MOVEMENTS OF THE EARTH[1]

II.

Measurement of Time

It has been shown how, by the application of geometrical and optical principles, the measurement of angular space has been carried down to the 1/100th of a second of arc, such a quantity being 1/129,600,000th part of an entire circumference, and when such an accuracy as this has been attained, and the altitude or the azimuth of the sun, or moon, or any other heavenly body can be correctly stated with this exactitude, it will be seen how much better off in the way of defining positions is the modern astronomer than was Hipparchus with his 1/3rd, and Tycho Brahé with his 1/4th of a degree. To do this, however, is not enough. It is not only necessary accurately to define the position of a heavenly body, it is necessary also to know at what particular time it occupied that position. The next thing to be done, then, is to see how far we moderns have got in another kind of measurement, no longer the measurement of arc—the measurement of angular distance—but the measurement of *time*.

The measurement of time, however, is not quite so simple a matter as was the measurement of space. A certain angular measurement of space, or the angular distance between two bodies, whether that distance be a degree, or a minute, or a second, is a very definite thing, having a beginning and an end; but time, so far as we can conceive, has neither beginning nor end; so that the problem of the measurement of time has to be attacked rather in a different way. Here again it will be as well that the matter should be studied historically.

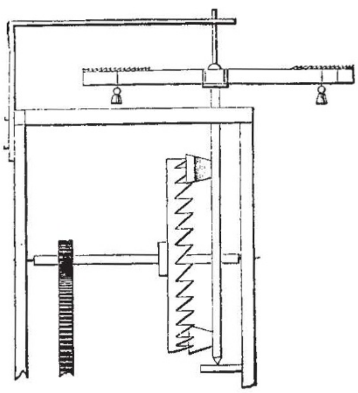

FIG. 18.—Ancient Clock Escapement.

What more natural than that man having got the idea of the flow of time, should have begun to measure it by the flow of water, or the flow of sand? The earliest time measurers were really made in this way; water or sand being allowed to drop from one receptacle to another. There were difficulties, however, in thus determining the flow of time. In the first place the thing was always wanting to be wound up, so to speak, something was wanted to continue the action, and to prolong it; and the first appeal to mechanical principles was made with that view.

The first real clock put up in England was put up in Old Palace Yard, in the year 1288, by the Lord Chief Justice of that time, who had to pay the expense of it as a fine for some fault he had committed. Its construction was somewhat after this wise. One method of dealing with the flow of time was to call in the aid of wheelwork; but, as is well known, if a weight acts upon a train of wheels the velocity increases as the rotation goes on. Therefore the science of mechanics was called in to supply some principle which could be applied to prevent this unequal velocity of a train of wheels. Consider the arrangement shown in Fig. 18.

The wheelwork train is capable of being driven by a falling weight. On the same axis as the smallest wheel, and therefore the one which turns most rapidly, will be seen another wheel provided with saw-like teeth. Then at the top is a weighted cross-bar, from the centre of which a perpendicular rod, provided with pallets, comes down to engage the teeth of the pallet-wheel. Now suppose the clock to be started. The weight is allowed to fall, and the wheels, including the pallet wheel, begin to revolve; then begins a reciprocating action between the swinging bar and the wheel with which it acts, because the pallets which act on the bar as they are on either side of the centre of motion really drive the bar first in one direction and then in the other. The teeth of the pallet wheel are continually coming into contact with the pallets of the swinging bar. First suppose that one of the teeth has encountered the upper pallet; it pushes this aside, and swings the bar in one direction. No sooner, however, has this been done than another tooth in the wheel at the bottom of the bar encounters the pallet and swings it in the opposite direction. In this way it is obvious that the bar is continually meeting and being met by the teeth of the rotating wheel, swinging first in one direction, and then in the other, the result of this reciprocal action being to prevent the increase in the velocity of the wheels which would otherwise take place.

It is in this way, then, by the performance at constant definite intervals of an equally constant definite amount of work, that the regularity of action of the clock is produced. The greater the distance of the weights on the cross-bar from its centre of motion, the longer will the bar take in swinging, the slower will be the action of the clock; so that the clock may be regulated by altering the position of these weights, bringing them nearer to, or removing them further from the centre of motion of the bar, according as it is desired to hasten or retard the action of the clock's mechanism. Yet at whatever distance from the centre of motion the two weights be placed, assuming always that they are both at the same distance from it, there is still this constantly-recurring performance, at equal intervals, of an equal amount of work which produces the regular action of the clock. This was the kind of clock then which was put up in Old Palace Yard. But that did not go well enough, giving such inaccurate results that Tycho Brahé had to discontinue its use. Fortunately some few years later two most eminent men, Galileo and Huyghens, had their attention drawn to this very problem. The first of these, Galileo, was at that time studying medicine. He happened one day to be in the Cathedral at Pisa, where, it will be remembered, they have a most beautiful lamp which swings from a great height in the cathedral. Galileo was at this time working at that branch of his medical studies which deals with the pulse, and he looked at this lamp and found that its swinging was perfectly regular. To-day perhaps it may seem very natural that this should be so, but Galileo had the advantage of being before us, and that is why it did not seem quite so natural to him. There was at that time no known reason why it should swing in perfect regular rhythm. He found that the lamp when swinging, no matter with what amplitude, took practically the same time for each swing, timing it by his pulse. His idea was that this would be an admirable method of determining the rate of a man's pulse, and the first clock on this principle was constructed from that medical point of view, being called a Pulsilogium. Some years afterwards, however, the extreme importance of such an arrangement from an astronomical standpoint became obvious, and very much attention was given to it. It is unnecessary to add that this swinging body is nowadays called a pendulum. The most perfect pendulum made in those early days is represented in Fig. 19.

The fundamental difference between that and the modern pendulum is that part of the pendulum between S and A was elastic. It was made elastic for the reason that although Galileo could not find any difference between the times of the oscillations of the lamp in Pisa Cathedral, according as its amplitude of swing was large or small, yet such a difference did exist, although it was only a slight one; and the only method of getting a perfect pendulum which should make its swing in exactly equal times, independent of its arc of oscillation, was to construct this so-called cycloidal pendulum. It was so named because in its swing its elastic portion was held by the curved guides seen in the figure, and made to bend in that particular curve. By this means the pendulum instead of swinging through the arc, K U R, was made to oscillate through D U L. But when the pendulum was at the points D and L, it was practically a shorter pendulum than when at rest. In other words, whilst the pendulum was swinging from U to D and from U to L, its curvature, and consequently its vibrating length was continually changing. In that way, by continually varying the length of the swinging part, it was found possible to make a pendulum which, independent of the length of its arc of oscillation, would make its swing in times which for all practical purposes were absolutely equal in length. That was the most

[1] Continued from vol. xxviii. p. 604.

perfect pendulum of that time. Nowadays, the cycloidal pendulum has been replaced by one which swings through a very small arc, and the continual shortening during the oscillation in the cycloidal pendulum is by this means dispensed with, whilst the friction also being much reduced, there is less interference from that source. With this very small swing the difference between the arc of the circle described and the cycloid in which the cycloidal pendulum swung is practically indistinguishable.

The great difference between the modern clock and the ancient one is that in the former the pendulum is interfered with as little as possible whilst swinging, and makes each swing under precisely similar conditions. To attain this is to have done much. In the first place, if the clock has a heavy weight, that weight will probably interfere a good deal with the swinging of the pendulum. The clockweight, therefore, must be as light as possible. Secondly, if the wheelwork is always in contact with the pendulum, this also will interfere with its free and natural movement. There must be, then, such an arrangement that the wheelwork shall be brought into contact with the pendulum only for the shortest possible time. Thirdly, it must be remembered that the different substances which it is most convenient to use in the construction of pendulums, vary their dimensions with the variations of the temperature and moisture of the air in which they are placed, and great care must be taken to eliminate any errors which might arise from such a

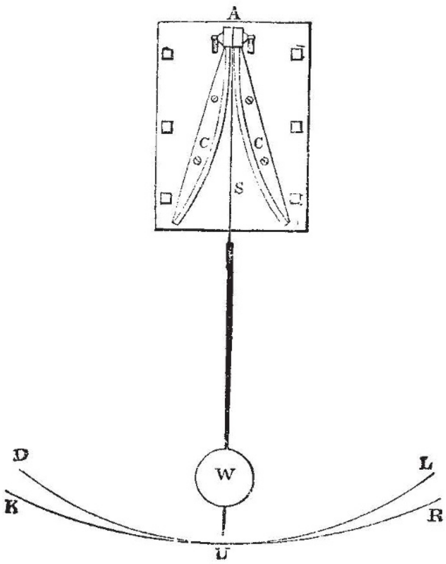

FIG. 19.—Cycloidal Pendulum.

source. How are these various conditions complied with? The first, that the clockweight must be small, is not difficult to adhere to; but it will be well to consider the way in which the second condition, that the action between wheelwork and pendulum shall be the least possible, is met. This is done by employing what is called an escapement. It is so named because the pendulum in its swing is allowed to escape from the wheelwork, and thus retain a perfect freedom. The particular form of escapement about to be described is that which, for a reason that will appear immediately, is called the dead-beat escapement (see Fig. 20).

The escape wheel is the modern representative of the toothed wheel of the old clock, whilst the projections W and D are modifications of the pallets on the swinging bar in that instrument. Let the pendulum move in the direction of the arrow. The tooth T has just been released, thus permitting the tooth V to engage the other pallet D. Now whilst the tooth remains on the pallet, the escape wheel remains locked, while the pendulum is quite free to swing, there being nothing to retard it save the very slight friction between the tooth and the surface of the pallet. The rotation of the escape wheels, however, brings the tooth on to the oblique edge of the pallet, and with it in this position the pendulum is aided in its forward swing. Then the pallet escapes, receiving an impulse, but since this is received almost as much before the pendulum has reached its vertical position as after it has passed that point, no increase or diminution in the time of its oscillation takes place. It is in this way that the second of our conditions is complied with, the wheelwork being effectually prevented from interfering with the regularity of the pendulum's swing. It is called the dead-beat escapement, because when the tooth falls on the circular portion of the pallet and locks the escape wheel, the seconds-hand fitted to it stops dead without recoil, because the arc of the surface of the pallet is struck from the centre of motion. In an astronomical clock a still more modern form of escapement, called the gravity escapement, is sometimes employed.

It will perhaps be convenient at this stage to compare the fineness of the division of time given by a clock of this description with the fineness of the division of the second of arc we have already discussed. There is, however, a little difficulty about this, because at present there seems to be no special reason why any particular unit of time should be selected. Ordinarily a day is divided into twenty-four hours, each of these twenty-

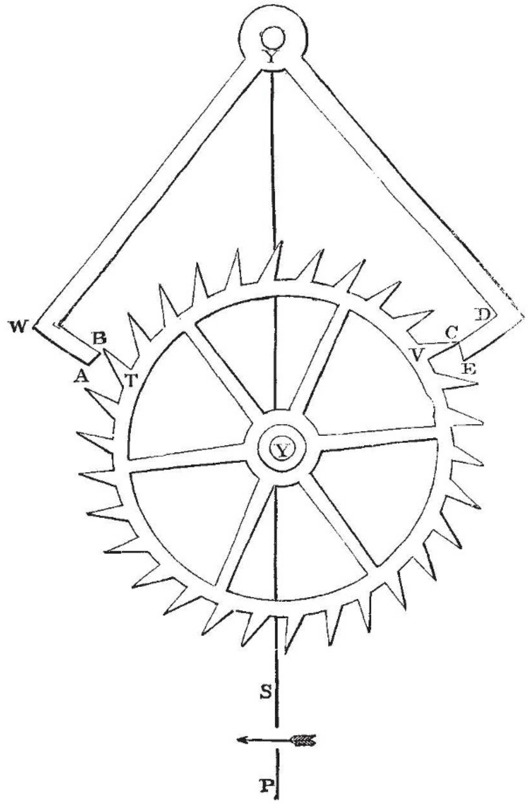

FIG. 20.—Dead-beat Escapement.

four hours is subdivided into sixty minutes, these again being each divided into as many seconds. The origin of this division of time will be seen later on; for the present let the fact remain that it is so.

Now a modern clock beats practically true seconds, and astronomers after a little practice gain the power of mentally breaking that second up into ten divisions, each of which is of course one-tenth of a second, so that we can say that a day may be divided into 864,000 parts, and in this way institute a comparison of the fineness of the division of time with those minute measurements of angular space with which we so recently dealt.

It is a familiar fact that the length of a pendulum which vibrates seconds is some thirty-nine inches, and it is easy to understand that there are many conditions in which a clock of this kind, with its pendulum of more than a yard long, cannot be used. Not only indeed is there this inconvenient length of the pendulum, but it is necessary that the clock to which it belongs should be rigidly fixed in an upright position. The question therefore arises, is this clock which deals out seconds of such accuracy the only piece of mechanism that can record and divide our time, or is any other time-measuring instrument available? Fig. 21 shows part of such an instrument, known as the Chronometer, in which, whilst the principles necessary to be followed in the construction of the clock have been adhered to, the pendulum has been dispensed with, and the perfect stability and verticality of position so important to the clock, are here unnecessary.

In this instrument the pallets of the dead-beat escapement have been replaced by a detent, D. Let us consider the action. The escape-wheel, S, is advancing in the direction of the hands of a clock. One of its teeth meets the detent, and the wheel is locked. Then what happens is this: when the balance-wheel, R_1, swings, the circle, R_2, centred on it shares its motion. This, it will be seen, is armed with a little projection.

We left the escape-wheel locked. Now assume that the balance-wheel is swinging in the direction of the arrow. It carries the small circle with it, and the piece, P_2, in its motion, coming into contact with the end of the spring, seen projecting beyond the arm of the detent, raises it and the detent, so releasing the tooth of the escape-wheel. The slight retardation which the balance receives in consequence of this action is immediately compensated. The moment the escape-wheel moves on again, one of its teeth meets the projection, P_1, and the balance-wheel receiving this fresh impulse goes on to complete its swing. Then it returns and swings in the opposite direction, this time without acting in any way on the detent. When the balance-wheel made its first swing and the point P_2 met the projecting end of the spring, the

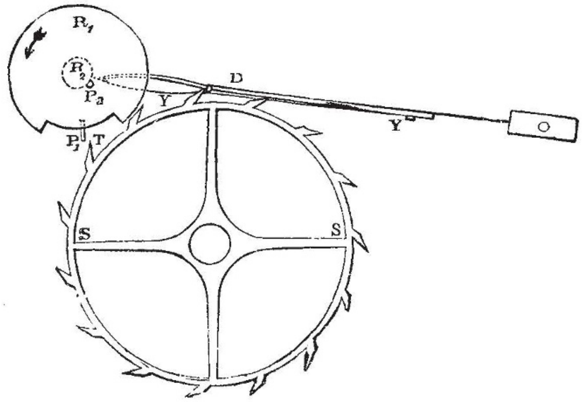

FIG. 21.—Chronometer Escapement.

latter could then only bend from the end of the arm with which the detent is provided and against which the point P_2 forced it. But on the return swing the spring is found capable of bending from the more distant point of its attachment to the shank of the locking-piece. It is therefore easily pushed aside; there is no change in the position of the detent, nor is any resistance offered to the motion of the balance-wheel, which goes on to complete its swing. Then another tooth is caught, the escape-wheel is again locked, and again released by the lifting of the detent. So the action goes on, the teeth of the escape-wheel being constantly detained and as constantly released by the action of the point P_2. The balance-wheel, it will be noted, receives its impulse only at every alternate swing, whereas in the clock the pendulum receives its impulse at each vibration.

Time then can be divided down to the 1/10th of a second, or as we expressed it, down to the 864,000th part of a day, not only by a clock, but also by this chronometer. Having obtained this 1/10th of a second by these instruments, the question arises as to whether it be possible to get a still finer division. It will be seen that a very much finer division than this can be obtained, the 1/100th part of a second being a measurable quantity; not that such a small fraction of time as this is ever necessary in astronomy, nor will it be until the present astronomical methods have ceased to exist. If it were possible to get *all* observations made by photography, then it would be worth while recording with such minuteness, because photography would always behave in the same way, whereas two observers never have the same idea as to the time of occurrence of any phenomena which they observe. Yet, although so great an accuracy as this is not attempted, it will be quite worth while to consider the means by which this exquisite fineness of the division of a second of time has been arrived at. We shall see that just in the same way as an appeal to mechanical principles resulted in an improvement in the construction of our clock, so this fineness in the division of time has been obtained by an appeal to the principles of electricity. Let it be assumed that the seconds pendulum of our clock swings with perfect accuracy and with absolute uniformity from second to second, in spite of changes of temperature and other perturbing influences; and having assumed this, let us see how electricity can be made to aid in the measurement of time. The instrument used is called a chronograph. It consists of a metal cylinder revolving by clock-work and covered with cloth, over which a piece of paper can be stretched. Below the cylinder and parallel with it is a track along which a frame carrying two electromagnetic markers or prickers is made to travel uniformly by the same clock that drives the cylinder. Wires connected with a battery lead from one of these magnets to a clock and from the other to a key, which can be depressed whenever an observation is made, and a current so sent to the magnet. The effect of this is to cause it instantaneously to attract its iron armature and cause the pricker with which it is connected to make a mark on the paper above.

The connection of the chronograph with the clock is as follows:—The bearing shown in the middle of the diagram (Fig. 22) is a continuation of the bearing on which the seconds hand of the clock is supported, and there is a little wheel which does its work quietly at the back of the clock in exactly the same way that the seconds hand does its work quietly in front of it. What

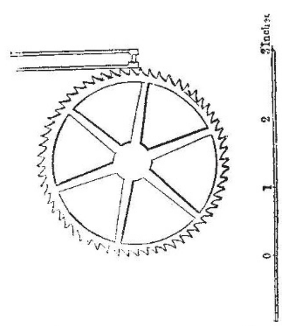

FIG. 22.—Electrical contact apparatus at back of clock.

that wheel does is this. Every time that each of its teeth—and there are sixty of them—comes to the top of the wheel it touches a little spring. That little spring then makes electrical contact, and a current is sent flowing through parts of the apparatus already described. Now the teeth in that wheel, being regularly disposed around its circumference, always succeed one another after exactly the same interval of time, and there is no difference or distinction from second to second, or from minute to minute. But suppose that before the clock is started one of these teeth is filed off, and so filed off that when the seconds hand points to 0 seconds, and the minute hand to a completed minute, this part of the wheel shall be at the top, and there shall be no electrical contact established, for the reason that the tooth of the wheel is not there to act on the spring. In that way it is easy to manage matters so that the beginning of each minute shall be distinguished from all the other fifty-nine seconds which make up the minute. Let the cylinder, covered with paper, revolve once in a minute. In that case, the electrical current will make a hole or a mark on that paper every second, and as matters are so arranged that the prickers shall be travelling along at the time that the dots are made upon the revolving paper they are thus made along a continuous spiral, and since we have supposed the cylinder to revolve once in a minute, the beginning of each minute will be in the same line along the spiral. Then, according to the length of the cylinder, a second of time will be obtained written in dots, sixty of them round the cylinder representing sixty seconds. Suppose now that a man with a perfect eye makes an observation, recording it by sending a current through the apparatus and making a dot on the paper. He will then have an opportunity of observing on the paper the precise relation of the dot which represents the time at which the observation was made to the other dots which represent the various seconds dotted out by the clock, and not only the exact distance of the observation prick from the nearest *second*, whether it be ½, or 1/10th, or 1/100th of the distance between that second and the next, but the omission of the record of the first second in the minute will give the relation that observation has to the nearest *minute*.

For the sake of simplicity the case of one observer making one observation has alone been considered; but if the work be properly arranged, then not only one electromagnet, but two, or three, or four, may be at work upon the same cylinder at the same time, each making its record, and that is how such work is being done at the Greenwich Observatory.

Observing Conditions

This power of measuring and dividing time then having been obtained, we seem to have reached our subject, "The Movements of the Earth." Yet even now there are one or two other matters which require to be discussed before we consider the movements themselves. The first of these is the important fact that the earth is spherical in its form. There have been many views held at different times as to the real shape of the earth, but the only view we need consider is that stated. In going down a river in a steamboat, or, better still, in standing upon the sea-shore at some place, such as Ramsgate, where there are cliffs, and where, consequently, one may get from the sea-level to some height above it, it is observed that when any ship disappears from our view by reason of its distance it seems to disappear as if it were passing over a gentle hill.

It does this in whatever direction it goes. This familiar fact is a clear proof that the earth is a sphere, and is so obvious that it may seem unnecessary to mention it, but it was as well to do so for a reason which will appear shortly. Besides this argument in favour of the spherical shape of the earth there is the argument from analogy: the moon is round, the sun is round, all the known planets are round. The stars are so infinitely removed from us that it cannot be determined whether they also

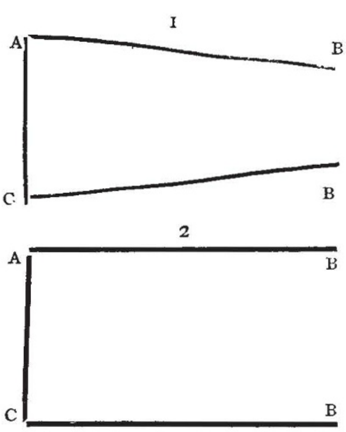

Fig. 23.—Model to illustrate parallax.

are spherical, but doubtless they are as round as the earth. This point of the tremendous distance of the stars is an important one to bear in mind. Their distance cannot be conveniently stated by thousands, nor even by millions of miles, it is something far greater than that. It may be asked why it is that such a statement can be thus positively made. For this reason: the stars have been observed now for many ages, and the historical records of ancient times show that the chief constellations, the chief clusters of stars visible in the heavens now, were seen then. In the Book of Job, for instance, there is a reference to the well-known constellation of Orion, and there is very little doubt that for thousands and thousands of years that constellation has preserved the familiar appearance of its main features. The constellation called Charles's Wain, or the Great Bear, was also known to the ancients. If the stars were very near to the earth this could not be. If they were close to us the smallest motion either of earth or star would at once change their apparent position, and would prevent this fixity of appearance, and the skies would be filled, not with the constellations with which we are so familiar, but with new and ever-changing clusters of stars. This constancy of the constellations, not only from century to century, but from era to era, clearly proves then that the stars of which they are made up must be at an infinite distance from the earth.

Let us consider the question of distance a little further. If two pieces of wood (see Fig. 23) joined together by a cross-piece be taken, a moment's thought will make it obvious that the angles which A B and C B make with the cross-piece A C, will vary with the distance of the body, which can be seen first by looking along A B and then by looking along C B. If these pointers be directed to a very near object in the room, they must be greatly inclined (as in 1). If something more distant be taken, there is less inclination, and if it were possible to sight St. Paul's by looking first along A B and then along C B, there would be still less. And if something at a still greater distance were sighted, say St. Giles's at Edinburgh, the inclination of A B and C B would be still smaller than it was in the case of St. Paul's, because St. Giles's is at a much greater distance. It follows then that in sighting an object so infinitely removed from us as a star, the light from it will be in a condition of parallelism, and A B and C B consequently be placed quite parallel in viewing it (see 2). That is another reason for saying that the stars are at this infinite distance from the earth. Why it is so important to insist on this point will appear very clearly by and bye.

Now suppose that in the centre of this lecture-theatre a little globe were hung to represent the earth, the walls of the theatre and the people in it representing the heavens surrounding the earth. Now in such a case it is clear that the appearances presented would be the same whether the heavens moved round the earth or the earth itself were endowed with motion. Let us, without making the assertion, assume that the earth does move. It is perfectly obvious, since the apparent motions of the heavens are so regular, that if that be so she must move with wonderful constancy and regularity; she does not first move in one direction and at one inclination, and then at another; that would be very serious.

If she rotates she must rotate round some imaginary line called an axis. This introduces an important consideration because, whether the earth itself rotates on an axis or the heavens move round the earth—and in the latter case the heavens must also move round an axis—in either case the motion must be an equable one; so that if the matter is thus limited to a constant axial rotation or a constant revolution, as it would be called in the case of the stars, several things will happen. Let us take the former case, in which the earth itself moves. Then the motion of the surface of the earth will be least at those points which are nearest the ends of the axis on which it turns. Take the case of an observer at such a point, he will be carried a very little distance round during each rotation; similarly, if the stars move, a star near the ends of the axis on which the stars move will be carried a very little distance round during each revolution of the celestial sphere.

Change the position of the man on the earth from the pole to the equator. Then he will be carried a very considerable distance round in each rotation of the earth: similarly with the stars; if they move, a star in the celestial equator will be carried round a very great distance during a revolution. That is the first point. Another point is that if we assume the earth to rotate we must carefully consider the varying conditions which are brought about by the different positions of an inhabitant of the earth under those circumstances. For instance take the case of a man at the equator, he looks at things from an equatorial point of view, and in the rotation of the earth he plunges straight up and straight down. Similarly, if the stars' daily revolution belongs not to the earth but to the stars, to an observer at the equator of the earth they would appear to move straight up and straight down; and now in dealing with this question and endeavouring to ascertain whether it be the earth or the stars which move it is most necessary to consider the relation of the movements or apparent movements of the stars to the place from which they are observed, and in so doing it is found that there is an immense difference between the conditions which obtain at the poles and at the equator with reference to the phenomena which are observable in each case.

Let us take a globe to represent the earth, and let London be considered the central point for our observations. Now at all places on the earth, in whatever direction we look, we see an apparent meeting of earth and sky; and supposing our observation to be made on an extended plain or at sea, the surface of the earth or sea may for simplicity's sake be considered as a plane bounded by the circle where the earth and sky seem to meet. This is known as the circle of the horizon. To repre-

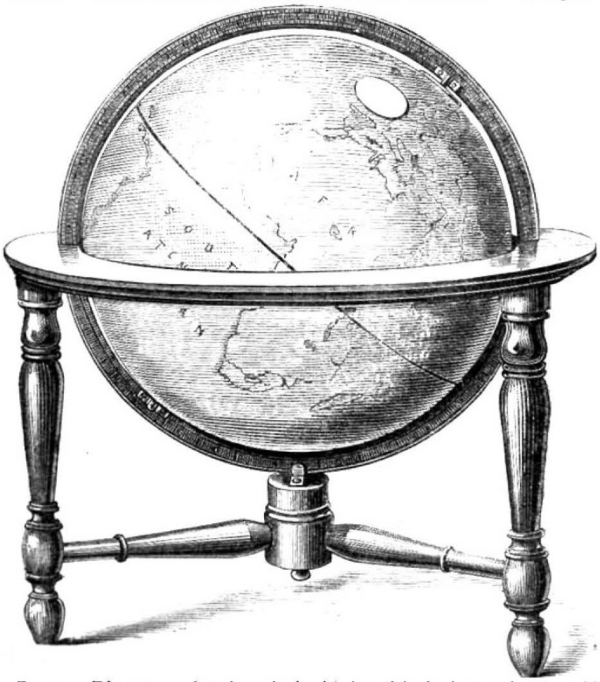

Fig. 24.—Diagram to show how the inclination of the horizon of London will change with the rotation of the earth.

sent this, a piece of paper may be put over London on our globe (see Fig. 24), and London may be brought to the top. When that has been done, remembering that the stars are placed at so infinite a distance, the horizon which cuts the centre of the

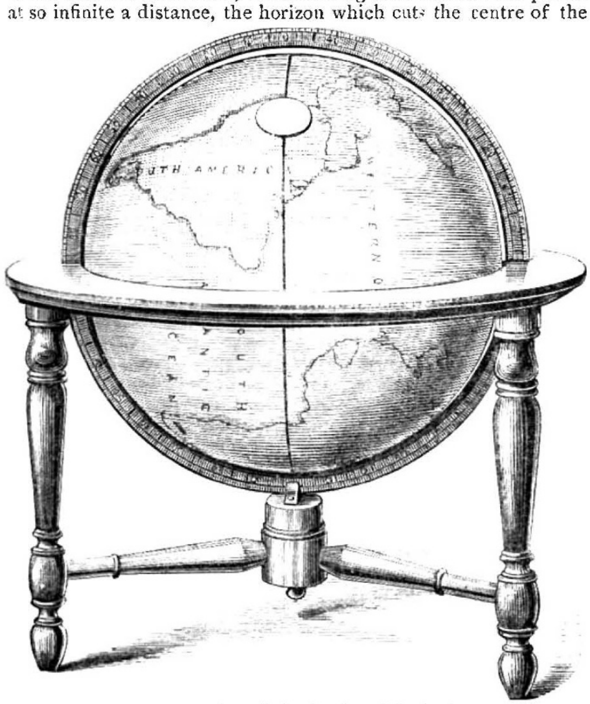

Fig. 25.—Diagram to show how the inclination of the horizon of a place on the equator changes in one direction only.

earth, and which is called the true horizon, may be considered as being practically the same thing as the small sensible horizon of London, represented by our piece of paper, when at the top of the globe, because the two planes will be parallel. For, whether a star be seen from the equator or from London, owing to its tremendous distance it will appear to occupy the same position in space. Now let the globe be made to rotate, then the inclination of the plane of the horizon of any place, of our horizon of London for instance, is continually changing during the rotation (Fig. 24). An exception, however, must be made with regard to the poles of the earth. At these two points the inclination will be constant during the whole of the rotation.

If now a point on the equator be brought to the top of the globe, it will be seen, as the globe is rotated, that the observer's horizon rapidly comes at right angles to its first position (see Fig. 25). This will show that the conditions of observation at different parts of the earth's surface are very different, and this whether it be the earth or the stars which move.

Let us now consider with a little greater detail the conditions which prevail in the latitude of London. Let London be again brought to the top of the globe. Let O (Fig. 26) represent an observer in the middle of the horizon, S W N E. Let Z be the zenith, which, of course, would be reached by a line starting from the centre of the earth, and passing straight up through the middle of the place of observation. S′ is a star, and we want to define its position. How can this be done? Imagine first a line drawn from the observer to the zenith. Imagine next another line going from the observer to the star, or, what is the same thing, from the centre of the earth to the star. Then the angle inclosed by these two lines will give us the angular distance of that star

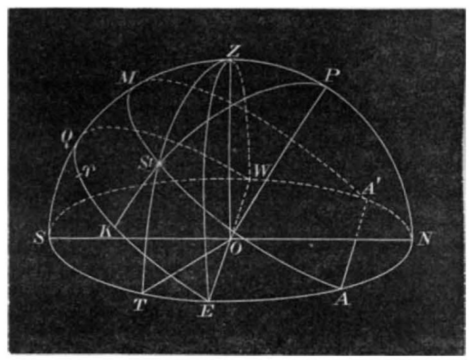

Fig. 26.—Observing condition at London.

from the zenith, or similarly we may take the angle included between imaginary lines joining observer with horizon and star, and thus obtain the star's altitude.

Again, its position may be stated not only with regard to the zenith and to the horizon, but to some other point, say the north point. In that case a line or plane, Z E W, is imagined passing from the zenith through the observer, and the distance between E and N will give the star's angular distance from the north point of the horizon. Again, suppose it be desired to define the star's position with reference, not to the zenith, but with reference to the pole of the heavens, that point where the earth's axis if prolonged into space would cut the skies. In that case since P in our diagram marks the position of the pole, a line P S′ will give what is called the polar distance of the star; and lastly, if the angular distance of the star from the equator of the heavens be required, since the prolongation of P S′ would cut the equator, the distance from S′ to the point of intersection will give the angular distance of the star from the equator; in other words its declination.

We have taken London, but of course each place on the earth has its sphere of observation with its zenith and the north, east, south, and west points. With regard to the axes of the earth and the heavens, they both possess north and south points, and in the heavens as in the earth, the equator lies midway between them.

J. Norman Lockyer

(To be continued.)

OUR ASTRONOMICAL COLUMN

The Observatory, Chicago.—Prof. G. W. Hough has issued his annual Report to the Board of Directors of the Chicago Astronomical Society, detailing the proceedings in the