HISTORY OF PHYSICS

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Gravitation and Action at a Distance

THE STUDY of gravitation was intimately connected with the genesis of mechanics. Of course, the human mind has dealt with this phenomenon through all ages, from antiquity to the present, and no topic in physics, with the exception of atomistics, has given rise to as much speculation as the reasons for the force of gravity. What is actually known about it is due to those who limited themselves to the question: How does it act? Galilei went into this most extensively. He simply accepted as fact that bodies close to the earth's surface receive a constant acceleration perpendicularly downward; this assumption sufficed for the derivation of his laws of falling bodies. Newton's famous "hypotheses non fingo" at the close of his *Principia* should also be recalled here. Both of them, however, laid great stress on the proof that all bodies experience the same acceleration, and tested this not only with freely falling bodies, but also by showing that the period of a pendulum is independent of the nature of the swinging body. The most thoroughly conceivable opposite would be to postulate that the force of gravity is proportional to a "heavy mass" that is different from the inert mass. The equality of both masses is one of the most prominent features of the theory of gravity.

The idea that gravitational attraction is not confined to proximity to the earth, but is a general property of all matter, and therefore is active also between the heavenly bodies, is likewise quite old. Indications of it can be found, for instance, in the writings of Nikolaus Copernicus and R. Hooke. More respect was accorded during the seventeenth century, and by some even until well into the eighteenth century, to the theories of the great philosopher René Descartes (1596-1650).

He rejected a void as a *contradictio in adjecto* and thought of the interstellar space as filled with a whirling fluid which carried along with itself the planets "afloat" in it. Newton devoted a considerable part of his *Principia* to the hydrodynamic refutation of this theory. When tracing out the origin of the Newtonian law of universal gravitation (the force of attraction is proportional to both masses and inversely proportional to the square of the distance between them), it is essential to call attention to the following great trio: Tycho Brahe (1546-1601), who made particularly accurate, well-planned series of observations of the positions of the planets; Johannes Kepler (1571-1630), who from the Tychonic data, deduced the three laws that bear his name (elliptical orbits; equal areas swept out in equal times by the radius-vector; the squares of the times of revolution are proportional to the cubes of the great axes), and who, like some of his contemporaries, already sensed the decrease of the force with the square of the distance; and finally, Isaac Newton, who proved this law by quantitatively confirming it with respect to the acceleration on the earth's surface, and that experienced by the moon, and, in addition, mathematically deduced from it the laws of Kepler and his own universal law of motion. The latter rightly bears his name. Although many before him, such as Robert Hooke, had spoken of universal attraction between all bodies, none had understood how to derive from it, by rigid mathematics, the laws of Kepler together with the slight deviations from them due to the mutual disturbances of the planets, to point out the anomalies in the motion of the moon, and to elucidate the connection with the ebb and flow of the tides. These accomplishments must have made a tremendous impression on his contemporaries. This is readily understandable because hitherto the positions of the planets had been considered to be the direct result of divine will. With a single stroke, this new knowledge demolished the structure of astrology, which, up to then, had been highly esteemed. Certainly, nothing in its previous history had contributed so powerfully to the establishment of respect for the young science of physics as did the Newtonian computation of the orbits of the planets. From then on, this science has been a great mental empire, which no other power may ignore with impunity.

The Newtonian law signified also a complete change in the conception of the systems of fixed stars. From Aristotle up to and including Kepler, with the exception, of course, of Giordano Bruno (see Chapter VI), the fixed stars were thought of either as being attached to the surface of a sphere, which had the sun as its center, or as being in a relatively thin spherical shell, beyond which there was thought to be absolutely nothing, not even space. Kepler himself had refused to regard the sun as merely one of many fixed stars. Now it became clear that the system of fixed stars does not represent something static, but instead forms a dynamic whole, held together by gravitation, but subject to internal movement, i.e., to the succession of the constellations. There immediately arose such questions as: "How far away are the various fixed stars?" and "Do the stars have a motion of their own in the celestial vault?" These problems were attacked successfully only at a later period, but the concept of an unlimited universal space and the inclusion of the sun among the fixed stars was nevertheless a necessary deduction from the Newtonian law.

The law of gravitation contains a proportionality factor, the gravitational constant, which represents the force with which two masses of one gram each attract each other when they are one centimeter apart. Astronomy can compare the masses of various heavenly bodies with each other, but it cannot determine this constant. The requisite experiment was carried out by Henry Cavendish in 1798. He used a torsion balance, an instrument that had been employed as early as 1785 by Coulomb (see Chapter V) for electrical measurements. The value of the constant is 6.7×10^{-8} $cm^3/gm\text{-}sec^2$, from which the mass of the earth has been calculated to be 6×10^{27} grams.

In conjunction with the universal law of gravitation, it should be pointed out that in 1777 Joseph Lagrange defined potential, whose gradient yields the force of attraction; that Pierre Simon Marquis de Laplace derived for this function the coordinates of the partial differential equation ($\Delta\varphi = 0$), which bears his name, and that, in 1812, this expression was modified in the well-known manner by Simeon Denis Poisson (1781-1840) to apply to the interior of matter. These were important advances preparatory to the potential theory of electrostatics (see Chapter V). The Laplace-Poisson differential equation is the generalized expression of the Newtonian law of attraction. It follows from the latter, but also leads back to it, when applied to mass points (or homogeneous spheres).

The law of gravitation provided a firm foundation for theoretical astronomy, whose most important problem, the calculation of the perturbations of the planetary orbits because of the mutual attraction of the planets is, of course, still occupying the attention of astronomers and mathematicians. Some of the mathematical methods of mechanics have developed from this law. A milestone on this road was the *Mécanique celeste* of Laplace, which was published about 1800. The excellence of the law was illustrated most conspicuously by the discoveries of Neptune and Pluto, since even before these outermost planets were ever seen, their positions were computed from the perturbations of the orbits of the next inner planets. Neptune was found in 1846 by Johann Gottfried Galle (1812-1910) on the basis of calculations by Urbain Jean Joseph Leverrier (1811-1877), and Pluto in 1930, from the computations of Percival Lowell (1855-1916), at the observatory named after him at Flagstaff, Arizona. Only a minimal lack of agreement remained. Because of the deviation of the affected planetary orbit from the elliptical form, the perihelion, i.e., the position of the shortest distance of the planet from the sun, slowly rotates in the plane of the orbit. The perturbation theory explains this in quantitative agreement with the observations for all the planets except the innermost one, Mercury. In this instance, a deviation of 42 seconds of arc per century remained unaccounted for. In 1916 Einstein's general relativity theory (1913 on) explained this as being a result of the warping of space, which according to this theory accompanies every gravitational field, but becomes appreciable only in the neighborhood of a tremendous body, such as the sun. The fact that a result of 42 seconds positive was obtained by a computation based on the mass of the sun, the gravitational constant, and the distance between Mercury and the sun, constitutes one of the two empirical supports of this brilliant law, which, however, cannot yet be regarded as fully verified.

Newton's law of gravitation, if literally construed, assumes direct action at a distance. The possibility of such action has been doubted in all times, including Newton's; in fact, he himself was by no means unaware of this objection. The speculations, mentioned above, about the causes of gravitation frequently originated in efforts to discover a transmission mechanism for gravity. Nevertheless, as a consequence of the amazing effect produced by the Newtonian discovery, the idea of action at a distance was carried over into other fields of physics. Certainly, one of the factors contributing to this spread was the fact that the simple and elegant mathematical potential theory can be derived from it. Whereas, close-up actions are employed exclusively in the mechanics of deformable bodies, the earliest theories of electrical and magnetic phenomena became distant action theories. The change did not occur until the second half of the nineteenth century, when the influence of Michael Faraday (1791-1867) and J. Clerk Maxwell (1831-1879) made itself felt. This movement prevailed after the discovery (1887) by Heinrich Hertz (1857-1894) of electrical waves that travel with the velocity of light. This brought about also some loss of standing to the distant action of gravitation, and matters really became serious when the special relativity theory (1905) stated that the velocity of light represents the maximum for the velocities of propagation of all physical actions. The general relativity theory (1913 on) also states that gravitational force travels at the velocity of light and also postulates the existence of gravitational waves, whose production in observable strength of course cannot overcome the insuperable experimental difficulties. This theory retains the Newtonian gravitational law as an approximation.

A humorous demonstration of the stifling prestige of the Newtonian ideas is given by the fact that some scientists of the eighteenth century relegated meteors to the status of a legend, despite numerous observations, from antiquity on, that testified to their actual existence. Newton's unworthy followers believed that the chaotic descent of stones and masses of iron "from heaven," was incompatible with the cosmic orderliness revealed by the master. It was not until 1794 that Ernst Friedrich Chladni, well versed in law, collected and made a critical study of most of the testimony, and from the widespread agreement between entirely independent accounts, concluded that the observers had seen real objects. When, in addition, a great swarm of meteorites descended in 1803 in the vicinity of Laigle (Department of Orne), and Jean Baptiste Biot (1774-1862) was able to study this shower, the Paris Académie found itself forced to abandon its negative attitude. There were indeed more things between heaven and earth than "are dreamt of in your philosophy."[1]

1 "Hamlet was certainly correct in this statement, but, in return, "philosophy" likewise contains things of which no trace can be found between heaven and earth." This witticism is ascribed to the Göttingen physicist Georg Christoph Lichtenberg (1742-1799).