EXPERIMENTAL STUDIES ON MASS AND GRAVITATION IN THE EARLY TWENTIETH CENTURY: THE SEARCH FOR NON-NEWTONIAN EFFECTS

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Abstract: From the late nineteenth century to the early twentieth century, before the development and acceptance of the theory of general relativity, much attention was devoted to the experimental search of some hypothetical non-Newtonian gravitational effects. The influences that were investigated included eventual violations of the principle of equivalence between gravitational and inertial masses; the influence of radioactivity on gravitation; the hypothetical absorption of gravity by matter; the influence of temperature on gravitation; and the influence of chemical reactions upon weight. This paper presents an overview of those experimental investigations, which were mostly forgotten.
Keywords: gravitation; mass; non-Newtonian effects; experiments on gravitation

1. INTRODUCTION

From Isaac Newton onwards, it has been generally accepted that the gravitational attraction between two bodies depends only on their masses, distance, and geometrical factors (size and shape of the bodies). However, the young Newton himself suspected that the gravitational force could be influenced by several other factors, and he wrote in one of his notebooks

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(*Quæstiones quædam philosophicæ*, *circa* 1664) a list of experiments that should be tried to check whether some effects did exist:

> Try whither the weight of a body may be altered by heate or cold, by dilatation or condensition, beating, poudering, transfering to severall places or severall heights or placing a hot or heavy body over it or under it or by magnetisme whither leade or its dust spread abroade, whither a plate flat ways or edg ways in heaviest, whither the rays of gravity may bee stopped by refecting or refracting them, if so a perpetuall motion may bee made one of these two ways. (Newton, MS Add. 3996, Cambridge University Library, fol. 121v; McGuire & Tamny, 1983, p. 430)

In his student days, when Newton began to develop his new cosmological outlook, he pondered about the cause of gravity. The notes he took at this time allows us to get an insight into his early thoughts. Following – as it seems – the ideas of Kenelm Digby, Newton speculated about a downwards flow of matter that would press the bodies towards the Earth. According to this hypothesis, there would be a steady flow of particles from the heavenly space towards the centre of the Earth, and from the Earth to the space. Those particles would act upon bodies, through impact, both at their surfaces and through their pores. However, if this were the cause of gravity – so Newton thought – there would be several observable consequences (McGuire & Tamny, 1983, pp. 279-282). The effect of gravity upon a swiftly falling body would be smaller than upon the same body at rest – because the impacts would have a smaller effect. The gravitational push could also, in principle, be altered by a change of the condensation of the body. Hypothetically, the flux of particles could also be altered by heat, by magnetism or other effects.

We don't know whether Newton made or did not make all those tests. However, in his mature writings – more specifically, in the *Principia* – we find no suggestion similar to those that were registered in his Notebook. If gravitation were produced by any kind of penetrating particles, one could expect that the gravitational force would not be *exactly* proportional to the amount of matter of very large bodies – such as the planets and the Sun. However, Newton noticed that this proporcionality seemed to hold. This was a strong argument against any "ether stream" hypothesis.

In the century following the publication of the *Principia*, as Newton's gravitational theory became widely accepted, it seemed to most people that ho hypothesis was needed to explain gravitational forces. The concept of forces at a distance ("attraction", as it was simply called) did not lead to any search for strange effects.

However, in the 19th century, the situation slowly changed. The study of electricity and magnetism led to new ideas – and, although there were approaches such as Weber's, that used distant action, Maxwell's successful theory introduced an intervening aether. The discovery of energy conservation was regarded by several people – including Faraday – as a sign of an underlying unity of all physical forces. Accordingly, there could be a relation between electromagnetism and gravitation, in two relevant senses: there could be a similarity between their modes of action; and there could be gravito-electromagnetic phaenomena (as there were electro-magnetic effects). Under the influence of those developments, there arose theoretical speculations for a *mechanism* of gravitation and a parallel search for non-Newtonian effects.

Towards the end of the 19th century, there was an impressive rise of speculations concerning the nature and mode of action of gravitation. Most of those speculations were mere explanatory hypotheses: they just tried to explain known facts, without suggesting any new phaenomena. However, the bare assumption of any kind of mediated gravitational action opened the way to considerations about the possibility of influencing the gravitational force. Towards the end of the 19th century, a new field of research was developing: the experimental study of gravitation and the search for non-Newtonian effects (Woodward, 1972).

From the last decade of the 19th century to the decade of 1920, there was an intensive exploratory experimental research on the properties of mass and gravitation. Most of this work has been forgotten, since no new regular effects were observed. Besides that, the rise and development of the theory of general relativity – which did not predict any of those effects – led to a fast neglect of that exploratory activity. However, several interesting investigations have been developed by a lot of competent researchers. The history of those researches deserves a detailed study.

The main episodes that I have been able to detect are shortly described below[1].

2. CONSERVATION OF MASS IN CHEMICAL REACTIONS

During the 19th century, there was a general acceptance of the law of mass conservation in chemical reactions. However, in 1891 Damian Kreichgauer observed small variations of the weight of a closed system where a chemical reaction occurred. The observed changes were of about 1/20,000,000. Shortly after this publication, Hans Landolt began a series of tests of the law of mass conservation (see Martins, 1993; Martins, 2019). His first results were presented in 1893. He observed weight

[1] Most of this paper was contained in a research project written in 1994. Its Introduction was added in 1995, when I presented a talk on this subject at the Laboratoire de Gravitation et Cosmologie Relativistes, Université Pierre et Marie Curie (Paris, France). The paper has not been previously published. Only a shorter version, in Portugueses, appeared a few years later (Martins, 1997). When the paper was written, I had already published accounts of the episodes described in sections 2 and 4, in Portuguese. I have not expanded or updated the content of the paper; I have only made slight changes. I also added the bibliographic references of some of my later publications on those subjects.

changes as large as 1/1,000,000 in chemical reactions produced inside hermetically closed glass tubes.

Landolt's work was reproduced in several journals. Several researchers tried to reproduce his experiments, with different results. Fernando Sanford and Lilian Ray (1897, 1898) and Antonino Lo Surdo (1904, 1906) observed no change of weight. Adolf Heydweiller (1900, 1901) detected relevant weight reductions in several experiments.

All those experiments measured the weight changes (that is, variation of passive gravitational mass) of the system containing the chemical substances. Lord Rayleigh (1901) suggested an important question: are there changes of inertia related to those weight changes? This question was investigated by Joly (1903), who used a delicate torsion balance. He detected a regular effect, but much smaller than was expected from the previous experiments.

Landolt resumed his experiments (1906). He was able to build a balance that could detect mass changes of 1/10,000,000. With an improved experimental technique, some reactions now exhibited no significative mass change.

At this time, the theory of relativity was being developed and there appeared the famous mass-energy relation $E=m.c^2$. Max Planck (1907) discussed the possibility that the observed effect could be due to energy exchanges, but he computed that the relativistic effect would be much smaller than that measured by Landolt.

Landolt (1908) and Constantin Zenghelis (1909) discussed the possibility that the observed mass variation could be due to the passage of small quantities of matter through the glass of the vessels. Landolt also studied the effect of small temperature and humidity variations in the experiments. After the elimination of several sources of systematic error, the measured mass variations were gradually reduced – but not eliminated.

After Landolt's death, in 1910, all those studies have been quickly forgotten. It seems that there was only one single new experiment, by John Manley (1913). He reproduced those of

Landolt's experiments that had produced the smallest mass variations and he observed no change of weight greater than 1/100,000,000.

Several years later, Roland von Eötvös and his group (1922) published some measurements of the ratio of inertial and gravitational masses for some of the chemical substances used by Landolt and Heydweiller. No anomalies were observed. The conclusion was that, within the limits of the experimental error (1/100,000,000) there was no change of the ratio of inertial to gravitational mass in chemical reactions.

3. INFLUENCE OF TEMPERATURE ON MASS AND GRAVITATION

It is well known that during the 18th century there was much speculation about the role of heat (caloric, flogiston) in chemical reactions and about its weight. The chemical aspects of this subject were elucidated by the works of Lavoisier, Cavendish, etc. On the physical side, the subject was investigated by Count Rumford (1799). He established that the freezing of water produces no change of its weight, within the experimental errors of 1/1,000,000.

During the 19th century, Augustin Fresnel (1825) and other researchers have observed an effect of repulsion due to the heating of bodies in rarefied air. William Crookes (1874) observed the same kind of effect. After a series of experiments (Crookes 1875-1879), he concluded that the repulsion was due to the residual air (radiometer effect) – it was not a direct repulsion produced by hot bodies.

Some anomalies were also observed in the measurement of the gravitational constant. In 1883, William Hicks used the date of Baily's 1842 research on gravitation and noticed a correlation between temperature and the observed attraction in a Cavendish balance. There seemed to be a steady increase of attraction with temperature – a variation of 7,8% for a 100° F.

Hick's paper motivated John Henry Poynting and Percy Phillips (1905) to develop measurements of weight of bodies at different temperatures. They have observed no regular effect. Hicks himself also developed an apparatus to measure the influence of temperature on weight. The measurements were made by Leonard Southerns (1907) who was unable to find any regular effect, too.

Those results were not incompatible with Hicks' observations, because only the temperature of the attracted test body was changed in the experiments of Poynting and Phillips, and of Southerns. It was suggested that they were inconclusive, since the temperature of the Earth could not be changed.

In 1916, Philip Shaw published the result of a long series of measurements of gravitational attraction, using a torsion balance. He detected a regular increase of attraction with temperature, corresponding to 0,12% for a variation of 100° C. Shaw's work was presented to the Royal Society by Boys – the greatest authority in gravitational measurements of that time.

There was an immediate reaction of the community. Several letters were published in *Nature*, discussing theoretical aspects of the relation between temperature and gravitation. No other researcher tried to repeat Shaw's experiments. But Shaw himself, with the help of Cecil Hayes (1917), improved his measurements and the observed effect was about 10% greater than the previous results. But Shaw was not satisfied with the experiment. After improving the control of the position of the attracting bodies, the effect vanished, as described in the last paper by Shaw and Norman Davy (1923). The final conclusion was that any thermal effect must be smaller than $2x10^{-6}$/°C.

4. ABSORPTION OF GRAVITY BY MATTER

At the end of the 19th century several authors speculated about possible effects of intervening matter between two attracting bodies (see Martins, 1993; Martins, 1999; Martins, 2002a; Martins, 2002b; Martins, 2004). John Henry Poynting (1900) suggested that matter could affect the gravitational force between two bodies either as occurs in electromagnetism, or that the "gravitational rays" could be absorbed as light or radiation.

In 1897, Louis Austin and Charles Thwing studied the effect of interposing screens of different materials between the attracting bodies in a torsion balance. The attraction of the screen itself was compensated by the experimental arrangement. Any temperature changes were avoided, together with several other experimental precautions.

Austin and Thwing tested the effect of different groups of substances, such as lead and mercury (because of their high density) or water, alcohol and glycerin (for their high dielectric constant). Only in the case of iron screens there was a measured effect greater than the expected errors (of about 1/500). The conclusion was that there was no effect similar to "gravitational permeability" and that the iron effect was spurious (due to magnetic – not gravitational – forces).

Fritz Laager, in 1904, published the results of similar experiments with null results. He used spherical shells around the test bodies, in order to avoid the attraction of the interposed matter. In 1908, Theodor Erismann also published the result of investigations of the same kind, with no effect greater than the experimental errors (of about 1/1,000).

The next year, Crémieu (1905) described a strange effect. He suspended small olive oil drops in a solution of water and alcohol. The density of the solution was equal to the density of the drops and they remained in equilibrium in this solution. However, after some time, the drops began to approach to one another. There was no classical explanation for this phenomenon: the approach could not be ascribed to gravitation, capillary or hydrodynamic effects.

These observations led Victor Crémieu to measure gravitational forces inside a liquid, using a Cavendish balance (Crémieu, 1905-1907). There seemed to be an increase of the gravitational attraction, in water, of about 7%. But after a long series of investigations, Crémieu found some unexpected problems with the experiment. He afterward concluded that it is impossible to compare the experiments inside water to experiments in air because of systematic errors amounting up to 10% (Crémieu 1909-1917).

In 1909, Hugo von Seelinger suggested that the attraction between the Moon and the Sun could decrease during eclipses, due to the absorption of gravity by the Earth. Kurt Bottlinger (1912) developed the theory of this effect and compared the computed effect to observed irregularities in the longitude of the Moon. There was a nice agreement, and Bottlinger computed that the maximum decrease of gravitational attraction between the Moon and the Sun was of 1/60,000.

Bottlinger's results were criticized by Willem De Sitter (1912, 1913). Using slightly different auxiliary hypotheses, De Sitter obtained results that were similar to those of Bottlinger for small time periods, but widely different for large periods. However, latter studies by Bottlinger (1914) showed even better agreement between theory and observation than his previous results.

The Italian physicist Quirino Majorana brought the problem back to laboratory. First, from astronomical data, he was able to limit the value of the gravitational absorption of gravity to 7.65×10^{-12} cm^2/g (Majorana 1919). He then devised very delicate experiments to detect this small effect. His measurements, using mercury and lead, led to absorption constants of 6.7×10^{-12} and 2.5×10^{-12} cm^2/g, respectively (Majorana 1919-1921).

Majorana's experiments were discussed by Henry Norris Russell (1921). He argued that the astronomical consequences of the effect would be too high to escape notice. However, Eddington (1922) showed that Russell's arguments were not conclusive. The main problem of the concept of gravitational absorption, according to Arthur Eddington, would be the possibility of a gravitational perpetual motion.

No other scientist repeated Majorana's experiments. Roland von Eötvös *et al*. (1922) tried to detect gravitational absorption using a torsion balance, with null results. However, even after the improvement of his instruments, Majorana still obtained gravity absorptions greater than 10^{-12} in 1930.

5. THE MASS OF RADIOACTIVE SUBSTANCES

The discovery of radioactivity led to the suspicion that several basic physical laws should be changed (Lodge 1912). The continuous heat developed by radioactive substances (first measured in 1903 by Pierre Curie and Albert Laborde), was very difficult to explain. One of the several suggested explanations was that radioactive bodies obtain their energy from the gravitational field – therefore their weight should exhibit some kind of anomaly.

Adolf Heydweiller (1902) was the first to test the constancy of weigh of radioactive substances. He suspended a glass tube with 5 g of strongly radioactive substance to a balance and observed a decrease of its weight (-0.02 mg per day). After a few weeks the weight reduction amounted to 0.5 mg.

Heydweiller tried to explain this decrease. The gravitational potential energy of 0.02 mg corresponds to 1.2×10^{7} erg. The heat generated by the radioactive material amounted to about 10^{7} erg per day. Heydweiller concluded that the radioactive body transformed its gravitational energy in heat.

This experiment was repeated by Ernst Dorn (1903). He used a small piece of radioactive material (just 30 mg) and observed a weight reduction of 0.001 mg after three months. Since his sample was ten times more radioactive than Heydweiller's, it should have exhibited a much higher weight variation, according to the energy transformation hypothesis.

Robert Geigel (1903), Carl Forch (1903) and Walter Kaufmann (1903) tested the effect of placing a radioactive body between a test body and the Earth. Geigel observed a reduction of the weight of the test body and ascribed the effect to the absorption of "gravitational rays". Foch observed no effect. Kaufmann observed effects similar to those measured by Geigel, but explained the weight reduction by convection currents produced by the heat generated by the radioactive substance.

A few years later, Georges Sagnac (1906) tried to detect any difference between the inertial masses of equal weights of barium and radium compounds. His experiment could observe only large differences (of about 1%). No irregularity was noticed.

Joseph John Thomson (1909) and Leonard Southerns (1911) compared the ratios of gravitational to inertial mass of radioactive bodies and their decay products (such as lead). Thomson's pendulum experiments established an upper limit of 1/2,000 to any variation of this ratio. Southerns, using Bessel's method, obtained an upper limit of 1/200,000.

Eötvös also tried to detect any change of the ratio of gravitational to inertial mass of radioactive substances, using a torsion balance. The experimental setup could observe changes of 1/2,000,000. No effect was detected (Eötvös *et al.*, 1922). Zeeman (1918) has also used a torsion balance to test the same effect, with a similar result.

6. VIOLATION OF THE PRINCIPLE OF EQUIVALENCE

Several of the experiments on mass and weight of the early 20th century were motivated by speculations concerning the existence of gravitational waves or rays. In 1911, Charles Brush suggested that gravitation is produced by electromagnetic waves of very short wavelength. Those waves should be able to pass through matter with little absorption, except in the case of a few substances. Diamagnetic bodies – such as bismuth – should, however, exhibit high absorption and anomalous gravitational effects (Brush, 1914).

Brush compared the gravitational attractions of zinc and bismuth, using a Cavendish balance. According to his report (Brush 1921-1922), the attraction produced by bismuth was only 72% of the attraction produced by an equivalent weight of zinc. He also made pendulum experiments and measured a difference of about 1/50,000 between the ratio of inertial and gravitational mass for those substances.

Harold Potter (1922) and Harold Wilson (1922) tested the proportionality between inertial and gravitational mass for bismuth and other substances and detected no anomaly. Potter's experiments were not sensitive enough, but Wilson, using an Eötvös balance, reached a sensitivity of 1/1,000,0000.

Potter produced a series of further experiments (Potter, 1923, 1927) to test the proportionality between inertial and gravitational mass of several substances. The main motivation of those investigations was to test whether the nuclear structure of the chemical elements could affect their mass ratio. The conjecture that hydrogen could have an anomalous behaviour had been suggested by Owen Richardson (1910, 1922). However, Potter was unable to detect any effect.

Notwithstanding the negative results of other researchers, Brush went on with his studies. In a series of articles (Brush, 1923-1928) he presented further anomalous results. In a free fall experiment, he measured a difference between the accelerations of lead and aluminum of about 1/10,000. The crystalline state of the material also seemed to affect the results.

Brush speculated that gravitational attraction should be produced by gravitational waves and that some substances could transform the energy of those waves and exhibit a spontaneous heating. Using a calorimeter (Brush, 1926) he indeed detected that several non-radioactive substances maintained a higher temperature than their environment. This was the case for several complex silicates. He also described that those substances had a smaller gravitational acceleration.

Brush's work has been largely ignored by the scientific community both at the time of his original publications and afterwards.

7. OTHER INVESTIGATIONS

Several other researches were developed during the period from the last decade of the 19th century to about 1920. Arthur

Mackenzie (1895), John Henry Poynting and Peter Gray (1899), Pter Zeeman (1918) and Paul Heyl (1924) looked for the existence of an anisotropy of the gravitational attraction of crystals. No regular effect was detected.

A secular increase of the gravitational acceleration at Paris was claimed by Édouard Caspari in 1895. He used the results of measurements from 1794 to 1890 and obtained a variation of about 1/8,000 in one century. Karl Koch, in 1904, described the variation of the gravitational acceleration at Stuttgart. He measured an increase of about 1/300,000 in four years – a value consistent with Caspari's results.

Periodical variations of the gravitational field of the Earth have been claimed by several authors. Gerald Drossbach (1895) observed a daily variation of gravity of about 1/1,200. Ralph Hartsough (1922) observed a small effect that was ascribed to lunar tides. Leopold Courvoisier (1927) claimed that there was a daily variation of gravity due to the Lorentz contraction of the Earth (Martins, 2011). Rudolf Tomaschek and Walter Schaffernicht (1932) looked for short period variations of the gravitational field of the Earth. They were able to measure the tidal effects of Moon and Sun and found no anomalous result. A strange effect was however claimed by Russel Goudey (1922). He described an annual variation of the gravitational acceleration of about 1/1,000,000, detected by the comparison between astronomical observations and pendulum measurements.

A few experiments tried to find any influence of electricity or magnetism upon gravitation. In 1909, Southerns detected a difference between the weight of bodies with positive and negative electrical charge. L. Simons (1922) made experiments very similar to Southerns' and obtained no anomalous result. Paul Agnew and William Bishop (1912) measured the weight of a capacitor and found no difference between the charged and uncharged states. Francis Nipher (1917) used a shielded torsion balance and described a strong influence of the electric potential of the system upon gravitational attraction.

Louis Bauer (1907, 1909) noticed that the weight of a magnet varied with its position, even in a region where the magnetic field of the Earth was uniform. He also measured a weight difference between unmagnetized and magnetized iron. Lloyd (1909) repeated Bauer's experiments and noticed no anomaly.

Several authors suggested, in the 19th century, that the gravitational forces could be influenced by the velocity of the attracting bodies. In 1896, the brothers Benedict and Immanuel Friedländer tested the influence of a gyroscope upon a torsion balance. They found a small effect. August Föppl (1905) and Victor Crémieu (1917) also tried to measure the influence of a gyroscope upon a common balance and upon a torsion balance. They noticed no effect.

8. GENERAL COMMENTS

This short overview shows that from the end of the 19th century to the 1920's there has been intense experimental research on gravitation and the search for several non-Newtonian effects. It seems that those episodes have been forgotten by both physicists and historians of science[2].

This kind of experimental effort subsides and seems to disappear after 1930. It is likely that the confirmation of general relativity was the reason of this historical change. The conjectured anomalous effects that were investigated were not compatible with the theory of general relativity (or, if compatible, the predicted effects were several orders of magnitude smaller than the available experimental sensibility). As confidence in the theory of general relativity grew, the search for such effects was regarded as worthless effort[3].

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[2] Some of the above described experiments have been cited in recent review papers on gravitation (see, for instance, Cook 1988). But it seems that no systematic and critical study of those episodes has ever been produced.

[3] This is a historical hypothesis that should be investigated. In the case of Landolt's studies on mass variation in chemical reactions, there was

It seems to me that this set of researches, together with their broader scientific context, deserves a careful study. Maybe some of the scientists that devoted their time to those experiments were just cranks[4]. But some of them were highly respected scientists. It seems that the search for non-Newtonian gravitational effects was probably regarded as a respectable, relevant part of scientific research during about three decades.

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a clear influence of the special theory of relativity (the mass-energy relation) in the dismissal of the anomalous effect.

[4] Brush is a likely candidate to this group.

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[6] This is a short abstract of the paper of equal title published in the *Proceedings of the American Philosophical Society*.

[7] This paper is a verbatim reproduction of the communication to the *Société Française de Physique* (1905 c).

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