension towards a great unification was a long-lasting commitment: they tried to include all properties of matter, energy and interactions in a unified view.

The comparison between Larmor's aether and Einstein's aether leads us to a more general comparison involving the nature of their mental representations, namely their (*third level*) meta-theoretical options. Differently from Miller, I find that Einstein's methodological attitude, and therefore his interpretation of theoretical physics, was closer to «Hertz's brilliant use of axioms as organizing principles» than to Boltzmann's «mental pictures».[69] His models were quite different, for instance, from J.J. Thomson and Larmor's specific models for the structure of matter and fields, namely aethereal electrons and electric tubes of force. I find that Einstein's «mental pictures, such as ideal measuring rods and clocks or point masses of electrons» are imagery and models which cannot be associated either to Boltzmann's *German* models or to J.J. Thomson and Larmor's *British* models. The microscopic structures devised by *British* and *German* physicists were quite different from Einstein's abstract macroscopic rods and clocks, or from Einstein's equally abstract microscopic electrons and *quanta*[70].

Getting back to Einstein's 1905 first paper, we notice that the title shows its theoretical *flavour*: a «heuristic point of view» concerning «the production and transformation of light». Purely theoretical was the starting point of the paper, namely «the deep formal difference between the theoretical models» of matter and electromagnetic radiation. He remarked that matter was represented by means of «a very great number of atoms and electrons», endowed with specific positions and velocities, while electromagnetic radiation was represented by means of «a continuous function through space». Electromagnetic energy, in particular, was represented as «a spatially continuous function», while energy of matter was represented as a discrete «summation over a finite number of atoms and electrons». Einstein thought that the deep asymmetry between matter and radiation could be overcome by the assumption that «the energy of light propagated in a discontinuous way through space». That assumption was consistent with phenomena like «black body radiation» or «the creation of cathode rays by means of ultra-violet light». In brief, electromagnetic energy was supposed to «consist of an endless number of *Energiequanten* localised in points of space».[71] Another phenomenon consistent with the hypothesis of electromagnetic *quanta* was the photoelectric effect, wherein light of suitable frequency forced metal plates to send out negative electric charges[72].

The year before (1904), J.J. Thomson had published a booklet, *Electricity and Matter*, wherein he collected together some lectures he had held in Yale in 1903; within a few months, Thomson's booklet was translated into German. In the third chapter, «Effects due to acceleration of the Faraday's tubes», Thomson focussed on the interaction between Röntgen rays and matter. He remarked that «Röntgen rays are able to pass very long distances through gases, and as they pass through the gas they ionise it». What he found difficult to explain was that «the number of molecules so split up is, however, an exceedingly small fraction, less than one billionth, even for strong rays, of the number of molecules in the gas». The question was: why were not all the molecules crossed by that kind of radiation affected in the same way? In other words, «if the conditions in the front of the wave are uniform, all the molecules of the gas are exposed to the same conditions»: how could the fact «that so small a proportion of them are split up» be explained? Perhaps the concentration of energy able to modify the microscopic structure of matter had its seat not in Röntgen rays but in matter itself. Perhaps only high-energy molecules could experience the ionisation when interacting with the rays. Nevertheless, in this case, the probability of the ionisation would have shown some kind of dependence on gas temperature, namely on its internal energy: «the ionisation produced by the Röntgen rays ought to increase very rapidly as the temperature increases».[73] This was not the case and therefore J.J. Thomson resorted to his 1893 theoretical model of electromagnetic radiation as a bundle of discrete tubes of force. He thought that the selective ionisation could be explained only if, «instead of supposing the front of the Röntgen ray to be uniform, we suppose that it consists of specks of great intensity separated by considerable intervals where the intensity is very small». According to that hypothesis, the microscopic properties of electromagnetic radiation were similar to the properties of microscopic particles: in J.J. Thomson's words, «the case becomes analogous to a swarm of cathode rays passing through the gas». Indeed, that flux of elementary corpuscles showed the same behaviour of X-rays: «the number of molecules which get into collision with the rays may be a very small fraction of the whole number of molecules». In 1904, J.J. Thomson imagined tubes of force «as discrete threads embedded in a continuous ether, giving to the latter a fibrous structure». He assumed that both aether and electromagnetic waves were endowed with a discrete structure: it was a solution, he remarked, «which I have not seen noticed»[74].

Obviously we must underline the different features of J.J. Thomson and Einstein's theories. I have already pointed out that the deep similarity is not to be found in those specific features but in the common attempt to integrate complementary conceptual streams. Besides the attempt to integrate discrete with continuous models for electromagnetic radiation, I find in J.J. Thomson a wider project of integration and unification between macroscopic and microscopic models, between physics and chemistry, and between mechanics and electromagnetic phenomena. I find in Einstein a commitment to integrate macroscopic with microscopic models, and electrodynamics with thermodynamics[75].

In 1967, R. McCormmach stated that the conceptual link between J.J. Thomson and Einstein deserved some attention: he found that Einstein's «views have certain close similarities with Thomson's, and they should be examined». When he drew his conclusion he claimed that «Thomson's theory of light was inconclusive» and «the predicted structure remained largely qualitative in theory and undetectable in the laboratory». This assessment seems to me not convincing, because some quantitative explanations appear in J.J. Thomson's 1904 booklet, and because the heart of the matter is elsewhere. The fact is that Einstein, differently from Thomson, did not put forward any specific model: any further inquiry into the specific structure of quanta was not required. Einstein had not made any claim about it. I do not find J.J. Thomson's theoretical attempt meaningful and fruitful because of its first-level specific features, but because of its second-level general model. The most interesting contribution to the history of physics was not his specific discrete model of radiation, but the commitment to integrate discrete and continuous aspects of radiation, and the commitment to bridge the gap between the microscopic structure of matter and the microscopic structure of radiation. In this perspective we can appreciate J.J. Thomson's contribution to theoretical physics. Only in this perspective do I find intelligible the last lines of McCormmach paper, where he stated that «Thomson contributed to the twentieth-century revolution in the theory of light».[76] Outside my perspective, without a definite distinction between the two levels, I would be unable to see why his theory should be both «inconclusive» and «revolutionary». In my historiographical framework, if «inconclusive» should be referred to the first level, then «revolutionary» should be referred to the second level.

Now the question is: why, in more recent secondary literature has not the conceptual link between J.J. Thomson and Einstein (however problematic it may be) been taken into account? I must stress that what appears as a sort of *missing link* in recent literature, was acknowledged as an important link by some physicists in the first half of the twentieth century[77].

In a paper published in 1910 in the *Annalen der Physik*, Planck associated Einstein and J. Stark to J.J. Thomson and Larmor. He noted that the four physicists had put forward an extremely radical interpretation of electromagnetic radiation: even in the case of «electromagnetic processes in pure vacuum», they had imagined «diskreten Quanten» or «Lichtquanten». He made reference to a paper Einstein had published in 1909 in the *Physikalische Zeitschrift*, where the young scientist had shown that energy fluctuations of radiation, and momentum fluctuations, involved two terms: an expected wave-like term and an unexpected particle-like term[78]. Although Planck did not explicitly quote from it, in 1909 Larmor had published a paper (in the *Proceedings of the Royal Society*) devoted to the statistical interpretation of electromagnetic radiation. According to Larmor, a «ray», or «filament of light», was represented as «a statistical aggregate»: the statistical «constitution of the ray» mirrored the statistical distribution of energy «in the radiant element of mass». The «general thesis» he developed was a «molecular statistics of distribution of energy», which gave birth to a re-derivation of «Planck's formula for natural radiation»[79].

In the end, Planck stated that every «Korpuskulartheorie» appeared weak and unreliable to physicists «relying on the electromagnetic nature of light». He thought that a radical assumption of discontinuity in the structure of light would have led physics back to the old debates which had taken place in the eighteenth century. Could a physicist put in danger the fruitful alliance between the wave theory of light and Maxwell's electromagnetic theory, for the sake of a questionable hypothesis? Although he acknowledged the existence of some connection between his view and J.J. Thomson, Larmor and Einstein's views, for the time being, Planck restated his trust in «Maxwell-Hertz's equations for empty space, which excluded the existence of energy quanta in vacuum».[80] Planck's review was really oversimplified: neither the differences between J.J. Thomson and Einstein, nor the differences between J.J. Thomson and Larmor were taken into account.

Millikan, both in *The Electron*, the book published in 1917, and in his 1924 *Nobel lecture* took explicitly into account the link between J.J. Thomson and Einstein. He thought that the existence of aether could neither be denied nor had actually been denied by the upholders of the theory of *Relativity*. Nevertheless, he acknowledged that some difficulties arose «after the discovery of the electron and in connection with the relations of the electron to the absorption or emission of such electromagnetic waves». According to Millikan, J.J. Thomson had been the first to point out explicitly the query in 1903, in the lectures held at Yale.[81] The photo-electric effect and X-rays scattering could be accounted for «in terms of a corpuscular theory», wherein «the energy of an escaping electron comes from the absorption of a light-corpuscle». Einstein's 1905 hypothesis seemed to Millikan a daring implementation of Thomson's theoretical model. The former appeared to Millikan definitely unreliable: «I shall not attempt to present the basis for such an assumption, for, as a matter of fact, it had almost none at the time».[82] In any case, and independently from the unsatisfactory theoretical foundations, he acknowledged that the process of «emission of energy by an atom is a discontinuous or explosive process». That «explosive» feature suggested to Millikan the hypothesis that the cause of the photoelectric effect or X-rays scattering was placed in matter rather than in radiation. That alternative model was called by Millikan the «loading theory», because the process of accumulation of energy inside the atom was its main feature. According to Millikan, an unknown mechanism concerning the structure of the atom, and some unknown structure of aether were involved. In this way, he completely overturned the meaning of Einstein's *quantum* theory: not only, in his words, the «Thomson-Einstein theory throws the whole burden of accounting for the new facts upon the unknown nature of the ether», but Thomson and Einstein were associated in their supposed attempt to make «radical assumptions about its structure».[83] That J.J. Thomson had always been committed to investigating the supposed structure of aether, sounds quite reasonable; that Einstein was credited with having shared, in 1905, the same commitment, sounds quite strange. That Einstein's theoretical model did not require any aether was perhaps beyond Millikan's conceptual horizon.

After seven years, in his 1924 Nobel lecture, he recollected his efforts to find «some crucial test for the Thomson-Planck-Einstein conception of localized radiant energy.» According to Millikan, Einstein's theory combined Thomson's conception with «the facts of quanta discovered by Planck through his analysis of black-body radiation», in order to obtain «an equation which should govern, from his viewpoint, the interchange of energy between ether waves and electrons». Although «the reality of Einstein's light quanta may be considered as experimentally established», he thought that «the conception of the localised light quanta out of which Einstein got his equation must still be regarded as far from being established»[84].

Two elements are worth mentioning: first, Millikan failed to acknowledge Thomson's 1893 theoretical contribution, and, second, he misunderstood the nature of the conceptual link between J.J. Thomson and Einstein[85].

In order to appreciate the conceptual distance between J.J. Thomson and Einstein, it is worth reading what the former wrote in 1936 in his autobiography, in the last chapter, «Physics in my Time». The beam of X-rays appeared «like a series of bright spots on a dark background», as if the energy was «concentrated in separated bundles». He considered that picture as one of the two roots of «what was afterwards known as the Quantum Theory of Light», the other root being «Planck's Law that the energy in each bundle is equal to *hv*»[86].

J.J. Thomson stressed the electromagnetic origin of the *relativistic* effects: if «we take the view that the structure of matter is electric», he claimed, those effects «follow from Maxwell's equations without introducing relativity». He found it reasonable «to regard Maxwell's equations as the fundamental principle rather than that of relativity». Two consequences emerged: first, aether should be regarded as «the seat of the mass momentum and energy of matter», and, second, lines of force should be regarded as «the bonds which bind ether to matter». The nature of space, time and matter appeared to Thomson deeply linked to the existence of some kind of aether. To sum up, he claimed that «space must possess mass and structure»; in that case, he concluded, «it must possess the qualities postulated for the ether». It was a pity that on Einstein's *General Relativity* he avowed that «there is much of it I do not profess to understand»: he could have found in that theory, and in Einstein's Leiden lecture, some connection with his own remarks[87].

Bibliography

Barone, M., 2004, “The Vacuum as Ether in the Last Century”, *Foundations of physics* 34, 12, pp. 1973-82.

Boltzmann, L., 1899, “Über die Entwicklung der Methoden der theoretischen Physik in neurer Zeit”, in Boltzmann L. 1905, *Populäre Schriften*, Barth, Leipzig, pp. 198-227; Engl. transl. “On the development of the methods of theoretical physics in recent times”, in McGuinness B. (ed.) 1974, pp. 77-100.

Boltzmann, L., 1905, “The Relations of Applied Mathematics”, in Rogers H.J. (ed.) 1905, *Congress of Arts and Science, St. Louis 1904*, vol. I, Houghton, Mifflin and C., Boston and New York, pp. 591-603.

Bordoni, S., 2008, *Crossing the boundaries between matter and energy*, Università degli Studi di Pavia – La Goliardica Pavese, Pavia.

Bordoni, S., 2011, “Beyond Electromagnetic and Mechanical World-views: J. Larmor’s Models of Matter and Energy in the Early 1890s”, *Centaurus*, 53, 1, pp. 31-54.

Brush, S., 2007, “How ideas became knowledge: The light-quantum hypothesis 1905-1935”, *Historical Studies in the Physical and Biological Sciences*, 37, 2, pp. 205-46.

Buchwald, J.Z., 1985, *From Maxwell to Microphysics*, University of Chicago Press, Chicago.

Cantor, G.N., and Hodge M.J.S. (eds.) 1981a, *Conceptions of ether – Studies in the history of ether theories 1740-1900*, Cambridge University Press, Cambridge/London/New York.

Cantor, G.N., and Hodge M.J.S. 1981b, “Introduction: Major themes in the development of ether theories from the ancients to 1900”, in Cantor G.N. and Hodge M.J.S. (eds.) 1981a, pp. 1-60.

Cassidy, D.C., 2005, “Einstein and the quantum hypothesis”, in Renn J. (ed.) 2005, *Einstein’s Annalen Papers*, WILEY-VHC VelagGmbH & Co. KGaA, Weinheim.

Cohen, I.B., 1985, *Revolution in Science*, Harvard University Press, Cambridge Massachusetts.

Darrigol, O., 2000, *Electrodynamics from Ampère to Einstein*, Oxford University Press, Oxford.

D’Agostino, S., 2000, “On the Difficulties of the Transiction from Maxwell’s and Hertz’s Pure-Field Theories to Lorentz,s Electron”, *Physics in Perspective*, 2, pp. 398-410.

Einstein, A., 1905a, "Über einen die Erzeugung und Verwandlung des Lichtes betreffenden heuristischen Gesichtpunkt", *Annalen der Physik* 17, pp. 132-48.

Einstein, A., 1905b, "Zur Elektrodynamik bewegter Körper", *Annalen der Physik* 17, pp. 891-921.

Einstein, A., 1905c, "Ist dieTrägheit eines Körper von seinem Energienhalt abhängig?", *Annalen der Physik* 18, pp. 639-41.

Einstein, A., 1909, "Zum gegenwärtige Stand des Strahlungsproblems", *Physikalische Zeirschrift* 10, pp. 185-93; see also Stachel J. (ed.) 1989, *The Collected Papers of Albert Einstein*, vol. 2, Princeton University Press, Princeton, pp. 542-50.

Einstein, A., 1912, "Gibt es eine Gravitationswirkung, die der elektrodynamischen Induktionswirkung analog ist?", Springer, Berlin 1920; in Klein M.J., Kox A.J., Renn J. and Schulmann R. (eds.) 1995, *The Collected Papers of Albert Einstein*, vol. 4, Princeton University Press, Princeton, pp. 175-9.

Einstein, A., 1920, *Äther und Relativitätstheorie*, Springer, Berlin 1920; English trans. in Janssen M., Schulmann R., Illy J., Lehner C., and Kormos Buchwald D. (eds.) 2002, *The Collected Papers of Albert Einstein - English translation of selected texts*, vol. 7, Princeton University Press, Princeton, pp. 160-82.

Einstein, A., 1949, "Autobiographical Notes", in Schilpp P.A. (ed.) 1951, *Albert Einstein: Philosopher-Scientist*, Tudor Publishing Company, New York.

Einstein, A., 1953, "Foreword", in Jammer M. 1993, *Concepts of space: the history of theories of space in physics*, Dover, New York.

Falconer, I., 1987, "Corpuscles, Electrons and Cathode Rays: J.J. Thomson and the 'Discovery of the Electron'", *British Journal for the History of Science* 20, pp. 241-76.

Funkenstein, A., 1986, *Theology and the Scientific Imagination from the Middle Ages to the Seventeenth Century*, Princeton University Press, Princeton.

Galison, P., 2003, *Einstein's Clocks, Poincaré's Maps – Empires of Time*, W.W. Norton & C., New York/London.

Giannetto, E., 2007, "The Electromagnetic Conception of Nature and the Origins of Quantum Physics", in Garola C., Rossi A. and Sozzo S. (eds.), *The Foundations of Quantum Mechanics – Historical Analysis and Open Questions*, World Scientific, Singapore, pp. 178-185.

Giusti Doran, B., 1975, "Origins and Consolidation of Field Theory in Nineteenth-Century Britain: From the Mechanical to Electromagnetic View of Nature", *Historical Studies in the Physical Sciences*, VI, pp. 133-260.

Hesse, M., 1961, *Forces and Fields*, Nelson and Sons, New York and London.

Holton, G., 1973, *Thematic Origins of Scientific Thought – Kepler to Einstein,* Harvard University Press, Cambridge-Massachusetts.

Holton, G., 1982, "Introduction: Einstein and the Shaping of Our Imagination", in Holton G. and Elkana Y. (eds.) 1997, *Albert Einstein – Historical and Cultural Perspectives*, Dover Publications, New York, pp. vii-xxxii.

Holton, G., 1986, *the Advancement of Science and its Burdens*, Cambridge University Press, Cambridge/ London/ New York.

Jammer, M., 1961, *Concepts of mass in classic and modern physics*, Harvard University Press, Cambridge, Massachusetts.

Klein, M., 1963, "Einstein's First Paper on Quanta", *The Natural Philosopher* 2, pp. 59-86.

Klein, M., 1964, "Einstein and the Wave-Particle Duality", *The Natural Philosopher* 3, pp. 3-49.

Kostro, L., 2000, *Einstein and the Ether*, Apeiron, Montreal.

Kuhn, T.S., 1987, *Black-Body Theory and the Quantum Discontinuity, 1894-1912* (with a new Afterword), The University of Chicago Press, Chicago and London.

Lami, E.O., (ed.) 1881-1891, *Dictionnaire encyclopédique et biographique de l'Industrie et des Arts industrielles 1881-1891*, 9 vols., Librairie des Dictionnaires, Paris.

Larmor, J., 1895, "A Dynamical Theory of the Electric and Luminiferous Medium – part II", *Philosophical Transactions of the Royal Society* 186, pp. 695-742.

Larmor, J., 1897, "A Dynamical Theory of the Electric and Luminiferous Medium – part III: Relations with Material Media", *Philosophical Transactions of the Royal Society* 190, pp. 205-300.

Larmor, J., 1900, *Aether and Matter*, Cambridge University Press, Cambridge.

Larmor, J. 1902, "On the Application of the Method of Entropy to Radiant Energy", *British Association for the Advancement of Science, Report* 1902, p. 546.

Larmor J., 1909, "The Statistical and Thermodynamical Relations of Radiant Energy", *Proceedings of the Royal Society* 83, pp. 82-95.

Laudan, L., 1977, *Progress and its Problems*, University of California Press, Berkeley/ Los Angeles/ London.

Leibniz, G.W., (1714) [online] *La monadologie*. Available online at: http://classiques.uqac.ca/classiques/Leibniz/La_Monadologie/leibniz_monadologie.pdf (accessed 21 December 2009).

Maxwell, J.C., 1875, “Atom”, ninth edition of *Encyclopaedia Britannica*; in Maxwell J.C. 1890, *The scientific papers of James Clerk Maxwell*, (Niven W.D. ed.), vol. 2, pp. 445-84.

McCormmach, R., 1967, “J.J. Thomson and the structure of light”, *British Journal for the History of Science* 3, pp. 362-87.

McCormmach, R., and Jungnickel, C., 1986, *Intellectual Mastery of Nature*, 2 vols., The University nof Chicago Press, Chicago/London.

McGuinness, B., (ed.) 1974, *Ludwig Boltzmann - Theoretical Physics and Philosophical Problems*, D. Reidel Publishing Company, Dordrecht/Boston.

Miller, A.I., 1984, *Imagery in Scientific Thought – Creating 20th-Century Physics*, Birkhäuser, Boston/Basel/Stuttgart.

Millikan, R.A., 1917,*The Electron*, The University of Chicago Press, Chicago.

Millikan, R.A., 1924, “The Electron and the Light-Quant from the Experimental Point of View”, Nobel Lecture, in *Nobel Lectures, Physics 1922-1941*, Elsevier Publishing Company, Amsterdam, 1965, pp. 54-66.

Navarro, J., 2005, “J.J. Thomson on the Nature of Matter: Corpuscles and the Continuum”, *Centaurus* 47, 4, pp. 259-82.

Norton, J.D., 2006, “Atoms, entropy, quanta: Einstein’s miraculous argument of 1905”, *Studies in History and Philosophy of Modern Physics*, 37, pp. 71-100.

Planck M. 1887, *Das Princip der Erhaltung der Energie*, B.G. Teubner, Leipzig.

Planck, M., 1910, “Zur Theorie der Wärmestrahlung”, *Annalen der Physik* 31, pp. 758-68.

Poincaré, H., 1900, “La théorie de Lorentz et le principe de réaction”, in Poincaré H. 1934-1953, *Oeuvres de Henri Poincaré* , Gauthier-Villars, Paris, vol. 9, pp. 464-488.

Poynting, J.H., 1885, “On the connection between Electric Current and the Electric and Magnetic Inductions in the surrounding field”, *Philosophical Transactions of the Royal Society* 176, pp. 277-306.

Renn, J., (ed.) 2006a, *The Genesis of General Relativity*, Springer, Dordrecht.

Renn, J., 2006b, “Classical physics in disarray”, in Renn J. (ed.) 2006a, Vol. 1, pp. 21-80.

Renn, J., and v. Rauchhaupt, U., 2005, "In the Laboratory of Knowledge", in Renn J. (ed.) 2005, *Albert Einstein chief engineer of the universe – One hundred authors for Einsteins,* WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim, and Max Planck Institute for the History of Science, Berlin.

Rogers, H.J., (ed.) 1905, *Congress of Arts and Science, St. Louis 1904*, vol. I, Houghton, Mifflin and C., Boston and New York.

Shapin, S., 2005, "Hyperprofessionalism and the Crisis of Readership in the History of Science", *Isis* 96, pp. 238-43.

Siegel, D.M., 1981, "Thomson, Maxwell, and the universal ether in Victorian physics", in Cantor G.N. and Hodge M.J.S. (eds.) 1981, pp. 239-68.

Stachel, J., 2006, "The first two acts", in Renn J. (ed.) 2006a, Vol. 1, pp. 81-111.

Stuewer, R.H., 2006, "Einstein's Revolutionary Light-Quantum Hypothesis", *Acta Physica Polonica* 37, B 3, pp. 543-58.

Tait, P.G., 1885, *Properties of Matter*, Adam and Charles Black, Edinburgh.

Tarsitani, C., 1983, *Il dilemma onda-corpuscolo*, Loescher, Torino.

Thomson, J.J., 1883, *A Treatise on the motion of Vortex Rings*, MacMillan and Co., London.

Thomson, J.J., 1888, *Applications of dynamics to physics and chemistry*, MacMillan and Co., London/New York.

Thomson, J.J., 1891, "On the Illustration of the Properties of the Electric Field by Means of Tubes of Electrostatic Induction", *Philosophical Magazine* 31, pp. 150-171.

Thomson, J.J., 1893, *Recent Researches in Electricity and Magnetism*, Claredon Press, Oxford.

Thomson, J.J., 1904, *Electricity and matter*, Yale University Press, New Haven.

Thomson, J.J., 1936, *Recollections and Reflections*, G. Bell and Sons, London.

Topper, D.R., 1980, "To Reason by means of Images: J.J. Thomson and the Mechanical Picture of Nature", *Annals of Science*, 37, pp. 31-57.

Warwick, A., 2003, *Masters of Theory – Cambridge and the Rise of Mathematical Physics*, The University of Chicago Press, Chicago/London.

Wheaton, B.R., 1978, "Philipp Lenard and the Photoelectric Effect, 1889-1911", *Historical Studies in the Physical Sciences* 9, pp. 299-322.

Wheaton, B.R., 1983, *The tiger and the shark*, Cambridge University Press, Cambridge/New York/Port Chester.

Note

[1] See Maxwell 1875, in Maxwell 1890, vol. II, pp. 470-1: «In the first place, it is quantitatively permanent, as regards its volume and its strength, - two independent quantities. It is also qualitatively permanent, as regards its degree of implication, whether 'knottedness' on itself or 'linkedness' with other vortex rings. At the same time, it is capable of infinite changes of form, and may execute vibrations of different periods, as we know molecules do.»

[2] Hesse M. 1961, p. 166.

[3] See statements 10, 11, 13, 15, 21, 61 and 69 in Leibniz's *La Monadologie*. For a detailed analysis, see Jammer M. 1961, pp. 76-80.

[4] Tait P.G. 1885, p. v and p. 2.

[5] Tait P.G. 1885, pp. 3-6.

[6] See Poynting J.H. 1885, in particular pp. 277-8, the first footnote of page 277 included.

[7] See Planck M. 1887, pp. 244.

[8] Planck M. 1887, pp. 245: «Nach der Infinitesimaltheorie dagegen kann Energie, wie Materie, nur stetig mit der Zeit ihren Ort verändern. Die in einem geschlossenen Raum befindliche Energie kann vermehrt oder vermindert werden nur durch solche äußere Wirkungen, die durch physikalische Vorgänge in der Grenzfläche des Raumes vermittelt werden, man kann also auch hier von einem Hindurchgehen der Energie durch diese Fläche reden. Dann läßt sich die Energie eines materiellen Systems stets in Elemente zerlegen, deren jedes einem bestimmten materiellen Element zukommt und in diesem ihren Platz findet […]»

[9] Even recently, in a historical survey of the «light-quantum hypothesis, S. Brush pointed out that Planck's 1900 assumption of «an integer number of energy elements was only a mathematical device». Although I agree with Brush and «Kuhn and other historians» on «the evidence that Planck in 1900 did not propose physical quantisation of electromagnetic radiation», I do not find any evidence that Planck actually had previously refused physical concept like «energy elements». Planck's 1887 treatise shows many clues as to his commitment to look for new models for the transfer of energy. That general theoretical commitment is however consistent with his subsequent refusal of Einstein's 1905 specific theoretical model of quantisation. See Brush S. 2007, pp. 212-14.

[10] Poincaré H. 1900, p. 468: «Nous pouvons regarder l'énergie électromagnétique comme un fluide fictive […] qui se déplace dans l'espace conformément aux lois de Poynting. Seulement il faut admettre que ce fluide n'est pas indestructible et que dans l'élément de volume dτ il s'en détruit pendant l'unité de temps une quantité […] ; c'est ce qui empêche que nous puissions assimiler tout à fait dans nos raisonnements notre fluide fictif à un fluide réel.»

[11] I agree with Falconer when he states that J.J. Thomson's «experiments in 1897 were not the origin of the corpuscle hypothesis; instead they acted as a focus around which Thomson synthesized ideas he had previously developed.» (Falconer I. 1987, p. 254) I disagree with Navarro, when he states that J.J. Thomson was «the discoverer of the first discrete subatomic particle», in spite of his faith in «metaphysical continuity of nature». (Navarro J. 2005, p. 277) According to J.J Thomson, continuity was only one of the sides of the coin.

[12] I disagree with Noakes when he states that «Larmor and J.J. Thomson came to represent the different approaches to electrodynamics adopted by the increasingly distinct corps of experimental and mathematical physicists.» (Noakes R. 2005, p. 420)

[13] For the institutional aspects, see McCormmach R. and Jungnickel C. 1986, II vol., pp. 33, 41-3, 48 and 55-6.

[14] See Thomson J.J. 1891, p. 150: «We may regard the method from one point of view as being a kind of molecular theory of electricity, the properties of the electric field being explained as the effects produced by the motion of multitudes of tubes of electrostatic induction; just as in the molecular theory of gases the properties of the gas are explained as the result of the motion of its molecules.»

[15] See Thomson J.J. 1891, p. 151.

[16] See Thomson J.J. 1893, p. 3.

[17] See Thomson J.J. 1893, p. 4.

[18] See Thomson J.J. 1893, p. 4: «Thus, from our point of view, this method of looking at electrical phenomena may be regarded as forming a kind of molecular theory of Electricity, the Faraday tubes taking the place of the molecules in the Kinetic Theory of Gases: the object of the method being to

explain the phenomena of the electric field as due to the motion of these tubes, just as it is the object of the Kinetic Theory of Gases to explain the properties of a gas as due to the motion of its molecules. The tubes also resemble the molecules of a gas in another respect, as we regard them as incapable of destruction or creation.»

[19] I agree with J. Navarro when he stresses J.J. Thomson effort to attain a unified representation of physical and chemical phenomena, but I do not find that the «metaphysics of the continuum» was the unifying element. See Navarro J. 2005, pp. 272-3.

[20] Thomson J.J. 1893, p. 11.

[21] Thomson J.J. 1893, p. 42: If there is no reflection the electromotive intensity and the magnetic force travel with uniform velocity v outwards from the plane of disturbances and always bear a constant ratio to each other. By supposing the number of tubes issuing from the plane source per unit time to vary harmonically we arrive at the conception of a divergent wave as a series of Faraday tubes travelling outwards with the velocity of light. In this case the places of maximum, zero and minimum electromotive intensity will correspond respectively to places of maximum, zero and minimum magnetic force.

[22] Thomson J.J. 1893, p. 43: «This view of the Electromagnetic Theory of Light has some of the characteristics of Newtonian Emission theory; it is not, however, open to the objections to which that theory was liable, as the things emitted are Faraday tubes, having definite positions at right angles to the direction of propagation of the light. With such a structure the light can be polarised, while this could not happen if the things emitted were small symmetrical particles as on the Newtonian Theory.»

[23] For further remarks on J.J. Thomson's theoretical researches between 1891 and 1893, see my forthcoming paper in the journal *Physis*, «J.J. Thomson's Models of Matter and Radiation in the Early 1890s».

[24] See Larmor J. 1894, p. 771.

[25] See Larmor J. 1894, p. 805: «A cardinal feature in the electrical development of the present theory is on the other hand the conception of intrinsic rotational strain constituting electric charge, which can be associated with an atom or with an electric conductor, and which cannot be discharged without rupture of the continuity of the medium. The conception of an unchanging configuration which can exist in the present rotational aether is limited to a vortex-ring with such associated intrinsic strain: this is accordingly our specification of an atom.»

[26] Larmor J. 1894, p. 807.

[27] See Larmor J. 1894, p. 808: «It may be objected that a rapidly revolving system of electrons is effectively a vibrator, and would be subject to intense radiation of its energy. That however does not seem to be the case. We may on the contrary propound the general principle that whenever the motion of any dynamical system is determined by imposed conditions at its boundaries or elsewhere, which are of a steady character, a steady motion of the system will usually correspond, after the preliminary oscillations, if any, have disappeared by radiation or viscosity. A system of electrons moving steadily across the medium, or rotating steadily round a centre, would thus carry a steady configuration of strain along with it; and no radiation will be propagated away except when this steady state of motion is disturbed.»

[28] It is worth mentioning that, since the dawn of natural philosophy, two general conceptions on the link between *macroscopic* and *microscopic* world had been on the stage. On the one hand, the conception of an invisible small-scale structure as a tiny copy of the large-scale world; on the other hand, the conception of an invisible small-scale structure endowed with specific features, following different laws. The main hallmark of ancient atomism was the physical gap between the ordinary, visible world, and the invisible world of atoms: the latter was an *explanation* of the former.

[29] Larmor J. 1894, p. 811. For further remarks on Larmor's theoretical researches between 1894 and 1895, see Bordoni S. 2011, «Beyond Electromagnetic and Mechanical World-views: J. Larmor's Models of Matter and Energy in the Early 1890s», *Centaurus*, 53, 1, pp. 31-54.

[30] A different appraisal can be found in Darrigol O. 2000, pp. 168 and 174. Darrigol claimed that Poynting and J.J. Thomson's theoretical model of electric current as an effect of the convergence and dissolution of tubes of force «preserved a Maxwellian intuition of the electric current». On the contrary, the *electron* Larmor introduced in 1894, represented an alternative to Maxwell's leading theoretical model, as well as *particles* (1892) and *ions* (1895) which Lorentz introduced in the same years.

[31] This was claimed by B. Giusti Doran and D.R. Topper respectively, some decades ago. The title of Topper's 1980 paper «To Reason by means of Images: J.J. Thomson and the Mechanical Picture of Nature», suggests the link between *mechanicism* and *imagery*. I agree with Topper on the statement that J. J. Thomson was committed to «the creation of a unified picture of nature integrating matter, ether, energy, electricity and magnetism». (Topper D.R. 1980, pp. 32, 38 and 40). I cannot agree with the

attempt to insert all *Victorian-age* scientists in the class of a mechanical world-view. On this attempt, see also Siegel D.M. 1981, p. 263. I cannot accept that Larmor's unified view be qualified as «providing the field-theoretic view with an electromagnetic basis». The identification of Larmor's view with an electromagnetic world-view hides its most interesting commitment, namely the attempt to bridge the gap between mechanical explanations and electromagnetic entities. (Giusti Doran B. 1975, pp. 134-6 and 206).

[32] The so-called *empty* space of recent physics is represented as a sea of virtual particles and radiation. In late nineteenth century aether, some dynamical structures gave rise to particles and fields. In general, apart from their specific features, the two models have much in common. See, for instance, Barone M. 2004, p. 1976. See also Cantor G.N. and Hodges M.J.S. 1981b, pp. 53-4.

[33] On the awareness of social advantages brought about by electric technologies, see, for instance, *Dictionnaire encyclopédique et biographique de l'Industrie et des Arts industriels*, *Supplément*, 1891 (Lami E.O. editor), p. 743: «En effet, l'électricité fournissant une lumière pure et fixe, ne chauffant pas et ne viciant pas l'air, constitue non pas un éclairage de luxe, mais un éclairage sain et salubre, et, par conséquent, véritablement de première nécessité. Détrônant le gaz pour cet usage, l'électricité ne le bannira pas de la maison : bien au contraire, elle lui ouvrira tout grand son débouché normal, qu'il n'a jusq'ici envisagé que timidement et comme pis-aller, le chauffage.» On the effects of the widespread telegraphic net, see Galison P. 2003, pp. 174-80.

[34] According to the four criteria for the existence of a *Revolution* in science, established by I. B. Cohen in 1985, we would not be allowed to speak of a revolution. See Cohen I.B. 1982, chapter II.

[35] Boltzmann L. 1905, pp. 592-5.

[36] I find worth mentioning Renn's general interpretation of Einstein's 1905 papers. The hypothesis of light quanta was interpreted as an attempt to solve the problems at the borderline between electromagnetism and thermodynamics. The hypothesis of the equivalence between electromagnetic radiation and inertial mass was interpreted as an attempt to solve the problems at the borderline between mechanics and electromagnetism. See Renn J. and von Rauchhaupt U. 2005, p. 32. See also Renn J. 2006b, p. 43.

[37] «A Differential History» is the title of the third section of Funkenstein's *Introduction*. He claimed that what we look upon as «new», often «consists not in the invention of new categories or new figures of thought, but rather in a surprising employment of existing ones». (Funkenstein A. 1986, p. 14). E. Giannetto has recently remarked that «nature and origins of quantum physics» had meaningful roots in Larmor's theoretical researches. He found that, in Larmor's theory, on the one hand, «electromagnetic field must present wave but also corpuscular aspects to explain the origin of matter»; on the other hand, «matter particles must present corpuscular but also wave aspects as long as they derive from the electromagnetic field». An intrinsic integration between different and complementary models emerged long before the manifold attempts to devise a *Quantum theory*. See Giannetto E. 2007, pp. 178 and 181.

[38] See Miller A.I. 1984, pp. 312. I think that my sketch does justice to the old-fashioned concepts of *forerunner* and *anticipation*. At the level of specific theoretical features of a theory, these concepts make no sense, because specific features are untranslatable. At the level of general conceptual models, we find persistence or recurrent re-emergence of themes or models: therefore nobody can claim to have *anticipated* a long-term tradition.

[39] See Boltzmann L. 1899, in Boltzmann L. 1974, p. 95: «[…] others felt that physics must henceforth pursue the sole aim of writing down for each series of phenomena, without any hypothesis, model or mechanical explanation, equations from which the course of the phenomena can be quantitatively determined; […] This is the most extreme form of phenomenology, which I should like to call mathematical, […]»

[40] See the first pages of Thomson J.J. 1893.

[41] I would like to specify that my historiographical sketch cannot be looked upon as an epistemological framework suitable for the whole history of physics or the whole history of science. It is an interpretative framework concerning theoretical physics in the late nineteenth century and its connections with theoretical physics of the early twentieth century. Although I think that conceptual streams are long-term phenomena, I find that the explicit acknowledgement of their existence, the explicit role they played in scientific practice, and the existence of an explicit debate involving them were specific hallmarks of that historical period.

[42] Laudan L. 1977, p. 72.

[43] Laudan L. 1977, pp. 78-9 and 81-2. Although both a *research tradition* and a *conceptual stream* have «a number of specific theories which exemplify […] it», we can say that those theories «partially constitute it» only with reference to a research tradition. The fact is that conceptual streams are entities less complex than scientific theories, and therefore less complex than research traditions. Both every research tradition and every conceptual stream has undergone «a number of different, detailed […] formulations and generally has a long history». Nevertheless, that those formulations are «often mutually contradictory» makes sense when referred to a complex research tradition, but makes not sense when referred to a simple conceptual stream.

[44] See Laudan L. 1977, pp. 60-62. In general, I do not find that «worldviews difficulties» emerged «traditionally» or «most often» from tensions «between science, on the one hand, and either theology, philosophy or social theory, on the other hand». Conceptual tensions leading to different world-views also emerged within the (fluctuating over time) boundaries of science.

[45] See Holton G. 1973, pp. 11, 13, 29, 51, 57, 99 and 192. That his *themata* were «unverifiable» and «unfalsifiable», even though «not arbitrary», conceptions, was pointed out by Holton even in subsequent years. See Holton G. 1986, p. 53. In 1986 Holton still stressed the «orthogonal» relationship between «*phenomenic propositions*», and «*analytic propositions*», but it is questionable whether something like a pure empirical component or «dimension» can really exist. The three-dimensional Cartesian space envisaged by Holton, and endowed with *phenomenic*, *analytic* and *thematic* axes, is obviously a useful but simplified idealisation. See Holton G. 1986, p. 5 and 18.

[46] See Hesse M. 1961, p. 293.

[47] See, for instance, Holton G. 1982, p. xxvii, and Holton G. 1986, p. 15.

[48] See Holton G. 1973, p. 61. On the persistence of general themes, and the variability of their specific implementation, see, for instance, Tarsitani C. 1983, p. 15.

[49] See D'Agostino S. 2000, p. 409: «In contrast to the mutation of physical concepts, there is a striking permanence in the mathematical structure of physics, that is, in the form in which physical laws are represented by mathematical equations. […] This asymmetric behaviour in the mathematical and physical structures of theories is prominent in the historical development of physics. Against the mutation of conceptual structures as a product of cultural evolution, mathematics thus can be taken as one of these 'artifacts' that, according to Jürgen Renn, are transmitted from one generation to the next and guarantee continuity in the development of science.»

[50] On the *historicity* of every historiographical framework and every *epistemology*, see Tarsitani C. 1983, p. 25.

[51] In the 1980s, Buchwald saw a conceptual overturn in the passage from late nineteenth century electromagnetic theories to twentieth century *quantum* theories, whereas I see both elements of continuity and discontinuity. See Buchwald J.Z. 1985, p. 41.

[52] The so-called community of *Maxwellians* was not at ease with the most successful interpretations of *Relativity* theory and *Quantum* theory. See Warwick A. 2003, chapters 7 and 8.

[53] In the subsequent years, the role of meta-theoretical debates became less and less important in theoretical physics. I find that, in the last decades of the twentieth century, theoretical physics has suffered a sort of *formalistic drift*, corresponding to an analogous and more general formalistic drift in physics training. I am indebted to B. Bertotti for informal talks on this subject.

[54] The deep conceptual links among electrodynamics, inertia of energy and light *quanta* in Einstein's 1905 papers were pointed out by M. Klein some decades ago. See Klein M. 1964, p. 6. More recently, B.R. Wheaton claimed that an «integral part of Einstein's rejection of the medium for light waves was his suggestion of the lightquantum hypothesis». See Wheaton B.R. 1983, p. 106.

[55] On 18 Mars 1905, the journal *Annalen der Physik* received the paper «Über einen die Erzeugung und Verwandlung des Lichtes betreffenden heuristischen Gesichtpunkt» the young Einstein had sent the day before. The paper, then published in the *Annalen*, put forward a new interpretation of the generation and transformation of light. On 30 June the *Annalen* received the paper «Zur Elektrodynamik bewegter Körper», which correspond to what we now call Special Theory of Relativity. On 27 September, the short paper on the inertia of energy, «Ist die Trägheit eines Körpers von seinem Energieinhalt abhängig?», was received.

[56] See Einstein A. 1905c, p. 641: «Gibt ein Körper die Energie L in Form von Strahlung ab, so verkleinert sich seine Masse um L/V^2. Hierbei ist es offenbar unwesentlich, dass die dem Körper entzogene Energie gerade in Energie der Strahlung übergeht, so dass wir zu der allgemeineren Folgerung geführt werden: die Masse eines Körpers ist ein Maß für dessen Energieinhalt; […]»

[57] Larmor J. 1895, pp. 695, 697 and 706.

[58] See Giusti Doran B. 1975, p. 258. Miller quoted a letter sent from Einstein to Lorentz on June 1916, where Einstein, for the first time, took into account a new kind of aether consistent with his General Relativity. Other conceptual developments can be found in a subsequent paper published in 1918, «Dialog über Einwände gegen die Relativitätstheorie». See Miller A.I. 1984, p. 55. There were some changes in Einstein's theoretical attitude towards aether, in the course of his scientific career. For a wide discussion on the nature of Einstein's *aether*, see chapter 5 of Kostro L. 2000. In particular, on the words «aether», «physical space» and «field», or «total field», in Einstein's papers published from 1918 to 1955, see pp. 184-5.

[59] Larmor J. 1897, pp. 207 and 215.

[60] Larmor J. 1900, «Preface», pp. vi-vii. Larmor thought that all theoretical models were provisional and not complete, and he guarded against the pursuit of «the impossible task of reducing once for all the whole complex of physical activity to rule». See pp. x, xiv and xv.

[61] Larmor J. 1900, pp. 23-24. Larmor traced back his general model to recent and less recent traditions of Natural Philosophy. At the dawn of modern science, «the ideal towards which Descartes was striving», namely the identification of matter with space, appeared to Larmor an instance of a long-lasting conceptual stream. He found that W. Thomson had implemented «on a precise scientific basis» Descartes' ideal, having put forward a theory connecting matter to aether.

[62] Larmor J. 1900, pp. 26 and 86.

[63] Einstein A. 1920, in Janssen M., Schulmann R., Illy J., Lehner C., and Kormos Buchwald D. (eds.) 2002, pp. 165-7.

[64] Einstein A. 1920, in Janssen M., Schulmann R., Illy J., Lehner C., and Kormos Buchwald D. (eds.) 2002, pp. 171-4. According to Einstein's view, there is not an *empty* space but a *physical* space whose nature is specified by electromagnetic or gravitational fields. In this sense, we can imagine an aether, which can be identified with that physical space: such an aether could not be conceived as a specific reference frame. See, for instance, Einstein A. 1953, p. XVII: «[…] there is no space without a field.»

[65] Einstein A. 1912, in M.J., Kox A.J., Renn J. and Schulmann R. (eds.) 1995, p. 177. See the quotation and J. Stachel's remarks in Stachel J. 2006, pp. 90-1. See also Einstein A. 1949, in Einstein A. 1951, p. 29.

[66] Einstein A. 1920, in Janssen M., Schulmann R., Illy J., Lehner C., and Kormos Buchwald D. (eds.) 2002, p. 177. See Renn J. 2006b, p. 40, footnote 36: «The observation that the assumption of the aether being immobile amounts to the assignment of a mechanical property is due to Einstein, […]»

[67] Einstein A. 1920, Janssen M., Schulmann R., Illy J., Lehner C., and Kormos Buchwald D. (eds.) 2002, pp. 176-80.

[68] Giusti Doran B. 1975, p. 256.

[69] In many essays Boltzmann stressed subjective and historical aspects of physical models and physical world-views. He, for instance, qualified the choice between atomism and energetics as «a matter of taste». In another essay he repeated that «[a]ll our ideas are subjective». Then he focused on the intrinsic, historical nature of «theoretical physics» and «all branches of man's intellectual activity». See Boltzmann L. 1974, pp. 36, 41 and 79. Miller noted the difference between Hertz's trust in the laws of thought «in the Kantian sense», and Boltzmann's more dynamic and plastic representation of conceptual models evolving «in the Darwinian sense». See Miller A.I. 1984, pp. 48, 49 and 51.

[70] Miller A.I. 1984, pp. 51, 82 and 87. It is worth mentioning also Einstein's subsequent self-criticism about *rod* and *clocks*: «[…] strictly speaking measuring rods and clocks would have to be represented as solutions of the basic equations […], not, as it were, as theoretically self-sufficient entities.» (Einstein A. 1949, in Einstein A. 1951, p. 59)

[71] See Einstein A. 1905a, p. 132: «Zwischen den theoretischen Vorstellungen, welche sich die Physiker über die Gase und andere ponderable Körper gebildet haben, und der Maschwellschen Theorie der elektromagnetischen Prozesse im sogennanten leeren Raume besteht ein tiefgreifender formaler Unterschied [...] Nach der Maxwellschen Theorie ist bei allein rein elektromagnetischen Erscheinung, also auch beim Licht, die Energie als kontinuierliche Raumfunktion aufzufassen, während die Energie eines ponderabeln Körpers nach der gegenwärtigen Auffassung der Physiker als eine über die Atome und Elektronen erstreckte Summe darzustellen ist. [...] Nach der hier ins Auge zu fassenden Annahme ist bei Ausbreitung eines von einem Punkte ausgehenden Lichtstrahles die Energie nicht kontinuierlich auf größer und größer werdende Räume verteilt, sondern es besteht dieselbe aus einer endlichen Zahl von in

Raumpunkten lokalisierten Energiequanten, welche sich bewegen, ohne sich zu teilen und nur als Ganze absorbiert und erzeugt werden können.»

[72] Some decades ago, M. Klein pointed out that Hertz's discovery of such an effect was one of the «most ironic turns» in the history of physics: just when Hertz was corroborating the existence of Maxwell's electromagnetic waves, he found an effect «impossible to understand on the basis of Maxwell's theory». (Klein M. 1963, pp. 76-7) At that time, the effect was really difficult to understand in the context of Maxwell's electromagnetic theory: Lenard put forward an explanation, which had more success than Einstein's hypothesis. It should be remarked that, in 1905, the scientific community did not see a meaningful link between the photoelectric effect and the structure of light. See Wheaton B.R. 1978, p. 300.

[73] Thomson J.J. 1904, pp. 63-4.

[74] Thomson J.J. 1904, pp. 63 and 65.

[75] The latter integration can be considered as the keystone of the second part of Einstein's paper: he showed that the dependence of entropy from volume, in the case of low-density and low-temperature monochromatic radiation, followed the law good for perfect gases or dilute solutions. See Einstein A. 1905a, pp. 139-43.

[76] See McCormmach R. 1967, p. 387. McCormmach reported J.J. Thomson's personal to subsequent developments of Quantum Physics. According to McCormmach, J.J. Thomson was committed to show that «Faraday's lines of force and Newtonian mechanics were sufficient to account for all the results of the quantum theory of light». (p. 385) The last pages of the autobiography J.J. Thomson published in 1936 are consistent with McCormmach's remarks. See Thomson J.J. 1936, pp. 431-33.

[77] A recent historical survey of Einstein's 1905 paper on light *quanta* begins with the sharp sentence: «Einstein was the first to propose that light behaves in some circumstances as if it consists of localized units, or quanta». Einstein's approach is compared to Planck's approach but any reference to J.J. Thomson's 1904 booklet or previous texts is missing. See Cassidy D.C. 2005, pp. 15 and 17. In a detailed and authoritative paper, J. Norton made subtle remarks on the model of *quanta* put forward by Einstein, in particular on queries concerning volume fluctuations, isothermal transformations and variability of the number of *quanta*. Nevertheless, in his «Introduction», he claimed that, differently from «special relativity and the inertia of energy», which he looked upon as «a fulfilment of the 19th century tradition in electrodynamics», Einstein's hypothesis of «spatially localized quanta of energy – stands in direct contradiction with that most perfect product of 19th century science». See Norton J.D. 2006, p. 72. The reason for this narrowing of historical perspectives can perhaps be found in what Shapin recently called «Hyperprofessionalism», namely a phenomenon involving «a narrowing of intellectual focus.» Historians are probably frightened of the phantom of the old-fashioned, «big picture» history of science. See Shapin S. 2005, p. 238 and 241.

[78] See Planck M. 1910, p. 761: «Am radikalsten verfährt hier von den englischen Physikern J.J. Thomson, auch Larmor, von den deutschen Physikern A. Einstein und mit ihm J. Stark. Dieselben neigen zu der Ansicht, daß sogar die elektrodynamische Vorgänge im reinen Vakuum, also auch Lichtwellen, nicht stetig verlaufen, sondern nach diskreten Quanten von der Größe $h\nu$, den ‚Lichtquanten', wobei ν die Schwingungszahl bedeutet.» See Einstein A. 1909, pp. 188-190.

[79] See Larmor J. 1909, p. 91. He reminded the reader that in 1902 he had already published a very brief *Report* (eleven lines), «in which it was essayed to replace Planck's statistics of bipolar vibrators by statistics of elements of radiant disturbance.» (Larmor 1909, pp. 86-8 and 91) See Larmor J. 1902 p. 546: «[…] various difficulties attending this [namely Planck's] procedure are evaded, and the same result attained, by discarding the vibrators and considering the random distribution of the permanent element of the radiation itself, among the differential elements of volume of the enclosure, somewhat on the analogy of the Newtonian corpuscular theory of optics.» For some remarks on Larmor's papers and their diffusion, see Kuhn T.S. 1987, pp. 136-7 and 314.

[80] See Planck M. 1910, pp. 763-4 and 767-8.

[81] See Millikan R.A. 1917, pp. 217-9. After having reported four reasons in favour of «the ether or wave theory» of light, he regretted that «a group of extreme advocates of the relativity theory» had recently expressed «some opposition of a rather ill-considered sort». Nevertheless, Millikan thought that *Relativity* theory, as it was «commonly regarded», had «no bearing whatever upon the question of the existence or non-existence of a luminiferous ether». He claimed that aether was the «carrier for electromagnetic waves, and it obviously stands or falls with the existence of such waves *in vacuo*». It seemed to him that «this has never been questioned by anyone so far as I am aware».

ISSN 2037-4348 | Settembre 2011 | pp. 1-44

[82] Millikan R.A. 1917, pp. 221-3. Einstein's «lokalisierten Energiequanten» appeared to Millikan nothing more than a specific feature of J.J. Thomson's *fibrous aether*. In eight pages (from p. 231 to p. 238), there are eight occurrences of expressions like «Thomson-Einstein theory», «Thomson-Einstein hypothesis of localized energy», «Thomson-Einstein theory of localized energy», «Thomson-Einstein assumption of bundles of localized energy travelling through the ether», or eventually «Thomson-Einstein semi-corpuscular theory».

[83] Millikan R.A. 1917, pp. 234-7.

[84] Millikan R.A. 1924, pp. 61-65. Once again he only saw two alternatives: either «the mechanism of interaction between ether waves and electrons has its seat in the unknown conditions and laws existing within the atom», or such a *mechanism* «is to be looked for primarily in the essentially corpuscular Thomson-Planck-Einstein conception as to the nature of the radiant energy ».

[85] R. Stuewer pointed out two elements. First, «Millikan, in common with almost all physicists at the time, rejected Einstein's light quantum hypothesis as an interpretation of his photoelectric-effect experiments of 1915». Second, Millikan himself, in his Autobiography, published in 1950, revised his appraisal and stated that the phenomenon «scarcely permits of any other interpretation than that which Einstein had originally suggested». Stuewer qualified that sharp change as an instance of «revisionist history». On this issue, and on the attitudes of the scientific community towards Einstein's hypothesis in the 1910s, see Stuewer R.H. 2006, pp. 543-8.

[86] Thomson J.J. 1936, p. 410.

[87] Thomson J.J. 1936, pp. 431-33. Thomson claimed that, although Einstein had made «no mention of an ether but a great deal about space», if space has a physical meaning, then it «must have much the same properties as we ascribe to the ether». In other words, space cannot be a mere geometrical entity but «must therefore have a structure». With regard to the concept of time, he remarked that «there must be in space something which changes», in order «to distinguish one instant from another»; on the contrary, there would be «nothing to supply a *clock*». With regard to mass, he started from the fact that «the mass of a body increases as the velocity increases»: as a consequence, «if the mass does not come from space it must be created».

The scientific revolution began with Nicolaus Copernicus' (1473-1543) heliocentric theory and the rediscovery of ancient Greek atomism in the fifteenth and sixteenth centuries. But it was not until the end of the seventeenth century, after Isaac Newton's (1643-1727) work, that it was clear to educated people in Europe that a full-blown scientific revolution had occurred. What were the main ideas of the scientific revolution? Some of the key ideas and theories that came out of the scientific revolution were that Earth revolves around the Sun, matter is composed of small particles, eve