'Beneath our feet stretches the open country of the Hungarian Plain, crowned with hills. Over the years this region has shaped itself naturally, as it wished. I wonder what it was like in former days. What sort of hills have been eroded and what valleys filled with loose deposits before this fertile area of golden grain came into being, this life-giving Hungarian plain? As I walk upon it and eat its bread my mind dwells upon these question which would give me such joy to anser.'

(Eötvös)

Eötvös Loránd 1848 - 1919

ONE HUNDRED YEARS OLD: THE EÖTVÖS TORSION BALANCE

Zoltán SZABÓ

In 1991 we are celebrating the 100th anniversary of the completion of Eötvös' first torsion balance and the first field observations carried out on Ság hill, Transdanubia, Hungary.

The invention of the torsion balance represented an important milestone in the history of applied geophysics: it was the first instrument to be employed in oil exploration. This centenary provides an opportunity to commemorate Loránd Eötvös the man, and Loránd Eötvös the scientist and organizer.

1. Eötvös the Man

Loránd Eötvös was born in Buda in the capital of Hungary on 27th July 1848, the year of the Hungarian revolution and fight for independence. His father, József Eötvös, came from an impoverished noble family. As a writer and politician of great renown, he was one of the leaders of the movement for reform. Because of his eminence in the political field, he was elected minister of religion and education in the first independent government of Hungary after the revolution. As a reformer, Eötvös was appalled by the violent path taken during the struggle for independence, so left the country with his family, returning to Hungary only in 1850. During his period abroad he interested himself primarily in matters of state and philosophy. On returning home he strove to establish peace between Hungary and the ruling Habsburg dynasty, a policy which did not at first gain undivided support. During the fifteen years that followed, those in favour of agreement managed to achieve a compromise. As a result, in the Hungarian government established in 1867, József Eötvös was again appointed minister of religion and education.

In recognition of his literary work, József Eötvös became an associate member of the Academy in 1835, an honorary member in 1839 and in 1866 he was elected president.

From an early age his son, Loránd, was educated by private tutors and he later attended the Piarists' high school, from where he matriculated in 1865. In those days it was assumed that sons of aristocratic families who wished to receive higher education had to enter some branch of the law. The law failed to satisfy Eötvös, but he always managed to find time to attend lectures in the natural sciences.

In March 1866 he wrote the following words to his father: *'I was born with ambition and a sense of duty not only to one nation but towards the whole of humanity. In order to satisfy these urges and to retain my own individual independence, my aim in life will best be achieved, as far as I can see at present, by following a career in science.'* Despite the fact that he had completed his law studies, his dearest wish was *'to study at a university abroad under the guidance of enlightened professors'* in order to fully understand the natural forces at work in the scientific field.

In 1867, with his father's consent, he took the final decision to follow a career in the natural sciences, and to this end he enrolled at Heidelberg

University. There he became a student of Kirchhoff, Bunsen and Helmholtz. First of all he studied physics, maths and chemistry. The following six months he spent at the University of Koenigsberg, but found the lectures too abstract and returned to Heidelberg.

During his university years he kept up a regular correspondance with his father. These letters reveal the depth of understanding and sincerity in the relationship between father and son. Thirsty for adventure, in 1869 the young Eötvös planned to join Petermann the German geographer on his expedition to Spitzbergen. His father disagreed with his son's plans and wrote the following: *'On this occasion, however, I do see the need to warn you of my situation, which demands that economies be made by the whole family, including yourself. For years I've almost always been in a situation in which my expenses exceed my income ... I willingly give whatever is necessary to further your scientific studies ..., but I must ask you to forgo certain luxuries for the sake of us all — and your planned expedition is one of them. I'm not referring to the Transylvanian expedition but the one to the Arctic.'*

At his father's request Loránd Eötvös gave up his plan to travel with Petermann and applied all his energy to preparing for his examinations. In his letter of 8th July, 1870 he says: '... *I've had the results of my doctorate today. And my greatest delight is that this news will bring you pleasure. I passed my finals with first class honours, a distinction envied by many.'*

Shortly after his return home in February 1871, his father died — *'the best and truest friend'*. On his death bed he warned his son that his future happiness depended on his devoting himself to science and keeping out of politics. After his father's death, Eötvös successfully applied for the post of lecturer advertised by the faculty of theoretical physics at Pest University; this university now bears his name. It was characteristic of the social climate of the time that the majority of the students attending his inaugural lecture did so because they were curious to see a real baron giving a lecture on physics at the university.

After a short period of lecturing in 1872 he was publicly honoured by the king, who awarded him the chair of theoretical physics. In 1874 he was asked to give lectures in experimental physics; four years later he became professor in this field. He was then given the task of combining the departments of experimental and theoretical physics, and was appointed director to the newly established Institute of Physics.

In 1873 he became an associate member of the Academy, a full member in 1883, and in 1889 he was elected president. Among his offices he became minister of religion and education for seven months in 1894.

Eötvös was a modest scientist who shunned the limelight. He disliked uproarious ceremonies and did not seek moral or financial reward. In spite of this he was acclaimed and received awards at home and abroad for his scientific work and for his skill as an organizer. The more important honours included the French Legion of Honour, the Franz Joseph award from the Hungarian king, the Saint Sava award from the King of Serbia. He was also elected honorary member of the Prussian Royal Academy of Sciences in Berlin and was given honorary doctorates from Jagello University in Cracow and the Norwegian Royal Frederick University in Oslo (known as Christiania at the time). In addition to the above he received several other awards during his life and was elected president or a leading member of various social and scientific societies.

Eötvös was a well balanced individual. Besides his intensive mental work he always found time for relaxation and sport. He often went riding and regularly made the eleven kilometre journey from his home to the university on horse back. In the summer he often cycled and indulged in his passion for mountaineering . In the classic time of alpinism he ranked among the best. As an enthusiastic photographer, he took hundreds of pictures during his mountaineering expeditions. In his later years his doughters accompanied him on his expeditions, and also became keen alpinists. Eötvös' climbing achievements in the southern Tirol made the Hungarian professor's name so well-known that in 1902 one peak of 2837 m in the Dolomites (Italy) was named after him — el Cima di Eötvös — the Eötvös Peak. In the company of friends he often jokingly said that he was prouder of his mountaineering successes than his discovery of the torsion balance. For many years as president of the Hungarian Touring Society, he did a great deal to popularize tourism in Hungary.

With advancing years, he strove to avoid prestigious appointments in order to devote himself entirely to research. This prompted him to give up his position as president of the Academy in 1905. The last years of his life were clouded by severe illness, but he continued to lecture at the university so long as it was humanly possible.

Up to the last moments of his life he followed torsion balance field work with great interest. Initially he asked his colleagues to inform him of the daily results of their survey by telegram because he was very anxious to know how far the results of the survey supported his theories. He had never been able to tear himself away from his research, even during his summer trips to the mountains. When on holiday he always kept up a regular correspondence with his co-workers. He continued his scientific work from his sick-bed and sent his last paper to be published only a few days before he died on 8th April 1919.

The international scientific community and the whole of Hungarian society mourned his death. Hungary had said farewell to one of the last great representatives of classical physics and to the country's greatest natural scientist. Through his work, however, his name will live forever in the history of physics and geophysics.

2. Eötvös the Scientist

In his scientific research Loránd Eötvös was not interested in those topics that were fashionable at that time, and that would have brought him immediate public acclaim. Instead, he was concerned with capillarity, gravitation and magnetism, phenomena so taken for granted that a superficial observer would fail to see the mysterious powers at work within them.

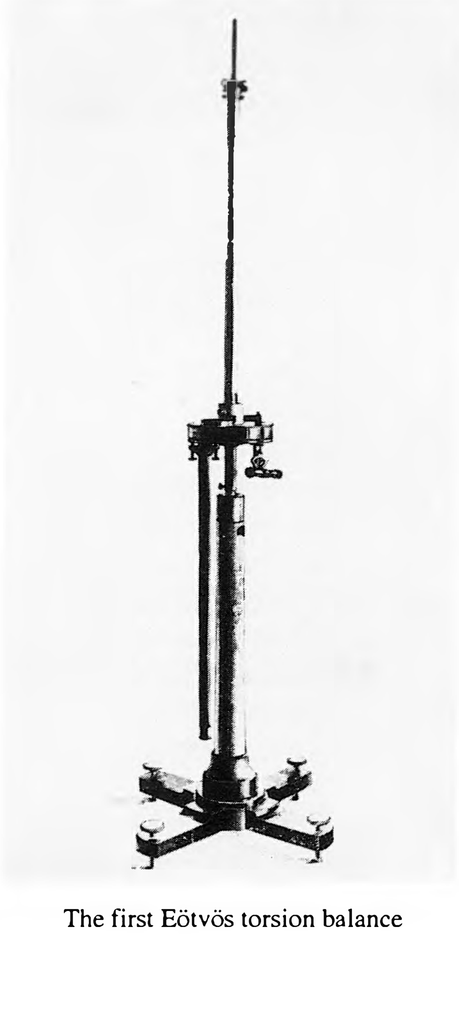
He was still a university student when he began to concern himself with capillarity under the guidance of F. Neumann. This force governs the shape of the surface of water in a glass; due to its effect drops of water are rounded and water is caused to rise in capillary tubes. Eötvös worked out a new way of determining surface tension called the reflection method. This method made it possible to determine the exact surface tension of different liquids. During his experiments Eötvös found that there was a relationship between the surface tensions of liquids and their molar weight.

Based on this perception the rule, later to become known as the Eötvös rule, could be concluded which states that the rate of change of molar surface energy with temperature is a constant for all liquids. For liquids this constant is as fundamental as is the universal gas constant for gases.

After studying capillarity Eötvös turned his attention to gravitation and magnetism. From then onwards for the nearly forty years until his death, he was concerned with these two fields. In his research on the spatial changes in gravitation, he used a modified version of Coulomb's balance.

His research method was based on two fundamentals: one was the strict theoretical physical aspect of the process; the other was the construction of an unbelievably sensitive instrument.

Eötvös built two different types of torsion balance for carrying out his gravitational investigations. The first type was a light horizontal beam suspended on a torsion wire with platinum masses attached to each end so that the masses were at the same level (curvature variometer). This type was identical in form with the instrument used by Cavendish. The curvature variometer measures the 'curvature' values which give the deviation of equipotential surfaces of gravity from spherical shape, and give the directions of minimum curvature.



The first Eötvös torsion balance

The second type has a platinum mass attached to one end of a horizontal beam, while on the other end a platinum cylinder hangs on a wire so that this cylindrical mass is at a lower level than the mass at the other end (horizontal variometer). In both cases the beam turns around the torsion wire in a horizontal plane and is deflected from the torsion-free position of the wire by the horizontal components of the forces of gravity. This seemingly insignificant modification was Eötvös' most important invention, in fact this second version is known as the Eötvös Torsion Balance.

The horizontal variometer gives the 'gradient' of gravity which is defined as the rate of change of gravity over a horizontal distance of 1 centimetre. The horizontal variometer also furnishes the curvature values if the instrument is set up in at least five azimuths. The unit of gradient and curvature are named after Eötvös. 1 EU = 10^{-6} mGal/cm; that is, if the horizontal gradient is 1 EU the gravity acceleration at two neighbouring points 1 cm apart difference 10^{-12}g.

Of his instrument Eötvös himself said the following: *'It is as simple as Hamlet's flute, if you know how to play it. Just as the musician can coax entrancing melodies from his instrument, so the physicist, with equal delight, can measure the finest variation in gravity. In this way we can investigate the Earth's crust at depths that the eye cannot penetrate and the drilling rig cannot reach.'*

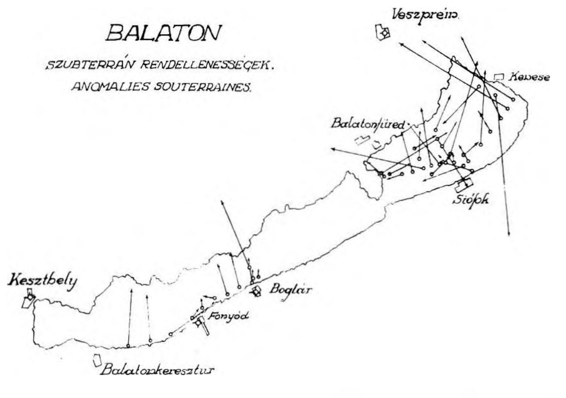
The mechanical parts of the instruments were designed and built in 1890 under the guidance of Eötvös in cooperation with N. Suess in Suess' Mechanical Workshop. Calibration of the instruments were carried out in Eötvös' Laboratory and the first instrument was completed in 1891. In the same year the first observations were carried out.

A modified version of the horizontal variometer specially designed for field work, was completed in 1898. It was shown and awarded a prize at the Expo of Paris in 1900.

In order to increase the efficiency of field work, Eötvös constructed a double instrument with two balances in antiparallel arrangement (1902).

At the beginning Eötvös experimented with his instruments in the laboratory of the university, then later in the garden of his summer house. He carried out his first field measurements on Ság hill in Transdanubia in 1891, where he proved that errors had been made in the relative pendulum measurements carried out by Sterneck; Sterneck was an Austrian geodetic surveyor who had carried out measurements in the same area seven years earlier. Eötvös' first report on gravitation was written in 1888 for the Academy. In 1896 he published his fundamental paper entitled Studies in the Field of Gravitation and Magnetism, in which he gave a theoretical and practical summary of his experiments to date.

The first experiments on a larger area using the Eötvös balance took place in the winter of 1901 on the frozen surface of Lake Balaton. Eötvös chose the mirror-like frozen surface of the lake to carry out his measurements so that he would not have to concern himself with the disturbing effect of topographic masses. He continued his survey work in the winter of 1903, completing measurements at altogether forty different stations. From the results of his torsion balance survey it was established that parallel to the axis of the lake ran a tectonic line. This was the first geological conclusion based on torsion balance measurements.



The first gradient map, obtained on the frozen lake Balaton (1901-03)

As a results of his success when he presented his results in Paris in 1900, Eötvös' gravitational experiments became the focus of international attention. The high degree of sensitivity of his instrument was doubted by some. And it was not until the XV Congress of the Internationale Erdmessung held in Budapest in 1906 at which he spoke about his latest experiments that Eötvös' claims received general recognition. He also made it possible for interested foreign scientists to observe his torsion balance measurements carried out in the field — in the Arad region. The participants of the conference found Eötvös' research so significant that they petitioned the Hungarian government requesting that increased financial help be given for gravitational research. The Hungarian government agreed to the suggestion and from 1907 onwards a separate fund was allocated for Eötvös' gravitational studies. From this time onwards geophysical research was recognized in Hungary as a separate field of science in its own right.

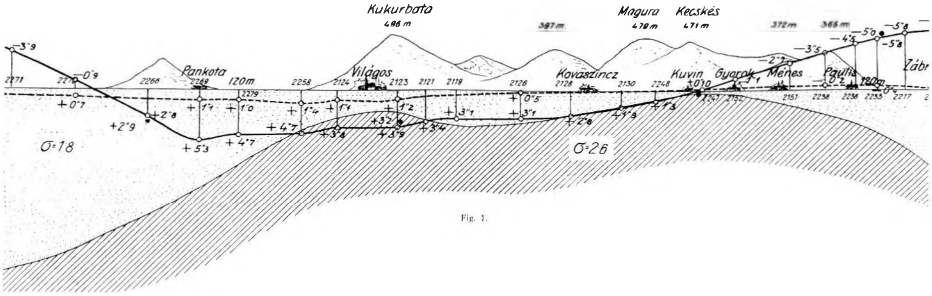


Fig. 1.

Lotabweichungen nach Osten längs des Breitenkreises von Ménes (φ = 46°8').

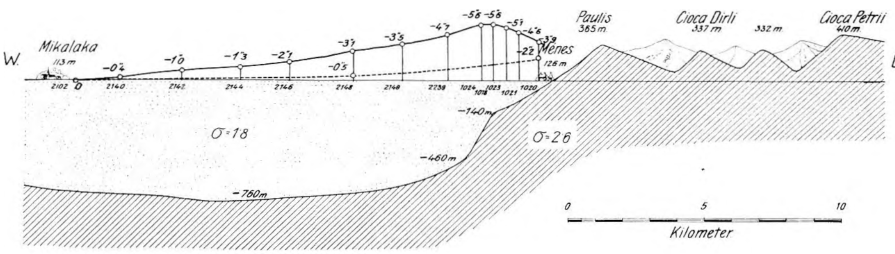
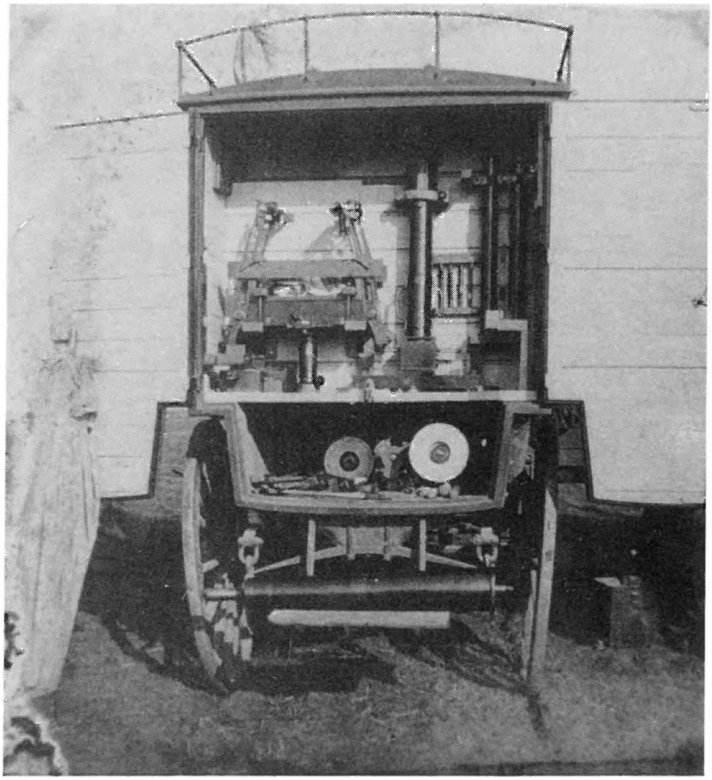


Fig. 2.

Geological interpretation of the torsion balance survey carried out in the region of Arad (1906)

At first Eötvös' gravitational measurements were carried out for geodetical purposes, but from the very beginning Eötvös had wondered what geological conclusions could be deduced from the results of his work. At the XVII Congress of the Internationale Erdmessung held in Hamburg in 1912 Eötvös wrote the following in his report of the practical application of the torsion balance: *'Geologists seem to agree that the most substantial discharges of gas occur in the immediate vicinity of gas-bearing anticlines, and overlying sediments. Experience gained in America (Ohio) and observations in Transsylvania, where the subsurface geological structures could be determined from superficial indications, further endorse these assumptions. Such geological indications, however, are absent in the sand and humus covered surface of the Great Hungarian Plain. He who searches for* *gas-bearing anticlines in this or similar areas should not fail to take note of conclusions drawn from torsion balance observations.'*



The Eötvös torsion balance packed in a horse cart used for transportation in the filed (1907)

In 1916, on the initiative of Hugo Böckh, an eminent Hungarian geologist, torsion balance measurements were carried out in the region of Egbell, where oil was produced from a recognized anticlinal structure. The aim of these measurements was to establish the extent to which the effect of the oil-bearing anticline is reflected in the results of torsion balance measurements. On the basis of the survey carried out at 92 stations the contours of the anticlinal oil field were clearly ascertained. These results proved the efficacy of the torsion balance in oil exploration and paved the way towards world renown for Eötvös and his balance. After his death, in the 1920s and 1930s, hundreds of oil fields were discovered throughout the world with the help of Eötvös' ingenious instrument.

Siesta in the camp, Eötvös is sitting before the tent

Among Eötvös' gravitational instruments, his gravity compensator is also worthy of mention. This instrument is strictly speaking a curvature variometer provided at both ends with sector-shaped deflectors, whose position can be changed by rotation about a horizontal axis. If the deflectors are in a vertical position their attraction to the balance is zero, in a horizontal position their effect is maximum. If the beam of the balance is in the centre of its case, the attraction of the deflectors is zero because of the symmetrical disposition but if the beam is not in the central position because of deflection by some outside mass, the deflectors become effective since they are now not symmetrically positioned with respect to the beam (astatization). If the position of the deflectors is changed with respect to the horizontal direction, the sensitivity of the gravity compensator can be further increased up to the point of instability.

Although best known for his torsion balance, Eötvös also developed a gravimeter. It was completed in 1901, and was based on the bifilar principle. The experimental measurements carried out with this instrument, however, failed to meet his expectations, so he did not publicize his activities in this field. His gravimeter still exists today, an indication of the extent of his love for experimentation.

In 1890 Eötvös worked out a method, the dynamic method, for measuring the gravitational constant. The dynamic method was based on the concept that the period of oscillation of a pendulum placed between two parallel lead walls was depending on whether it oscillated parallel or perpendicular to the walls. If one measures the periods of oscillation in both positions and determines the exact mass of the attracting walls the gravitational constant can be calculated.

In physics, mass can be defined in two ways, viz. inertial and gravitational. The inertial mass of a body determines the acceleration given by an applied force (Newton's second law); the gravitational mass of the body determines the force it experiences due to the gravitational attraction of another body. Eötvös became concerned with the question of the ratio of proportionality of the inertial and gravitational mass as early as 1880. In order to examine this phenomenon, he used his sensitive torsion balance. He examined the state of equilibrium of the balance by attaching masses of different composition to each end of the arm of the balance. If the quantity of gravitational force depended on the composition of the mass, when placing bodies of different composition on to the balance, the state of equilibrium should change in each case. This phenomenon did not occur. In 1908 Eötvös and his colleagues, Jenő Fekete and Dezső Pekár, perfected their measurements to such an extent that they were able to establish that the difference between the inertial and gravitational mass was at most 1/20,000,000. Their paper on the subject won them the Benecke award at Göttingen University. The experiments carried out by Eötvös and his colleagues on the proportionality of the inertial and gravitational mass supports Einstein's theory of relativity. The reexamination of the results published in their paper recently led E. Fischbach to the debated hypothesis of the existence of a 'fifth force'.

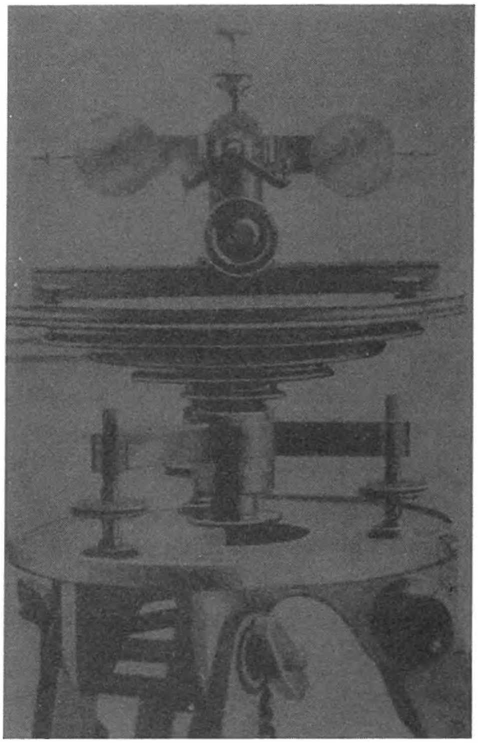
Eötvös was also interested in the question of gravitational absorption. His method was the following: the beam of a horizontal variometer is placed perpendicularly to the direction of the rising or setting sun. Let us suppose that two straight lines are drawn from a fixed point on the sun, one directed to the upper weight on the balancing rod, and one to the lower. If the sun is just below the horizon, the parts of the two straight lines passing through the earth will differ in length. For example, if the straight line drawn to the upper weight just touches the earth, then the line directed to the weight which is one metre below will pass through the earth for seven kilometres. If this layer of the earth could change the attraction of the sun, deflection would be indicated by the variometer. The instrument did not show any definite deflection at sunrise or sunset. The degree of sensitivity of this instrument was such that Eötvös could state that if the upper layer of the earth changes the sun's attraction the effect was less than 1:100,000,000.

In the last years of his life, Eötvös carried out experiments which showed that the weight of moving bodies on the earth's surface changed depending on the direction and speed at which they were proceeding. A clear explanation of this change can be given on the basis of the mechanics of Galileo and Newton. The gravitational force of the earth is the resultant of two forces: the principal one caused by attraction according to Newton's law, the second one the centrifugal force caused by the earth's rotation. Since the distribution of the masses in the earth and the speed at which the earth rotates are constant, the weight of objects on the earth's surface is also constant. The situation is different, however, in the case of moving objects. As the earth rotates from west to east, the centrifugal force on a moving object is greater if its motion on earth is towards the east than towards the west. As a result of this phenomenon the weight of a body moving eastwards will decrease, while that moving westwards will increase.

It is interesting to note the circumstances that initiated Eötvös' research on this topic. O. Hecker, an eminent research worker at the Institute of Geodesy in Potsdam, led a team to the Atlantic Ocean in 1901 and then in 1904-1905 to the Indian and Pacific Oceans, to carry out gravity measurements on moving boats. While studying Hecker's results in the published report, Eötvös noticed that no consideration had been given to the forces developed by the motion of the boat. In a letter to Hecker, Eötvös pointed out his error, but Hecker at first refused to give credence to this criticism. His colleagues, however, persuaded him that Eötvös was right and so in 1908 new measurements were carried out in the Black Sea to prove this phenomenon. Observations were made in two boats, one moving towards the east and one towards the west. The results substantiated Eötvös' claim.

The international scientific world recognizes this phenomenon as the Eötvös Effect. The Eötvös Effect has special importance nowadays in the field of sea- and air-borne gravimetry.

In 1915 Eötvös constructed a special instrument to demonstrate this phenomenon. The device is basically a balance with a horizontal axis, with weights attached to the ends of the arm. The balance stands on a tripod, which rotates evenly. When the balance is rotated the weight moving towards the west will become heavier, the one moving towards the east lighter. The balance will, therefore, deflect from its state of equilibrium. If rotation period equals the period of oscillation resonance gradually increases its amplitude.



Instrument to demonstrate the Eötvös effect (1915)

This experiment is yet further proof of the earth's rotation, and has even greater significance than Foucault's famous pendulum experiment carried out in the Pantheon in Paris.

Parallel with their field work utilizing the torsion balance, Eötvös and his colleagues determined the horizontal component and the declination and inclination of the earth's magnetic field at every observation point. The extensive observational data available enabled them to give an integrated geological interpretation of the measurements.

In order to study the characteristics of the earth's magnetic field, Eötvös designed an instrument on the analogy of his torsion balance, called a magnetic translatometer. It differed from the torsion balance in that the lower weight was replaced by a magnetic needle. The needle could be rotated around its horizontal axis and could thus be positioned in the direction of the earth's magnetic field. The suspending wire of the magnet became the centre of the rotation axis of the instrument. Because of the instrument's high sensitivity Eötvös was able to determine the magnetic moment of rocks and other bodies exhibiting weak magnetism. He carried out similar measurements on old bricks and clay pots. During the baking and cooling of the bricks and pots, several hundred years earlier, they had acquired a remanent magnetization in the direction of the ambient magnetic field. Since it was easy to recognize the sides of the bricks and the bottoms of the pots on which they had rested during baking, it was possible to position them in the same way. After having determined the direction of their magnetization, the inclination of the magnetic field at the time of their cooling could be defined. In 1900 Eötvös gave a lecture on his studies in this subject, entitled 'Magnetic Inclination in the Past'.

3. Eötvös the Organizer

In addition to activities as a research worker and lecturer, Eötvös played an important role in organizational work, thus promoting the development of the natural sciences in Hungary.

In 1885, in the company of other university lecturers, he took part in discussions on the latest scientific results. This group later became known as the Mathematical Society, in which physicists played an ever increasing role. As a result, in 1891 the Mathematical and Physical Society was formed, with Eötvös as its president. The society's journal was entitled the Mathematical and Physical Papers. The society was split in the year 1949, the Physical Society took the name of Loránd Eötvös and the Mathematical

Society was called after one of Hungary's great mathematicians, János Bólyai. In 1894, not long after Eötvös was appointed minister, the Physical Society gave their president a festive welcome, and to honour the occasion they announced a mathematical and physical competition for secondary school children, the winners of which would receive an Eötvös award.

During his career as a teacher Eötvös quickly realized that a great number of talented and hard working students were forced to stop their studies, due to lack of financial support. He wished to help solve this problem and so during the time he was minister, he established a residental college, which was named the József Eötvös College — after his father. Within the framework of the college future secondary school teachers received excellent tuition and took part in special tutorials to promote and develop individual scientific work. In order to assist the poorest students no fees were required for thirty of the one hundred places.

The financial situation of some of the students is characterized by the following story. In 1918, on the seventieth birthday of the now seriously ill Eötvös, the leaders of the college and six of the students visited him on his sick bed. During the conversation Eötvös asked how the six representatives of the students had been chosen. One of the students gave this explanation: 'Honourable sir, it was a question of jackets. It was only those with proper jackets who came.' The Eötvös College trained numerous excellent research workers and teachers in the following decades.

To promote the natural sciences Eötvös convinced Andor Semsey, a great Hungarian patron of the sciences to establish a scholarship which was to be awarded to young graduates who wished to devote themselves to scientific studies.

Eötvös kept in close touch with several international scientific organizations. The foremost of these was the Internationale Erdmessung, precursor of the international Union of Geodesy and Geophysics (IUGG). Eötvös regularly attended the general meetings of this organization and on each occasion reported on his research. As already mentioned, the 1906 general meeting of the Internationale Erdmessung held in Budapest played an important role in the further development of geophysical research in Hungary.

From 1907 onwards Eötvös' torsion balance project was financed by a special fund. After his death geophysical research became financially independent of the University Institute of Physics, under the name of

Eötvös Loránd Geophysical Institute (ELGI). This group of scientists, which, during Eötvös' lifetime consisted of a few members, has developed into a research establishment of about five hundred members, all striving in his name to further develop the science of geophysics.