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Einstein's Gyros

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Einstein's life-long effort to develop a theory that unifies gravitation and electromagnetism was not a purely theoretical enterprise. The technical environment of a gyrocompass factory triggered his search for a novel connection between the rotation of an electrically uncharged body and its magnetic field. The dimensional equality of the electric unit charge and the mass of a body multiplied by the square root of the gravitational constant hinted at a nonsensical electric charge, to which he gave the name "ghost charge." He felt that he found a fundamental unity of gravitating mass and electricity, a hitherto undiscovered law of nature. Two physicists offered to assist him in finding evidence of this peculiar electric charge. Peter Pringsheim performed experiments with deionized gases and Teodor Schlomka made measurements of the earth's magnetic field from balloons and airplanes; Schlomka also executed a thorough literature search and placed Einstein's efforts in their historical context.

Key words: Einstein; electrogravitational coupling; rotation and magnetism; terrestrial magnetic field.

In 1992, W. Schröder and H. J. Treder called attention to Albert Einstein's short but fascinating detour into geophysics.[1] At the time, they were able to rely only on published papers—in the case of Einstein, on a footnote in his paper on the ether.

Since that time, Einstein's correspondence of the period has been published and we can draw a more detailed picture of why he embarked on a field so seemingly distant from his main interests. In October 1921, two engineers of the gyrocompass factory of Hermann Anschütz-Kaempfe in Kiel, Germany, launched a series of experiments. They rotated a brass cylinder around its axis, heated it by hot oil, and wondered whether a magnetic field arose around it.[2] It seemed to be a routine test, for there were several gyroscopes rotating in each gyrocompass the firm manufactured and if a magnetic field were to be produced by their mere rotation, it would seriously influence their operation.

Their reason for pursuing these experiments, however, was different: "Even though I cannot yet imagine clearly that a positive effect is to be expected, it is still for me the only reasonable possibility to bring the *heat current* together with the

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earth currents, since the latter can only be caused by an *irreversible* process." These lines were written in December by Albert Einstein, who had persuaded the engineers to perform the experiment.[3] Heat currents? Earth currents?

In a letter written to Hermann Anschütz-Kaempfe, the owner of the factory, Einstein called the possible positive result "of enormous interest."[4] Did he mean this with regard to the development of the gyrocompass? No. When, in June 1922, after several failed attempts, the engineers had given up, Einstein remarked, "I thank you very much for repeating the heat-rotation experiment. In thinking about the nature of the Earth's field, I have got bogged down in improbabilities."[5] By "field," he meant the magnetic field of the earth. Thus, the goal of the experiment was to check on a laboratory scale whether the sources of the geomagnetic field are the electric currents circulating in the earth that are sustained by its internal heat. However, before continuing, let us see how Einstein found himself at a gyrocompass factory.

In November 1914, Elmer Sperry, an American inventor, offered his gyrocompass to the German navy. Because, in the decade before the Great War, Germany intended to develop a navy comparable to or even more impressive than the British navy, substantial business was at stake. This detail was sufficient for Anschütz, the inventor of the first usable gyrocompass, to sue Sperry for infringing two of his patents.

The case was to be decided in Berlin, and the court wanted an impartial expert living not far from Berlin to assist by providing his opinion. They chose Einstein from among a list of candidates, not only because he was a resident of the city but perhaps also because it was known that Einstein had been a first-class expert in the Swiss Patent Office. At the first hearing, Einstein's verbal opinion was confused and superficial, and the written opinion he provided at the court's request was no better. However, at the third hearing in August 1915, after adequate preparation, he unequivocally proved that Sperry's gyrocompass fell in the area protected by Anschütz's two patents, and Anschütz won the case.[6]

Thus began an almost two-decade friendship between Einstein and Anschütz. Einstein served as Anschütz's expert in several subsequent patent cases, and, from 1919 onward, he spent part of his summer holidays in Anschütz's factory in Kiel, often with his sons, where he participated in the development of the gyrocompass to such an extent that from 1928 to 1938, he was given patent fees for his contributions to German patent DE 394667.[7]

On Gyroscopes

These cooperative efforts were useful for both Anschütz and Einstein. In addition to hospitality, a luxury apartment in Kiel, and a piano and sailing boat at his disposal (all of which were arranged expressly for him), Einstein enjoyed the intellectual challenge of the gyrocompass itself. Pondering actual gyroscopes, two special gyros emerged in his mind's eye: one the size of a molecule and another the size of earth.[8]

André-Marie Ampère had hatched the idea of the molecular gyro in 1820; he attributed the magnetism of ferromagnetic and paramagnetic materials to circular currents flowing in their molecules.[9] Einstein decided to examine this idea experimentally in collaboration with Johannes W. de Haas, Hendrik A. Lorentz's son-in-law, who was working at the University of Berlin at the end of a visiting appointment there and with no position in his home in the Netherlands. Apparently Lorentz mentioned this problem to Einstein because in the summer of 1913 Einstein, in the process of moving from the University of Zurich to Berlin, apologized: "Regarding your son-in-law, I do not know how to begin at the moment, because I have neither an institute, nor an assistant in Berlin … perhaps I may still be able to do something for him one of these days."[10] And because Einstein did not get an institute at the university, he used his acquaintance with the president of the Physikalisch-Technische Reichsanstalt, Emil Warburg, to secure a place for their experiment. Warburg was happy to host an enterprise in pure science and paid de Haas from the money he had raised from industry.[11]

The experiment involved suspending an iron cylinder in a solenoidal coil. By reversing the current in the coil according to the proper frequency of the cylinder, they expected a to-and-fro swing that would prove that these circular currents, as revolving electrons with inertial mass (that is, randomly directed gyroscopes), turn in the same direction under the influence of the outer magnetic field, and that these changes in angular momenta are balanced by the change of the angular momentum of the cylinder as a whole, as required by conservation of momentum. The experiment proved that a changing magnetic field does make a ferromagnetic mass turn.[12]

In their theoretical considerations, they mentioned that a different experiment, namely, the reverse of theirs, would also check the existence of Ampère's currents: a rotated mass could be expected to induce a magnetic field. They added that, from this, it would follow that "a magnetomotoric field corresponds to the Earth's rotation which shows in north-south direction and has an approximate intensity of 10^{-11}. Maybe this is the cause of the rough coincidence of the magnetic and rotational axes of the Earth."[13] The careful formulation may indicate that this reverse effect could be expected if the inner mass of the earth were rich in ferromagnetic materials. However, when Einstein informed Hendrik A. Lorentz of the positive result, he was less reserved, stating: "we have also found the reason why the magnetic axis of the Earth almost coincides with its axis of rotation."[14]

The reverse experiment, magnetization by rotation, had already been performed in 1909 by Samuel J. Barnett. In contrast to Einstein, Barnett had made it explicit at the outset that he aimed to find the cause of terrestrial magnetism: "Some time ago, while thinking about the origin of the Earth's magnetism, it occurred to me that any magnetic substance must, according to current theory, become magnetized by receiving an angular velocity."[15] However, Einstein took note of Barnett's two papers published in 1915—only a half year after the publication of his paper with De Haas.[16] Einstein remarked that he and De Haas wanted to see whether a torque appeared when they changed the magnetization of a cylinder,[17] whereas Barnett's goal was the reverse: to induce magnetism in a metal test body by putting it in a rapid rotation, an experiment that Einstein and De Haas considered "incomparably more difficult" than their own.[18] Einstein also learned from Barnett's papers that James Clerk Maxwell had been the first to guess that magnets would behave like gyroscopes if the Ampère currents in them had material character.

In addition to the qualitative result of the existence of molecular currents, another, quantitative result of the experiments of Einstein, Barnett, and others was the determination of the gyromagnetic ratio, extensively discussed by Peter Galison.[19]

As we saw, the finding that circulating electrons are responsible for molecular and macroscopic magnetism led Einstein to the idea that geomagnetism should also be the result of charges rotating with the earth. His next attack on the case of geomagnetism was launched almost a decade later, in 1923.

I will not reconstruct the desperate—in Barnett's case obsessive—efforts to measure the gyromagnetic ratio, but I hope to show that Einstein's experiments with the "molecular gyros" were warming up exercises for his use of "cosmic gyros," the sun and the earth, for finding a connection between the (translational and rotational) acceleration of an uncharged mass and its magnetism, by which he thought indicated a path toward grand unification.

Electrically Charged Neutral Matter

There is a rumor that "you have a new theory on the connection of the metric and electromagnetic field," wrote Max Born to Einstein in the spring of 1923, "which should lead to a relation between gravitation and the Earth's field."[20] In his reply, Einstein confirmed this rumor: "currently I have a very interesting problem connected with the affine field theory. Prospects exist for understanding the terrestrial magnetic field and the electromagnetic budget of the Earth and testing this interpretation experimentally."[21] This was a hint at an experiment Hermann Mark had performed for him. The title on the first page of a manuscript reveals its general purpose: "On a plausible hypothesis on the source of the geomagnetic field and its experimental refutation."[22] Even though only this single page from among three or four survived the Gestapo raid of Mark's home after the Nazi seizure of power, we can learn from Einstein's correspondence and from his appendix written to the German translation of Arthur Stanley Eddington's book that the "plausible hypothesis" was the existence of a "space charge," in addition to the corpuscular electric charge and current (electrons).[23] He arrived at field equations different from Eddington's, and one of the two seemed to contradict experience, "for it requires that the electromagnetic field vanish wherever the charge density vanishes. This objection however does not hold, since in fact we do not know whether very small densities of the electrically charged masses aren't associated with electromagnetic fields."[24] Consequently, Mark's task must have been to prove or disprove the existence of such a charge. The experiment was performed over almost a year; it was August 18, 1923, when Einstein first mentioned that he was to perform an experiment "on space charge."[25]

The connection between rotation and terrestrial magnetism bewitched Einstein's imagination in the following years. After failing to finding a space charge in August 1924, he proposed an experiment to Peter Pringsheim, a physicist at the University of Berlin. The question was whether the cause of geomagnetism were electric charges of neutral masses revolving with the earth. We can reconstruct what the experiment might have been from a single letter of Pringsheim's.[26]

To test whether there is something similar to electricity in an uncharged body that would interact with the geomagnetic field, Pringsheim suspended a steel sphere 30 mm in diameter on a wire and made it swing, that is, made it move with acceleration, without torsional rotation. However, the sphere started to rotate when magnetized and swung either in the east-west or in north-south directions. This was "just the expected effect," Pringsheim noted. Apparently, the magnetized version of the experiment was performed to check whether the sphere, when magnetized, exhibited the expected torsional swing. However, the disturbances of the laboratory environment were difficult to eliminate and a conclusive result with a non-magnetized sphere was not achieved.

As a consequence of this failure, Einstein realized that only a radically new idea would help. "Overall, it seems today that we are much farther away from an understanding of the electromagnetic elementary laws than seemed to be the case at the beginning of this century," he observed in October 1924 in a lecture in Lucerne.[27] According to Maxwell's theory, he expounded, the magnetic fields of the earth and the sun should be the result of an electric current flowing in a direction opposite to their circulation. However, because neither conductive nor convective currents can exist within them in adequate intensity, there is nothing left but to attribute the magnetic field to the cyclic motion of electrically neutral matter, even though Maxwell's theory does not allow such a hypothesis. "Nature indicates here a fundamental relationship which has not been dealt with theoretically," Einstein said.[28] He even proposed a formula:

$$dh = \left(\sqrt{K}/_{c} \times dm \times {}^{[v,\ r]}/_{r^2}\right),$$

where dh is the magnetic field induced by a mass dm that rotates at a peripheral velocity v at a distance r from the center of its rotation, K is the gravitational constant, and c is the velocity of light. This relationship may stand only for cyclic motions and as a first approximation, he remarked. Regardless, the formula correctly yields the magnitude of the ratio between the sun's and earth's magnetic fields, and when applied to the rotating earth, the order of magnitude of the geomagnetic field also comes out correctly. "These relations deserve attention, but they could be a matter of chance," he added carefully.[29]

Auguste Piccard, a member of the audience at Einstein's Lucerne lecture, later remembered that in the discussion following the lecture, Einstein explained the curious formula by hypothesizing that the charge of the proton is larger than that of the electron; consequently, there would be more electrons in an electrostatically neutral material than protons, and the circulation of these charges with the earth and sun would be sufficient to explain their magnetic fields.[30]

Einstein repeated these considerations in a letter to Louis A. Bauer, director of the Department of Research in Terrestrial Magnetism at the Carnegie Institution in Washington. "It seems to me as good as excluded," he wrote, "that the magnetic field of the Earth, the sun and sunspots can be explained by electric conduction or convection currents. The impression is much rather that rotating neutral matter would be magnetically active in a similar way to a negative electric charge proportional to the matter's density."[31] However, he was unable to justify this strange relationship with a reasonable theory.

Piccard was ready to examine this idea. Einstein proposed to test whether electric charge remains in a completely neutral (deionized) gas. Because the expected effect was of the magnitude of 10^{-19}, Piccard embarked upon a bold enterprise.[32] He evaporated a mass of water to produce ion-free vapor, condensed it quickly in an insulated vessel that was connected to an electrometer,[33] and expected an electric charge. The experiments lasted for months, and Piccard, working in Brussels, kept Einstein informed. The final result did not prove the hypothesis, but Einstein comforted himself by saying, "it actually is thoughtlessness to believe a priori that protons and electrons would have the same charge.... It does not matter if a hope has to be buried; it joins a large and good company,"[34] referring to his earlier, similarly futile ideas.

Einstein also noted at the Lucerne lecture that any unification of the theory of gravitation (general relativity) with Maxwell's theory would entail that this theory should be modified such that the magnetic field induced by electric charges circulating with the earth would not be exactly perpendicular to the plane of their circulation; that is, the magnetic field would not be parallel to the axis of rotation of the earth.

Louis Bauer and Albert Wigand found deviations when checking their earlier measurements,[35] but, as Einstein wrote to his friend, Paul Ehrenfest near the end of November 1924, "The business is completely foggy and groggy."[36] The next February, Einstein confessed why he was so interested in geomagnetism: "I myself have been grappling with this problem [the unification of gravitation and electromagnetism] entirely in vain up till now. It often seems to me that the Earth's magnetic field is based on a still unknown relationship between gravitation and electromagnetism; but I cannot find my way out of inconsistencies."[37]

In September 1926, at a scientific meeting in Düsseldorf, Einstein was approached by Teodor Schlomka, a young specialist in atmospheric electricity and geomagnetism from Jena. Their conversation turned to Einstein's idea of how neutral matter can have a "ghost charge," as Einstein called it. As Schlomka recounted in January 1927,[38] Einstein had talked with him at the time about his plan to check whether an observer moving with respect to the earth's surface will detect a different magnetic field from another observer at rest. Einstein had even mentioned that he had performed an "experiment" on a Berlin suburban train.

We learn further details of this "experiment" from Einstein's secretary, who was asked to buy tickets on a north-south line. Einstein's "experimental setup" consisted of a pocket compass with which he intended to check whether he could detect a deviation from true magnetic north when moving northwards. He even requested the officers entering the cabin to keep their swords still to avoid influencing the local magnetic field. Perhaps it is no surprise that the "experiment" failed.[39]

No deviation of compasses from true north had been observed on Atlantic liners (moving in east-west and west-east directions), Einstein told Schlomka. Apparently, he had asked this question of the ship captains during his sea travels to South America for a lecture tour in April and May 1925! From all these observations, he concluded that the source of the geomagnetic field could not be a "ghost charge" circulating with the earth.

Schlomka considered this conclusion premature. According to his calculations, when moving in the east-west or west-east direction, a change in the direction of the magnetic field would not be observed, but a change in its intensity would, supposing that we could move with a velocity comparable to that of the rotation of the earth. When moving in the north-south direction, the 10 m/sec velocity of a commuter would only produce a field that would deflect the compass needle by 2°, which, owing to the disturbing effects of surrounding iron structure and the lack of precision of Einstein's experimental setup, would be difficult to observe. Moreover, on ocean liners and airplanes, deviations of a few degrees would be overshadowed by waves and air turbulence despite the higher speed of travel. In addition, ships en route to the Americas travel along lower geographic latitudes, where the expected effect is smaller. However, when flying from the south to the north, a velocity of 30 m/sec would be sufficient for obtaining a deviation of approximately 6°; with a velocity of 40 m/sec, a deviation of almost 8° could be achieved.

In addition to his calculations, Schlomka performed a thorough literature search, from which Einstein could learn he was not the first to attempt unifying gravity and magnetism in this peculiar manner. The "ghost charge" could be explained, Schlomka wrote, by three theories:

i) Octaviano F. Mossotti, Friedrich Zöllner, Wilhelm Weber, and Lorentz supposed that the attraction between opposite electric charges is somewhat greater than the repulsion between identical charges. Based on their results, Richard Gans and Fritz Wacker developed a theory according to which a body is "uncharged" (that is, no force acts upon it in a homogeneous electric field) when there is a somewhat more negative charge in each of its volume elements than a positive charge; conversely, when there are as many positive charges in each of its volume elements as negative ones, the body will have a surplus positive charge.[40]

ii) The above theory was modified by Arthur Schuster, Schlomka continued, by supposing that the repulsion of two negative charges is 1α, and that of two positive charges is 1β, while the attraction of opposite charges is 1. This difference between attraction and repulsion appears as a net electric attraction between two neutral bodies, which may be interpreted as gravitation.[41] To explain geomagnetism, Schlomka concluded, it would be sufficient to suppose that the positive charges repel each other less than the negatives by 10^{-21} ($\beta - \alpha = 10^{-21}$).

iii) In 1926, William Swann modified the Maxwell–Lorentz equations by taking into consideration Lorentz's hypothesis regarding the difference between the attraction and repulsion of elementary charges. He set up the field equations for negative and positive charges separately and added two terms to the current density in the field equations for positive electricity, leaving the equations for negative electricity unchanged. He was thus able to explain not only geomagnetism but also geoelectricity. In addition, his theory satisfied special relativity and predicted that the charge generated by a laboratory-scale neutral sphere rotating at the highest attainable velocity would be too small to be measured.[42]

These three theories conclude that geomagnetism is produced by the circulation of electric charges. Schlomka offered to test this conclusion via measurements in flight. In his reply to Schlomka, Einstein considered the expected effect too small to be observed, and wrote: "if we neglect any theory and suppose that the magnetic field is produced directly by the mere rotation of the mass, then it can also be expected that the translational motion of the mass also produces magnetic field.… I think that the Americans should have observed this rough effect with their wooden motor ship used for magnetic measurements."[43] He was referring to the nonmagnetic research vessel, "Carnegie," of the Department of Research in Terrestrial Magnetism at the Carnegie Institution. Because he was skeptical of Schlomka's offer, Einstein requested a detailed research program,[44] which Schlomka presented.[45] "Your experiment would turn out positive," Einstein replied, "only if it were completely wrong to view the electromagnetic field as an antisymmetric tensor and if there were a far closer relationship between electricity and gravitation than it has been supposed until now. I have spent considerable time to hunt for such a theory, but I have not yet found it."[46]

Even though, in his further letters, Schlomka disputed Einstein's theoretical objections, he eventually admitted that, according to the contemporary state of affairs, a positive effect could not be expected in laboratory experiments either, since even three men as "diligent" as Michael Faraday, Piotr Lebedev, and Harold A. Wilson had attempted to find this effect in vain.[47] Schlomka only mentioned these names, but I will sketch their ideas as well.

In the mid-nineteenth century, Faraday, led by "the long and constant persuasion that all the forces of nature are mutually dependent," had set out to find "something in gravity which would correspond to the dual or antithetical nature of the forms of force in electricity and magnetism."[48] His idea was to check whether an electric current develops when two gravitating bodies approach and a current of the opposite direction appears when they depart from each other. Expecting a very small effect, he chose the earth as one of the test bodies and let bodies made of copper, bismuth, iron, glass, shellac, and sulfur fall either together with a coil around them or through a coil placed under them. The coils were connected to an electrometer. He also moved the bodies up and down with sudden stops and velocities higher than achievable by gravitational fall in laboratory conditions. No effect was observed. "The results are negative. They do not shake my strong feeling of the existence of a relation between gravity and electricity, though they give no proof that such a relation exists," he concluded.[49]

Working in Moscow, in 1912, Lebedev launched a series of experiments upon reading of George E. Hale's finding that the Fraunhofer lines in the spectrum of solar spots exhibit the Zeeman effect,[50] and that the sign of their optical polarization depends on the direction of rotation of the photosphere around the spot as if it conveyed a surplus negative electric charge.[51] He supposed, in line with J. J. Thomson, that matter consists of negative electrons moving freely between positive atoms. He made cylinders of ebonite, brass, water, benzene, and aluminum and rotated them around their axis of symmetry at 30,000 rpm, which yielded a fifth of the linear velocity of the earth's equator. He expected the electrons to be driven to the outer layers of the cylinders by the centrifugal force. In this manner, three layers should form in them: an outer one consisting of electrons, an inner one consisting of positive atoms, and an intermediary one with equal amount of positive and negative charges, that is, neutral. The outer circular current has higher intensity than the inner one because of the higher velocity of electrons due to their greater distance from the axis of rotation; the inner current, consisting of the same amount of charge, but positive, flows in the opposite direction in a circle of smaller radius. He expected to detect the difference between the two magnetic fields induced by these circular currents. No magnetic field was indicated by the measuring instruments, but Lebedev did not exclude that, with devices of higher sensitivity, a positive result could be obtained. He died, however, before he could perform a second test.

The third person Schlomka mentioned, Wilson, considered the Maxwell-Lorentz equations modified by Swann to be the most promising suggestion among many others to explain geomagnetism,[52] and intended to check their feasibility via experimentation. As he wrote:

> [geomagnetism] may be due to a slight modification of the laws of electrodynamics from the commonly accepted form. Electrically neutral matter is believed to consist of an intimate mixture of enormous amounts of positive and negative electricities, the electric and magnetic effects of which are usually supposed to balance each other. If the balance were not quite exact, then small residual effects would be expected, among which gravitation and the earth's magnetic field might be included.

On such a hypothesis we might expect moving matter to produce a magnetic field similar to the field due to moving electricity, and we should expect some relation between the magnetic field due to moving matter and its gravitational action.[53]

He then "expected" that the gravitational unit of matter, $m\sqrt{K}$ (which attracts an equal mass at one centimeter with a force of one dyne), produces a magnetic field of the same order of magnitude as an electrostatic unit of electricity would. Based upon this assumption, he arrived at a geomagnetic field, the horizontal component of which was three times greater than the observed one, that is, of the same magnitude.

To test this consequence, he let a horizontal iron bar with a length of 2 m and a diameter of 6 cm swing. A coil was fixed around its middle and connected to an electrometer. The expected magnetic field, changing its direction and intensity due to the swing, would indicate any electric current induced in the coil. The experimental results showed that the effect observed was less than 5×10^{-3} times the calculated results.

In his next letter of July 30, 1927, Schlomka reported that he performed flight measurements and found a 3° deviation from true north when flying in the north-south direction and a deviation between 14.5° and 21° when flying from east to west. However, he did not consider the results decisive because a second compass gave different results.[54] Einstein did not accept these values,[55] but further details are missing because their extant correspondence is incomplete.

Schlomka made efforts to raise money for further experiments and was happy to announce to Einstein that a better opportunity emerged because the flight experiments were assumed by the German Aviation Research Institute in Adlershof and they solved the problem of the instability of ordinary compasses by using an American-made "massless" induction compass. Schlomka hoped these tests would deliver a definitive solution.[56]

There are no documents regarding their further collaboration for five years. Then, in February 1932, Schlomka reported to Einstein that he had prepared a thesis entitled "Gravitation and Terrestrial Magnetism" for *Habilitation* as Privatdocent and had been working on a theory of the electrodynamics of moving systems and another theory rib electron stability.[57] His only publication from this period, however, is on gravitational absorption.[58] His Habilitation thesis, published in 1922, that is after the Nazi election victory, contains no reference to Einstein's inspiration or help. No wonder: he had been member of the National

Socialist German Workers' Party (the Nazi party) since 1927. His cooperation with Einstein, a prominent Jew, could be explained only by his strong ambition to get a chair at any means.

In his reply to Schlomka, Einstein confessed that, although a uniformly moving, electrically uncharged mass cannot produce a magnetic field, due to the negative results on a train and ship, "I cannot understand what the decisive factor can be that appears upon rotation. Until now, all my theoretical efforts on this matter have proved unsuccessful."[59] Einstein's geomagnetic interest was known among physicists, even though he did not publish anything on geomagnetism; the two cases (those of Hale and Millikan) I will mention below give a rare insight into the importance of oral communication.

Early in December 1926, George E. Hale, honorary director of the Mount Wilson Observatory in Pasadena, turned to Einstein with a question: "Dr. Baade … tells me that you have developed a new theory which may account for the general magnetic fields of the earth and sun. He said you wished to know how closely our measures of the strength of the sun's general field can be relied upon, and I am therefore sending you some comments on this question."[60] He then referred to his earlier work, which was well known to Einstein (Hale's four papers on the magnetic fields of the sun, earth, and sunspots can be found in Einstein's reprint collection), and went into some detail about the paper he coauthored with his colleagues.[61]

Hale had sent a copy of this letter to Walter Baade, at the time a guest astronomer at Mount Wilson from the University of Hamburg, who immediately informed Einstein of the details of his conversation with Hale. "I enthusiastically told Hale what my friend W. Pauli had told me last summer," he wrote, "that according to your opinion the Sun's general magnet. field might find its explanation in the link between gravitation and electrodynamics and that on the basis of such considerations the measured magnet. Fields of the Sun and Earth agreed with each other.… Millikan declared that he had already known about it for a while and that a paper by you on this matter had recently appeared."[62] Einstein and Robert A. Millikan, both members of the Committee on Intellectual Cooperation of the League of Nations, met in Geneva and Paris. Regarding the paper by Einstein on solar and terrestrial magnetism, this reference may be to his Lucerne lecture.[63]

In his reply to Hale, Einstein summarized the history of his struggle with the charged neutral mass:

> The original idea was this:
> There is a dimensional equation
>
> $$\text{Electrostatic quantity of electricity} = \sqrt{\text{constant of gravitation}} \times \text{ponderable mass, in symbols } \varepsilon = m\sqrt{\kappa}.$$

> This dimensional relation suggested to me that ponderable mass had electromagnetic function of some kind and that the ponderable mass *m* somehow behaved like the electrostatic charge. If, for example, one considers that this action was such that a rotating ponderable body produced a magnetic effect like a corresponding rotating charge density (of negative sign), then one gets the terrestrial magnetic field in the right order of magnitude.
>
> In this way, the ratio of the solar field to the terrestrial field is also obtained, in order of magnitude. Finally, this point of view, found in a kind of delirium, additionally 'explains' that the vortices of solar spots produce the strong magnetic field as you had established.
>
> I tried very hard, of course, to set up a theory that puts these phantasmagorias into a logical form. But that has not worked for me in any way whatsoever. Experiments that I have thought up in loose connection with this approach also came out negative. So, I did not reach the goal, but I still don't know whether a very fundamental unknown effect was participating in the field of rotating celestial bodies, after all. In any event, all the attempts at an explanation up to now appear to me to be untenable, and I am also convinced that the hitherto known laws are incapable of explaining this confounded phenomenon.[64]

Hale agreed with Einstein's considerations, replying: "Professor Swann of Yale University has been trying to develop similar initial conceptions regarding magnetism, but does not know whether he has made any progress. We fully agree with you in thinking that no other explanation of terrestrial or solar magnetism is of any value, and therefore greatly hope that you will see a way to continue your investigations."[65] When Einstein visited Caltech during the winters of 1932 and 1933, they continued the conversation. "He [Einstein] still regards the mag[netic]. fields of spots and of the sun as very fundamental phenomena," Hale wrote on February 22, 1932, "but has not yet been able to account for them by any general theory."[66]

Review of Electrogravitational Research

In his thesis,[67] Schlomka not only expounded his proposal for solving the problem of whether the rotation of uncharged mass can produce a magnetic field, but also gave a list of theories that looked for the source of geomagnetism in the earth's rotation, in the ether, and in geoelectricity. He essentially put the historical sketches that he had sent to Einstein earlier in a comprehensible form. Einstein's name appears twice among the rotational theories: in his "magnetomechanical (gyromagnetic) theory" and in a theory about the rotation of the earth with a "quasi-charge" (Einstein's ghost charge). The first, coauthored by De Haas, is nothing but the theory and experiment regarding Ampère's molecular currents.

Einstein and De Haas offered only a tentative reference to the earth's magnetic field.[68] Was it Schlomka who concluded from the experiment that the rotation of the Earth could explain geomagnetism? The remark in Einstein's letter to Lorentz reveals that the revolving rod in the experiment could have also been a laboratory-scale model of the rotating earth with molecular currents in it, and so it is just possible that it was Einstein who told Schlomka in 1926 that the main purpose of this experiment was to explain the cause of geomagnetism.[69] The other person mentioned among magneto-mechanical or gyromagnetic theories is Samuel Barnett.[70]

In Schlomka's list, Schuster's theory is the first among those that attribute geomagnetism to the rotation of neutral matter. In 1891, Schuster asked, "Is every large rotating mass a magnet?"[71] Then, he quoted Lord Kelvin saying that same year, 1891: "I find it unimaginable but that terrestrial magnetism is due to the greatness and the rotation of the earth." In considering various possibilities, Schuster continued, "if magnetisation be due to a circulation of electrons within the molecules, these should to some extent behave like gyrostatic compasses, setting themselves parallel to the axis of rotation of the body which contains them." Schlomka's list of theories relying on the "charged neutral" mass is not complete.

From 1905 to 1906, an interesting dispute was provoked in *Physikalische Zeitschrift* by Victor Fischer's paper, which stated:

> The present development of the theory of electricity hints more and more at that gravitation and electricity should be based on the same foundation … If we consider the electric charge and the usual mass as equivalent coefficients of matter, then we find that the unit of the first is about 1.5×10^7 times larger than that of the second, or to put in another way,[72]

$$\frac{e}{m} = 1.5 \times 10^7.$$

Fischer's contribution led to the publication of a paper that the American Bergen Davis had submitted to *Physikalische Zeitschrift* a year earlier. His starting point was the same as Fischer's: "The hypothesis that matter consists of electrons is well founded today. This matter that shows gravitation is a conglomeration of electrons which, on the other side, exert electric effects. The present paper intends to find the most likely connection between these two forces which act between the masses in two combinations."[73] Davis arrived at the conclusion that the ratio of the electrical force to the gravitational force of a certain mass is the fourth power of the velocity of light without dimension.

The editorial board of *Physikalische Zeitschrift* had first refused to publish Davis's paper on the ground that this numerical coincidence must be accidental, but because Fischer's paper attacked the same problem, they yielded, but simultaneously published two further papers,[74] noting that both Fischer and Davis compared numbers with different dimensions or expressed in different units (with

Einstein, both the gravitational mass and the electrostatically measured electric charge have the dimension of $cm^{3/2}\ g^{-1/2}\ s^{-1}$).

From 1923 to 1924, Gustav Angenheister rehashed the topic with the conclusion that, with the hypothesis, the ratio of the earth's magnetic field to that of the sun can be obtained almost exactly, but it is physically difficult to accept that so strong a real electric charge and concomitant electric field can exist in the earth's core.[75] Apparently Schlomka did not check French sources. The relation in the form of also appeared in a publication by the French Louis Décombe regarding an electric theory of gravitation in 1913.[76]

After a two-decade dormancy, the connection between rotation and magnetism was taken under closer examination by Schuster's successor at the University of Manchester, Patrick S. Blackett. Just coming back from the British navy where he fought during World War II, he began reorganizing the physics laboratories to make them suitable for his research of cosmic rays. When pondering on the possible influence of the magnetic fields of stars in the galaxy on cosmic ray phenomena, he observed that the ratio of the sun's magnetic moment to the angular momentum of its rotation is close to that of the earth: $10^{-15.}$ Furthermore, the ratio of this ratio to the Bohr magneton is 10^{-22}, a value very close to the ratio of the gravitational mass of the electron to its charge—the ratio that captured Einstein's attention twenty years earlier.[77] Blackett derived the formula

$$P = \beta \frac{\sqrt{G}}{2c} U,$$

where P is the magnetic field the unit gravitational mass generates when rotating with an angular momentum U, G is the constant of gravitation, c. is the velocity of light, and β a factor of proportionality.[78]

Blackett, an excellent experimenter, looked to detect this magnetic field. Due to its extreme weakness, only cosmic masses looked promising. He turned to R. Chandhrashekar for advice, who informed him of a novel finding: Horace W. Babcock succeeded in measuring the magnetic field of 78 Virginis,[79] a star with high density and substantial rotation. Blackett found it to be in agreement with the value calculated from his formula. He also remarked that this relationship had already been found to be valid for the earth and the sun and "has been known for a long time … though lately little regarded."[80] He was of the opinion that "the above equation must be taken seriously as a possible general law of Nature for all massive rotating bodies."[81]

Blackett did not accept the assumption that the two types of electricity present in the earth can be separated by some mechanism (for example, centrifugal force) to provide an electric current that can produce the magnetic field. He rather assumed that virtual electric charges (similar to Einstein's "ghost charges") are involved:

> Charges which produce a magnetic field but not an electric field. A hint of how this might be done may possibly be obtained from considering the field of the neutron.… In some current meson-field theories, the difference between the magnetic moments of the neutron and proton are attributed to the existence of virtual mesons, thus bringing in virtual but not real electric charges. Perhaps this might be taken as a hint that the magnetic field of a massive rotating body might be attributed to such a virtual charge separation. The observed linear variation of H with ω [that of the magnetic field with the velocity of rotation] shows that such a virtual charge separation cannot be the result of the rotation but must be a property of a massive body at rest."[82]

According to a personal remark of Silvan S. Schweber to the Blackett biographer Mary Jo Nye, Blackett had talked about his theory in a colloquium at Princeton University in 1949, which was a rare opportunity to see Einstein's participation.[83] Nye guesses Einstein's motive may have been to show solidarity with Blackett's opposition to the nuclear weapons policy of the United States and Great Britain.

The documentary evidence, however, puts Blackett's Princeton visit in 1946, the time of the bicentennial celebration of the university, which lasted from September 22, 1946, until June 17, 1947, and was attended by more than one hundred guest scholars from all over the world. Blackett was to participate in a conference about the future of nuclear science on September 23 and to deliver a Vanuxem lecture on cosmic rays on September 26.[84] This lecture could be the seminar mentioned by Schweber. Later information does not mention him but adds Einstein to the participants.[85]

Could Blackett and Einstein have discussed their "pet" idea in Princeton? I do not think so. Blackett had been preparing to announce his idea in 1947 at a session of the Royal Society and aimed to publish it in *Nature* as quickly as possible. Why? The May 29 issue of *News Review* gives the answer: its science column published Newton's, Einstein's, and Blackett's portraits under the headline "Newton, Einstein—and now Blackett." Thus, Blackett was eulogized as the discoverer of a new law of nature: "If true, Blackett's 'Law' suggests that the explanation of the stars' magnetic fields is far more fundamental than previously suspected and establishes the link between electromagnetism and gravity long sought by Einstein and others."[86] To confirm the theory, Blackett planned to use an "artificial star," a metal ball rotated "at a speed so great that it nearly flew apart by centrifugal force," and measure any magnetic effect, the *News Review* continued. After several attempts and ingenious development of a very sensitive magnetometer, Blackett gave up.

The next wave of interest in the Schuster-Wilson (or Wilson-Blackett) effect, now called electrogravitational induction, was aroused circa 1980 as a consequence of the successful unification of weak and electromagnetic interactions, but none of the investigations or suggestions was of experimental character. James F. Woodward decided to make use of the progress made in instrumentation since Blackett's time to experimentally look for the hypothetical magnetic effect of accelerated neutral mass ("gravitomagnetic interaction"). No doubt, it was part of his program of "advanced and exotic propulsion."[87]

He had to choose between Blackett's rotating acceleration and Faraday's translational acceleration of masses.[88] The second option seemed to be easier to perform and offered higher precision. Woodward let metal samples approximately 1 kg in mass fall on an impact plate and observed whether a transient "effective" electric charge was induced in the mass during acceleration, as Faraday supposed. His conclusion was that his experiments set the upper limit for inductive coupling of the electromagnetic and gravitational fields about two orders of magnitude lower than that established by Blackett. Between 1980 and 2012, no alternative explanations for the observed charges were proposed.[89]

Conclusion

The "ghost charge" was not the only appearance of a "ghost" in Einstein's oeuvre. According to Born, Einstein used this concept for De Broglie's or Schrödinger's wave field, which does not carry energy or impulse but determines the probability of the route a corpuscle should take, and so deserves the name "guiding field" or "ghost field." On November 30, 1926, he wrote to Einstein, "I am quite satisfied, because my thought of conceiving Schrödinger's wave field as a 'ghost field' in your sense is increasingly proving its worth."[90]

Ghosts reappeared in physics thirty years later in the form of ghost fields in papers by Ludvig Faddeev and Viktor Popov.[91] As Faddeev explains, "in the terminology of theoretical physics, the term 'ghost' is used to identify an object that has no physical meaning,"[92] but he did not know who the first was who "coined" the expression "Faddeev-Popov ghost field." Was it someone who met with Einstein's ghosts in Born's paper? Another case of oral communication? Be that as it may, the ghosts appeared earlier to Einstein.

The expression, for which Blackett was eulogized as of the same rank as Newton and Einstein in discovering a new fundamental law of nature, had been discovered by earlier scientists, but that it was found also by Einstein and without knowledge of his predecessors was revealed by new archival sources. Einstein's dimensional consideration leading to fits into the sequence of early attempts by Davis and Fischer to find numerical coincidences between constants of nature, $\varepsilon = m\sqrt{\kappa}$,[93] leading to Eddington's and Dirac's controversial proposals in the mid-1930s.[94]

What was Einstein's expectation? To find a direct connection between rotation and magnetism, or to admit that there must be a link between them, namely, electric charges, even though that link appears in an unusual manner? None of his predecessors dared eliminate electric charges, and Blackett's bravery in dropping them was fueled by the spectacular development of physics that had occurred in the twenty years since 1927. Einstein's expectation for Piccard's experiment was to find a direct connection between rotation and magnetism, with equal sizes of negative and positive elementary charges. This, as he later confessed, was a thoughtless presupposition.[95] In his letter to Hale, he did not mention anything but the dimensional equality of gravitational mass and electric charge.[96] The experiment with the rotating cylinder in Kiel—similar to Barnett's, but with brass, a nonferromagnetic substance—seems to have been performed in the hope of directly connecting rotation with magnetization without the intermediary role of molecular currents or electric charges. However, why was the cylinder heated? Was it to make electron gas in the metal crystal lattice move more easily and be driven to the surface of the cylinder by the centrifugal force as Lebedev (and Thomson) considered? If so, it would prove that electricity was at the back of his mind, but no clear statement corroborates this.

Perhaps the strongest argument in favor of his search for a direct connection is that, at least since December 1925,[97] Einstein had known about the proposal of George Uhlenbeck and Samuel Goudsmit that the electron has a peculiar property: spin.[98] In addition, when Einstein participated in the celebrations of Lorentz's fiftieth doctoral jubilee from December 11–15, 1925, he met with Goudsmit in person. "Every day we had a meeting, a get together with Bohr, Einstein and Ehrenfest about the problem of the spin and all those things, at Ehrenfest's home," Goudsmit remembered in 1971.[99] Maybe Ehrenfest forgot this opportunity, because the next April, he mentioned Uhlenbeck and Goudsmit's hypothesis to Einstein as news.[100] In any case, in his correspondence with Hale or Schlomka, Einstein never mentioned the electron spin as a promising solution of his fundamental problem. However high his theoretical expectations were, he was awaiting decisive approval via experimentation. As he wrote to Walter Lauterjung on December 28, 1927, "the magnetomotoric effect of ferromagnetic bodies has already been proven by experiments [by Barnett]. Unfortunately, we cannot conclude from these experiments that the carriers of magnetism are electrons that revolve around nuclei or those that rotate around their own axes or both of them together. It has not yet been proved directly that electrons have gyroscopic features."[101]

So as not to leave any loose threads, let us say a few words about contemporary views regarding the source of geomagnetism. Currently, geophysicists vote for geoelectricity. The mechanism that has evolved is that of the so-called self-sustained dynamo. Upon the effect of an initial magnetic field, the internal layers of the earth, rich in iron, induced electric currents by their different rotations and displacements, which strengthened the initial magnetic field. As soon as this "dynamo" started up, the initial magnetic field became superfluous, and the dynamo has been sustained by the convective motion of the outer layers of the earth.[102] The main question left unanswered is that of the source of the initial magnetic field.

The main question for Einstein, namely, how to find an observational background for his effort to unify gravitation and electromagnetism (the reason for which the earth and its magnetic field was dragged into play), also remained unanswered during his lifetime. In subsequent theories and ideas about electro-gravitational coupling, physicists had to delve more deeply into the realm of elementary particles.

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