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THE oft repeated legend of the apple falling from the tree and hitting Isaac Newton on the head may or may not be authentic history, but the tale has served to publicize Newton's formulation in 1686 of the law of universal gravitation. This has usually found its way into textbooks thus: every body in the universe attracts every other body with a force that is directly proportional to the product of the masses of the two bodies and inversely proportional to the square of the distance between their centers.[1]

This general law contains a wealth of information. The book on the desk is attracted by the clock on the wall. The stone hurled through the air pulls on each mango on the tree. But no one is aware of these minute forces, and even the laboratory experimenter with his refined techniques would be

[1] *The Philosophiae naturalis principia mathematica* of Newton is one of the cornerstones of physical science. The principle of universal gravitation is there set out in mathematical form in Book III. Proposition VII Theorem VII states: "That there is a power of gravity tending to all bodies proportional to the several quantities of matter which they contain." After the explanation and proof Newton puts the first corollary: "Therefore the force of gravity towards any whole planet arises from, and is compounded of, the forces of gravity towards all its parts." The quotations are from the English translation by Andrew Motte, published in New York 1846 by Daniel Adee, p. 317. Newton of course wrote in Latin.

hard put to it to devise a method of measuring them. Where the quantity of matter in the two bodies involved is small, the attraction is insignificant unless the distance separating the bodies becomes vanishingly small.

Yet the gravitational attraction of the moon for the earth and of the earth for the moon is an enormous force in spite of a separation between the two bodies of about 238,000 miles. The sun also exerts its gravitational influence on the earth. Though the sun is many times more massive than the moon (25 million) it is likewise about 92 million miles away. Attractions of the sun and the moon are responsible for the tides on the earth.[2] How the moon attracts the earth may be seen graphically in Figures 1 and 2.

If the influence of the moon is neglected, the sun acting independently would also produce tides by its gravitational attraction. The influence of the sun alone is less than half of that due to the moon alone. Though the sun and the moon act independently, still their effects are additive. At one time the sun, earth and moon can be in the same straight line. Then the tides due to the combination of the sun and the moon become exceptionally high and are called *spring* tides. When the sun and the moon take positions at right angles as viewed from the earth, the tidal influence of the moon is modified by that of the sun. The name given to this tide is *neap* tide. The water level is lower under this kind of tide.

Oceanic tides are conditioned by many other circumstances. In the Bay of Fundy, tides sometimes pile the water as high as fifty feet. The shape of the land which locks the Bay is significant in this case. If the ocean depth of the water at certain places is suitable for a resonance effect, the heights of the tidal waves may also be remarkably augmented.

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[2] One of the classic works on tides is that of George Howard Darwin *The Tides* (New York 1898). The famous scientific ninth edition of *The Encyclopeadia Britannica* contains a mathematical description by the same author. Though old, these works have a place in the history of tides. Tides in the sea are described in most astronomy books. For example, see Russel, Dugan and Stewart *Astronomy* Vol. I (New York 1945) pp. 292 sqq.

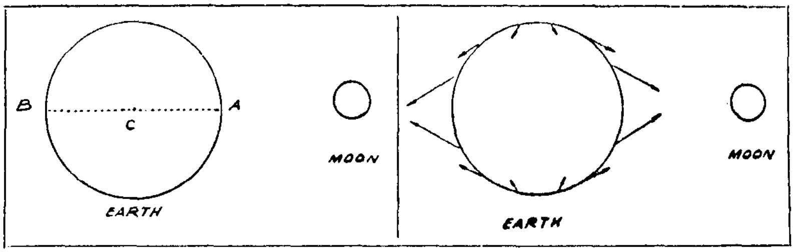

Fig. 1 Fig. 2

Consider the earth as a viscous, non-rigid sphere with a radius of four thousand miles and that the moon is in the position indicated in Figure 1. Since the point A is nearer the moon than the point C or B, the moon exerts a stronger force on the particles of matter at A. This results in pulling the matter away from the earth, and a rise in the level of the earth occurs at A. The point C is nearer the moon than point B. The moon attracts the matter more at C than at B. If the particles at B are free to move, being attracted, they will appear to move away relative to C. In Figure 2 the arrows drawn about the sphere indicate the relative displacements caused by the moon. The effect is an elongation of the earth in the line of the direction of the moon from the center of the earth. Also there is a flattening of the sphere along the other line at right angles. The earth rotates on its axis once a day. Considerations of this nature applied to the real earth show that there should be tides in the ocean or rises in the water level twice a day, first for points nearest the moon, and secondly for points most removed from the moon. At points intermediate the water level will be lower than normal. While the earth is making one rotation, the moon moves along a part of its orbit. Because of this motion, tides due to the moon occur about fifty minutes later each day.

Tides in the sea and ocean are the most familiar manifestations of the gravitational influence of the moon and sun. But the law of universal gravitation is not at all restricted to liquids. It applies just as forcefully to gases and solids. The analysis outlined in connection with Figures 1 and 2 then applies to the gaseous envelop of the earth and also to the *solid earth itself.* In reality there are tides in our atmosphere and bodily tides in the solid earth.

TIDES IN THE ATMOSPHERE

The gavitational attraction of the sun and moon produces tides in the atmosphere. The first and clearest indications of these tides appear on the records of the barometer or barograph. This instrument indicates the values of atmospheric pressure at different times of the day. On a normal day (for example when no typhoon is in the vicinity) the barometric readings are high twice daily, at ten o'clock in the morning and ten at night, with low readings at four o'clock in the morning and four in the afternoon. These changes take place around the world at the same local time. Scientific harmonic analysis of the barogram has further shown the contribution of the sun and the moon to the oscillations of barometric pressure.[3]

Just as the moon's influence on tides in the sea is more than twice that of the sun, so, in accordance with the law of gravitation a similar effect might be expected in the gaseous atmosphere. But unexpected results are observed due to differences in the oceans and in the atmosphere. The solar tide in the atmosphere is some fifteen times the lunar tide! This remarkable effect has been traced predominantly to the resonance of the natural period of the atmosphere with the imposed period of the sun's gravitational attraction.

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[3] Father Charles Deppermann S.J., late Director of the Manila Observatory, just before his death in May 1957 had started research of this nature: "the Fourier Analysis of barometric data at Baguio." On the scientific achievements of Father Deppermann see PHILIPPINE STUDIES V (1957) 311-329. For a complete bibliography of his published works see *ibid.* 330-335.

Resonance or sympathetic vibration is a common effect throughout the realm of physics. A familiar instance is had in the case of troops marching across a bridge. They are told to break step lest their rhythmic beat coincide with the natural period of vibration of the bridge. This could force the bridge into an exceptionally large vibration beyond its breaking point. Since the period of the sun's attraction is just a few minutes more than the natural period of oscillation of the earth's atmosphere, the displacements are greatly increased. The way a man pushes a child in a swing illustrates this: his pushes come at just the right time to increase the swinging distance.[4]

Other elements play their part in making the solar atmosphere tides about one hundred times their anticipated value. Water is scarcely compressible but the atmosphere is highly compressible. Besides, the gases in the atmosphere respond to the heating effects of the sun while the moon's effect is entirely gravitational.

Much is known about tides in the atmsophere but many problems remain to be solved. Mathematical and statistical analysis has been able to separate various agencies each producing its own effect. Further geophysical data at all altitudes in the atmsophere will serve to help our understanding of unsolved problems associated with atmospheric tides.

BODY TIDES

The law of gravitation applies to all ordinary matter, whether liquid, gaseous or solid. The liquids and gaseous parts of our earth have their tides. So, too, does the solid earth. Terra firma which seems so rigid is pulled up and down twice a day by the inconstant moon, just as the seas rise twice a day.

Earth tides as we might expect are so slight that it is very difficult to detect them. However A. R. Michelson devised a simple experiment not only to detect but also to measure these tides. Two pipes, each five hundred feet long, were half filled with water. One was very carefully levelled in the north-south

[4] N. C. Gerson *Unsolved Problems in Physics of the High Atmosphere,* in *Advances in Geophysics* ed. H. E. Landsbery Vol. I pp. 155 ff.

direction and the other at right angles to it. Windows were placed at the four ends corresponding to the fourth principal directions. A microscope was used to read changes in water level at each window. Due to the attraction of the sun and the moon, tides were produced in the pipes. Though these tides were less than one one thousandth of an inch, still they could be measured. Spring and neap tides produced measurably different results. While these tidal values agreed remarkably with the theoretical values, still there was one noticeable departure. The magnitude was about 31% too small. This difference was attributed to the deformation of the solid earth produced by tidal forces. The accepted conclusions from this experiment are: (1) the solid earth is on the average about as rigid as a steel ball but it does yield to sufficiently great forces; (2) it is almost perfectly elastic rather than viscous since it follows at once the stresses which are applied to it. The greatest displacement, the rise and fall in the surface of the earth, that at spring tides, was computed to be about nine inches as a consequence of this experiment.

MODERN METHODS FOR TIDAL MEASUREMENTS

All material objects on the surface of the earth exist in a field of force—the gravitational field. The earth itself acting as a unit at its center attracts each and every chunk or particle of matter according to the gravitational law. This field of force results in definite objects having definite weights. Really the "weight" of an object is the pull of gravity on that body. It is not a property of the body in itself. Recent developments of satellites and the possibility of space travel have brought this consideration out of the ivory towers and into the market place. People are wondering what physical and psychological effects the weightless condition found in space will have on persons. In itself any body has mass (and therefore inertia) but any body can be ideally placed so that the gravitational attraction of the earth for it can be reduced to smaller and smaller values, or even to zero when a weightless condition is reached.

Gravity, or the attraction of the earth for a particular body, undergoes certain changes in magnitude as the body is moved around. If a body were flown in a high rocket, its weight would not be the same as it is at sea level. The magnitude of the earth's attraction depends on the distance from the center of attraction. Due to changes in the density of the surface of the earth, there are also local variations in the weight of a body. Mining explorers use sensitive equipment which effectively determines changes in weight due to a more dense or less dense deposit in a particular vicinity. Actually the quantity measured is not the weight but rather a quantity directly associated with weight, viz. the acceleration due to gravity. To a first order of approximation, on the surface of the earth this quantity is 32 feet per second per second or 980 centimeters per second per second. That value is often memorized and suffices for rough calculations.

Measurements of the gravitational field can lead to knowledge of geological deposits or stratified formations in the earth. To obtain that information very sensitive instruments are needed.[5] Delicate and refined instruments of this type can also be used to give information about earth tides. To have an indication of the refinement of these measurements one can consider the unit in which they are made. The term *gal* is used to take the place of that long expression "centimeter per second per second." The word is taken from the first letters of the name of the man who made some original studies on pendulums, Galileo. In undergraduate college work, students consider they have done well in their experiments to determine the acceleration due to gravity if their error is as small as five gals. But the gal for certain measurements, is too large a unit and and so the *milligal* or one one thousandth of a gal is used. To measure the length of a room one would not use the kilometer but rather the meter as a convenient unit. The milligal has the same relation to the gal as the meter to the kilometer. If measurements are precise to one milligal, that is considerable refinement. It is about one part in a million. A smaller unit is currently being applied: the *microgal* or one one thousandth of a milligal, or one one millionth of a gal. In making gravity

[5] C. A. Heiland *Geophysical Exploration.* (New York 1940) pp. 85 ff.

measurements on the surface of the earth to one microgal, the accuracy is one part in a billion.

GRAVIMETRIC SURVEY OF THE PHILIPPINES

In 1938 Father Pierre Lejay S.J., then Director of the Observatory of Zi-ka-wei in Shanghai, who died a few months ago, made a gravimetric survey of the Philippine Islands. He visited more than two hundred stations, taking observations at each. The instrument developed by Father Lejay and used in these observations was capable of reading changes in gravity of one or two milligals. The values he obtained at the many stations were all with reference to the location of the Manila Observatory in the Ateneo de Manila campus on Padre Faura Street, which he determined as 978,360 milligals. Father Lejay's purpose was not to measure earth tides but rather to make a geological survey of the distribution of masses of the earth in the Philippine archipelago. At the time of his work his instrument gave just about the finest accuracy then available. It is still a very useful device.[6]

MEASURING EARTH TIDES

The sun and the moon attracting the solid earth and also its parts tend to deform the shape of the earth. If conditions are favorable, a measurable tilting of the earth's surface is produced. As the earth rotates, a tidal variation in gravitational intensity may be measured by instruments which are capable of recording small differences in gravity.[7]

In a letter dated 16 May 1957 Dr. Louis B. Slichter, Director of the Institute of Geophysics of the University of Cali-

[6] Pierre Lejay S.J. *Etude gravimétrique des Iles Philippines* Shanghai 1939).

[7] Harold Jeffreys *The Earth* (Cambridge 1952) pp. 201 ff. Papers published in *Monthly Notices* of the Royal Astronomical Society, Geophysical Supplement, Vol. 6 (London) discuss work on earth tides. A few titles are given here: L.H. Tarrant "Tidal gravity experiments at Peebles and Kirklington" pp. 278-285; R. H. Corban "A determination of the earth tide from tilt observations at two places" pp. 431-441; R. T. Tomaschek "Harmonic analysis of tidal gravity experiments at Peebles and Kirklington" pp. 286-302.

fornia, wrote as follows to the Director of the Manila Observatory:

> As part of its contribution to the International Geophysical Year the Institute of Geophysics of the University of California at Los Angeles is planning to make Earth Tide Observations at a number of stations around the world. It is planned to take continuous observations of gravity for a period of 31 days at each station....using a Lacoste-Romberg automatically recording gravimeter.
>
> Is there a suitable site at the Manila Observatory?

The Manila Observatory welcomed the University of California project. The seismic vault of the Manila Observatory on Mirador Hill at Baguio, with its constant temperature and humidity, provided a superior location for the instruments. After further correspondence Dr. Ronald Forbes arrived on 13 September 1957 with his special type of recorder.

The University of California tidal study was conducted by two different parties. One party went eastward from California to set up stations at convenient intervals around the world. Dr. Forbes came westward. His first three stations were at Wake Island, Baguio and Saigon. The entire project was sponsored by the United States Navy in conjunction with the University of California.[8]

The instruments for this survey were unquestionably the most sensitive gravity meters now being made. They have been described in recent articles.[9] Designed to meet the requirement of measuring a change in gravity of less than one microgal, the instruments record automatically and continuously changes which are infinitessimal.

The meter is sealed within a box so that barometric pressure changes would not affect the system. Pressure within the

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[8] J. T. Pettit, L. B. Slichter and L. LaCoste "Earth Tides" *Transactions of the American Geophysical Union* Vol. 34 No. 2 (April 1953) 174-184. John T. Pettit "Tables for the Computation of the Tidal Acceleration of the Sun and Moon" *ibid* Vol. 35 No. 2 (April 1954) 193-202.

[9] H. N. Clarkson and L. J. B. LaCoste "An improved instrument for measurement of tidal variations in gravity" *Transactions of the American Geophysical Union* 37 (June 1956) 266-272; "Improvement in tidal gravity meters and their simultaneous comparison" *ibid* 38 (Feb. 1957) 8-16.

box does not vary 0.1 of a millimeter. An electronic thermostat keeps the temperature of the meter constant to about one one thousandth of a degree centigrade. This was possible, for an outer box was maintained at a temperature controlled to about one tenth of a degree. Possessing the merits of stability, the meter can stand the vibrations required of a portable instrument. A photo-electric optical system operates in conjunction with gravity responsive element. At the latter's null position "the light intensity falling on the photocell is constant. As the gravity responsive element moves away from the null position in either direction, the light intensity varies and the magnitute of the variation is proportional to the deflection from null." The variations in current from the photocell by suitable electronics, are sent to a recording meter which writes the record on a moving roll of paper.

As in the Michelson experiment, in order to know the deformation of the earth's surface due to the attraction of the sun and the moon, theoretically computed values of gravity for a rigid earth are compared with the observed changes in gravity. In other words, the observed changes in gravity under the tidal force are due to two parts: 1) the attraction of the sun and moon on the instruments and 2) the change in shape or deformation of the non-rigid earth. The second effect is considerably smaller than the first.

The gravity measurements at Baguio were recorded from 19 September to 4 November 1957. The curves shows the gravitational variations with various positions of the moon and sun. At this time of writing, the data have not been reduced to give a numerical description of the motion of the earth's crust at Baguio under the tidal forces. However, as part of this same project, in November 1956 at Honolulu "a maximum amplitude of tidal motion of the earth of about four inches" was reported.[10] The variations at Baguio are likely to be of the same magnitude.

Baguio in the Philippines will in the future be one of the reference points for further work in gravimetric studies.

[10] *IGY Bulletin* National Academy of Science, No. 1 p. 14 (July 1957).