This chapter is the provisional draft of chapter 7 of the book project I submitted to your attention. Alterations are expected because of its connection with conceptual and historical issues to be fully articulated in chapters that I expect to come before this one. I expect these alterations to impact mostly on sections 7.0 and 7.

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Chapter 7. Problems of electrodynamics. A special relativistic interlude

7.0 Introduction

The preceding chapter has presented the analysis of a scientific achievement that was momentous in various senses. The explanation of the Zeeman Effect is a genuinely predictive result provided by Lorentz's Theory of Electrons (LTE). LTE is a sophisticated attempt to marry classical mechanics and Maxwell's electromagnetism. It treats electromagnetic phenomena as results of the dynamics of charged particle of subatomic size in the ether[1]. LTE was an eminent part of a research program aiming at a grand unification through a fundamental theory of electricity, light, magnetism and matter[2]. Zeeman's experiment, the first successful detection of an effect of interference of a magnetic field on a source of light, constituted a genuinely novel confirmation of LTE and, hence, of that research program. The experimental set up consisted of a source of polarized light placed in a strong magnetic field. A split was observed in the spectral lines of the emitted light and also very accurate measurements of their width were obtained. Lorentz's framework explained the splitting as a precession in the period of oscillation of a charged particle of a given size. The role of the size was indirectly captured by the mass to charge ratio on which the formal machinery depended. Through the measurements of the width of the spectral lines and the correlation that the theory established between them and the frequency of light Zeeman was able to provide the first accurate value of the charge to mass ratio of the charged particle (later deemed electron). This value was confirmed by the early reproductions of the experiment by Lodge and Preston and, indirectly, by Thompson's independent research on cathode rays that, just few months later, provided the value of the mass to charge ratio. (Arabatzis 2006, 93) Finally, Zeeman's experiment brought out just one instance of a class of phenomena of interference between light and magnetism that found a complete treatment only in the quantum framework after the introduction of the spinning electron[3].

7.1 Comparing Lorentz's Theory of Electron with Relativistic Electrodynamics. Historiographical considerations

This chapter main aim is to highlight the theoretical assumptions developed in the successful circumstances just summarised and that seem to find complete application in the successive history of the investigation of the Zeeman Effect (and in other magneto-optical phenomena that will be considered later). As we have seen in the previous chapter, considerations regarding the size of the charged particle were crucial for Lorentz to even begin to consider the possibility of a phenomenon of the kind investigated by Zeeman. Lorentz was expecting to be able to place at the core of his theory the electrolytic ion. The ion of the electrolysis was supposed to be the charged particle responsible for the vibrations producing electric and magnetic perturbation in the ether and light waves. Now if the source of light was as small as an electrolytic ion it was conceivable that the force acted on it by a strong magnetic field was intense enough to alter the period of its oscillations enough to produce the interference that Zeeman was after. As we have seen the size of the corpuscle plays a direct role in the derivation where it features indirectly as the ration between charge and mass. We will see that in LTE this feature needs to be associated with the idea that the corpuscle is an extended body. This specific theoretical feature will be lost in quantum mechanical treatments of these phenomena and in theoretical developments concerning the electron in general. It is my contention that the loss of this feature does not occur in the quantum domain and has its origin both in a failure of LTE to deliver a credible model of an extended electron and in the prohibition that Relativistic Electrodynamics (REL) imposes on the possibility itself to have and extended charged particle. This point relates directly to the aim of exploring what conceptual resources of the classical domain are left over for the successive quantum theorisation to exploit and requires an appropriate investigation of the similarities and differences between LTE and REL. In order to effect this comparison, I leave aside any further reference to the derivation of the Zeeman Effect coming back to some details just by the end. Rather, I concentrate on isolating those theoretical factors that were more directly relevant to the nature of the charged particles in LTE and in REL as they historically emerged. To summarise the narrative structure of the chapter is articulate in two tasks: i) I indicate in what sense LTE is profoundly different from its relativistic successor; ii) I will show that the property of being an extended body is indispensable to the electrons of Lorentz theory. In order to fulfil those tasks, firstly, I will analyse the *theorem of corresponding states.* It[4] characterizes and reveals the whole physical conception underlying the theory and leaves open problems that make it indispensable for the theory to postulate an extended electron. Lorentz obtained a first partial version of the theorem in the *Versuch* of 1895[5]: the Zeeman Effect was predicted at the end of 1896 through an application of the theory presented in the *Versuch*. I will consider the two versions of the theorem that Lorentz provided with respect to their relation to the Lorentz-Fitzgerald contraction hypothesis. Among the other things, this strategy will show that the result was grounded in a physical reading profoundly different from the relativistic one.

The differences between the two theories are frequently overlooked by historians precisely with regard to those features that are concerned with the conception of mass and structure of electrons. Those are precisely the features are most significant for the present project. Partly, the overlooking I am referring to is due to the formal similarities and the current "relativistic naturalness" with which we conceive of certain processes[6]. In this sense, perhaps this chapter can be, marginally, intended also as taking a position in the historical debate concerning the nature of the relationships between LTE and REL and the exact meaning of the Lorentz-Fitzgerald contraction hypothesis. More importantly, the analysis of the Lorentz-Fitzgerald contraction hypothesis will naturally lead us to reconsider -as Lorentz actually did- the related notions of mass and structure of the electron. These are two notions involved in the prediction of the Zeeman Effect and also associated with the change introduced by the relativistic picture.

7.2 Corresponding states vs Lorentz' invariance

Lorentz's Theory of electrons (LTE) is, as mentioned above, since its initial 1892 formulation, a large project aiming to put together Newtonian Mechanics and Maxwell Electromagnetism. LTE is meant to provide a unified picture of matter, light and magnetism (Buchwald 1985; McCormach 1970 a and b). The successive formulations until its mature final version of 1905 never alter this program and the combination of concepts on which the program is grounded. The model of material interactions is provided by Newtonian Mechanics, the framework that also contributed the conception of space and time. Put in simple terms, matter in LTE behaves as prescribed by Newtonian laws, moving in a three-dimensional space in which time is equal in all systems of reference. On the other hand, LTE sees optical and magnetic phenomena as governed by Maxwell laws for electric and magnetic fields. The distinction in the laws corresponds to a dualism in the ontology and a division in the picture of natural phenomena.

The framework put forward by Lorentz in 1892, analysed in the previous chapter, embodies precisely this split in the conception of the forces of nature[7]. Electric and magnetic fields, governed by Maxwell's laws, are conceived of as states of the Ether. Ether and matter do not interact otherwise than through the action of charged particles[8]. The electromagnetic interactions occur to material bodies through charged particles. Charged particles generate fields in the Ether and those fields act in turn on matter via the particles of which matter is made. The combination of electromagnetic ether and Newtonian granular conception of matter determines the conceptual resources used by this theory for the analysis of electricity, magnetism, light and matter. It also characterizes the sort of results — such as the Lorentz transformations, for instance, or the velocity-dependence of mass — that the theory delivers to successive science. The endeavour of reconciling those two sorts of physical processes by treating them as depending solely on the dynamics of charged particles, as well as the effort to account for some important phenomenologies, contributed to yielding such enduring results.

7.2.1 Null results of the attempts to detect the ether

LTE borrows its conception of space and time from Classical Mechanics. This means that physical processes are meant to take place in a geometrically Euclidean scenario in which time is (allegedly) equal for all systems of reference in inertial motion. Such a choice presents Lorentz with a conceptual puzzle: how can Classical Mechanics and Maxwellian Electromagnetism be compatible? We could say that the problem is that Maxwell's laws are not Galilean invariant[9]. Nonetheless, Lorentz is not bothered by a problem of (lack of) invariance at all. In 1895, LTE approaches the issue from a different perspective. As long as Maxwellian ideas are accepted the issue is the behaviour of the Ether with respect to ordinary matter. The answer is that the Ether is *at rest* and it permeates perfectly all material bodies[10] (Lorentz, 1895). It is, therefore, not surprising that Maxwell's equations do not hold for systems of reference in motion within the Ether because, as noticed above, Maxwell's equations describe the configurations of the states of the Ether, the electric and magnetic fields. Fields are conceived as the states of something at absolute rest. Here we can count a first element of divergence with the post-relativistic perspective. Fields are not part of the fundamental ontology of LTE whose dualistic ontology treats fields as properties or states of the Ether. Interestingly, the REL picture of electromagnetic phenomena is essentially field-based but in REL electric and magnetic fields are not fundamental either. With Special Relativistic kinematics in place the electromagnetic field is introduced, represented by a tensor, as the entity responsible for electromagnetic interactions. Electric and magnetic fields are frame dependent manifestations of the electromagnetic field[11].

When an ensemble of material objects apt for the detection of optical phenomena moves through the ether it *does not* detect the same states of the ether that would occur if the system were at rest. With motion the physical situation changes so the states of the Ether change. In this view, Maxwell's equations are *not* expected to be invariant for change of frame of reference. Such sort of relativity was thought at the time to be inapplicable to something like a field that is meant to be an intrinsic state of the Ether. For most of the Ether theorists to seek for an invariance of the frame of reference for electric (magnetic) fields would have been similar to searching for the invariance of the atomic number of an element (Rynasiewicz, 1988). In 1895 Lorentz was one of them. So the non-Galilean invariant equations describe variations that actually take place. Such a situation is perfectly coherent at least with the conception of the stationary Ether. It is coherent but it is highly problematic since every attempt to detect by means of optical experiments variations in the state of the medium when a system moves through it had failed. Such attempts would have shown the existence of the medium. Consequently, the existence of the luminiferous Ether was still far from being experimentally confirmed. This was, of course, a situation that was highly unsatisfactory. Perhaps surprisingly, it was not unsatisfactory in the sense of casting doubts about the existence of the medium[12]. Ether theorists were instead concerned with the divergence between the experimental results and the theoretical expectations. In a nutshell, various experiments, on which I will provide a few details shortly, should have shown some effect on the light patterns associated with the motion of the apparatus through the Ether, the so called Ether drift. Such experiments were consistently giving no result. With a strongly phenomenological approach Lorentz set out the theory of electrons first of all to respond to those results.

So, what problems were keeping in turmoil the best optical research of the time? The results in question are of two kinds. They are referred to in the literature as experiments of the order of precision v/c and as experiments of the order of precision v^2/c^2, where v is supposed to be the velocity of the system with respect to the Ether and c is, of course, the velocity of light. Measures of the differences between optical phenomena at rest and optical phenomena measured in motion with respect to the Ether of the order of v^2/c^2 allow for the detection of very small variations and, of course, are more accurate than the others[13]. To mention a few historical samples, Fizeau's experiment with light beams in different media, or Arago's refraction experiments are of the first type; Michelson & Morley interferometer-based experiment is of the second type. It is worth noticing that by 1895 the genuinely troubling results were only the ones of second order. The first order cases were explicable in any framework in which Fresnel's Ether drag coefficient was derivable. The problem facing Lorentz with respect to this first sort of result was purely theoretical: he had to derive the dragging coefficient whilst denying the physical premise on which it was grounded. Lorentz, as we have seen, had assumed the Ether was at absolute rest, so he was denying that there was anything dragged. The 1895 version of LTE accounted for the first order results making also room for the explanation of the second order ones at the condition of implementing an extra premise.

Here is a simple instance of a situation in which, following the classical wave theory, we should expect interference in the light patterns due to the motion of the system. Suppose we have a refracting telescope with which we aim to determine the position of a star. We point the telescope to a star and the light emitted strikes the surface of the glass lens at the top of the telescope and gets refracted to the bottom where we see it. In any – classical – version of the wave theory of light postulating a stationary medium, this is unproblematic only if the telescope is at rest in the Ether. Nevertheless if, as it happens when we study the position of a star in an observatory on the earth, the telescope is allegedly in motion through the Ether, then, since light strikes the glass perpendicularly the effect of the motion as implemented in the ordinary laws of refraction – the Snell laws – should interfere with the refraction determining a change in focus. The change can be calculated in the order of v/c, and, to put it simply, the telescope should not work as it ordinary does![14] In the theory of 1895 Lorentz set out to explain the cancellation of that first order effect of the motion through the Ether and presented a sophisticated attack on the genuine conundrum of the Ether theories: the Michelson & Morley experiment.

Before getting down to business and showing in detail where LTE and REL diverge profoundly in the underlying conception of the physical world, it will help to give a brief sketch of the Michelson & Morley's experiment. The basic idea of the experiment can be summarized as follows. In front of a light source is placed with an appropriate angle a beam splitter (bs), i.e. a surface that has the property to partly reflect and partly transmit light. The light source sits at one end of an arm at the other end of which is placed a mirror (m_1) so that the bs is between the other two devices. A second arm fixed at right angles with the first has a second mirror (m_2) at one extreme and a telescope at the other.

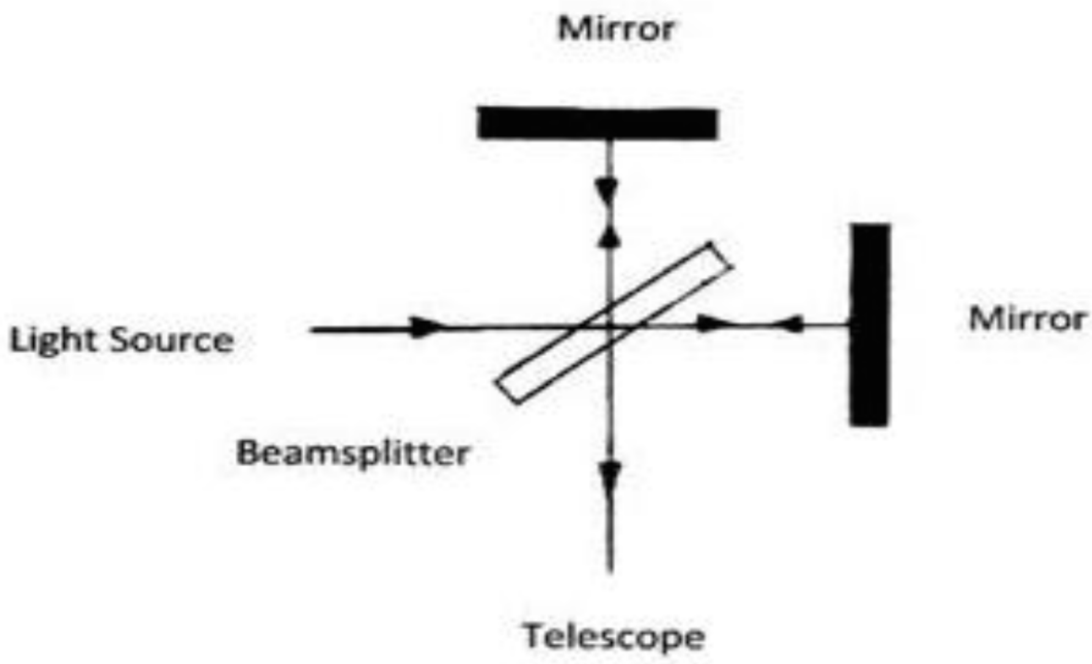

Fig 1. Scheme of the Michelson and Morley interferometer and relative experiment[15]

The light beam travels from the source to the beam splitter where it is split in two beams. The two beams at this point travel back and forward one on each arm of the interferometer respectively between bs and m_1 and between bs and m_2. The two beams are reunited in bs and reflected to the telescope where their interference patterns are detected. Suppose that in virtue of the motion through the Ether the system experiences an Ether drift of velocity *v*. The experimental set up is arranged in such a way that it can be rotated and one of the two arms can always be placed in a position parallel to the motion whereas the other will be, of course, perpendicular to it. A calculation of the velocities of the two beams has to take into account the velocity of the Ether that affects the beam travelling parallel to it but not the one travelling perpendicularly to it. The straightforward result is that the former beam should be slower than the latter by a factor of the order of v^2/c^2. Given the fact that the two arms of the interferometer are of the same length, the result can be seen as a time dilation due to the effect of the Ether drift. The mentioned dilation should be detected as a shift in the interference patterns seen through the telescope. None of the repeated and increasingly accurate experiments performed since 1881 had ever shown any shift. These are the null results that Lorentz had set to account for. It is worth noticing that the actual experiments were more complicated and further details will be provided before introducing the response to the null result that we find in LTE. What follows is the response of LTE to these results.

7.2.2 The response in terms of corresponding states and its physical meaning

In the *Versuch,* LTE is presented as a partial solution to this problem: in particular the theory accounted for optical experiments with a degree of precision of first order in the ratio between the velocity of the system and the velocity of light. We will see that the physical (and mathematical) reasoning underlying that solution reveals the distance between Lorentz's views and Special Relativity and also helps to understand why the electron had to be an extended structure. In the following I present in an updated notation the result as it is presented in the *Versuch*[16].

Consider the source free Maxwell's equations

(1)

$$\nabla^0 \circ \boldsymbol{E} = 0$$

$$\nabla^0 \circ \boldsymbol{H} = 0$$

$$\nabla^0 \times \boldsymbol{E} = -\frac{1}{c}\frac{\partial \boldsymbol{H}}{\partial t_0}$$

$$\nabla^0 \times \boldsymbol{H} = \frac{1}{c}\frac{\partial \boldsymbol{E}}{\partial t_0}$$

The equations in this form describe the behaviour of electric and magnetic fields for a system S_0 at rest in the Ether. As indicated above, the electric field ***E*** and the magnetic field ***H*** are conceived as states of Ether and of course are functions of x_0, y_0, z_0 and t_0. Notice that for the sake of mathematical accuracy here t with respect to S_0 is indicated with t_0 but in LTE there is one time only equal for all system of reference as in Newtonian Mechanics. Lets now proceed to consider the solutions for a system S_m in uniform motion through the Ether along the direction x. Lorentz attacks the problem as follows. Consider the coordinate substitutions below:

a) $x' = x - vt$
b) $y' = y$
c) $z' = z$
d) $t' = t - (v/c^2)x' = (1 + v^2/c^2)t - (v/c^2)x$

and the following substitutions for the field variables:

e) $\boldsymbol{E}' = \boldsymbol{E} + (\text{v}/\text{c})\,(\vec{\text{x}}\times\boldsymbol{H})$

f) $\boldsymbol{H}' = \boldsymbol{H} + (v/c)(\vec{\boldsymbol{x}}\times\boldsymbol{E})$

If second order terms are ignored the substituted quantities E' and H' obey exactly the Maxwell's equations:

(2)

$$\nabla^1 \circ \boldsymbol{E^1} = 0$$

$$\nabla^1 \circ \boldsymbol{H^1} = 0$$

$$\nabla^1 \times \boldsymbol{E^1} = -\frac{1}{c}\frac{\partial \boldsymbol{H}}{\partial t_0}$$

$$\nabla^1 \times \boldsymbol{H^1} = \frac{1}{c}\frac{\partial \boldsymbol{E}}{\partial t_0}$$

Put in anachronistic terms, Lorentz found a first order approximation of the invariance equations that are named after him. There are good reasons to consider this anachronistic comment a misleading interpretative criterion. Notice that Lorentz's main target with this result was not to provide transformations for Maxwell's equations – where transformations are intended in the sense in which Galilean transformations are transformations for Classical Mechanics. This is not a procedure aiming to show in what sense Maxwell's laws are the same in every inertial system. Rather, LTE accounts for the null experimental results presented above, in particular the null results of optical experiments with an order of accuracy for values of the velocities of the moving system of the order of v/c. Thus, because of his purely explanatory perspective, Lorentz could ignore the second order terms in the resulting equations and exploit a mathematical property highlighted by his procedure. Precisely, the above mentioned stipulations introduce two functions of x', y', z', t' namely $\boldsymbol{E'}$ and $\boldsymbol{H'}$, that are for those variables the same functions that $\boldsymbol{E}$ and $\boldsymbol{H}$ are of x_0, y_0, z_0, t_0.

What does this tell us about the system in motion? In Lorentz's own words the core of the Corresponding States theorem is as follows:

"If for a system of stationary bodies, the fields ***E*** and ***H*** are dynamically possible, then, in the case in which the system of bodies undergoes a uniform translation v, there is a dynamically possible field such that ***E*** ' and ***H*** ' are exactly the same functions of x', y', z' and t' that ***E*** and ***H*** are of *x, y, z*, and *t*." (Lorentz, 1895; translated in Rynasiewicz 1988, p 69).

So how do we know what is happening in the system in motion S_m ? First we write the equations of the fields for the system in motion. In such equations we introduce the terms that represent the motion of S_m with velocity v with respect to S_0, the space structure is the Euclidean one, so for Lorentz the two systems are related by the usual Galilean relations:

g) $x = x^0 - vt^0$
h) $t = t^0$

The equations so obtained, of course, are not Maxwell's equations:

(3)

$$\nabla_m \circ \boldsymbol{E_m} = 0$$

$$\nabla_m \circ \boldsymbol{H_m} = 0$$

$$\nabla_m \times \boldsymbol{E_m} = -\frac{1}{c}\frac{\partial \boldsymbol{H_m}}{\partial t} + \frac{\partial \boldsymbol{H_m}}{dx}$$

$$\nabla_m \times \boldsymbol{H_m} = \frac{1}{c^2}\left(\frac{\partial \boldsymbol{E_m}}{\partial t} - v\,\frac{\partial \boldsymbol{E_m}}{\partial x}\right)$$

Making use of stipulations (e) and (f) we can define:

i) $E'_m =_{df} E_m + (v/c)(\vec{v}\times H)$
j) $H'_m =_{df} H_m + (v/c)(\vec{v}\times E)$

Given what is established in (2) for the primed quantities we can now exploit definitions (i) and (j) to calculate through Maxwell's equations the fields of the moving system. More precisely, we have found the states of the Ether for the system S_m *corresponding* to those of S_0. In a nutshell, we could say that Lorentz's approach is to explain away the divergence between the equations for the system in motion and those for the system at rest in two steps: first, both sets of equations are correct and they both represent correctly what happens; second, from a physical perspective, there appears to be a coincidence: certain states of the system in motion correspond to the states of the system at rest. Such states are what is usually detected in our optical experiments. In this way Maxwell's equations are correctly predicting an alteration in the states of the Ether but thanks to the new set of solutions they are also capturing the null results. So there is motion thorough the Ether but the detection of such motion is affected by this correspondence of states.

It is worth to notice few more details that make Lorentz's approach indeed *non-relativistic*. Firstly, notice that Lorentz treats t', *Orseitz*, - "local time"- as a calculation device. Lorentz never attaches to this magnitude any physical meaning. He does not refer to it as a coordinate transformation suggesting that local time can be the time measured by an observer in uniform motion with the system. Lorentz's conception of time is Newtonian, so for him there is only one "true" time and it is the one we denoted by t_0[17]. A further point is semantic: 'system' here indicates *system of bodies,* e.g. an arrangement of lenses, light beamers, detectors etc. It does not indicate a *system of reference* (Rynasiewicz, 1988 p 69). The system in motion in the Ether is from an electromagnetic perspective a different physical situation from the system at rest. So it does not give rise to the same electromagnetic field observed from a different system of reference. Let me elaborate on this. Consider the refracting telescope illustrated above for the cases of first order null results. Through Maxwell equations we have certain electric and magnetic fields permitted in relation to the system. Now, suppose that the whole arrangement is set in motion at velocity v in the Ether and the observation repeated. Lorentz is searching for a couple of fields that are supposed to be different from the ones at rest but corresponding to those in the sense of being to the new physical situation what the electric and magnetic fields dropping out from Maxwell's equations were to the rest one. The substitutions cannot be invariance equations for various reasons. Firstly, for Lorentz theory in a Euclidean space with time equal in all systems of reference the Galilean transformations are *the transformations*. He indeed proceeds to implement them. In the first step of the calculation above they lead to equations (3). To put it somewhat differently, the motion of the system with respect to the Ether is already taken into consideration in (3), thus from his perspective the account needs something else. Secondly, and accordingly, Lorentz does not think that he is dealing with the same fields at all, setting the system in motion as I said above, means that we are to think in terms of a different physical situation. So the fields we are talking about are different fields. The search for such a correspondence is a particularly delicate one because the experimental evidence shows no differences between optical phenomena in moving bodies and in bodies at rest.

The quest is for a means to establish which state (or states) of the Ether related to the system in motion *corresponds* to the state of the Ether related to the system at rest. The question became, thus, how to calculate the former situation through a set of equations that holds only in the latter and in such a way that the results explain the experimental negative evidence. Therefore, the role of the primed functions introduced in (e) and (f) is analogous to that of the *local time*. They are not real fields at all. They are a mathematical device designed to introduce a one-to-one correspondence between two genuinely different states of the Ether, namely the real fields E and H of S_0 and the real fields E_m and H_m of S. One *caveat* is important at this point, one that indeed should help in clarifying to what extent the stipulations (a) to (f) are just aiming to introduce mathematical auxiliaries. The analysis might have been read as suggesting that Lorentz was setting out a procedure to show what fields a system generates if it is set in motion, given the state of the Ether when the system was at rest. This is not the case. Observe (i) and (j): the primed fields are related through definitions to the real fields of the system in motion. There is no physical link between the state of the Ether when the system is at rest and the state of the Ether when the system is in motion. *The correspondence is mathematical not physical*. (Rynasiewicz 1988, p 70; Janssen 1995, chp3 pp 16-18). So what was Lorentz really after here? In a slogan, he was after a way to show why everything in a system in motion goes as if the system was at rest. To obtain this result Lorentz introduced a method to find a solution of the Maxwell's equations in a moving situation such that the optical effects would look the *same* as the effects obtained for the values of the fields calculated through Maxwell's equations in the stationary situation. This has nothing to do with a physical link between the two situations. For velocities small compared to *c*, the system of bodies constituting the experimental set up is assumed as unaltered by the motion. The fields, i.e. the states of the Ether in the two cases, are different as shown by the equations (3). The answer to the null results of the Ether drift experiments can be only in the nature of the relation between fields and experimental apparatus in the two situations. The relation has to be such that the two couples of fields give the same results in the two different situations. Lorentz's theorem of corresponding states provides precisely the tool to obtain this outcome in a purely mathematical fashion[18]. Strictly speaking the theorem does more. It shows that the one-to-one correspondence between the two situations can always be found. Such theoretical results explained the fact that first order Ether drift effects are not detected making them *in principle* undetectable. Moreover, there is no need for the physical situations to be equal because Lorentz wanted the formalism to show that everything could *look like* everything was at rest although the system was actually moving. As a theoretical confirmation of the depth of his treatment, Lorentz derived from its transformations Fresnel's dragging coefficient[19]. What about the second order effects? What about the Michelson and Morley experiment? The analysis of Lorentz's account will be shortly compared with the relativistic response to that experiment. The difference between the two visions that emerges here is going to influence the nature of the electron and in particular the conception of the properties that were conceptually necessary to the theory that delivered the prediction of the Zeeman Effect.

7.2.3 Integrating the Lorentz-Fitzgerald Contraction Hypothesis

The *memoir* of 1892 discussed in chapter 1 had already proposed to explain the null result of the Michelson and Morley experiments by introducing the contraction hypothesis formerly developed by Fitzgerald. The *Versuch* introduced the hypothesis altogether with what Janssen has called a plausibility argument. I will examine the contraction hypothesis and then briefly the plausibility argument. In order to understand the "contraction hypothesis" let us see what the structure of the prediction of the shift in the interference pattern was. The velocity of light (in vacuum), in classical electromagnetic theories, is constant, independent of the state of motion of the source, isotropic and its value is *c*. Since light was expected to retain its characteristics only in the rest frame of the Ether, the velocity of propagation of light was expected to be anisotropic in any inertial frame of reference in motion with respect to the Ether, the Galilean transformations providing the velocity-dependent quantitative value in such frames. The experiment of Michelson and Morley was designed to exploit this connection between light and Ether in order to detect the presence of the medium. Its aim was to detect a phase shift in the interference patterns of the light detected in the telescope described above (fig.1 above). In the following I will refer to Brown's (2001) reconstruction. It has the advantage of enlightening a crucial point in the treatment of the searched phase shift in the Michelson and Morley experiment respecting the structure of the original strategy of the experimenters. Actually, Michelson and Morley calculated the various time dilations in relation to the rest frame of Ether, and then they applied the usual Galilean kinematical relations in order to obtain the phase shift that was supposed to mark the anisotropy of light when the system of detection moves with respect to the rest frame of the Ether.

Suppose that S is the reference frame of the Ether whereas S' is the frame of the laboratory assumed (over a brief period of time) to be in uniform motion with respect to the Ether. At rest relative to S' the interferometer has arm A along the positive x' and x axes, assuming that the direction of motion of S' with respect to S is along such axis. The B arm is perpendicular to A and thus lies along the y'-axis. The classical expectations on the outcome of this experiment where expressed in the form of a time dilation in the arrival of one of the light beams with respect to the other determining the phase shift. In order to understand how the contraction hypothesis is formulated it is useful to see how the time dilation is arrived at and how it determines the phase shift. In S a light pulse travelling along A from the beam splitter bs (see fig. 1) to the mirror m_1 and back takes a time T_A that can be calculated as follows:

$$T_A = 2\gamma^2 (L_A/c)$$

where γ is the usual Lorentz factor and L_A is the length of the arm. We are approaching the calculation from a general perspective so we are not assuming that the interferometer had arms of equal length (Brown 2001, *preprint,* 3).

The time T_B taken by the light beam to travel along B from the beam splitter bs to the mirror m_2 and back is:

$$T_B = 2\,\gamma\,(L_B/c)$$

where L_B is the length of B . The time dilation based on the two expressions above can be calculated as follows:

$$D = T_A - T_B = 2\gamma^2 (L_A/c) - 2\,\gamma\,(L_B/c) = 2\,\gamma\,(\gamma\, L_A - L_B)/c$$

Now we want to consider that difference in the times when a rotation of 90° of the arms of the interferometer brings A into a position along the y' axis and the arm B along the x' axis but in the negative direction. Let us call D^{rot} the difference between the two times in the new situations. By analogy with the calculation above we have [20]:

$$\Delta^{rot} = T^{rot}_A - T^{rot}_B = 2\,\gamma(L^{rot}_A - \gamma\, L^{rot}_B)/c$$

The telescope in which the split light beams have ended their travels has detected a superposition of two monochromatic light beams[21]. Due to the rotation it is expected that the telescope detected a phase shift. Suppose that n and n^{rot} are the number of periods of oscillation of the light waves associated with the time delay obtained before and after the rotation respectively. The phase shift due to the rotation was calculated as follows:

$$\Delta n = n - n^{rot} = (\Delta - \Delta^{rot})(c/\lambda)$$

where λ is the wavelength of light (Brown 2001, 5).

Now in S', the change in orientation of the interferometer arms allow us to exploit the assumed anisotropy of light given the fact that light beams are now considered in their journey in the opposite direction with respect to the preceding case and thus with respect to the relative direction of motion of S and S'. Michelson and Morley arranged for the arms of the interferometer to be of the same length and given that lengths are constant in classical kinematics, the length of the interferometer arms in S' is *L′,* where $L_A = L_B = L'$. This yields the following result for the phase shift in S'

$$\Delta n \sim 2(L'/\lambda)(v^2/c^2)$$

The value predicted was between 20 and 40 times bigger than the phase shift observed (Brown 2001, 5). Now it is evident the role played by the classical assumption that *L does not* change when we consider the interferometer in motion thorough the ether in yielding a prediction in disagreement (a huge disagreement!) with the experimental results. Lorentz's considerations attack the problem exactly on that assumption. Following Fitzgerald, he hypothesised the material structure of the arm to be deformed by the motion through the Ether. Interestingly, LTE is not equipped to provide a proper derivation for this hypothesis. Lorentz provides instead a plausibility argument for it[22]. In the essay of 1892, where the contraction hypothesis was firstly discussed in connection with LTE, Lorentz observes:

“What determines the size and the shape of a solid body? Evidently the intensity of the molecular forces; any cause that would alter the latter would influence the shape and dimensions. Nowadays, we may safely assume that the electric and magnetic forces act by means of the intervention of the ether. *It is not too far- fetched to suppose the same to be true of the molecular forces*. But then it may make all the difference whether the line joining two material particles shifting together through the ether, lies parallel or cross wise to the direction of that shift. It is easily seen that an influence of the order of *p/V* is not to be expected, but an influence of the order of p^2/V^2 is not excluded and that is precisely what we need.”[23] (Lorentz 1892, p.221).

7.2.4 The Lorentzian interpretation of the motion of matter through the Ether

In the quotation, Lorentz is clearly relating the plausibility of the hypothesis to the possibility that the intermolecular forces behave in an electromagnetic-like way. Now, this argument – apart from its historical value – is interesting because in expressing a deficiency of LTE at the time – the theory did not have the resources to go beyond a mere plausibility argument in 1892 neither did it have in 1895 – reveals two elements for our general analysis.

A) The non-relativistic character of the picture of Electromagnetic phenomena discussed so far:

- Local time is just a mathematical function as well as all the fictive fields put in place in order to account for the null results of first order Ether drift experiments.
- Ether drift is, at any rate, a fact of nature. The theory does not deny it; it explains why we do not detect it.
- The picture in which the problem is explained is inherently dynamical: charged particles do generate in the Ether the states described as electric and magnetic forces as well as those that are responsible for light. The contraction hypothesis, thus, concerns and needs to concern the structure of matter. It is a dynamical hypothesis: because of the nature of the forces tying molecules together an effect of contraction is to be expected.

The physical reasoning does not even approximate the relativistic one in this phase. The theory is a bold combination of classical orthodoxy and heretical solutions. We shall see that LTE can evolve and did evolve into something “more relativistic”, so to speak, but with the result of loosing its grip on what electrons are and what is the function of the Ether. This issue deserves to be probed further. Cannot we really take LTE in its original version to embody a fundamentally relativistic element that can explain why the theoretical framework could deliver the treatment of the first order null results? More specifically Lorentz thinks that the whole explanatory work is done by fictive fields that are supposed to be no more than mathematical devices conceived similarly to the local time as mathematical auxiliaries. Indeed such magnitudes are introduced by stipulations in the theory and they are designed to make Maxwell's equations turn out with the right results. It is legitimate to wonder if this makes sense at all. It is a null result what LTE has to account for but it is also something that is expected to tell us about the nature of one of the two fundamental entities – the other being the electron – in Nature. How can something about the physical nature of the Ether – literally telling that it is undetectable – be treated in the theory as a purely mathematical device devoid of any physical significance?

Those are two related but different questions and the answer can only be in two stages. Indeed the historical reconstruction might be insufficient. Lorentz never thought that he could have been seen as telling the same physical story of Einstein, but he could well have been wrong in evaluating his own theory. My answer implies that to some extent a process of self-correction is prompting the development of the theory in this phase (Poincaré did corrected Lorentz work thoroughly in that phase, (Darrigol, 1995)). So the issue here has to do with what we take LTE to be about. So far it has been my contention that LTE is not responding to the problem of the null Ether drift experiments (both of first and the second order) in a relativistic manner, I want to insist on this point qualifying it further. For what concerns the treatment of the null results of the first order Ether drift experiments, interpreting the theorem of Corresponding states as a set of cunning mathematical auxiliaries could even be tenable. We could buy into Lorentz's early reading and think that what really matters is providing the means to "calculate out" an absence of detection using a device – the Maxwell's equations – that have served us well so far. In order to do so we need to identify the correct form that field vectors and time need to assume to be solutions of Maxwell equations in the situation of motion corresponding to the ones at rest. We neither need them being identical with nor being caused by the fields that were expressed by the solutions obtained in the case in which the system was at rest in the Ether. We just need a mathematical correspondence. Can we add the values of velocity representing the motion of the system through the Ether to the Maxwell's Equations and obtain solutions of the Maxwell's Equations? Lorentz' s answer sounds: "yes if you add them properly, picking up fields and time in a certain way". There are shadows in the story but Lorentz can live with them. The case of the second order Ether drift experiments is far more concerning, though. Poincaré does not press this point, which is not pressed by the successive sympathisers of Special Relativity either. Lorentz himself stresses this point. When we have to explain the results of the Michelson and Morley experiments Lorentz abandoned the language of "fictive fields" and constructs the plausibility argument discussed above on the grounds of a dynamical hypothesis. The contraction hypothesis is not a fictive process[24]. It is an assumption about what happens to matter when we move it through the Ether. The deformations (Brown, 2005, 53) that the arms of an interferometer experiences when it moves through the Ether are physical facts about the nature of the laws that ties molecules together. So, pure considerations of symmetry between explanations of the first order and explanation of the second order (lack of) effects of the Ether drift experiments should suggest reconsidering the original narrative about fictive fields and mathematical auxiliaries. We could profitably reformulate the whole story in terms of *local time* measured by different observers and invariance group of the Maxwell's equations capturing a version of the relativity principle. To be sure, this is the interpretation considered by Poincaré in his 1905 "Sur la dynamique de l'electron"(Darrigol, 1995, pp 2 and 3; Brown 2005, p 62). Now, it has been observed that the "contraction" hypothesis that Lorentz introduces is not in itself different from the relativistic one (Brown, 2005, *ibidem*). So should not we conclude that after all LTE is just approximating Relativity? And should not we take its explanatory effectiveness as due to its closeness with the relativistic picture? I do not think so. Even embracing the "relativistic" reading due to Poincaré we do not go as relativistic as we might think. In particular, Poincaré, exactly as Lorentz, thought (Brown 2005, 63) that the contraction hypothesis presupposes that the fundamental building blocks of matter experience opportune deformation in order to explain the null results of Michelson and Morley experiment. The contraction for none of the two physicists follows from Lorentz invariance. This is not due to a misunderstanding of the significance of the Lorentz invariance. Poincaré, in particular, anticipated Minkowsky in perceiving the demand for a different geometry encoded in the Lorentz group. The difference is in the physical justification that it supposed to be given to the contraction. As we will see, in its various developments LTE remains a research program aiming to provide an overarching theory of matter (and light and electricity and magnetism). It is the dynamics that constitutes the core of that theory of matter that has to establish the contraction hypothesis. This kind of justification simply is not the kind of justification offered by Special Relativity. We might think that this kind of justificatory step is of secondary importance *vis a vis* the similarities between the relativistic explanation and the pre-relativistic one. Again I think that more consideration should be given to the physical picture projected by LTE. As we shall see later, length contractions and time dilations are detectable effects in Special Relativity. When, instead, such facts are conceived as consequences of the electrodynamics of a charged extended particle they are not.

B) Some of the properties that the theory ascribes to the electron, and importantly among them the ones involved in the derivation of the Zeeman Effect, are conceptually necessary in LTE.

- Given the entities that the theory postulates to account for the structure of material bodies, the justification of the contraction will have to be down to the dynamics of the electron.

- The conception of mass and structure of the electron in particular – still under investigation in 1895 – is profoundly influenced by the need to implement coherently the idea of matter contracting in virtue of the velocity of its motion through the Ether.

In the next paragraphs I will discuss those properties and what we make of them in the relativistic context. Before moving on, it will be helpful in order to fully appreciate the conceptual difference between LTE and REL to comment on the experimental situation arranged by Michelson and Morley from the relativistic perspective.

7.2.5 The Relativistic Perspective on the Experiment of Michelson and Morley

A short relativistic answer to the result of the Michelson & Morley experiment is also the most obvious: there is no detection because there is nothing to detect. There is no Ether. This, nonetheless, is half of the answer, since without a relativistic reading of Lorentz invariance, still we would have no agreement between the form taken by Maxwell's laws for systems in motion and the experimental results. In what follows, I am interested in highlighting the peculiarity of the relativistic reasoning rather than insisting on the formal aspects, that, by the way, are very similar to the ones I have summarized above for the Lorentzian case.

Relativistic frameworks all conform to the following two principles that establish their kinematics:

1. The postulate of relativity. The laws of a physical system should be the same in any frame of reference in uniform motion and should not depend from any particular frame.

   In other terms there is no way to experimentally show an absolute motion and there is no Ether intended as the privileged frame.

2. The postulate of light. Light has the same velocity in every inertial reference frame, independently from the velocity of the source[25].

In his beautiful 1921 essay "*The theory of Relativity"* Wolfang Pauli, comments in the following way on the apparent incoherence between the light postulate and the relativity principle:

"For, let us take a light source L which moves relative to an observer A with velocity *v*, and consider a second observer B at rest with respect to L. Both observers must then see as wave fronts spheres whose centres are at rest relative to A and B, respectively. In other words they see different spheres." (Pauli (1921), Engl. transl., 1958, p 9)

Prima facie, it looks like either the velocity of light is equal to *c* or the reference frames are equivalent. We can think about the Michelson and Morley experiment as instantiating the situation described by Pauli. Now, the explanation provided by Lorentz is constructed precisely from the point of view portrayed by the quotation: the beams of light travelling on the two arms of the interferometer are two different waves. Indeed, for Lorentz the principle of relativity did not hold for electromagnetic phenomena. Consequently, the time dilation follows from the fact that the motion through the Ether interferes with light patterns – with the genuine patterns it has in the Ether – and the contraction of the arm moving through the Ether *might follow* from the fact that the intermolecular forces are tightened because of the motion through the medium. The structure of matter is thus altered being itself permeated by the universal medium. Between the situation of rest in the Ether and the situation of motion through it there is no symmetry whatsoever. The proper condition of light and matter is at rest in the Ether. The system set in motion is a system in an altered state. The two alterations, the temporal dilation and the material contraction, originate from the same electro-dynamical source, and cancel each other. In this sense, the proper and the altered state *correspond*. Let us now turn to relativity. Pauli glosses in the following way about that *apparent* incoherence indicated above:

"This contradiction disappears, however, if one admits that space points which are reached by the light simultaneously for A, are not reached simultaneously for B. This brings us directly to the relativity of simultaneity:" (Pauli, (1921), Eng. Transl. 1958, p.9)

This is precisely the gist of the relativistic response to the experiment: the two waves are the same physical phenomenon, the two light beams travelling on the two arms of the interferometer travel at the same velocity. The two observers (in the case of the interferometer, the measures referring to the two arms) measure the same physical process but each of them measures the time and the distances proper to its own reference frame. Thus, points of space that the wave front reaches at the same time for one observer are reached at different times for the other. The time dilation expresses the relativity of simultaneity, the difference between measures of time taken in the two systems. The length contraction is the spatial counterpart of this fact about our way of measuring light beams in different inertial frames.

The relativistic treatment is, as I said, formally identical to the Lorentzian one[26]. It, also, "corrects" by a factor $\gamma = 1/\sqrt{(1 - v^2/c^2)}$ time and length, leading to the null result. The underlying physical reasoning is, nonetheless, radically different. The effects of contraction and dilation are not consequences of the electro-dynamical conditions of certain entities. They follow from constraints that any moving object is requested to obey no matter what kind of dynamical – mechanical, electro-dynamical - laws govern it. Time is, thus, relative to the frame of reference in which is measured since it is relative to it the simultaneity that characterizes all the circumstances in which time is measured. Put in different terms, it entails that "local time" - *Ortseizt* as Lorentz called it-, is not a mathematical auxiliary[27], but the time measured by observers in relative motion. Hence, there is no universal Newtonian time. Finally, length contraction does not presuppose a theory of matter to support the treatment[28] of the Michelson and Morley experiment. Length contraction in Relativity is not a property of the material constitution of bodies (such like an interferometer or a measuring rod). Length contraction is, instead, a relation between bodies moving relatively to each other. Notice that, on the contrary, the contraction *has to* be a property of the arm of the interferometer or of a measuring rod in LTE, because it depends on their material constitution. It has to, since it is in virtue of the forces that confer to the body its shape that it undergoes to the deformation. The fact that length contraction is not a property of the material structure of bodies, rather a relation between bodies in relative motion, has the consequence that the relativistic contraction *in principle* is – as much as the time dilation – detectable. Its pre-relativistic counterpart is precisely in the opposite condition. We can appreciate this point, following Pauli's lead in considering a thought experiment suggested by Einstein in 1911 (Pauli, (1921), 1958, p 12). Consider two rods $A_1 B_1$ and $A_2 B_2$ of the same rest length l_0, which move relative to the frame S with equal and opposite velocity v. We mark the points A^S and B^S in S in which the point A_1 overlaps the point A_2 and the point B_1 overlaps the point B_2. When we measure the length $A^S B^S$ in S, it has the value

$$l = l_0 \gamma$$

Now, detecting such an effect would be tricky considering that it would involve the use of rods (or in general rather big objects) moving with velocities very close to *c*. Nonetheless, the effect is in principle detectable[29]. As noticed above, it is not in LTE. These final considerations conclude this comparison between the two frameworks. It should be clear that a characterization of the structure of the electron and of the nature of its mass is indeed needed in order to make sense of the contraction hypotheses. Accordingly, I will now turn to examine the details of the structure of the corpuscle.

7. 3 A deformable charged particle.

7.3.1 Introduction

What about the fact that Lorentz actually obtained a generalized version of his Corresponding states theorem? We know that Lorentz generalized that result by 1899[30] and with few corrections due to Larmor and, independently, to Poincaré, the Lorentz invariance was a theoretical acquisition before Relativity appeared[31]. So, should not we think that once the corresponding states are extended to the second order terms, the original reasoning underpinning the contraction hypothesis becomes redundant? After all, Lorentz's contribution to relativity begins with such a generalization. Indeed, many historians have interpreted Lorenz's 1899 work in this way. Miller (1981), McCormach (1970 a and b), Darrigol (1994) have all taken for granted that the second order theorem "absorbs" *the contraction hypothesis*. This is not an accurate reading, though. There are good historical motivations to reject this view and they are all been put forward and effectively defended in Janssen (1995; 2004), Janssen and Stachel, (forthcoming), Janssen and Meckelenburg (forthcoming). In the following I will draw from those analyses. My motivations to resist what we could call the "relativistic reading" of Lorentz theorem of Corresponding states are also conceptual and philosophical. LTE left to successive science much more than the Lorentz transformations. Lorentz's model of the electron satisfies the relativistic relations between energy, momentum, mass, and velocity. The theoretical motivations of such design are in the need of LTE to establish a theory of matter underpinning the contraction hypothesis. Downplaying this link would change the relation between LTE and the successive research in a way that would affect negatively our philosophical aims.

A few details might help. *Per se* the Lorentz invariance does not explain anything in LTE[32]. In LTE it is just a formal device permitted by the group-theoretical structure of Maxwell's equations. The explanatory power is supplied by the material conception of the contraction. The generalization of the Corresponding States theorem did not absorbed the hypothesis. It simply made it clear that only a theory of matter whose fundamental entities *contract,* if set in motion through the Ether, could sustain the explanation it supplied. The status of that invariance changes in REL where it embodies the two principles on which the theory is built. Overlooking this point would lead us to miss the extent of the continuity in the explanatory sense. The point is not the invariance rather the properties of the electron that have to substantiate the contraction. Those properties constructed as invariant under the Lorentz transformations in the final version of LTE are one of the permanent features appropriated by the relativistic worldview. They confer explanatory power to the dynamics of LTE. In REL they constitute the structure of the kinematics. Such a result has a cost. Seen from the relativistic perspective, the classical electron is not an electron at all it is just a relativistic piece of matter. The relations it satisfies are the kinematical relations between mass, energy and momentum. There is nothing specifically dynamical that yield them; there is nothing proper of the electron as such in them. Every relativistic particle satisfies those relations. On the other hand we cannot claim that when Lorentz used the term "electron" he actually referred to a generic relativistic particle. This would miss the point that in LTE there is *nothing else* that is supposed to have the structure of an electron. The electron, in fact, has a structure designed to modify the fields and to respond by accelerating to the forces acted upon it by the fields. It is to a large extent an electro-dynamical item. There is no room to argue that in LTE, the Ether, for instance, is referring to the relativistic electromagnetic field, either. Indeed, in the light of the previous analysis I do not see how this could be the case. The Ether in LTE is the one of the two elements of a fundamental ontology, the fields are just its states: visible light is nothing else than a visible state of *perturbation* of the medium. With no sources of perturbation, with no moving and accelerating charges, we would still have the Ether but there would be no perturbation and hence no fields. The fields are therefore entirely *reduced to* the interaction between Ether and charged particles. Fields are not fundamental items in LTE. It is with Relativity that our understanding of electromagnetic phenomena comes to be based on the electromagnetic field as the fundamental entity. It is now time to verify the claims I have made so far about the indispensability of an extended structure for the Lorentzian electron.

7.3.2 The Model of the Electron.

LTE, as indicated above, was a mixture of electromagnetism and classical mechanics. As a consequence, the template for the forces acting on the particle was Newtonian and the Lorentz Force was initially conceived in those terms as well. Nonetheless, because of their nature as charged particles the corpuscles subjected to such force allowed for far-fetched speculations on the inner nature of physical properties such as mass and momentum. In particular notice that the equation of motion of an electron in an external field has to be

$$\mathbf{F}_{ext} + \mathbf{F}_{self} = 0 \quad (4)$$

The first addendum on the left side of the equation expresses the force exerted by the external field on the particle whereas the other represents the force due to the self-field of the particle i.e. the force that can act on a particle is due partly to the field it generates because it is charged and partly to the fields that it finds itself in. Now, the general expression of the Lorentz Force is

(5)

$$F = e(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{H})$$

in this expression *e* represents the electric charge, $\boldsymbol{E}$ and $\boldsymbol{H}$ the electric and magnetic field, and $\boldsymbol{v}$ is the velocity vector. From the general expression a simple reasoning based on a structural analogy with the classical template yields the idea of electromagnetic momentum (Janssen & Meckelenburg forthcoming, p. 8).

It proceeds as follows. From (5) we derive the expression for the component of (4) due to the self-field:

(6)

$$F_{self} = \int \rho \ (\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{H}) \ d^3x$$

where ρ is the charge density of the particle, $\boldsymbol{E}$ and $\boldsymbol{H}$ are the electric and magnetic fields respectively.

Through (6) we also define a new magnitude, the electromagnetic momentum,

(7)

$$P_{EM} = \int \epsilon_0 \ (\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{H}) \ d^3x$$

Since in Classical Mechanics force can be expressed as the time derivative of the momentum, the Force due to the self-field will be expressed by

(8)

$$F_{self} = -\frac{dP_{EM}}{dt}$$

The expression of F_{ext} is of course (8) with opposite sign. The expression for mass and energy can be found following a similar strategy. The equation of motion in classical physics is also written as the product of mass times the acceleration. So making use of the electromagnetic momentum, the electromagnetic mass of a moving electron can be obtained. Here the template will be the equation $\frac{d\boldsymbol{P}}{dt} = m\boldsymbol{a}$. Suppose the electron is moving with velocity $\boldsymbol{v}$ and assume that the momentum is in the direction of motion (Janssen and Meckelenburg, *forth.* p 9). The momentum so considered will have two components one parallel to the direction of motion and one perpendicular to the direction of motion. They emerge from the original treatment in the form of the following equation:

(9)

$$\frac{dP_{EM}}{dt} = \frac{dP_{EM}}{dv} a_{\parallel} + \frac{P_{EM}}{v} a_{\perp}$$

the two terms for the acceleration are the longitudinal and the transverse acceleration. The remaining two terms express the *electromagnetic* longitudinal and transverse masses[33]:

(10)

$$m_{\parallel} = \frac{dP_{EM}}{dv} \ ; \ m_{\perp} = \frac{P_{EM}}{v}$$

Considering that the LTE was meant to combine Classical and Maxwellian physics this is quite an iconoclastic result. Classical Mechanics seems to lose its conceptual primacy. The primitives of the theory, the items that should be ultimately responsible for the structure of matter seem to have a velocity dependent on the electromagnetic mass. In Classical Mechanics we think of mass as quantity of matter. It is what resists a force accelerating the body, in LTE this function, it seems, can be equally performed by a property that is electromagnetic in its nature[34]. Nonetheless for the program to be completed, LTE requires that the electromagnetic mass were contracted by a factor in the direction of motion when the particle was not a rest in the Ether. This is, in a nutshell, how *the contraction hypothesis* gets generalized. In order to obtain this result Lorentz needed to show that expressing the mass of the particle in terms of its electromagnetic energy yields the same result obtained in terms of its momentum. This is conceptually equivalent to showing that the relations between momentum and energy revolving in classical mechanics around the notion of mass as quantity of matter could be structured around a purely electromagnetic alternative. The purely electromagnetic equivalent yielding the desired mass velocity dependence would have completed the picture providing a theory of matter that could sustain the explanation of the Michelson and Morley's experiment. Lorentz as early as in 1899 (Janssen &Mecklenburg, *forth.* p. 11), indicated as follows what expression for the mass would have given the desired result: if m_0 is the mass of the electron at rest in the Ether, the mass of the electron in motion has to be:

(11)

$$m_{\parallel} = \gamma^3 m_{\,0}\,;\; m_{\perp} = \gamma m_{\,0}$$

Notice that the result is actually obtained in LTE. Nonetheless, it was historically entangled with the problem of the stability of the structure of the particle. Such stability resulted from the introduction of a *non-electromagnetic* force, known as Poincaré's "pressure". So the electron *contracts* in the desired way in the direction of motion, but its structure cannot entirely be due to its electromagnetic characteristics. Disentangling the lines of reasoning underlying this result will complete the profile of the electron we have been constructing so far and will prepare the ground for the step to the relativistic picture.

The headings here could be "structure and stability of an extended charged particle". A contracting electric charged particle *needs to be* an extended object whose (electromagnetic) mass varies depending on its velocity. The need for it to occupy a region of the tri-dimensional Euclidean space[35] – a spherical region when it is at rest, an ellipsoid if set in motion- comes with a problem of the stability of its structure (Miller 1981, p 74-75)[36]. Put in simple terms the electron is stable if it maintains indefinitely its structure when at rest and some force acts on it inducing a change, it is stable in other terms if:

(12)

$$F = \rho \boldsymbol{E} = 0$$

The electron is a charged particle, so it is clear that the result in (13) cannot be due to ρ= 0, since ρ represents the density of charge and we expect the electron to maintain its charge even when it is at rest. This means that when the particle is at rest, the condition of stability should depend upon its electric field *being null*. That, in turn, cannot be because of Gauss's law:

(13)

$$\nabla \circ \boldsymbol{E} = 4\pi\rho$$

Gauss's Law implies that if $\boldsymbol{E}$ = 0, then ρ = 0 as well. Hence, the electron's electric field at rest has to have a value different from zero. So its Coulomb field is going to be non-zero as well. The Coulomb field is a static force whose intensity increases proportionally to the inverse square of the distance between the charges; when the charges are of the same sign, the force is repulsive. Being a very small sphere uniformly charged, the parts of the electron are like small charges of the same sign, thus they should be pushed apart by a Coulomb force that should be very intense because the parts of the electron are very close to each other. The electron should explode then, unless it is equipped with cohesive forces that cancel the effect of the Coulomb field. The addition of those forces was one of the contributions of Poincaré to our story.

How does this issue relate to the problem of meeting the requirement expressed in (11)? Once the relations between energy and momentum of a moving electron are provided, the expression of the mass obtained by its energy diverges from (10) obtained from its momentum. Hence, the model of electron is inconsistent. It is inconsistent, unless we alter the expression of the total energy of the moving electron by a factor that cancels the divergence. Interestingly, the addition of the cohesive forces allows us to alter the expression of the total energy of exactly the desired cancelling factor. In other terms, introducing the Poincaré pressures, thus, the model will be not only structurally stable but, more importantly, a properly contractile charged particle.

A quick look to the physics will add substance to the discussion. Following the template of classical mechanics, the relation between energy and momentum for a moving electron can be rewritten (Janssen & Mecklenburg *forthcoming* p. 10) considering the work done as an electron moves in the x-direction in absence of external field. Classically work is a change or transfer of energy. In our case when an electron moves there is a change of its internal energy determined by the force due to its self-field. In classical mechanics work is $dU = \boldsymbol{F} \cdot d\mathbf{x}$, so its electromagnetic counterpart is $dU = -F_{self}.dx$ (the sign minus refers to the fact that the transfer goes in the internal energy). Using (8) and (9) we have:

(14)

$$dU_{EM} = \frac{dP_{EM}}{dt} \cdot dx = m_{\parallel} v dv$$

So the expression for longitudinal mass obtained as a function of the electromagnetic energy is,

(15)

$$m_{\parallel} = \frac{1}{v} \frac{dU_{EM}}{dv}$$

The calculations have to give the same values for (10) and (15) in order to satisfy (11) (Janssen &Mecklenburg forthcoming, 10). Abraham demonstrated these expression as they stood in the model developed by Lorentz did not gave the same values in 1905.[37] Calculating the mass of a charged particle in motion from (15) and from (10) leads to different results. Poincaré pressures change the characterization of U_{EM} and remove the inconsistency. We need not examine the details of this solution, for our analysis it suffices to observe that the forces added by Poincaré in order to balance the effects of the Coulomb field had to be non electromagnetic and thus non-electromagnetic is the component due to those forces added to the final version of the total energy of the system. Interestingly, once his corrections were implemented this was the mass obtained by Poincaré for the electron when the motion was characterized by small velocities:

(16)

$$m = U_0 / c^2$$

An expression that looks impressively similar to its celebrated successors: $E = mc^2$.

So where are we, then? Let's take stock. The particle responsible for the electromagnetic processes, in order to fulfill the explanatory program it was designed for, *has to* present the following features:

- It is an extended, deformable, spherical, uniform charge distribution
- It is equipped with internal mechanical cohesive forces (pressures) that vanish at the surface

- It has a mass dependent on the velocity that contracts when the particle is set in motion
- Its momentum is electromagnetic
- Its energy is partly electromagnetic and partly due to a mechanical component in turn due to the pressures
- Its mass is partly "mechanical" and partly electromagnetic.

This is the model of the charged particle and our narrative should have provided enough details to explain why all those features are necessary in order to make this particle work.

What happens to this model in the relativistic context? In the relativistic context it becomes clear that what Poincaré and Lorentz had found is a particle that can undergo the desired contraction and ultimately thus address the concerns raised by the Michelson & Morley experiment but for completely non-dynamical reasons. It is simply a relativistic body and relativistic bodies appear contracted when set in motion with respect to the frame of reference of the observer. The relations that Lorentz and Poincaré (and Abraham) proved for it are just the relativistic relations for mass, energy and momentum. So, Lorentz, although involuntarily, left with us much more than the Lorentz invariance. He contributed by also developing a piece of relativistic kinematics. This is a fascinating piece of history of modern physics. I will not tell here this piece of the story. It would be a digression from my main task. Nonetheless, I felt that it was useful for the reader to have a précis of the literature and, at the same time, technical evidence of my assertions above. So, the chapter is supplemented with a short appendix [*the appendix is omitted in this version*]. There I provide evidence of the correspondence between the characteristics of the model of the contractile electron and the kinematical relations that apply to any relativistic object.

7.4. Infinities

Have I proved that the Lorentz electron has to be an extended body, then? Is my main historical evidence provided? We are nearly there. A few technical considerations will end this long journey in the realm of pre-relativistic electromagnetic physics. What I have said so far shows that there were explanatory urgencies that made an electron with an extended contractile structure a desideratum. Elsewhere, I have shown that the first formulation of the theory postulated a rigid spherical structure with a constant radius. In that case as well, there were positive explanatory motivations: the electron was supposed to be the cornerstone of the architecture of a molecular theory of matter. That theory of matter had to account for all the phenomena left unexplained by

Maxwell's theory and held explicable only by a framework expressing the dynamics of charged matter. In a classical atomistic perspective assuming that a fundamental constituent of ponderable bodies was point-like would have sounded quite bizarre.[38]. Seen in perspective, these were certainly positive motivations to lean towards an extended structure, grounded in the explanatory expectations attached to the introduction of the particle. Nonetheless, the history of science tells us that the main actors of this story have also held convictions about the possibility that the electron was a disembodied perturbation in the Ether whose mass was of purely electromagnetic origin. A similar electron might well be structure-less and non-extended. Why has a similar model not been developed? The answer follows from conceptual motivations. Let us assume for the sake of argument that the electron is an extended sphere; a point particle will be a particular case of this scenario, the case of radius R = 0. An electron carries a unit charge uniformly distributed on its surface. The electric field carries energy and the electron will have a component of the energy due to its own field, the self-energy[39]:

(17)

$$W_{self} = \frac{e^2}{2R}$$

Now, if in the equation R goes to zero the self-energy turns out to be infinite. The self-force will also be infinite: that is, the force that acts on the electron as a result of the fields produced by its charge. Its self-stress will be infinite as well, and the Poincaré pressures mentioned above, forces needed in order to balance the self-stress, will be infinite as well. Finally the electron, as with any charge, is surrounded by an electric field, the Coulomb field, whose strength decreases with the distance from the charge itself. The strength of the electric field localized at the particle is infinite if R = 0:

(18)

$$E = \frac{e}{r^2}\hat{r}$$

Where it is assumed that r > R. This intuitively means that the field extends a bit further than the electron itself[40].

It is also relevant to my point to observe that in any discussion of relativistic electrodynamics (see for instance Rorhlich, 1991), compliance with the principles of relativity imposes that charges are point-like. Put it briefly, an extended charged particle would produce superluminal signals if accelerated in its rest frame (Frisch, 2005, Cp 2). This is something that was clear since the establishment of relativistic theories.

2.5. Conclusions

The conceptual considerations above have completed our analysis and our tasks for this chapter are complete. Our historical narrative has shown that:

1. LTE empirical successes contributed to give credit to the existence of electrons and to establish the value of its mass to charge ratio
2. Explanatory reasons due to the necessity of accommodating the null result of the Michelson and Morley experiment justified the choice of a contractile model of the electron after 1895.
3. Conceptual considerations lead to the exclusion of the possibility of point like charged particles and the failure to do without some mechanical notion of mass
4. The program of LTE actually failed to produce an electron that could posses such characteristics and yet owe them to purely electro-dynamical factors.
5. Despite some profound structural similarity LTE and relativistic electrodynamics rest on profoundly different worldviews
6. The rise of REL led to establish the credo that a charged particle was essentially point-like

Such findings left the scientific community with a wealth of theoretical and empirical knowledge about the subatomic domain: the point-like nature of electrons was arrived at in this context, and it was a fruit of this period that electrons were seen as responsible for the splitting observed by Zeeman.

Notes

1 Lorentz devoted to the theory of the Zeeman effect a large part of his 1906 Columbia University lectures then published as *The Theory of Electrons* (H.A. Lorentz 1909; 1915;1952). Since 1896 he considered the prediction an outstanding piece of evidence in favour of his framework. As a purely external detail consider that Lorentz and Zeeman shared a Nobel Prize in 1902 as a follow up of the findings of that extraordinary fall of 1896 in Leiden. The importance of the result, both at the experimental and at the theoretical level, can hardly be overstated.

2 The program initiated by Weber aimed to challenge many fundamental concepts of Classical Mechanics or to replace them with laws and concepts suited to develop electrodynamics into a final theory. From mid 19th century

throughout the early period of development of Quantum Mechanics and establishment of Relativity, the advocates of this project, developed various theoretical frameworks based on charged particles, violating various classical principles ranging from the existence of a limiting speed to the action reaction principle to a new version of conservation laws. Weber, in particular, turned out to be very influential on Lorentz and Lorentz's theory was considered a turning point in that research program (See McCormmach 1971, p 471-73). It is a peculiarity of this story that the ones indicated as its main heroes did not want to take up the role. Lorentz indeed was quite cautious in associating himself with the project and clung to its idea of a balanced mixture of Mechanics and Electromagnetism until the end of his career.

3 Preston - after Zeeman's result was of public domain- reproduced successfully the original experiment. Subsequently, he studied the phenomenon with magnetic fields of higher intensity and integrated the apparatus with a powerful camera. Under those new conditions, in December 1897, he photographed a splitting of the spectral lines double that of the one found by Zeeman and predicted by Lorentz's theory. Such result was later called Anomalous Zeeman effect and constituted one of the lasting puzzles that mature Quantum Mechanics managed to solve. (Weaire & O'Connor 1987, 633-35; See Also Massimi, M., 2005)

4 The invariance provided in the work of 1895 is for first order values of the velocity of a system moving through the Ether when compared to the speed of light, so the invariance neglects experiments that could detect second order effects. Notice that Lorentz never treats that result as an invariance. See Lorentz, Hendrick, Antoon (1895), "Versuch Einer Theorie der Electrischen und Optischen Erscheinungen in Bewetgen Kögen", in *Collected Papers,* (eds Zeeman, P., and Fokker, A.D.)Vol. 5, Hague: Nijhoff, 1935-1939.

5 Lorentz, Hendrick, Antoon (1895), "Versuch Einer Theorie der Electrischen und Optischen Erscheinungen in Bewetgen Kögen", in *Collected Papers,* (eds Zeeman, P., and Fokker, A.D.)Vol. 5, Hague: Nijhoff, 1935-1939. Most of the analysis will make extensive use of secondary literature on the topic or using, where appropriate, the definitive version of the theorem as it is presented by Lorentz himself in *The theory of Electrons* 1952 (1909) New York, Dover Publications.

6 I will follow a partly revisionist historiography on the topic, Janssen and Rynasiewicz to name a few. In doing so, on some relevant points I will disagree with authorities such as Miller (1981) or McCormach (1971).

7 Lorentz's version of the synthesis between Classical Mechanics and Electromagnetism entails various radical departures from the Classical worldview. Nonetheless, in comparison with the theories put forward by various physicists working at the time to a program dubbed "Electromagnetic view of nature", Lorentz's framework was not only the most successful but also the mildest.

8 Lorentz used the expression electrons only after Larmor's contribution (1897) of the term (See Arabatzis 2001 and 2006) to designate the new particle following the account of the newly discovered Zeeman Effect. In the earlier contributions the corpuscle is called an electric "ion".

9 For us it would be probably more appropriate to say that Classical laws are not Lorentz invariant. In general the problem can be put in the following way: as they are classically presented the two theories appear to postulate a different kind of scenario for the physical systems they investigate. Classical Mechanics treats the motion of objects in a tridimensional Euclidean space in which time is equal everywhere. In such a scenario Classical Laws are valid in any inertial frame of reference. We can obtain solutions for the equations representing such laws from other solutions by applying the operations of the Galilean group. If we project (as Maxwell or Lorentz did) Classical Electromagnetism in a tridimensional Euclidean space embodying a classical notion of time the Maxwell laws are valid only in a privileged rest frame. In fact, they are not Galilean invariant. If, on the contrary, we exploit the fact that their solutions form a Lorentz group and we see in this a physical fact concerning their applicability in any inertial frame of reference the geometry we are postulating is no longer Euclidean. It is a 4-dimensional differentiable manifold in which strictly speaking the classical mechanical assumptions about space and time are false. Lorentz and others thought at the time that this incompatibility could be solved grounding Classical Mechanics on Electrodynamics and in particular placing at the core of matter a wholly electromagnetic entity. (See below in this Chapter)

10 I am referring here to a passage of the *Versuch* published in English in Shaffner, K.F., (1972) *Nineteenth- century Aether Theories*, Pergamon Press, New York, p 250.

11This point can be fully appreciated reflecting on the different ways in which LTE and REL effect the unification of electromagnetic phenomena. Maxwell's equations strictly speaking do not say that electric and magnetic fields are the same thing, they say that they are deeply intertwined. A careful reading of the equations shows important aspects in which the electric and magnetic field are not unified in the theory. Their sources are different. Gauss laws, for instance, (the first and the second of Maxwell's equations) ascribe to the magnetic and electric charges different natures. Notice, in fact, that the Gauss' law for magnetism tells us that bearers of magnetic charge always carry both the negative and the positive poles. Magnets, for instance, are never found exhibiting just one polarity. In more precise terms, it follows from Gauss' law that there are no magnetic monopoles. Furthermore, Faraday's Law of induction indicates that the motion of a magnet in the vicinity of a conductor produces a magnetic field that generates a current in the conductor. If we set the conductor in motion keeping the magnet at rest there is no generation of current, though. Coupling this two consideration it is not difficult to conclude that magnetism and electricity are deeply entrenched phenomena but electric and magnetic fields are not the same thing. In particular, Maxwell's theory neither say that they are the manifestations of the same underlying substance – leaving this issue open- nor that one of the two fields is more fundamental than the other. On the other hand, the theory treated electric and magnetic fields as oscillatory motions and associated to them a Mechanical notion of energy (Maxwell, 1892, I, 564). This of course left open the issues of what is the medium that substantiates the perturbations and thus constitutes the ultimate repository of such mechanical energy. LTE solves this duality postulating a substance of which the electric and magnetic field are the states. They are properties of the Ether and they are due to the action of charged particles on the Ether. In this sense in LTE fields are not fundamental since they owe their existence to the action of a charge bearer on the Ether. Of course in a world in which LTE is the best theory of light, electromagnetism and matter, this would count as a unification. The landscape offered by REL is quite different. REL introduces a new entity, the electromagnetic field, represented by the electromagnetic tensor, whose manifestations are magnetic or electric fields depending on the frame of reference from which the electromagnetic field is observed. "When a current flows in the conductor, there is an electromagnetic field tensor in the vicinity of the conductor. There is simply no objective fact of the matter about whether or not there is an electric field near the conductor, or what the value of the magnetic field is. Electric and magnetic fields are not objectively real, they "arise" only when one chooses a certain reference frame relative to which the phenomena are to be described. Thus, the electric and magnetic fields are "unified" by being, in a way, eliminated entirely from the fundamental ontology, and by being replaced by a single, frame-in-dependent entity." (Maudlin, 1994, 132-33)

12 Or perhaps it was not surprising. The Ether, after all, was a reasonable consequence of conceiving of light as a wave. Waves are usually perturbations and a perturbation presupposes something in which the perturbation occurs.

13 An interesting historical analysis of those experiments and their relation to the ethereal hypotheses is in Janssen M., & Stachel J., "The Optics and Electrodynamics of Moving Bodies" in Petruccioli, S., (ed.) *Storia Della Scienza*. Istituto dell'Enioclopedia Italiana, (Forthcoming).

14 This is what Francois Arago was studying. Roughly in the case of Arago's null results, the Fresnel coefficient cancels the effect of the motion. Fresnel's explanation invoked a complicated underlying mechanism of partial dragging that has been successively tested and found in itself untenable. Nonetheless introducing the coefficient in the calculation, in a telescope in motion everything goes as if it was at rest in the Ether. For the technical details and a survey of the different fortunes of the Fresnel coefficient and its explanations see Janssen & Stachel (forthcoming). I am in debt for the example with Janssen op.cit p 4.

15 The scheme source is http://www.juliantrubin.com/bigten/michelsonmorley.html

16 The *Versuch* is available only in the partial translation mentioned above. Any reference to that text not yet translated as, partly, in what follows, is made through secondary literature and in particular Rynasiewicz 1988 and Janssen 1995.

17 This historical aspect of Lorentz work in relation to Special Relativity has been frequently a source of confusion leading to interpret LTE as a proto-relativistic theory. (See McCormach 1971 for instance). The best reconstructions I found are Ryansiewicz 1988, Janssen 1995 and Darrigol 1994. For a more recent discussion see Brown 2005. An important feature to discuss in Lorentz's theory is the evolution of his own interpretation of *local time* and the Corresponding states theorem. Till 1905 when the influence of the dialogue with Einstein was acute, Lorentz did not interpret his own transformations as highlighting the results of a measurement performed by an observer moving with the system

18 For the details of how this strategy makes in principle undetectable all the first order null results explaining Aberration and Doppler effect see Janssen (1995, Chp. 3, pp 18-22)

19 Lorentz's derivation of this coefficient is particularly interesting. First of all it shows that the mechanism of the partly dragged Ether, postulated by Fresnel, had nothing to do with the coefficient. We could add that the dragging coefficient can be derived from purely relativistic assumptions and this shows that the Ether *in general* had nothing to do with it. Secondly, in a sense, it is not surprising. The approach that led Fresnel to that coefficient was purely phenomenological. He needed a correction factor that accounted for the null result of the first order Ether detection attempts. The complex mechanism of partial dragging of the Ether is a successive integration probably aiming to provide an explanatory heuristics.

20 Precise reconstructions show that some features concerning the angular orientation of the beam splitter with respect to the angle formed by the arms of the interferometer have to be adjusted in order for the setup to yield the interference requested without suffering alterations due to the behaviour associated with light in the classical pre-relativistic theories. See Brown 2001 (pp 4-7).

21 Michelson and Morley arranged the mirrors to have straight fringes of interference. They also used burned sodium as a source of light. (See Brown 2001; Janssen 1995) It was a quite widespread practice at the time to obtain beams whose structure was easy to analyse like such monochromatic light beams. Zeeman did the same as we have seen in Chapter 1.

22 This point has been object of debate in the scholarly literature on the topic. Zahar, for instance, has treated Lorentz's argument as a derivation. Technically, this is simply wrong: Lorentz was not demonstrating the contraction hypothesis. For that matter, I find persuasive the idea that he was just trying to show in what sense the contraction was plausible in his theory. (see Janssen 1995 p28)

23 In physics literature, at the time the convention was V for the velocity of light and p for the velocity of the system. Translation from the Dutch original in Janssen (1995 Chp3., p38); *italics mine*.

24It can be shown that it is not even *ad hoc* as usually under the influence of Popper most of the philosophical literature reads it.(Janssen, 1995; 2000; Brown, 2005)

25 The version of the principles I am using is taken from, Allori,V., Dorato, M., Laudisa, F., Zanghì,N., *La natura delle cose,* 2005, Rome, Carocci. p81. The translation is mine.

26 I should say formally identical to the one offered by Lorentz in 1899. The 1895 theorem does not cover the second order cases.

27 Lorentz later in his career adopted a more relativistic friendly view on the issue of time. This was largely due to his acquaintance with the work of Einstein. Nonetheless his views, somewhat curiously, came to coincide with those of Poincaré. Although he accepted the idea of local time as the time measured by different observer he remain faithful to the assumption that when electromagnetic phenomena are concerned there was a "privileged observer", a privileged reference frame.

28 Harvey Brown's splendid monograph (*Physical Relativity*, Oxford University Press, 2005) has fuelled the recent debate on Special Relativity as a theory in need for a dynamic foundation. In light of such reading my claims might be seen as more contentious.

29 Time dilation has been indeed observed for the first time in 1941 by Rossi and Hall (Rossi, B and D.B., Hall, Phys. Rew. **59**, 223, 1941) in a research on the decay of muons. The time of decay for the particles crossing the atmosphere at a speed close to that of light turned out to be much slower than the time of decay of the particles at rest. They lived approximately ten times longer, in agreement with relativistic predictions.

30 Lorentz., A. H., "Simplified Theory of Electrical and Optical Phenomena in Moving Systems" Proc. Roy. Acad. Amsterdam, **1**, 427, in Shaffner, K.F., *Nineteenth-Century AEther Theories.* New York, Pergamon Press, 1972.

31 Larmor's result is probably the most interesting case of neglected significant contribution to science of that period. The first version of the Invariance equations is published in Larmor, J. (1897): 'On a Dynamical Theory of the Electric and Luminiferous Medium', *Phil. Trans. Roy. Soc.* 190, 205-300. Larmor, J. (1900) *Aether and Matter*. Cambridge University Press, will reproduce the same results in a more accessible form. Notice that the earliest renowned version of the Lorentz invariance –indeed dubbed there for the first time in this way is in Poincaré, H.J., (1904) 'Sur la Dynamique de 1'Electron', *Comptes Rendues*, 140, pp. 1504-8. It is seven years later than Larmor's earliest contribution. See Marcossan, M. N., (1986) "Note on Relativity before Einstein" Brit. J. Phil. Sci. **37**, 232-234

32 Poincaré introduced the expression *Lorentz invariant*. He was also the first who studied the group-theoretic structure related to the transformation that he called *Lorentz group*. Through that study he achieved an exact version of the transformations that he interpreted physically as expressing a version of the principle of relativity. He also improved Lorentz's model of the electron introducing the "pressures" that stabilize its structure. An interesting analysis of his outstanding contributions to this branch of physical science is in Darrigol (1995) "Henri Poincaré's Criticism of *Fien de Siecle* electrodynamics" Stud. Hist. Phi. Mod. Phys. 26, 1- 44

33 These two components were firstly calculated by Abraham in 1903 for his own model of the electromagnetic electron and successively used by Lorentz in his own treatment of the electron structure. For the details see Miller (1981, p.56)

34 The chain of reasoning could be pushed further and indeed it was by the likes of Abraham. If we consider the particle at rest in the Ether, the longitudinal and transversal mass are equal, the only force to be taken into account is the one due to an external field and the form of the equation of motion becomes identical to Newton's Second Law. Thus, in this account the Newtonian law $F = ma$ can be obtained treating its electromagnetic counterpart as more fundamental see Janssen &Mecklenburg, (*forth).* Miller (1981).

35 Lorentz never took the space of electromagnetic phenomena to be anything else than Euclidean.

36 This is part of the reasoning that drove Poincaré to the introduction of the forces that stabilized the electron: the Poincaré pressures.

37 Abraham, M., (1905) *Theorie der Electrizität,* Teubner, Leipzig p 188. Quoted in Janssen & Mecklenburg, forthcoming, p 21

38 See Buchwald, J.Z., (1985) *From Maxwell to Microphysics,* The University of Chicago Press, Chicago

39The recent debate on the (in)consistency of CED, springing from Frisch's (2005) deep analysis of the shortcomings or alleged inconsistencies of the theory, has insisted precisely on the nature of the classical electron having an extended structure. The extent to which is problematic to deal with a charge bearer in CED is witnessed not only by the debate in point but also by the extensive theoretical literature that in the last four decades has tried (unsatisfactorily) to deal with the issue featuring the names of Dirac, Feynman , Rohrilich, Spohn etc. See Vickers, P., (*forthcoming*) "Frisch, Muller and Belot on an Inconsistency in Classical Electrodynamics". Brit.Jour.Phil. Sci.

40 See Rohrlich, F., (1991) *Classical Charged Particles,* Addison Wesley, Menlow Park