THE

LONDON SCIENCE CLASS-BOOKS

EDITED BY

G. CAREY FOSTER. F.R.S.
AND
PHILIP MAGNUS. B.Sc. B.A.

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ASTRONOMY

BY

PROFESSOR R. S. BALL

THE LONDON SCIENCE CLASS-BOOKS

ELEMENTARY SERIES

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PROF. G. C. FOSTER, F.R.S. AND PHILIP MAGNUS, B.Sc. B.A.

ASTRONOMY

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ASTRONOMY

BY

ROBERT S. BALL, LL.D. F.R.S.

ROYAL ASTRONOMER OF IRELAND

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1877

EDITORS' PREFACE.

NOTWITHSTANDING the large number of scientific works which have been published within the last few years, it is very generally acknowledged by those who are practically engaged in Education, whether as Teachers or as Examiners, that there is still a want of Books adapted for school purposes upon several important branches of Science. The Series of which this is the first volume will aim at supplying this deficiency. The works comprised in the Series will all be composed with special reference to their use in school-teaching; but, at the same time, particular attention will be given to making the information contained in them trustworthy and accurate, and to presenting it in such a way that it may serve as a basis for more advanced study.

In conformity with the special object of the SERIES, the attempt will be made in all cases to bring out the educational value which properly belongs to the study of any branch of Science, by not merely treating of its acquired results, but by explaining as fully as possible the nature of the methods of inquiry and reasoning by which these results have been obtained. Consequently, although the treatment of each subject will be strictly elementary, the fundamental facts will be stated and discussed with the fulness needed to place their scientific significance in a clear light, and to show the relation in which they stand to the general conclusions of Science.

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G. C. F.,
P. M.

AUTHOR'S PREFACE.

THE present volume is intended for the use of those pupils of the higher classes in schools, who, having some elementary knowledge of Mathematics, desire to gain some information about Astronomy.

In selecting the subjects which are treated of in this volume, much pains has been taken to direct the attention of the reader to the fundamental principles of the science. It has, therefore, been necessary to suppress many descriptive details which, however interesting, are not essential to the object in view.

ROBERT S. BALL.

OBSERVATORY, DUNSINK, CO. DUBLIN :
September 1, 1877.

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ASTRONOMY.

CHAPTER I.

INTRODUCTION.

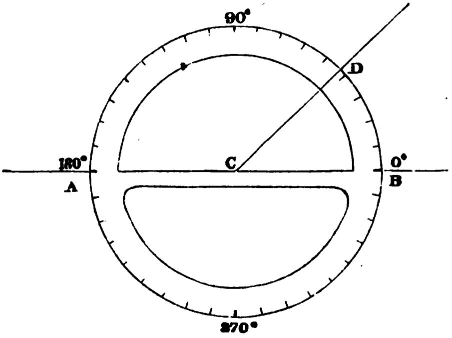
§ 1. **The Measurement of Angles.**—We assume that the pupil, before he begins to learn astronomy, knows at least as much geometry as is contained in the first three books of Euclid. It will also be greatly to his advantage to have some acquaintance with trigonometry; but this will not be indispensable for the reading of this volume, which is only an introduction to the science.

If a right angle be divided into ninety equal parts, each one of the parts thus obtained is termed a *degree.* If a degree be subdivided into sixty equal parts, each one of these parts is termed a *minute*; and if a minute be subdivided into sixty equal parts, each one of these parts is termed a *second.*

An angle is therefore to be expressed in degrees, minutes, and seconds, and, if necessary, decimal parts of one second. For brevity certain symbols are used: thus $49° \, 13' \, 11''{\cdot}4$ signifies 49 degrees, 13 minutes, 11 seconds, and four-tenths of one second.

We shall now explain what is meant by a *graduated circle.* Let the circumference of a circle A D B (fig. 1) be divided into 360 parts of equal length. The division lines separating these parts are denoted by 0°, 1°, 2°, &c., up to 359°. It is usual to engrave upon the circle only those figures which are appropriate to every tenth division. The actual numbers found on the circle are therefore 0°, 10°, 20°, &c. (fig. 1).

FIG. 1.



There is, however, no difficulty in finding at a glance the number appropriate to any intermediate division. To facilitate this operation the divisions 5°, 15°, 25°, which are situated half-way between each of the numbered divisions, are sometimes marked with a longer line, so that they can be instantly recognised.

The interval between two consecutive divisions on a circle is often, for convenience, termed a *degree.* The reader must, however, carefully remember that the word *degree* means an *angle*, and not an arc; with this caution, however, no confusion will arise from the occasional use of the word to denote the small arc of the circle instead of the angle which this arc subtends at the centre.

For the more refined purposes of science, the subdivision of the circle must be carried much farther than the division into degrees. The extent of the subdivision of each arc of one degree into smaller arcs depends upon the particular purpose for which the graduated circle is intended.

The most familiar instance of a graduated circle is the ordinary drawing instrument termed a *protractor*. The protractor is employed for drawing angles of a specified size. For example, suppose that from a point C in the line A B it is required to draw a line C D so that the angle B C D shall be equal to 43°. The centre of the protractor is to be placed at C, and the division marked 0° upon the protractor is to be placed upon the line A B; then a dot is to be placed on the paper at the division 43°, and a line drawn through the dot from the point C is the line C D which is required.

The extent of the subdivisions is limited by the size of the instrument; thus in a protractor of 20 centimetres in diameter the length of the arc of one degree is 1·745 millimetres. If this distance be bisected, the interval between two consecutive divisions is less than one millimetre; if any further subdivision be attempted, the divisions are so close together that they cannot be conveniently read without a magnifier: a protractor of this size is therefore usually only divided to 30-minute spaces.

For astronomical instruments the graduated circles are generally divided to a greater extent. In the instrument known as the meridian circle, the divisions of the circles are executed on silver, and two consecutive divisions are sometimes only two minutes apart. Thus the entire circumference contains $30 \times 360 = 10800$ divisions. The circles in this case are nearly a metre in diameter, and the divisions are read by microscopes.

Mechanical ingenuity has, however, obviated the necessity for carrying the subdivisions of the arc to an inconvenient extent. In the best circles we are now able to 'read off,' as it is termed, to the tenth part of one second. If this were to be effected by divisions alone, there would have to be 12,960,000 distinct marks upon the circumference, and this is clearly impossible with circles of moderate dimensions. Into the details of these contrivances it is unnecessary to enter.

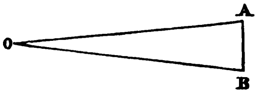
§ 2. **Measurement of an Angle in Circular Measure.**—There is another method of measuring angles, which, though unsuited for the graduation of astronomical instruments, is still of the greatest importance in many astronomical calculations. If we measure upon the circumference of a circle an arc of which the length is equal to the radius of the circle, and if we join the extremities of this arc to the centre, the joining lines include a definite angle, which is termed the unit of circular measure, or the *radian.* It will easily be seen that the magnitude of the radian is the same, whatever be the size of the circle.

We can now see how the magnitude of any given angle may be expressed by the number of radians and fractional parts of one radian to which the given angle is equivalent, and this number is called the *circular measure* of the given angle. It is often necessary to convert the expression for the magnitude of an angle in radians to the equivalent expression in degrees, minutes, and seconds. To accomplish this we first calculate the number of seconds in one radian.

Since the circumference of a circle is very nearly equal to 3·14159 times its diameter, the arc of a semicircle may be taken as equal to 3·14159 radii. Hence the angle subtended at the centre by the semicircle must be equal to 3·14159 radians, and hence it appears that 3·14159 radians must be equal to 180 degrees, whence by division it will be found that one radian is equal to 206265 seconds very nearly. We have often in astronomy to make use of the assumption that the length of a very small arc of a circle is practically equal to the length of the chord of the same arc. Perhaps there is no simpler way of justifying such an assumption than by actually exhibiting the difference in a particular case. If a circle be drawn with a diameter of one metre, and if an arc one centimetre in length be marked on its circumference, then the length of the chord of that arc is 0·99996 centimetres; so that the arc is only one twenty-five thousandth part longer than the chord. It is obvious that the difference between the length of the chord and the length of the arc in such a case as this may for all ordinary purposes be neglected.

To illustrate the application of this principle we shall state here a problem which very often occurs in astronomy. A distant object A B (fig. 2) subtends an angle θ'' at O, the distance O A being equal to d. It is required to determine the length A B. If a circle be described around O as centre to pass through the points A and B, the length of the chord A B may practically be considered to be equal to the arc A B. We may, therefore, compute the *arc* instead of the chord. Now, since the angles subtended by arcs are proportional to the lengths of those arcs, it follows that the required distance A B must bear to the angle θ'', subtended by it at O, the same proportion that the radius d bears to the angle 206265″ or

FIG. 2.



$$AB = \frac{\theta}{206265} \cdot d.$$

§ 3. **The Sphere.**—A *sphere* is a surface such that every point upon it is equidistant from one point in the interior, which is called the centre. If a plane be drawn through the centre of the sphere, it cuts the sphere in a circle, which is called a *great circle.* A plane which cuts the sphere, but which does not pass through the centre, has also a circle for the line along which it intersects the sphere; this is called a *small circle.* The radius of a great circle is of course equal to the radius of the sphere. The radius of a small circle may be of any length less than the radius of the sphere. We may suppose that a sphere is produced by the revolution of a circle about its diameter, and the radius of the sphere is then equal to the radius of the circle from which it has been produced.

Let O be the centre of a sphere and A and B any two points on its surface. Then a plane through the three points O A B cuts the sphere in a great circle. This may, for simplicity, be termed the great circle A B. The length of the arc of the great circle connecting two given points on a sphere of known radius is most conveniently measured by the angle which the arc subtends at the centre.

If three points A B C be taken upon the surface of a sphere, then the three great circles A B, B C, A C form what is called a *spherical triangle*. The sides of this triangle are measured by the angles which they subtend at the centre. The spherical triangle has also angles at its three vertices A B C; the angle at A, for example, is the angle contained between the two planes O A B and O A C. Thus the six quantities involved in the consideration of a spherical triangle are all angular magnitudes.

The three angles of a plane triangle are together equal to two right angles, but in the spherical triangle the sum of the three angles always exceeds two right angles.

CHAPTER II.

THE APPARENT DIURNAL MOTION OF THE HEAVENS.

§ 4. **Explanation of Terms.**—To an observer stationed in the middle of a plain where his view is not obscured in any way by mountains or other obstructions, or, better still, to an observer stationed on a vessel at sea and out of sight of land, the heavens appear like a hemispherical vault with a circular base resting upon the earth. This circular base, which seems like the intersection of the heavens with the earth, is termed the *apparent horizon.*

If a weight be suspended by a thread from a fixed point, then, when the weight is at rest, the thread is said to be *vertical.* That point of the heavens to which the thread points, and which it would appear to reach if it could be prolonged indefinitely upwards, is called the *zenith* ; while, if the direction of the thread were prolonged downwards through the earth, it would intersect that portion of the celestial vault which is below the horizon in a point called the *nadir.*

A straight line which is perpendicular to a vertical line is called a *horizontal line* ; and all the straight lines which can be drawn perpendicular to a vertical line through any one point in it lie in one and the same plane, which is called a *horizontal plane.*

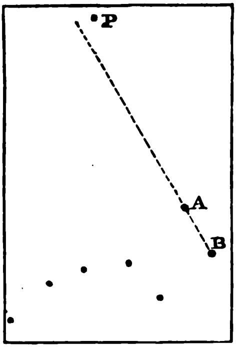
If the face of an observer (in the northern hemisphere) be directed towards that part of the heavens where the sun is at noon, the part of the heavens in front of him is termed the *south*, that behind him is the *north*, while the *east* is on his left hand and the *west* upon his right.

§ 5. **Stars and Constellations.**—To learn anything of astronomy thoroughly it is absolutely essential for the beginner to obtain a knowledge of some of the principal stars and constellations, so that he may be able to recognise them and observe for himself the apparent motions now to be described. For this purpose he must have the use either of a celestial globe or of a good set of celestial maps. The beginner will be saved much time if his teacher can actually show him on the heavens the principal constellations and impress their names and appearances on his memory.

To make the coarse observations which will be described to begin with, no telescope or other instruments are required. The following are the objects to which the learner should first direct his attention.

§ 6. **The Pole Star.**—This star can be seen on every clear night. To identify the Pole, it is necessary for the learner to know the constellation of the Great Bear, sometimes called the Plough (fig. 3). The two stars A and B are commonly called the *pointers*, for they point nearly up to the Pole Star P. The first thing to be observed about the Pole Star is that it remains constantly in the same position in the heavens. At different hours of the night or at different seasons of the year the Pole Star will constantly be seen in the north at about the same elevation above the horizon. It is true that with more careful observations this statement would be found to be not literally accurate, for the Pole Star *does* really change its position to a small amount.

FIG. 3.



§ 7. **The Great Bear.**—The student will next observe the Great Bear. He is carefully to note the position of the seven stars at an early hour in the evening, and if he then looks at them again a few hours later he will see a remarkable change. The relative positions of the seven stars have not changed *inter se*—the shape of the constellation is not altered—but the whole group has moved bodily in the heavens. He will still see the two pointers directed towards the Pole Star, which has remained where it was; and thus the idea will be suggested to him that the whole constellation has moved as if all the seven stars were fastened together with invisible rods, and as if each of the seven stars were fastened by an invisible rod to the Pole Star. If he continued his observations for the whole of the night and the following day (as he could do if he had a suitable telescope), he would find that the Great Bear, after ascending from the east, passed over the observer's head, then down towards the west under the Pole Star in the north, and round again to the east; and he would find that in a trifle less than twenty-four hours the constellation had returned exactly to its original position.

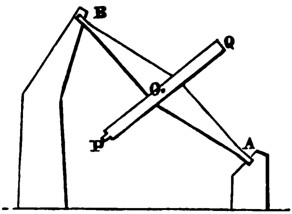
§ 8. **The Pleiades.**—This is a beautiful cluster of stars in the constellation of the Bull, and somewhat resembles a miniature of the Great Bear. This well-known group is visible at night throughout the greater part of the year, but it need not be looked for from the middle of April to the middle of June. Winter is the best season for observing it. In November it will be seen in the east shortly after sunset; it will then gradually rise until about midnight, when it reaches its greatest height; it will then gradually descend towards the west, where it will disappear. There is, however, a very great difference between the motion of the Pleiades and that of the Great Bear:

the latter could be followed (with a telescope) throughout its complete revolution; but this is not so with the Pleiades, for they actually go below the horizon on the west and come up again on the east. If, however, the time be noted which elapses between two consecutive returns of the Pleiades to the same position, the interval will be found equal to the time of revolution of the Great Bear. It will also be observed that the Pleiades appear to turn round the Pole Star in the same manner as the Great Bear.

§ 9. **The Equatorial Telescope.**—The motion which we have been describing is called the *apparent diurnal motion of the heavenly bodies.* To study this motion with the accuracy which its importance demands we employ the very important astronomical instrument which is called the *equatorial telescope.* For an account of the optical construction of the telescope we must refer to books upon Optics; we are now merely going to describe the manner in which the equatorial telescope is mounted.

The equatorial consists of a telescope P Q (fig. 4) attached at its centre O to an axis A B, called the polar axis; the telescope is capable of being turned round the axis passing through O, while the polar axis is capable of being turned round the pivots at A and B. By the combination of these two motions it is possible to direct the telescope towards any required point. To adjust the instrument, it is necessary to place the polar axis A B so that its direction if continued would intersect the heavens in a particular point very close to the Pole Star. This point is called the *Pole.* Let us now suppose that the telescope P Q is pointed towards a star shortly after it has risen, and that the telescope is then 'clamped,' so that it can no longer turn around the axis through O, but so that the motion of the polar axis round A B is not interfered with. It will then be found that, by simply turning the polar axis slowly round, the star can be kept in the field of view, although the angle B O Q remains unaltered. If the telescope be turned to any other star, the angle B O Q must first be altered until the star is brought into the field of view; then the telescope is clamped again, and the star may be followed by simply turning round the polar axis. If we turn the instrument to the Pole Star itself, we shall now see what the coarser observation failed to indicate—namely, that the Pole Star is itself in motion. In this case the angle B O Q is extremely small, being about 1° 21′.

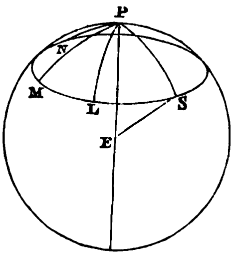
FIG. 4.



If the polar axis of the equatorial be not pointed exactly to the correct point of the heavens, it will not be found that a star can be followed from its rising to its setting without altering the angle B O Q. There is only one point visible in this hemisphere to which the polar axis can be directed so as to fulfil this condition. In the southern hemisphere there is of course a corresponding point, called the South Pole.

Let P denote the Pole (fig. 5), E P the direction of the polar axis, and E S the direction of the telescope when pointed to a certain star. Then the apparent motion of the star is such that the angle S E P remains constant. Now, since the arc P S is proportional to the angle P E S, it follows that the arc P S remains constant, and that therefore the arcs P S, P L, P M, P N, drawn from the Pole to different parts of the star's apparent path, must be all equal. Hence we learn the very important result that the apparent motions of the stars are in small circles on the surface of the heavens, and that all these small circles have the same point for their pole.

Fig. 5.



§ 10. **The Clock Movement.**—It having been ascertained by the equatorial that all the stars appear to move in small circles, the next question to be considered is the rate at which the movement of each star is effected. It is found that to follow the star the polar axis of the equatorial is to be turned round with perfect uniformity. In fact, a clock-work arrangement is generally adapted to the equatorial, which turns the polar axis round with a perfectly equable motion, and as the star is then seen to remain constantly in the field of the telescope, it follows that the star moves with uniformity in its apparent path.

Suppose now the clock be adjusted to move the polar axis of the equatorial telescope accurately for one star, and that then the telescope be directed to another star; it will be found that the telescope will likewise follow the second star with perfect regularity.

From this, the very important result follows that the time occupied in the apparent diurnal motion is the same for every star.

We may summarise the results at which we have arrived in the following way :—

(1) All the stars appear to move in circles round a point of the heavens called the Pole.

(2) Each star moves uniformly in its circle.

(3) The time occupied by each star in completing its motion is the same and is equal to 23 h. 56 min. 4 sec.

§ 11. **The Celestial Globe.**—If we imagine the angle of a pair of compasses to be placed at the eye, while each leg of the compasses is directed towards a particular star, the angle between the legs of the compasses is said to be the angular distance between the two stars. By an instrument founded on this principle it is possible to measure the angular distance between two stars with great accuracy, and from such measurements a celestial globe can be constructed. Two stars, A and B, suppose, are first to be set down at the proper distance apart; then the distance of a third star S is to be measured from both A and B, and the star S is to be marked upon the globe so that the two arcs, S A and S B, shall subtend at the centre of the globe the angles which have been observed. In this way all the principal stars can be marked down on the globe. Now, it is exceedingly remarkable that, notwithstanding the incessant diurnal motion, the positions of the stars with respect to one another remain constant for centuries.

The catalogue of Ptolemy enables us to draw the stars of the Great Bear as that constellation was seen nearly 2,000 years ago, and the differences between the drawing and the present appearance of the Great Bear are so slight that they may perhaps be entirely due to the errors which Ptolemy made.

We have spoken of the motion of the stars as apparent, and we have now to explain how we know that the motion is only apparent, and to show to what the apparent motion is really due. To do this we must first consider the figure of the earth.

We shall now introduce a convention which is very useful. The stars are no doubt at very varied distances from the earth, but, nevertheless, we have seen that the appearance of the heavens can be adequately represented on a globe where all the stars are at the same distance from the centre. Let us now suppose a colossal globe to be described with the earth at its centre and an enormously great radius. Then, if the stars were all bright points stuck on the interior of this globe, the appearance of the heavens would not be altered. This imaginary globe we call the celestial sphere.

CHAPTER III.

THE FIGURE OF THE EARTH.

§ 12. **The Earth a Sphere.**—To an observer situated upon the surface of the earth the contrast is very wide indeed between the appearance of the earth and the appearances presented by the sun and moon. The earth appears to be a flat plain, more or less diversified; the sun and moon appear to be globular; the earth appears to be at rest, while the sun and moon are apparently in constant motion; and, lastly, the earth appears to have a bulk incomparably greater than that of either the sun or the moon.

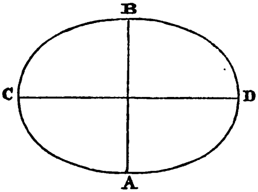
If, however, we could *change our point of view* to a suitable position in space, we should form a more just conception of the relation of the earth to the sun and moon. We would then see that each of the three bodies was really spherical, that each of them was really in motion, and that the earth, though larger than the moon, was very much less than the sun.

It is not an easy matter to determine accurately the form and dimensions of the earth. The shape of the earth is never actually seen except during an eclipse of the moon; the shadow thrown by the earth is then seen on the moon; and as the edge of this shadow is always a portion of a circle, we may infer that the earth, which forms the shadow, must be spherical.

§ 13. **Figure of the Earth.**—We must first understand clearly what is meant by the *figure of the earth.* Suppose that all the large tracts of land on the surface of the earth were intersected by numerous canals which communicated with the sea. Suppose that the sea was perfectly calm and uninfluenced by the tides. Conceive that the dry land was now pared away down to the level of the canals and the sea; then the figure which would be produced by these operations is called the figure of the earth.

It has been found by very careful measurement that the figure of the earth is such as would be produced by the revolution of the curve called an ellipse about its minor axis. In the case of the earth, the length of the axis A B (fig. 6) of the ellipse is 12,712 kilometres, while the axis C D is 12,757 kilometres. It will thus be seen that the earth does not differ very much from a sphere of which the radius is 6,370 kilometres (=3,958 miles). We do not at present enter into the details of the measurements by which these results have been obtained.

FIG. 6.



CHAPTER IV.

THE ROTATION OF THE EARTH ON ITS AXIS.

§ 14. **Rotation of the Earth.**—We now revert to the subject of the apparent diurnal motion of the heavens round the earth. This motion may be explained either by the supposition that there is *real* motion of all the stars, with the sun, moon, and planets, round the earth from east to west once every day, or by the supposition that the earth turns round from west to east, and thus produces the *apparent* motion.

Which of these two solutions are we to adopt?

We shall see hereafter that many of the celestial bodies are vastly larger than the earth, that they are situated at very great distances from the earth, and that some of these distances are very much greater than others. It therefore seems much more reasonable to suppose that the earth, which is a comparatively small body, should be in a condition of rotation, rather than that the vast fabric of the universe should all be moving round the earth once every day. Astronomers, therefore, now universally admit that the earth really does turn on its axis once every 23^h 56^m 4^s.

§ 15. **Shape of the Earth connected with the Diurnal Rotation.**—A remarkable confirmation of this conclusion is presented by the shape of the earth itself. We have already explained what is meant by the pole of the heavens (§ 10), and we can conceive a straight line drawn from the centre of the earth towards the north pole of the heavens. This straight line will cut the surface of the earth in a point which is called the north pole of the earth. Now by means of the surveying operations which have determined the figure of the earth, we are enabled to ascertain the point on the earth's surface which is the extremity of the shorter axis of the ellipse by the rotation of which the figure of the earth can be produced. It will be noticed that the apparent diurnal motion has nothing whatever to do with the surveying operations, so that it is exceedingly remarkable to find that the north pole of the earth is exceedingly close to, if not actually identical with, the extremity of the shorter axis of the ellipse. Thus we see that the axis about which the earth actually rotates coincides with the shortest diameter of the earth.

In this we have another very remarkable proof of the reality of the earth's rotation, for suppose the earth to have been originally in a fluid or semifluid condition, then the effect of the centrifugal force would make it bulge out at the equator and flatten it down at the poles, and thus impart to it an ellipsoidal shape, and the *shortest axis of the ellipsoid would coincide with the axis of rotation.* We are thus led to the belief that the observed coincidence between the axis of the apparent diurnal rotation of the heavens and the shortest axis of the earth is a proof that the apparent diurnal motion is really due to the rotation of the earth.

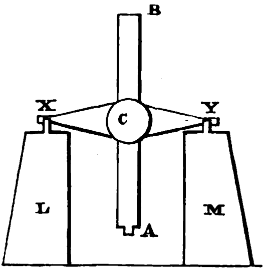
CHAPTER V.

RIGHT ASCENSION AND DECLINATION.

§ 16. **Introduction.**—We now proceed to consider how the positions of the stars and other celestial bodies on the *surface of the heavens* may be determined. We are not now speaking of the actual position of a celestial body in *space.* To know such a position we should require to know the distance of the body from the earth, and of this in the great majority of cases we are at present entirely ignorant. What we desire to ascertain now is the apparent place upon the surface of the heavens, so that we may know exactly where to look for the object, or, to speak more strictly, that we may be able to point a telescope so as to be sure of finding the object at once. It will be understood that we are not now speaking of the position of the object with reference to the horizon, which, of course, is changing every hour, but of its position with reference to the stars and constellations.

§ 17. **The Transit Instrument.**—It will be convenient at this point to give a description of one of the most important instruments in an astronomical observatory. The essential principles of the transit instrument may be explained by help of fig. 7. An ordinary telescope, A B, is fixed to an axis at right angles to the telescope. The shape of the axis and the method of attachment of the telescope thereto, are specially designed so as to secure as much rigidity as possible. At the extremities of the axis are pivots, X Y, which turn in suitable fixed bearings supported on solid masonry piers. Thus the transit instrument can be moved in one plane only. In the focus of the telescope, close to the eye-piece at A, are stretched a number of fine lines, usually spiders' webs; these are placed at equal distances apart, and perpendicular to the axis about which the telescope revolves.

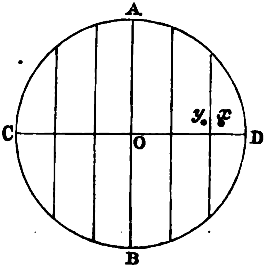
FIG. 7.



When the telescope is pointed to a star, the image of the star is formed in the same plane as the spider's lines, and as the star moves by the diurnal motion the image of the star is seen to pass across each of the lines in succession. The central line A B (fig. 8) passes through the optical axis of the telescope. In addition to the vertical lines, there is a horizontal line C D which is parallel to the axis about which the telescope revolves. The imaginary line joining the point of intersection O to the centre of the object glass of the telescope is called the *axis of collimation.*

The pivots are cylindrical, and the axes of these two cylinders are in the same straight line with the axis about which the telescope rotates.

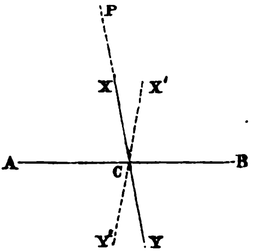
FIG. 8.



§ 18. **Adjustment of the Transit Instrument.**—We shall now explain the conditions which must be fulfilled in order that the transit instrument may be properly adjusted. In the first place the line of collimation of the telescope must be at right angles to the axis of the pivots. Now, although the instrument-maker can effect this to a high degree of approximation, yet the excessive delicacy of astronomical observation is such that minute errors, which entirely elude detection by ordinary measurement, become significant under the high magnifying powers with which the telescope is armed. We therefore require methods not so much for ascertaining whether each adjustment of the instrument is correct, as for measuring how far each one is incorrect, and then correcting every observation for the irregularity. For the present, however, it will be sufficient to point out the means whereby the instrumental errors (as they are called) can be detected.

§ 19. **Error of Collimation.**—Let A B (fig. 9) be the axis of the pivots and X Y the axis of collimation, and let the telescope be directed so that a distant mark P is on the axis of collimation ; when this is the case the mark is seen in the telescope to coincide with O the intersection of the central vertical wire with the horizontal wire (fig. 8). Now, suppose the telescope to be lifted out of its bearings and replaced with the pivots reversed—*i.e.*, the pivot which was formerly to the east is now at the west—and let the telescope be again directed to the distant mark, then if the axis of collimation be not at right angles to the axis of the pivots the telescope will now occupy the position of the dotted line X′Y′ and the object P will no longer be seen at the point O of the wires. The error of collimation is then equal to half the angle X C X′. To correct this error the frame containing the set of wires is to be moved until it is found that a distant object which coincides with O when the telescope is in one position also coincides with O when the telescope is in the reversed position.

FIG. 9.



When the collimation has been adjusted, if the telescope be turned round the axis of the pivots the axis of collimation moves in a plane which traces out a great circle on the surface of the heavens.

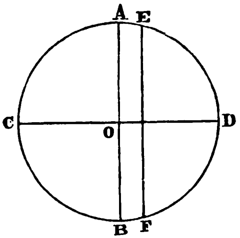
§ 20. **Error of Level.**—The next adjustment of the transit instrument consists in placing the axis of the pivots horizontal. This is effected by a spirit level, which can be hung from the pivots by hooks. On the tube of the spirit level a scale is engraved, so that the positions of the extremities of the bubble can be read off and thus the position of the centre of the bubble ascertained. The level is then reversed, so that the hook which was formerly on the east pivot is now on the west, and *vice versâ*. If the position of the bubble be unaltered, then the axis of the pivots is horizontal. If the bubble change its position with reference to the scale, then the axis of the pivots is not horizontal, and one of the pivots must be raised or lowered accordingly.

When the level of the pivots has been properly adjusted the great circle which the axis of collimation traces out on the celestial sphere will pass through the zenith (§ 4).

§ 21. **Error of Azimuth.**—For the third and last adjustment of the transit instrument, we have to resort to observations of the heavenly bodies. The great circle which the axis of collimation traces out must pass through the pole of the heavens as well as the zenith of the place of observation, the great circle thus defined being called the *meridian* of the place.

For this adjustment we require the assistance of a good clock to enable us to make observations of a star near the pole, preferably the Pole Star itself. Let A C B D (fig. 10) represent the apparent path of the circumpolar star around the true pole O. There will be but little difficulty in adjusting the transit instrument approximately in the true position, so that we may suppose the vertical circle which the axis of collimation describes on the heavens to cut the circle A C B D in the points E and F. The final adjustment will consist in placing the telescope so that this line E F shall coincide with A B. Now, in a period of $23^h\ 56^m\ 4^s$ which is often called the *sidereal day*, the star moves completely round the small circle. It would therefore as its motion is uniform take half a sidereal day to move from A through C to B. It would, however, take more than half a sidereal day to move from E round by A C and B to F, and less than half a sidereal day to move from F through D up to E. We therefore make the following observations.

FIG. 10.



We first note the moment by the clock when the star passes the middle wire of the transit instrument directed to E. About twelve hours afterwards we direct the telescope to F and note the time when the star passes the same wire, and again twelve hours after we repeat the observation at E. Now, if the interval of time as measured by the clock between the first and second observations is equal to the time between the second and the third observations, then the telescope is correctly adjusted; but if these intervals are not equal, then one of the pivots must be moved north or south until the adjustment is completed. The three adjustments having been made, the transit instrument is in working order.

We shall now describe the method of using the transit instrument in the observatory, and its adjunct the astronomical clock. The point in which the meridian cuts the horizon on the same side of the zenith as the pole is the northern point; thus the pivots of the transit instrument when properly adjusted point due east and due west, while the points on the horizon which can be seen in the transit instrument are the north point and the south point. If we could imagine the line of the meridian actually drawn upon the surface of the heavens we could then see the stars crossing this line, and could note the instant by the astronomical clock at which each star crossed. Now, the central wire of the transit instrument really coincides with the meridian, and therefore by noting the instant when the star passes across the wire we obtain the instant when the star crosses the meridian. We have, too, the advantage that the telescope renders minute stars visible, and by its magnifying power enables the coincidence of the star and the wire to be observed with great precision.

§ 22. **The Astronomical Clock.**—The first thing to be done is to make the clock keep accurate *sidereal* time. For this purpose the transit instrument is to be directed to any bright star, and the moment at which the star passes the central wire of the instrument is to be noted by the clock. The next day the same star is to be observed again, and if the clock be going correctly, it will show exactly a difference of twenty-four hours between the two observations. It is immaterial for this purpose what star be chosen; but it is, however, convenient to select a star at a considerable distance from the pole, for then its apparent motion is rapid, and the moment of its transit across the wire can be observed with accuracy. If the clock do not show an interval of exactly twenty-four hours between the two observations, then the length of the pendulum must be altered by screwing up the bob if the clock be too slow, or screwing down the bob if the clock be too fast. It will not be possible to make the clock go with perfect accuracy, but if the clock be going very nearly right, then the amount which it gains or loses in twenty-four hours is determined. This is called the *clock's rate*, and the test of a good clock is that the rate should remain uniform.

When the rate is determined, then all the observations can be corrected, so that we may suppose for present purposes that the clock is going correctly. We have now another point in the adjustment of the clock to attend to. Suppose that the pendulum is adjusted perfectly, and that the hands of the clock indicate $0^h\ 0^m\ 0^s$, and that you wish to start the clock, how are you to choose the instant at which to start it? There is a certain point in the heavens called the *vernal equinox*, the importance of which will be explained subsequently (§ 34). Now, if a star were situated exactly at the vernal equinox, then, when this star was seen on the central wire of the transit instrument, the clock should be started. Now, although there is no star actually situated at the vernal equinox, yet we know the position of this point so accurately that we can proceed as if we could actually observe the transit of the vernal equinox, and then at this moment start the clock.

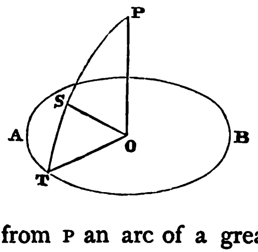
§ 23. **Determination of Right Ascensions.**—We shall now suppose that both the transit instrument and the astronomical clock are in perfect order, and we shall describe the use of them in determining the positions of stars. The observer having pointed the telescope so that the star which he wishes to observe shall shortly be brought into the field by the diurnal motion, takes his seat at the instrument, and after a glance at the clock commences counting the seconds. If he be looking towards the south, the star comes in at his right hand and approaches the wires. Let x be the position (fig. 8) which the star has at one tick of the clock, then by the next tick it will have passed across the wire and be found at y. The experienced observer will rapidly estimate to a fraction of a second the instant when the star coincided with the wire, and he will note this down. Without taking his eye from the telescope he repeats this operation for each of the five wires, and he takes the mean of the five observations for the time of transit over the middle wire. By this method he obtains the time of transit more accurately than he would have done if he had depended upon the single observation at the middle wire.

Let us suppose that the observation of the same star was repeated night after night, it would be found that the same star always returned to the meridian *at the same time* (subject only to certain minute differences which need not now be considered). The time at which the star reaches the meridian is called the *right ascension* of the star.

§ 24. **Declination.**—Suppose it was desired to give instructions to a transit observer to observe a particular star, he must in the first instance know the right ascension of the star, so that when the astronomical clock is getting near that hour he can take his position at the instrument. Suppose, however, the star were invisible to the unaided eye, then it is clear that the observer must be furnished with instructions as to *how high the telescope ought to be pointed*, as well as with reference to the time of transit. When once the time is known, and also the height at which the telescope is to be pointed, then it is clear that the position of the star is completely specified. We have now to consider the means which astronomers have adopted for specifying this second element of the position of a heavenly body.

If through the centre of the earth a plane be drawn perpendicular to the line drawn from the centre of the earth to the celestial pole, this plane cuts the celestial sphere in a great circle which is called the *celestial equator*. Every point of the equator is 90° from the pole.

FIG. 11.



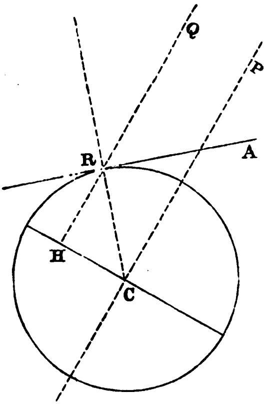
Let P (fig. 11) represent the celestial pole, and A T B the celestial equator, draw from P an arc of a great circle P S T passing through S, the position of a star upon the surface of the heavens. If we join O S and O T, the angle T O S is called the *declination* of the star S. The angle P O S is called the *polar distance* of the star, so that the polar distance is the complement of the declination. If the star be north of the equator, i.e. between the north pole and the equator, then the declination is positive; but if the star be south of the equator, so that its polar distance is greater than 90°, then the declination is negative.

The declination of a star and its right ascension completely define the position of the star, and they are both independent of the spot on the earth on which the observer may be situated. We have now to explain how the declination is connected with the angular elevation at which the telescope should be pointed in order to see the star in the centre of the field at its moment of transit.

§ 25. **Latitude.**—We must first explain what is meant by the latitude of a point upon the earth's surface. Let C (fig. 12) represent the centre of the earth, and let R be a point on the earth's surface; through C draw a line C P pointing to the celestial pole, then this cuts the surface of the earth in what are known as the North and South Poles respectively. Through C draw a plane perpendicular to C P, then this plane cuts the surface of the earth in a great circle which is known as the *earth's equator*. Join C R, then the angle R C H is the *latitude* of the place R. It will be seen at once that the latitude of a point on the equator is 0°, and that the latitude of the pole is 90°.

Suppose an observer at R looks towards the celestial pole, he will see it exactly in the same position with reference to the stars as if he were able to see it from the centre of the earth. The reason of this is, that the stars are so enormously distant from the earth that a change in the position of the observer on the surface of the earth produces only an insensible change in the apparent position of the stars. The line R Q *parallel* to C P is therefore the direction of the celestial pole viewed from R.

FIG 12.



The line R A drawn perpendicular to C R (we are for the present assuming the earth to be spherical) denotes the horizon, so that the angle Q R A expresses what is called the elevation of the pole above the horizon. Now since A R C is a right angle, it follows that Q R A and H R C must together make up a right angle, and since R H C is a right angle, it follows that H R C and H C R must together make up a right angle, whence taking away H R C in both cases, it follows, that Q R A must be equal to R C H. Hence we have the very important proposition which is thus stated :—

The elevation of the pole above the horizon is equal the latitude of the place.

§ 26. **Phenomena dependent on change of Place.** This proposition will explain the very remarkable changes in the appearance of the heavens which are presented to a traveller who makes a considerable change in his latitude. In the north the pole appears high up in the heavens, in fact at the north pole of the earth the celestial pole would be at the zenith. As the traveller proceeds towards the south, the pole gradually sinks, until when he is on the equator the pole will be in his horizon. At the equator all the stars will be seen to rise perpendicularly, and every star will continue above the horizon for half a sidereal day. The observer at the pole will only see half the heavens, as the equator constitutes his horizon, and all objects below the equator will be invisible to him; all the stars in the northern hemisphere will, however, be to him *circumpolar stars*, that is, stars which never set. The observer at the equator will, however, be able to see every star in the heavens, but he will have no circumpolar stars.

We shall now consider more fully the condition under which a star is visible at a given latitude. The meridian of a place extends right round the celestial sphere, consequently by the diurnal rotation of the heavens every star crosses the meridian twice each sidereal day. When a star reaches the meridian it is said to *culminate*, and the culmination which takes place above the pole is called the upper culmination, and that which takes place below the pole is the lower culmination. We have to consider when the star is visible at one or both of its culminations. Since the elevation of the pole is equal to the latitude of the place, it follows that the angular distance of the zenith and the pole is equal to the complement of the latitude of the place, or to what is called the *co-latitude* (§ 28).

In fig. 13 let P denote the pole, Z the zenith, and S, S′ the positions of a star at upper and lower culminations respectively. Let ϕ be the latitude and δ the declination of the star.

Then the zenith distance of the star at lower culminate is Z S′, but

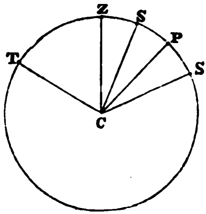
$$\begin{aligned} ZS' &= ZP + PS' \\ &= 90 - \phi + 90 - \delta = 180 - \phi - \delta. \end{aligned}$$

Now, in order that a star be visible it is necessary that its zenith distance be less than 90°. Hence for a star to be visible at lower culmination we must have

$$\begin{aligned} &180 - \phi - \delta < 90^\circ \\ \text{or}\quad &\delta > 90 - \phi. \end{aligned}$$

Hence if a star be visible at lower culmination its declination must exceed the colatitude. If a star be

FIG 13.



visible at lower culmination it will *à fortiori* be visible at upper culmination.

Now suppose a southern star at T (fig. 13). Its zenith distance is Z T, but

$$\begin{aligned} ZT &= PT - PZ \\ &= 90 + \delta - (90 - \phi) \\ &= \delta + \phi. \end{aligned}$$

Hence for the star to be visible at upper culmination we must have

$$\delta + \phi < 90°$$
$$\text{or} \quad \delta < 90 - \varphi,$$

hence the south declination of the star must be less than the colatitude.

For example, at the latitude of Greenwich 51° 28′ 38″·4 the colatitude is 38° 31′ 21″·6, consequently all stars are visible at upper culmination at Greenwich which have a smaller south declination than

$$- 38° \; 31' \; 21''\cdot 6$$

and all stars are visible at both culminations which have a larger declination than

$$+ 38° \; 31' \; 21''\cdot 6$$

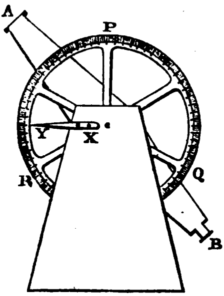
This statement requires a certain modification on account of refraction (§ 29), but this need not be further considered at present.

§ 27. **The Meridian Circle.**—In most modern observatories, the transit instrument described in § 17 is modified into a more useful instrument, called the meridian circle. By the aid of the meridian circle we are enabled to determine the declination of a star at the same time as we determine its right ascension.

The principle of a meridian circle may be explained by fig. 14. It consists primarily of a transit instrument A B, mounted with the usual precautions. Attached to the axis, near each of the pivots, there is a graduated circle, but only one such circle is shown in the figure. These circles turn with the axis of the telescope. Each circle is divided from 0° to 359°, each interval of one degree being again subdivided, in the best instruments, into spaces of two minutes. For the general purpose of explaining the method of using the meridian circle, we shall suppose that the circles are simply read by the aid of a pointer X Y. This pointer is attached to the solid masonry pier which carries one of the bearings on which the pivots of the instrument turn. In actual use the reading of the circles is effected by microscopes, and is an operation of such intricacy that we shall not describe it.

In the field of view of the telescope are the system of spider lines proper for a transit instrument and represented in fig. 10. We have already pointed out the use of the vertical wires, and now we are going to show the use of the horizontal wire C D. As the star moves across the field, the observer, by means of a slow movement of the telescope, places the wire C D immediately over the star so that, in consequence of the diurnal motion, the star appears to run behind the wire. The observer also takes the transits across the five vertical wires in the way already described. When the star has passed from the field, the observer then looks at the circles and observes the degree of the graduation which the pointer X Y indicates.

FIG. 14.



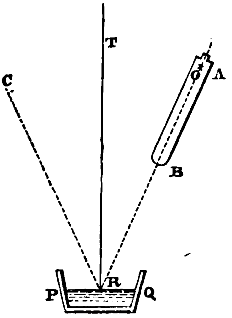
§ 28. **Observation of the Nadir.**—But this one reading of the circle is not sufficient to define the position of the star; we must now obtain a second reading with the telescope in a *definite position.* Thus, suppose in fig. 13 the direction in which the telescope was pointed was C T, then, if we were able to turn the telescope to P and read off the circle again, the difference between the two readings would indicate the angular distance between the pole and the star, or what is called the polar distance of the star.

There is, however, no star exactly at the pole, so that it is impossible to know when the telescope is pointed precisely towards the pole. We are therefore obliged to resort to a different process. Suppose that we were enabled to direct the telescope exactly to the zenith, then the difference between the two readings of the circle would give the zenith distance of the star. Here, again, we meet the same difficulty—how are we to know when the telescope is exactly pointed to the zenith? But though we are unable to accomplish this, we can do what is equally convenient, *for we have a means of pointing the telescope exactly to the nadir.*

The surface of a liquid at rest is a perfectly horizontal plane. A perpendicular to such a surface points upwards precisely to the zenith, and downwards precisely to the nadir. Now suppose we take a basin full of clean mercury, the surface is not only a horizontal plane, but it is also a brightly reflecting mirror. If we place this basin underneath the telescope, and turn the object glass of the telescope down towards the mercury, then when the system of wires are properly illuminated, we are able to see not only the wires themselves, but also their images reflected from the surface of the mercury.

To show that this enables us to direct the telescope to the nadir, look at fig. 15. Let A B be the telescope, and P Q the surface of the mercury, and let the small cross at O be the intersection of the wires. Now the rays of light diverging from the illuminated cross at O fall on the object-glass at B, and emerge thence in a parallel beam to fall on the surface of mercury P Q. Draw R T perpendicular to the surface of the mercury P Q. Then by the laws of reflection of light the beam after reflection from the mercury will proceed in a direction R C, so as to make the angle T R C equal to the angle T R B. It follows that in the circumstances depicted in the figure the reflected beam will not return to the telescope at all, nor will the reflected image of the wires be seen.

FIG. 15.

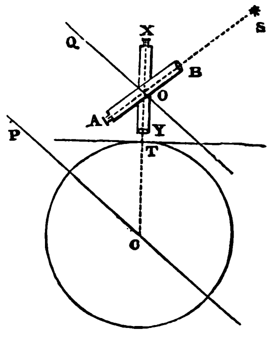


But now suppose that the telescope was placed with its axis *very close* to the line T R, then the reflected image would be visible in the field, and it would be possible to move the telescope until the *reflected image of the cross is absolutely coincident with the cross itself.* Under these circumstances we may be sure that the axis of the telescope is pointed exactly down to the nadir.

While the telescope is directed towards the nadir, we are to read off the circle again by the pointer, and the difference between the reading now obtained, and the reading when the telescope was pointed to the star, expresses exactly the angle through which the telescope has been turned when it is moved from the star to the nadir. This angle must evidently be equal to the supplement of the zenith distance of the star, and hence by this plan of observation the zenith distance of the star has been determined.

The important process of determining the zenith distance of a star may also be illustrated by fig. 16. The telescope in the position X Y points towards the centre of the earth (supposed spherical). The tangent plane to the surface of the earth at T coincides with the surface of the mercury. Hence when the middle wire coincides with its reflected image, the axis of the telescope is directed towards the centre of the earth C. In the position A B the telescope is directed towards a star. The angle S O C represents the angle through which the telescope must be turned, in order to be moved from the star to the nadir. Hence the angle X O S, which is the zenith distance of the star, is known.

FIG. 16.



O Q is parallel to the axis of the earth; hence the angle X O Q is equal to the angle T C P. This angle being the complement of the latitude is generally called the *colatitude*, and the angle Q O S, or the polar distance of the star, being equal to the sum of the zenith distance and the colatitude, is therefore known. The difference between the polar distance of the star and 90° is the declination.

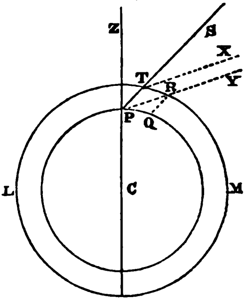
§ 29. **Refraction.**—The actual calculation of the *true* zenith distance of a star from the two observations is not, however, quite so simple a matter as we have described. The *apparent* zenith distance of the star which we have determined is always somewhat smaller than the *real* zenith distance, which is what we want to know. The difference between the real zenith distance and the apparent zenith distance is due to the presence of the atmosphere surrounding the earth. The real zenith distance is the zenith distance which we should observe if there were no atmosphere; the apparent zenith distance is what we actually do observe. This effect of the earth's atmosphere is termed *atmospheric refraction.*

Let C (fig. 17) represent the centre of the earth. P is a point upon the earth's surface, while the circle L T M is the bounding surface of the earth's atmosphere. Suppose there is a star in such a position that it would be seen in the direction P Y by an observer at P if there were no atmosphere, and let us consider what difference will be produced by the presence of the atmosphere.

The ray Y R, which, were there no atmosphere, would go straight to P, is deflected from its course when it meets the atmosphere, in consequence of the refracting power of the air. The ray Y R being thus deflected, will reach the surface of the earth at Q, and will thus not enter the eye of the observer at P. A full description of the phenomena of refraction exhibited by air in common with all transparent substances, may be found in works on Optics.

All the rays of light which reach the earth from so distant a body as a star are practically parallel; let us fix our attention upon the ray X T, which impinges upon the atmosphere at T, the direction X T being parallel to Y P. The ray X T is then deflected along T P, so that this ray is visible to the observer at P, but *to him* the light is coming along the direction T P, and therefore to him the star appears to be in the direction T S. If the line C P be produced up to the zenith, the observer at P will see the star with the zenith distance Z P S, and this is what is actually shown with the meridian circle. It is however clear, that the *real* zenith distance is Z P Y, whence we see that the real zenith distance is always greater than the apparent.

FIG. 17.



The angle S P Y, by which the real zenith distance exceeds the apparent zenith distance, is called the *refraction.*

For rays coming from a star at the zenith, the refraction is zero. As the zenith distance increases the refraction increases, nearly uniformly at first, and afterwards with an increasing rate until at the zenith distance of 45° the refraction is 57 seconds. As the horizon is approached, the refraction increases much more rapidly, until at the horizon it amounts to no less than 35 minutes, or upwards of half a degree.

We may here mention a somewhat remarkable consequence of refraction. If there were no atmosphere the sun would have completely risen when its lower edge was exactly 90° from the zenith; owing to refraction, however, the lower edge will *appear* to be on the horizon when it is really 90° 35′ from the zenith. Now as the apparent diameter of the sun is less than 35′, it follows that the sun is really entirely below the horizon at the time when it appears, in consequence of refraction, to have completely risen. As refraction anticipates sunrise so it retards sunset, and the consequence is that refraction actually increases the length of the day.

The *amount* of refraction at a given zenith distance depends to a small extent upon the temperature of the air and upon its barometric pressure. Into these details, which are, however, of great importance to the practical astronomer, we do not at present propose to enter.

We shall now show by what kind of observations astronomers have determined the amount of refraction at each zenith distance so accurately that they are able to allow for its effect on all observations, and thus obtain results *nearly though not quite* so accurate as they would obtain were they able to make their observations without the disturbance which refraction produces.

§ 30. **Calculation of Refractions.**—Select a circumpolar star, and observe its apparent zenith distance Z S, at its upper culmination (fig. 13). After an interval of about twelve hours, its apparent zenith distance Z S′ at its lower culmination can also be observed. Now if there were no refraction P S would be equal to P S′ and therefore

$$Z\,P = \tfrac{1}{2}\,(Z\,S + Z\,S')$$

whence Z P would be determined. Now the quantity Z P thus determined is the colatitude of the place, which is of course quite independent of the stars, so that we should get the same value for Z P, whatever be the circumpolar star adopted.

As a matter of fact, the values for Z P obtained from different stars differ, and the amounts of the refractions are determined by the condition that when the proper correction is applied to each observation, the colatitudes determined from each star shall be equal.

§ 31. **Latitude.**—We are now able to see how the latitude of the observatory is to be determined, for when by a multitude of observations of circumpolar stars the law of refraction has been accurately ascertained, we are able to determine how much the colatitude obtained by the observations of any particular star has been affected by refraction, and thus we are enabled to determine the true colatitude. When the true colatitude is known, then it is of course easy to determine the latitude itself.

By observations of this kind the latitude of an observatory can be determined accurately to a small fraction of a second.

CHAPTER VI.

THE APPARENT MOTION OF THE SUN.

§ 32. **The Sun appears to move among the Stars.** Having now explained how the right ascension and declination of any celestial body can be determined by the meridian circle, we may conceive the process to be applied to the observation of the sun. When this is done we find that though the right ascensions and declinations of the stars remain constant (or very nearly so), the right ascension and declination of the sun are continually changing. We are then led to the conclusion that the sun must be continually changing its place upon the celestial sphere with reference to the stars. The bright light of the sun prevents us from seeing the stars in its vicinity on the celestial sphere, but if we could see them, then we should perceive that the sun was slowly moving day by day from west to east.

That the position of the sun with respect to the stars on the celestial sphere is in a condition of constant change, may be inferred from ordinary observations without any telescope at all. Everyone must have noticed that in summer at noon, the sun is high in the heavens, while in winter he is low. On the other hand every star reaches the meridian at the same altitude whatever be the season of the year. We thus see that the polar distance of the sun is greater in winter than in summer, or that the declination of the sun is continually changing.

§ 33. **Observation of the Pleiades.**—We can also see by simple observation, though in a somewhat less direct manner, how the sun moves in right ascension. For this purpose it will only be necessary to look at the heavens at a fixed hour on a series of nights throughout the year, separated by intervals of perhaps two months. To give definiteness to these instructions you are recommended to look in the heavens for the Pleiades at 11 o'clock P.M. on the nights of January 1st, March 1st, May 1st, July 1st, September 1st, November 1st, and to observe the positions in the sky in which this little group is found. If the weather prevent you from seeing the stars on any of the nights named, then you must take the next fine night. I shall now describe to you what you will see. I presume of course, that you know the directions of north, south, east, and west from the place where you are stationed. I imagine you to be placed in the northern hemisphere at about the latitude of the British Islands. On the 1st of January you will see the Pleiades high up in the sky a little to the west of south. On the 1st of March they will be visible rather low in the west. On the 1st of May they are not visible. On the 1st of July they are not visible. On the 1st of September they are visible low in the east. On the 1st of November they are high in the heavens a little to the east of south. On the next 1st of January they will be in the same position as they were on the same day last year, and so on through the whole cycle. It is exceedingly desirable for the pupil actually to make these very simple observations for himself.

Let us now consider what information we gain from the results. It seems as if the Pleiades were at first gradually moving from the east to the west, that then they dipped below the horizon, and after a short time reappeared again in the east, so as to regain at the end of a year the position they had at the beginning.

The reader will, it is hoped, not confuse the *annual* motion which we are here considering with the apparent *diurnal* motion which we considered in § 8. In the apparent diurnal motion the phenomenon is observed by looking out at different hours on the same night. To observe the apparent annual motion the observer should look at the same hour each night, but his observations must extend over a year.

We shall now examine somewhat more closely into the apparent annual motion. In the first place what does 11 P.M. mean? It means that eleven hours have passed since noon; i.e. since the sun was on the meridian (at least very nearly, we shall see the difference afterwards). Now we find that at eleven o'clock on the 1st of March the Pleiades are farther from the meridian than they were at eleven o'clock on 1st of January. But as the sun is at the same distance (in time) from the meridian in the two cases, it follows that the Pleiades must be nearer to the sun on the 1st of March than on the 1st of January. It is, therefore, plain that the relative position of the sun and the Pleiades on the surface of the heavens must be changing. By comparing the sun in the same way with any other stars, it is found that the stars to the east of the sun are gradually approaching the sun. But we have already noticed that the positions of the stars *inter se* do not change, and therefore we are obliged to come to one of two conclusions; either, firstly, that all the stars in the universe have an annual motion from east to west relatively to the sun, which remains fixed, or that the sun has an apparent annual motion from west to east, while the stars remain fixed.

§ 34. **The Ecliptic.**—We shall now suppose that by the meridian circle the right ascension and declination of the sun has been determined for a large number of days throughout the year. We shall then be able to plot down upon a celestial globe the actual spot occupied by the centre of the sun on the celestial sphere for each day on which observations have been secured. When this is done, it is found that all the points thus marked lie in a plane, and that this plane passes through the centre of the globe. This proves that the *apparent annual path of the sun in the heavens is a great circle.*

This great circle is called the *ecliptic.* The constellations which lie along its track are known as the *Signs of the Zodiac.* The ecliptic is inclined to the celestial equator at an angle of 23° 27′. This is called the *Obliquity of the Ecliptic.* Each point on the ecliptic corresponds to a certain day in the year, i.e. the day on which the sun is situated in that point of its annual path. The ecliptic intersects the equator in two points; when the sun is situated in either of these points, the length of the day is equal to the length of the night. These two points are consequently called the *Equinoxes.*

The equinox through which the sun passes on 20th March is called the Vernal Equinox, and at this point the sun's declination is zero. The vernal equinox is one of the most important points on the celestial sphere, and, when it is on the meridian, an accurately adjusted sidereal clock should show 0^h 0^m 0^s. The importance of the vernal equinox in astronomy arises from this, that the right ascension of any star is equal to the interval of sidereal time between the moment of the transit of the vernal equinox and the transit of the star in question.

CHAPTER VII.

SIDEREAL TIME.

§ 35. **Sidereal Day.**—We are now going to consider the very important subject of sidereal time with more detail than has been possible in the few references which we have hitherto made to it. The first question to be considered is, *what is really meant by a sidereal day.*

We have said that the sidereal day is the interval between two successive culminations of the same star. Let us for the sake of example fix our attention upon the bright star Sirius. Now the interval between the culminations of Sirius on 1st January and 2nd January, 1877, is 24^h 0^m $0{\cdot}007^s$ of sidereal time. Is this interval constant or not? If we repeat the observations on the 1st and 2nd of March we find for the interval 23^h 59^m $59{\cdot}985^s$. Now it is true that each of these quantities only differs by an extremely small fraction of a second from twenty-four hours, but there still is a difference. Let us now compare the interval between two successive culminations of another bright star, Vega, with what we have already found. It appears that the interval between the successive culminations of Vega on 1st January and 2nd January, 1877, is $24^h\ 0^m\ 0{\cdot}013$

The reader will probably here observe that there must surely be something incorrect in the theory that the apparent diurnal motion is really due to the rotation of the earth upon its axis, for if this were the case the period should obviously be absolutely the same for all stars. To this we reply, that if we could see the *real* culminations of the stars the intervals of the successive culminations would be exactly the same for each star and constant for each one, but that the *apparent* culminations which are what alone we can see are affected by certain sources of error which are now understood. When due allowance is made for the effect of these errors it is then found that the interval between two successive culminations is the same for each star, and, allowing for what is called *proper motion*, that it is constant for each star at least for many centuries.

This constant interval of time it is which is called the sidereal day. Thus the sidereal day is really the period of the revolution of the earth upon its axis. It is possible that the length of the sidereal day may be increasing, though with such extreme slowness that it need not be considered at present.

The sidereal day is divided into twenty-four hours, each hour is divided into sixty minutes, and each minute into sixty seconds.

§ 36. **Setting a Sidereal Clock.**—We have now to explain how the sidereal clock is to be set so that it shall show correct sidereal time; in other words, we have to show how we can ascertain the time shown by our clock when the vernal equinox is on the meridian, i.e. the error of the clock.

It will be desirable (indeed necessary) to make this determination in or close to the time at which the sun is situated in one or other of the equinoxes. To give definiteness, I shall suppose that the sun is approaching the vernal equinox, and that for example on 19th March, 1877, we commence our observations. The sun is observed at transit with the meridian circle, and the declination found to be $-0° 23' 21''\cdot9$. The moment as shown by the clock at which the centre of the sun was on the meridian is also determined. The observation is repeated on the following day when the declination of the sun is found to be $+0° 0' 20''\cdot4$. It therefore follows that somewhere between noon on the 19th and noon on the 20th, the sun passed from having a south declination to having a north declination, that is, the centre of the sun must have passed through the point where it had no declination, that is, of course, through the equinox. Now as we know the declinations at the times of the two observations it is easy to calculate the time when the declination was zero. We thus know the time by our sidereal clock when the sun was on the equinox. If the sun happened to be on the equinox at the moment of culmination, then of course the clock should show $0^h\ 0^m\ 0^s$ at the instant of culmination, and the actual time shown by the clock would be the error of the clock.

It will, however, generally happen that the time of the sun's passage through the equinox does not coincide with the time of the sun's culmination, and consequently the sun will have moved away from the equinox in the interval which elapses between his passage through the equinox and the next succeeding culmination. The equinox will therefore culminate sooner than the sun, but we know the rate at which the sun is moving, and hence we know how far it will have moved from the equinox at the time of culmination. Hence from having observed the time of culmination of the sun by our clock we are able to compute the time of culmination of the equinox, whence we deduce the error of the clock.

We have now to explain the practical method by which the operation of determining the error of the sidereal clock is greatly facilitated. The process we have described, though the only absolute method, is yet exceedingly inconvenient for *ordinary* purposes. In our climate, culminations of the sun cannot be very frequently observed, and further, these operations can only be performed when the sun is at one of the equinoxes.

Suppose, however, that on one occasion we have succeeded in determining accurately the error of our clock in the way we have described. We then observe a bright star with the transit instrument or meridian circle, and we determine the instant of its culmination. The clock-time when properly corrected is really the right ascension of the star. It is in fact the interval between the time of culmination of the equinox and the time of the culmination of the star. Now does this interval of time remain constant? We may assume that the place of the star on the celestial sphere remains constant with respect to all the other stars. If then the position of the equinox with respect to all the stars remained constant, the right ascension of the star would remain constant. But as we shall see hereafter that the equinox is not absolutely fixed with respect to the stars, for it has a slow motion which in the course of years becomes very perceptible. The effect of this is, that the right ascension of a star is slowly but continually altering. Now the amount of this alteration is well ascertained; hence, if we know the right ascension of a star at one date we can calculate what the right ascension of the same star is at any other given date.

If, therefore, a number of stars be observed when the clock is correct, we have the means of finding the true right ascension of these stars for any subsequent date. In the 'Nautical Almanac' for each year a list of about 150 stars is given with the right ascension of each star at intervals of every ten days. It is by the aid of these stars that astronomers set their sidereal clocks, and the process is as follows:—

By referring to the 'Nautical Almanac' the astronomer will always find a star which will shortly come on his meridian; he then makes an observation with the transit instrument or meridian circle of the moment of culmination of this star by his sidereal clock. This is compared with the right ascension as given in the 'Nautical Almanac,' and the difference between the two is the error of the clock. Thus, for example, we have for Vega from the 'Nautical Almanac'—

		Right Ascension.		
		h.	m.	s.
1877.	Jan. 1 . .	18	32	44·85
	April 2 . .	18	32	47·28
	July 3 . .	18	32	49·46
	Oct. 2 . .	18	32	48·13

If the sidereal clock at any observatory show 18^h 32^m $51^s{\cdot}42$ at the instant of culmination of Vega on 3rd July, then the correction which must be applied to the clock time is $-1^s{\cdot}96$.

CHAPTER VIII.

MEAN TIME.

§ 37. **Mean Time.**—The reader may perhaps think that needless complexity is introduced by using one kind of time for astronomical purposes and another kind of time for ordinary civil purposes. We proceed to explain the reason why this distinction must be maintained.

The great convenience of astronomical time consists in this, that each *star* culminates every day at the same sidereal time (subject only to minute variations). But for the ordinary purposes of life sidereal time would not answer. We are obliged to regulate civil time by the sun, and custom has decreed that at the moment when the Sun culminates (or to speak more accurately, when the mean Sun, to be hereafter explained, culminates) our ordinary clocks should show noon or $0^h\ 0^m\ 0^s$. Now, the moment of culmination of the Sun, as shown by a sidereal clock, would be different every day because the Sun is moving from west to east among the stars, so that compared with the stars it comes on the meridian about four minutes later every day. We are, therefore, obliged to have a mean time clock, the going o which is regulated by the Sun, while the sidereal clock is regulated by the stars.

§ 38. **Apparent Solar Day.**—We have now to explain a little more fully what is to be understood by *mean* solar time. If we observe the transit of the centre of the Sun across the meridian to-day, and if we make the same observation again to-morrow, the interval between the two observations is an *apparent solar day.* We first notice that the apparent solar day as thus defined is not constant.

For example, taking four days as nearly as possible equidistant throughout the year, viz., 1st January, 2nd April, 3rd July, 2nd October, we have the following apparent solar days or intervals (in mean solar time) between the culmination of the Sun on the days named and on the following days :—

		h.	m.	s.
1877.	Jan. 1 to 2 . .	24	0	28
	April 2 to 3 . .	23	59	42
	July 3 to 4 . .	24	0	10
	Oct. 2 to 3 . .	23	59	41

It will be noticed that the first of these apparent solar days is 47^s longer than the last. We adopt as the definition of a *mean solar day* the average interval between two successive culminations.

§ 39. **The Mean Sun.**—We now introduce a convention which is known as the *mean Sun.* Suppose that we had an imaginary sun moving uniformly in the equator and completing its revolution in the same time as the true Sun, then when this mean sun is on the meridian, the properly adjusted mean solar clock should show noon. Thus the mean sun and the true sun will generally differ slightly in the times at which they arrive on the meridian, and the difference of the times is called the *equation of time.*

§ 40. **Mean Time at Apparent Noon.**—The following table exhibits (for each of the four dates already referred to) the time which should be shown by a mean-time clock which is going correctly, when the real Sun is on the meridian of Greenwich.

		h.	m.	s.
1877.	Jan. 1 . . .	0	4	0·32
	April 2 . . .	0	3	33·72
	July 3 . . .	0	3	55·81
	Oct. 2 . . .	11	49	14·53

For example, on January 1, 1877, the real Sun crosses the meridian of Greenwich at $4^m\ 0^s{\cdot}32$ P.M. The equation of time on that day is therefore $4^m\ 0^s{\cdot}32$.

§ 41. **Determination of the Mean Solar Day.**—We shall now consider the very important problem of determining the mean solar day.

By observations of the stars the error of the sidereal clock in the observatory can be determined. Suppose that we have rated our sidereal clock to go correctly, and that we observe the transit of the centre of the Sun across the meridian, we thus obtain the right ascension of the Sun. Let us suppose, for the sake of illustration, that these observations have been made upon the dates here given :—

Apparent Right Ascension of the Sun at Apparent Noon.

			h.	m.	s.
1875.	Jan.	1	18	46	41
1876.	Jan.	1	18	45	37
1877.	Jan.	1	18	48	59
	April	2	0	47	19
	July	3	6	50	24
	Oct.	2	12	34	27
1878.	Jan.	1	18	47	54

It is evident that from the apparent noon on January 1, 1877, to the apparent noon on January 1, 1878, 365 apparent solar days have elapsed; during this time the sidereal clock shows an interval of 366 days very nearly, or more accurately of 365 days 23 hours 58 mins. 55 secs. Hence the average length of one of 365 consecutive apparent solar days in sidereal time is

$$\frac{365 \text{ days } 23 \text{ hours } 58 \text{ mins. } 55 \text{ secs.}}{365}$$

$$= 24^h\ 3^m\ 57^s.$$

When the average length of each of a great number (say 100,000) of consecutive apparent solar days is taken, the mean length expressed in sidereal time is slightly different from the result we have found, and is

$$24^h\ 3^m\ 56{\cdot}5554^s.$$

This is therefore the equivalent in sidereal time to one mean solar day.

§ 42. **Determination of the Sidereal Time at Mean Noon.**—The hypothetical mean sun is on the meridian every day at mean noon. The interval between two consecutive returns of the mean sun to the meridian is equal to the length of the mean solar day. Suppose the mean sun comes to the meridian d seconds later every day, it follows that if A represent the right ascension of the mean sun at mean noon on a certain day that the right ascension of the mean sun at mean noon n days later will be

$$A + nd.$$

Hence we form the following table for the right ascension of the mean sun :—

Right Ascension of Mean Sun at Mean Noon.

1877.	Jan. 1 . . .	A
	Apl. 2 . . .	$A + 91\ d.$
	July 3 . . .	$A + 183\ d.$
	Oct. 2 . . .	$A + 274\ d.$

Now we want to make the mean sun, while still moving uniformly in right ascension, conform as far as this imperative restriction will permit with the actual motion of the true sun. We therefore compare the table just given with the table of § 41, and we seek to determine A so that these tables shall coincide as far as practicable. Now as we know d to be $3^m\ 56{\cdot}5554^s$ we can determine the value which A should have for each of the four dates so that the two right ascensions should coincide. The four values of A thus found are

		h	m	s
Jan. 1	. .	18	48	59
Apl. 2	. .	18	48	33
July 3	. .	18	48	55
Oct. 2	. .	18	34	11

and the mean of these values is

$$18^h\ 45^m\ 9^s.$$

When the value of A is computed from a very large number of observations, the value just given is slightly modified, and we have as the true sidereal time at mean noon on January 1, 1877

$$18^h\ 44^m\ 57^s{\cdot}72.$$

As we now know the sidereal time at mean noon on one day we are able to compute it for any other day.

Example.—Find the sidereal time at mean noon on February 11, 1878. Since 406 mean solar days have elapsed since January 1, 1877, the mean sun has gained in right ascension

$$406 \times 236^s{\cdot}56 = 26^h\ 40^m\ 42^s,$$

hence the sidereal time at mean noon on 11th February is

$$18^h\ 44^m\ 58^s + 26^h\ 40^m\ 42^s = 21^h\ 25^m\ 40^s.$$

§ 43. **Determination of Mean Time from Sidereal Time.**—In the 'Nautical Almanac' the sidereal time at mean noon is given for each day of the year. It is by the aid of this information that the mean time is to be computed in the observatory.

Example.—It is required to determine the mean time at Greenwich corresponding to $22^h\ 1^m\ 18^s$ of sidereal time on February 11, 1878. From the 'Nautical Almanac' we see that the sidereal time at mean noon on the day in question is $21^h\ 25^m\ 40^s$, hence the required mean time is $35^m\ 38^s$ of *sidereal time* past mean noon; but as we have seen that an interval of 24 hours of mean solar time is equal to $24^h\ 3^m\ 56^s{\cdot}55$ of sidereal time, we can easily calculate that an interval of $35^m\ 38^s$ of sidereal time is equal to $35^m\ 32^s$ of mean solar time. The correct mean time corresponding to the given sidereal time is therefore $35^m\ 32^s$ P.M.

§ 44. **Determination of Mean Time at a Given Longitude.**—The calculation just described must be slightly modified when it is desired to compute the mean time corresponding to a given sidereal time at a place which does not lie upon the meridian of Greenwich. The quantity we have called A, which is given in the 'Nautical Almanac' as the sidereal time at mean noon, is the right ascension of the mean sun when it is on the *meridian of Greenwich*; but as the mean sun is continually changing its right ascension it follows that the sidereal time at mean noon must depend upon the meridian which is under consideration.

We may here make a remark with reference to the method of estimating longitudes : for example, when it is stated that the longitude of Dunsink is 25^m 21^s west of Greenwich the statement may be interpreted in two ways, both of which are correct. It may mean that an interval of 25^m 21^s of *sidereal* time will elapse between the transit of a *fixed star* across the meridian of Greenwich and the transit of the same star across the meridian of Dunsink, or it may equally mean that an interval of 25^m 21^s of *mean solar* time will elapse between the transit of the *mean sun* across the meridian of Greenwich and the transit of the mean sun across the meridian of Dunsink.

Example.—Find the sidereal time at mean noon at Dunsink upon February 11, 1877. The meridian of Dunsink is 25^m 21^s west of Greenwich, consequently the mean sun will be increasing its right ascension during the mean solar interval of 25^m 21^s before it gets to the meridian of Dunsink. Now suppose that a fixed star and the mean sun came on the meridian at the same time at Greenwich, then the right ascension of the star is the sidereal time at mean noon at Greenwich; but when the star reaches the meridian of Dunsink, which it does in an interval of 25^m 21^s of *sidereal* time, the mean sun has not yet reached the meridian on account of its motion in the interval, and therefore the sidereal time at mean noon at Dunsink is not the right ascension of the star ; but as the mean sun is on the meridian at Dunsink in 25^m 21^s of mean solar time the difference between the sidereal time at mean noon at Greenwich and at Dunsink is equal to the interval of sidereal time corresponding to the difference between $25^m\ 21^s$ of mean solar time and $25^m\ 21^s$ of sidereal time, i.e. to 4^s. Hence the sidereal time at mean noon at Dunsink on February 11, 1878, is

$$21^h\ 25^m\ 44^s.$$

§ 45. **The Year.**—We may here point out how the length of the year is to be accurately determined. It has been found that the mean sun gains $3^m\ 56{\cdot}5554^s$ in right ascension in one mean solar day, hence the mean sun will gain 24^h, i.e. perform one complete revolution with respect to the equinox in

$$\frac{24^h}{3^m\ 56{\cdot}5554^s} = 365{\cdot}2421 \text{ days.}$$

CHAPTER IX.

THE PLANETS.

§ 46. **Meaning of the word Planet.**—We have already ascertained that the sun appears to move through the stars in a great circle called the ecliptic, the motion being completed in one year. But as the sun is much nearer to us than the stars, this apparent motion might be explained by the supposition that the sun was really at rest while the earth was in motion round the sun. The sun appears to move from west to east among the stars, but precisely this appearance could be produced by a real motion of the earth from east to west. It is, therefore, necessary for us to enquire which of these two explanations of the apparent motion is the correct one.

In connection with this question it will be desirable for us to consider some of the other celestial bodies which are termed the *planets*. We have already referred to the apparent fixity of the stars in their relative positions in the celestial sphere. The observer of the heavens will, however, notice a few objects which, though closely resembling the brighter fixed stars at a superficial glance, are yet of an entirely different nature. The most conspicuous feature of the class of objects to which we here refer is their apparent motion, and it is for this reason that they have been called *planets*. Of these objects there are five easily visible to the unaided eye at the proper seasons for seeing them. The names of these *planets* are Mercury, Venus, Mars, Jupiter, and Saturn. They were all well known to the ancients, and their movements appear to have attracted attention from the earliest times. The observer who is not provided with a globe or maps, and who is unacquainted with the heavens, might easily confuse the planets with the brighter stars. If, however, he had the use of a telescope, he would at once be able to tell the difference between one of these planets and a star. The stars, even in the largest and best telescopes, are little more than bright points of light. The planets, on the other hand, show a clearly defined disk, and suggest immediately to the observer that they are spherical, or nearly so. Even without a telescope, if the observer watch a planet for a few nights, and carefully compare its position by alignment with the stars in its vicinity, he will detect its motion.

§ 47. **Motion of the Planet Venus.**—We shall now fix our attention upon the planet Venus, and we shall inquire more closely into the nature of its motion. To make the observations which we shall here describe, it will not be necessary for the observer to use a telescope.

Shortly after sunset, at the proper season, Venus appears like a brilliant star in the west. On subsequent evenings, the distance between Venus and the sun gradually increases until the planet reaches its greatest distance, when it is about 47° from the sun. Venus then begins to return towards the sun, and after some time becomes invisible from its proximity to the sun. Ere long the same planet may be seen in the east, shortly before sunrise. It gradually rises more and more before the sun, until again Venus reaches the greatest distance from the sun, after which it commences to return, again passes the sun, and may be seen at evening in the west, as before.

It thus appears that Venus is continually moving from one side of the sun to the other, and the question is how these movements are to be explained. It is noticed that when Venus is at its greatest distance from the sun, its apparent movement is much slower than when it is nearer the sun. It is further seen by the telescope that when Venus is at its greatest distance from the sun it appears half illuminated, like the moon at first quarter. It is also on very rare occasions seen to pass actually between the earth and the sun, the phenomenon being known as the Transit of Venus, in which case the planet appears like a dark spot upon the surface of the sun.

From all these facts it is inferred that the planet Venus is really a dark globular body, which moves around the sun in 224 days, in an orbit of a shape which we shall presently consider. As the sun executes its apparent motion among the stars, the planet seems to accompany it, alternately appearing to the east and the west of the sun, and never more than 47° distant therefrom.

§ 48. **Apparent Motion of the Planet Mercury.**—Precisely similar, though on a smaller scale, are the apparent motions of Mercury. This planet does not go so far from the sun as Venus, its greatest distance or elongation, as it is called, being only 28°. The time in which Mercury revolves round the sun is 87 days.

§ 49. **The Earth is really a Planet.**—We thus see that there are two planets, Mercury and Venus, which certainly appear to move round the sun. Now if we compare Mercury or Venus with the earth, we find some striking points of resemblance. All three bodies are approximately spherical, and they are all dependent upon the sun for light. It is, therefore, not at all unreasonable to inquire whether the analogy between the three bodies may not extend further. Now we have already seen that the phenomena of the apparent annual motion of the sun could be explained by supposing that the sun is really at rest, and that the earth moves round the sun. When we combine this fact with the presumption afforded by the analogy between the earth and Mercury and Venus, we are led to the belief that the earth, Mercury and Venus, are all bodies of the same general character; and all agree in moving around the sun, which is the common source of light and heat to the three bodies.

We are now enabled to take a further step in the knowledge of the planetary system, and to determine, approximately at least, the forms of the orbits in which the planets revolve.

§ 50. **The Earth's Orbit is nearly Circular.**—Whichever explanation of the apparent annual motion of the sun be adopted, one thing is evident, and that is that the earth's distance from the sun does not greatly vary. This is manifest from the consideration that the angle which a diameter of the sun subtends at the eye, or the apparent size of the sun, remains practically constant. If, therefore, we admit that it is really the motion of the earth round the sun which produces the apparent motion of the sun among the stars, we must admit that the earth in its motion remains pretty much at the same distance from the sun, i.e. *that the earth must move very nearly in a circle which has the sun at its centre.*

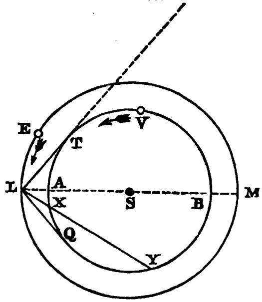
It is also easily established by observation, that though the rate at which the sun is apparently moving in the ecliptic is not quite constant, yet that it is very nearly constant. It therefore follows that the real motion of the earth in its approximately circular orbit must be approximately uniform.

§ 51. **The Orbit of Venus.**—The consideration of the annual motion of the earth suggests to us to try whether the motions of Venus and of Mercury cannot be explained by the supposition that each of them moves nearly uniformly in a nearly circular orbit about the sun as a centre. When this attempt is made, it is seen that the principal features of the motions of Venus and Mercury can be explained with great facility.

Let S (fig. 18) represent the sun. The inner of the two circles A T V B represents the orbit of Venus, and the outer circle E L M represents the orbit of the earth.

We shall, in the first place, neglect the motion of the earth, and consider the appearances which would be produced by the motion of Venus. We shall then show how these appearances would be modified by taking account of the motion of the earth.

FIG. 18.



Let us then suppose the earth stationed at the point L, and that Venus is at the point marked V, moving in the direction of the arrow. From L draw the tangent L T to the orbit of Venus. Then, as Venus is moving towards the tangent L T, the planet will appear to an observer stationed at L to be moving away from the sun, inasmuch as the angle V L S is continually increasing. As Venus approaches T, it gradually gets farther from the sun, until at T it appears to have reached its greatest distance from the sun. The planet is there said to be at its greatest elongation; and in the case of Venus, the angle T L S is equal to 47°. As Venus continues its motion it again begins to return towards the sun, until in the position A it passes between the earth and the sun. Still moving on, it reaches the point Q, which is the point of contact of the second tangent drawn from L. Venus then appears at its greatest distance on the other side of the sun, after which it again appears to draw near the sun, to pass behind it at B, and then to return to V to recommence the cycle which we have described. We thus see that the supposition of the circular motion of Venus explains the observed succession of the appearances of Venus as seen by the unaided eye.

§ 52. **Telescopic appearance of Venus explained.** We shall now consider how the telescopic appearances presented by Venus are to be explained. When the planet occupies the position V, that hemisphere of it which is directed towards the sun at S is illuminated by the sun light, but the other half of the planet is in darkness. Now, when the observer at L looks through a telescope, he is able to see the actual disk of the planet; and as the hemisphere of Venus turned towards the observer is somewhat different from the hemisphere turned towards the sun, only a portion of the hemisphere seen by the observer is illuminated; and, consequently, Venus appears to him not as an entire bright circle, but only as a portion of a circle. In fact, the observer is immediately reminded of the appearance of the moon, for all the phases of the moon are reproduced in miniature in the revolutions of Venus.

As Venus approaches T, less and less of the illuminated hemisphere is visible to the observer at L, and so Venus gradually becomes a narrow crescent, like the moon as seen in the west shortly after new moon.

When Venus reaches A, only its dark hemisphere is directed towards L, and, consequently, it is invisible. On rare occasions, however, Venus can be seen even in this position. We have spoken of the orbit of Venus as if it were exactly in the same plane as the orbit of the earth ; this, however, is not quite the case, for the planes of the two orbits are inclined at a small angle. If these two planes did really coincide, then whenever Venus was at A, it would be visible to the observer at L as a dark spot against the bright face of the sun. Owing to the fact that the plane of Venus's orbit is not exactly the same as the plane of the earth's orbit, it follows that when Venus is at A, it is usually slightly above or below the line drawn from L to S, and, consequently, is not seen. When Venus does actually come between the earth and the sun, the phenomenon is known as the Transit of Venus. (§ 68.)

After passing A, Venus again presents the crescent-shaped appearance. Now, if we draw the line L X Y from the point L, Venus will appear to be in the same *position*, whether it be at X or at Y, the only difference being that at X Venus is moving from the sun, while at Y Venus is moving towards the sun ; but the telescope at once reveals a wide difference between the appearances at X and at Y. At X Venus is a narrow crescent, and at Y it is nearly full. This is of course explained by the different aspect which the illuminated hemisphere of Venus turns towards the earth in the two cases. In the neighbourhood of B, Venus would appear quite *full* if we could see it, but the proximity of the bright light of the sun renders Venus invisible in this position.

§ 53. **Effect of the Annual Motion of the Earth on the Appearance of Venus.**—We shall now briefly consider what effect the annual motion of the earth in its orbit round the sun will have upon the apparent motions of Venus which we have been describing. For simplicity, we shall suppose that the orbits of the earth and Venus lie in the same plane. Now it is only the *relative* positions of Venus and the sun which we are considering ; and the relative position at any time is completely defined by the angular distance between the sun and Venus, as seen by an observer upon the earth. Now conceive that the orbits of both the earth and Venus are rotated about the sun, the axis of rotation being perpendicular to the plane of the orbits ; conceive also that the earth and Venus, in addition to their own motions in their orbits, are carried round by the rotation of the orbits, then it is plain that this rotation will not in the least affect the *relative* position of Venus with respect to the sun. Suppose, for the sake of illustration, that two passengers are walking on the deck of a ship round the mast, their *relative* positions do not in the least depend upon the motion of the ship as a whole.

Now imagine that the motion of rotation which we have supposed to be imparted to the two orbits takes place in the same time as the actual rotation of the earth around the sun (365·26 days), and in the opposite direction. The effect upon the relative motion will be unaltered. The effect upon the earth will be to bring it to rest. But what will be the effect on

Venus? Since the time which Venus takes to accomplish its orbit is 224·7 days, it follows that in one day it would move through an angle equal to $\frac{360^\circ}{224{\cdot}7}$. But in the hypothetical motion which we have assumed for the purpose of bringing the earth to rest the orbit of Venus would be turned through $\frac{360^\circ}{365{\cdot}26}$ in one day. Hence, in one day, Venus would actually gain on the earth an angle equal to

$$\frac{360^\circ}{224{\cdot}7} - \frac{360^\circ}{365{\cdot}26}$$

It follows that the number of days in which Venus would appear, when viewed from the earth, to have accomplished a complete revolution about the sun is

$$\frac{360^\circ}{\frac{360^\circ}{224{\cdot}7} - \frac{360^\circ}{365{\cdot}26}} = 583{\cdot}9$$

Hence we see that the effect which the real motion of the earth has upon the apparent motion of Venus is to increase the time of its revolution, but not otherwise to alter the general circumstances of the motion.

§ 54. **The Orbit of Mercury.**—The orbit of Mercury possesses the same general features which we have described in the case of Venus. These two planets are the only planets hitherto discovered which circulate round the sun in orbits lying inside the orbit of the earth. The success which we have found in the attempt to explain their motions by the supposition that they move in nearly circular orbits, suggests to us to try whether the apparent motions of the other planets may not equally be explained by the supposition that they revolve around the sun in nearly circular orbits larger than the orbit of the earth, and therefore surrounding it.

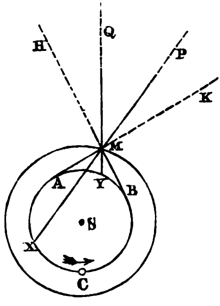
We should here first observe, that all the five principal planets are invariably to be found in or near to that great circle of the celestial sphere which is called the ecliptic. Now as the apparent motion of the sun in the ecliptic is really due to the motion of the earth, it follows that the orbit of the earth must lie in the plane of the ecliptic. As the planets never depart far from the plane of the ecliptic, it must follow that their orbits must lie very nearly in the same plane as the plane of the earth's orbit.

§ 55. **The Apparent Motions of Mars.**—We shall now endeavour to explain the apparent motions of Mars on the supposition that it moves in a nearly circular orbit about the sun. As the periodic time of Mercury in its orbit is 87·97 days, of Venus 224·7 days, and of the earth 365·26 days, it would appear that of two planets that which has the greater periodic time is at the greater distance from the sun. It is therefore reasonable to suppose that Mars, which has a greater periodic time than the earth, is more distant from the sun than the earth. We shall suppose that the outer of the two circles in fig. 19 represents the orbit of Mars, while the inner one is the orbit of the earth, s being the sun in the centre. Now, just as we showed that the *apparent* movements of Venus were unaltered by supposing the earth to be at rest and Venus to be moving with a slower motion, so now we may suppose

Mars to be at rest at M, and the earth moving in its orbit with a correspondingly slower motion.

Let us first suppose the earth to be at X, then Mars, which is situated at M, will be seen in the direction X M, and will be referred to the stars in the position P. As the earth moves on in the direction towards C, Mars appears to move towards H, but this motion will gradually become more slow until at the moment when the earth reaches B, which is the point of contact of the tangent drawn from M, the motion of Mars will apparently cease. As the earth passes from B towards Y, Mars will begin to move backwards, so that when the earth arrives at Y, Mars will have returned to Q; as the earth approaches A, Mars will move gradually towards K, so that when the earth reaches A Mars will have reached K, after which it will gradually return again towards H.

FIG. 19.



We thus see that if the motion of Mars be such as we have supposed, we should expect to find that the planet sometimes appears to be moving in one way, sometimes in another way, and sometimes to remain stationary. Now as all these varieties are seen in the motion of Mars, it follows that there is a presumption that the orbit of Mars, like that of Mercury or Venus, is very nearly circular.

CHAPTER X.

KEPLER'S LAWS.

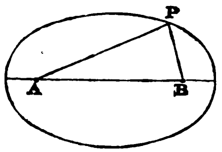
§ 56. **Orbits of the Planets are not Perfect Circles.** We have hitherto only been considering such general features of the movements of the planets as can be observed without the aid of telescopes, or with merely such optical power as is necessary to reveal the crescent appearances of the interior planets. We have now to discuss the more accurate knowledge which has been the reward of a more careful and detailed study of the movements of the planets with suitable measuring instruments.

By the aid of the meridian circle it is possible to determine a series of positions of a planet at different times, and thus to mark these positions on the celestial sphere with precision. When this is done it is found that although the *general features* of the motions are consistent with the supposition that the orbits are perfect circles, yet that when a more minute comparison is instituted between the results of this supposition and the results of actual observation, certain discrepancies are brought to light which are too large and too systematic to admit of being explained away as mere errors of observation.

§ 57. **Kepler's first Law.**—Kepler was the first to discover that the discrepancy between observation and calculation could be removed by the supposition that the planets moved round the sun in the curves called *ellipses* which, though resembling circles, differ from them in important respects. A method of drawing an ellipse is shown in fig. 20. Fix two pins at A and B into a sheet of paper on a drawing board. Let A B P be a loop of thread put over the pins at A and B, and let P be the point of the pencil; then if the point P be moved so as to keep the strings P A, P B, stretched, the point of the pencil will trace out the curve which is called an ellipse.

It will be seen that ellipses may be of different shapes, thus if the pins remained the same as before, and if the length of the string which made the loop were a little greater, the ellipse which would be traced out by the point of the pencil would be less oblong, and would approach more nearly to a circle; on the other hand, if the length of the string were shorter the ellipse would become more oblong.

FIG. 20.



The two points A and B of the ellipse are termed its foci.

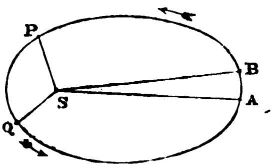
The first of the three discoveries which have immortalised the name of Kepler is thus stated.

The path of a planet round the sun is an ellipse in one focus of which the centre of the sun is situated.

Thus let S (fig. 21) represent the centre of the sun, then the ellipse A B P Q denotes the path of the planet. In the majority of cases the ellipse approaches very closely to a circle. In none of the principal planets is the deviation from a circle so great as it is represented in the figure, which has been designedly exaggerated.

§ 58. **Kepler's second Law.**—In speaking of the apparently circular motion of the planets we also assumed that each planet moved uniformly in its orbit. When this assumption comes to be rigidly tested by accurate observations, it is also found to be not absolutely correct. The planet is found to be moving more rapidly at some parts of its path than at others. The law of these motions was also discovered by Kepler, and is expressed by his second law which is thus stated :—

FIG. 21.



In the motion of a planet round the sun, the radius vector drawn from the centre of the sun to the planet sweeps over equal areas in equal times.

Thus, for example, in fig. 21, when the planet moves from A to B, its radius vector sweeps out the area A S B, and in moving from P to Q the radius vector sweeps out the area P S Q. Now Kepler's second law asserts that if the area A S B be equal to the area P S Q, then the time taken by the planet in moving from A to B is equal to the time taken by the planet in moving from P to Q.

We can now see how this will explain the variations in the velocity with which the planet is moving, for since the planet has to move from P to Q in the same time as it takes to move from A to B, and since the distance P Q is very much longer than the distance A B, it follows that the *velocity* of the planet must be greater when it is moving through P Q than when it is moving through A B. We hence see that the planet when near the sun must be moving with greater rapidity than when it is at a distance from the sun.

§ 59. **Kepler's third Law.**—In the two laws of Kepler already discussed we have been considering the motion of only one planet. We have now to consider the remarkable law of Kepler which relates to a comparison between two planets.

The squares of the periodic times of two planets have the same ratio as the cubes of their mean distances from the sun.

To explain this we should first remark that by the mean distance of the planet from the sun is to be understood a length equal to one half that diameter of the ellipse (fig. 21) which passes through the two foci. We shall illustrate this law by a comparison between the cases of Venus and the earth. The periodic times of the earth and Venus are respectively 365·3 days and 224·7 days, while the mean distances are in the ratio of 1·0000 to 0·7233. Now we have by an easy calculation

$$\left(\frac{365 \cdot 3}{224 \cdot 7}\right)^2 = 2 \cdot 643$$

and

$$\left(\frac{1000}{723 \cdot 3}\right)^3 = 2 \cdot 643$$

which verifies the law.

Kepler's three laws are found to be borne out completely, even to their minutest details, when proper allowance has been made for every disturbing element.

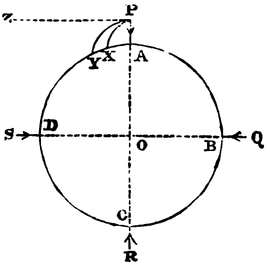
CHAPTER XI.

THE LAW OF GRAVITATION.

§ 60. **Gravitation of the Earth.**—We have now to refer to the splendid discoveries made by Sir Isaac Newton, by which he was able to reveal the true cause of those movements of the planets which the laws of Kepler so faithfully expressed. It is impossible in a book of this size to do more than glance at this subject, which embraces the most difficult problems in astronomy.

Let A B C D (fig. 22) represent a section of the earth, and suppose that A P, B Q, C R, D S are towers erected at the corresponding spots. Now, if stones be let drop from the top of the towers at P Q R S they will fall on the points A B C D respectively. The four stones will move in the direction of the arrows. From P to A the stone moves in an opposite direction to the motion from R to C, and from Q to B it moves from right to left, while from S to D it moves from left to right. These movements are thus in different directions, but if we produce their directions as indicated by the dotted lines they all pass through the centre O. We are so accustomed to the falling of a body that it does not

FIG. 22.



excite in us any astonishment, and rarely even provokes our curiosity. A clap of thunder, which every one notices, though much less frequent is not really more remarkable. We all look with attention upon the attraction of a piece of iron by a magnet, and justly so, for the phenomenon is a very remarkable one, and yet the falling of a stone is produced by a far grander and more important force than the force of magnetism.

We thus see that the earth must possess some power whereby it draws towards itself bodies situated near its surface. The ballast dropped from a balloon tells us that, even if we go to a great height, this power of drawing bodies towards itself still continues, nor does it require any great effort of the imagination to suppose that the earth would still continue to attract bodies towards it even though they were at very stupendous distances from its surface.

§ 61. **Gravitation towards the Sun.**—We can then conceive that the sun being a very great and massive body, vastly larger than the earth, may, like the earth, have the power of drawing bodies towards it, and we can show to a certain extent how this will explain the motions of the planets, though it is only possible for us here to give the merest outline of the subject.

In the first place, it is known that if a body be once set in motion it will continue to move on for ever uniformly in a straight line unless a force act upon it. Now, a planet is not moving in a straight line, and therefore it is plain that some force must be continually acting upon the planet. The force in question undoubtedly is the attraction of the sun.

The beginner will probably find some difficulty in understanding how if a planet were continually being attracted towards the sun it should, notwithstanding, continue to describe the same orbit for ever, and not ultimately fall into the sun. We proceed to explain this point.

If a planet were originally *at rest* there can be no doubt that the attraction of the sun would tend to draw it in directly towards the sun, and that after a time the planet would fall into the sun. The case is, however, materially altered when the planet is originally started with a velocity in a direction not pointing exactly towards the sun. In this case the planet will never fall into the sun.

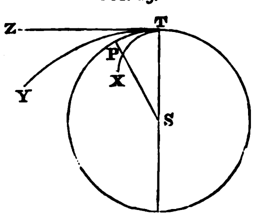
§ 62. **Illustration.** — A stone which is simply dropped from the top of the tower P A (fig. 22) falls along the vertical line P A to the ground at A. If, however, instead of simply dropping the stone we throw it horizontally, then it is well known that the stone describes a curved path and falls on the ground at X. If it were not for the attraction of the earth, the stone thrown horizontally from P would move in the direction P Z in which it was thrown ; thus we learn that the effect of the attraction has been to deflect the stone from the straight line, in which it would otherwise have moved, and to make it move in a curved line.

If the stone had been thrown from P with a greater velocity than in the case we have been considering, then the path which it takes may be represented by P Y. The difference between the two curves P X and P Y is due entirely to the difference between the initial velocities of the stone. The attraction of the earth was, of course, the same in both cases. We thus see that the greater the initial velocity the smaller is the curvature of the path produced by the attracting force of the earth.

§ 63. **Explanation of the Motion of a Planet in a Circular Orbit.**—We now proceed to explain how it is that a planet can continue to move for ever in an unaltered orbit, and though the orbits of the planets are not exactly circular, they are sufficiently nearly so to enable us for the sake of illustration to consider a hypothetical planet moving in a perfect circle of which the sun is the centre.

Let S (fig. 23) represent the sun, and let T be the initial position of the planet. Let us now make different suppositions with respect to the initial state of the planet. In the first place, if the planet be simply released it will immediately begin to fall along T S into the sun. If we draw T Z perpendicular to S T, and if we suppose that initially the planet was projected in the direction T Z, the attraction of the sun at S will deflect the planet from the line T Z which it would otherwise have followed, and compel it to move in a curved line. The particular curve which the planet will adopt depends upon the velocity given to it along T Z. With a small initial velocity it will follow the path T X, with a greater velocity the path T P, and with a greater still the path T Y.

FIG. 23.



Let us now consider the effect which the attraction of the sun will have upon the *velocity* of the planet. It is quite plain that if the planet had been originally projected directly towards S along the line T S, that the sun's attraction would tend to *increase* the initial velocity. It is equally plain that if the planet had been originally shot *away from* the sun along the line S T, that the effect of the sun's attraction would have been to *diminish* the velocity. But what would have been the effect upon the velocity in the intermediate cases; let us consider them separately. When the planet moves along the curve T Y it is at every instant after leaving T going further away from the sun. It is manifest that it is thus going against the sun's attraction, and that therefore its velocity must be *diminishing*. On the other hand, when the planet is going along T X it is constantly getting nearer to the centre of the sun, and consequently its velocity must be *increasing*. It is therefore plain that for a path somewhere between T X and T Y the velocity of the planet must be unaltered by the sun's attraction.

With centre S and radius S T describe a circle, and take P a point upon that circle exceedingly near to T. Now if we suppose that the planet be projected from T with a certain specific velocity it will describe the small arc T P. We can easily see that when the planet runs along this arc its velocity remains unaltered. The attraction of the sun always acts along the radius, and hence in describing the arc T P the planet has at every instant been moving perpendicularly to the sun's attraction. It is manifest that in such a case the sun's attraction cannot have altered the velocity, for it would be impossible to assign any reason why it should have accelerated the velocity which could not be rebutted by an equally valid reason why it should have retarded it. We thus see that the planet reaches P with an unchanged velocity, but at P the planet is precisely under the same circumstances as it was at the instant of its projection; it has the same velocity in each case, and it is in each case moving perpendicularly to the radius. It is therefore clear that after passing P the planet will again describe a small portion of the circle which will again be followed by another and so on; i.e. the planet will continue to move in a circular orbit.

What we have now shown amounts to this, that if a planet were originally projected with a certain specific velocity in a direction at right angles to the radius connecting the planet and the sun, that then the planet would continue for ever to describe a circle round the sun.

It will not be difficult to imagine that if the conditions we have supposed be not rigorously fulfilled, that is, if the velocity be not exactly the correct one, or if the direction of projection be not exactly perpendicular to the radius vector that then the orbit may still be a closed curve, not differing very widely from a circle.

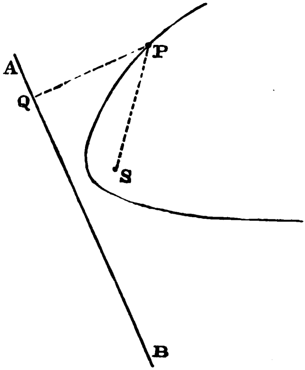
§ 64. **Motion of a Planet in an Ellipse.**—It can be proved by mathematical reasoning which we do not attempt to explain here, that, when the force of attraction is such that it varies according to the inverse square of the distance, the curve which a planet projected in any direction would describe must be, if not a circle or an ellipse, one or other, of the two remaining forms of the curves called conic sections, that is, it must be either an hyperbola or a parabola.

§ 65. **Motion of Comets.**—All the planets move in ellipses, but we have examples among the heavenly bodies of motion in the two other curves.

Comets are bodies which move around the sun under the influence of its attraction. Some comets describe ellipses of greater or less eccentricity. It more usually happens, however, that the path in which a comet moves is indistinguishable from a parabola.

The shape of the parabola may be inferred from fig. 24. A B is a fixed straight line, and S is a fixed point. Now if a point P move so that the distance P S is constantly equal to the length of the perpendicular P Q let fall from P upon the straight line A B, then the point P traces out the curve which is called a parabola. It can be shown that if we imagine one focus of an ellipse to remain fixed while the other focus is moved away to an indefinitely great distance the ellipse will become modified into a parabola. It is quite possible that a comet which appears to us to be moving in a parabolic curve round the sun

FIG. 24.



in the focus at s may often be moving in an ellipse which is so extremely long that the part of the orbit which we see near the sun is indistinguishable by our observations from an exact parabola.

CHAPTER XII.

PARALLAX.

§ 66. **Distance of the Moon from the Earth.**— To obtain precise knowledge of the movements of the heavenly bodies, it is necessary for us to ascertain the distances by which they are separated from the earth. We proceed to explain the methods by which some of these distances have been determined.

We shall, in the first place, consider the case of the moon, which is the nearest neighbour of the earth among the celestial bodies. It is very easy to observe that the moon moves round the earth once every 27·3 days. As the apparent size of the moon remains nearly constant, it is obvious that the orbit of the moon cannot differ very widely from a circle. In fact, just as the earth moves round the sun in obedience to the attraction of the sun, so the moon moves round the earth in obedience to the attraction of the earth. It would, however, be hardly correct to speak of the orbit of the moon as an ellipse. That this orbit is not exactly an ellipse is not in any way inconsistent with the truth of the theory of gravitation; it is, indeed, rather a confirmation of this theory, for it can be shown that it is the attraction of the sun which deranges the motion of the moon from what it would be were this disturbing cause absent. When these disturbances are taken account of, the laws of gravitation are found to be fulfilled.

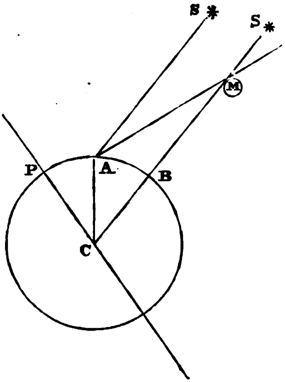
Some of the other planets are, like the earth, attended by one or more moons or satellites ; but for a full account of the circumstances of each planet in this respect, reference must be made to some work on descriptive astronomy.

To determine the distance of the moon from the earth, we require two observations of the moon made at places widely distant on the surface of the earth. We shall simplify the description of this operation as much as possible, for the purpose of presenting it in an elementary form.

Let A and B (fig. 25) represent two stations on the earth, having the same longtitude, from which the moon is observed. Let C P be the polar axis of the earth. Now, we may suppose that the station B has been so chosen that at the instant of observation the moon M is situated in the zenith of the observer at B. We have now to remark that the fixed stars are at least some millions of times more distant from us than the moon. The stars are in fact so distant that the lines drawn from different points of the earth towards the same star are all practically parallel. Let us now suppose that the observer at B sees a star at S, which is just visible to him beside the edge of the moon, and that at this moment the observer at A directs his attention to the same star, and observes its position relatively to the moon. The star is seen in the direction A S, which is parallel to B S, but the moon is seen from A in the direction A M, and, consequently, the observer at A sees the moon separated from the star by the angle M A S. Now, by suitable instruments, the angle M A S can be carefully measured, and from this measurement the distance of the moon can be determined.

Let us consider this triangle A C M. The side A C is equal to the radius of the earth, which, for this purpose, we may suppose to be a sphere. The angle A C B is the excess of the latitude of the station A over the latitude of the station B. This is, of course, known, because the stations are known. Also, since A S is parallel to B S, it follows that the angle A M C is equal to the angle M A S, and therefore the angle A M C is known. In the triangle A C M we therefore know one side, A C, and two angles. It follows that the triangle can be constructed to scale, and thus the length M C can be determined, or this length can be computed by the aid of trigonometry.

FIG. 25.



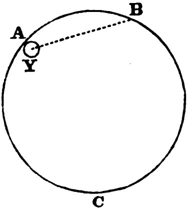
The angle A M C is termed the *moon's parallax.* We have in the figure greatly exaggerated this angle.

The distance of the moon from the earth, as determined by these observations, is about sixty times the earth's radius.

§ 67. **Distance of the Sun from the Earth.**—Owing to the comparative proximity of the moon to the earth, the determination of its distance is a much more simple problem than the determination of the distance of any of the other heavenly bodies. The scientific importance, however, of knowing the *scale* upon which the universe is built is so obvious that astronomers have paid a great deal of attention to the determination of the distance from the earth to the sun, which, as we shall presently see, is the standard of astronomical measurement.

§ 68. **The Transit of Venus.**—There are several distinct methods by which this problem has been solved. The best known of these methods, even if not the most trustworthy, depends upon observations of the phenomenon called the *Transit of Venus*, to which we have already referred.

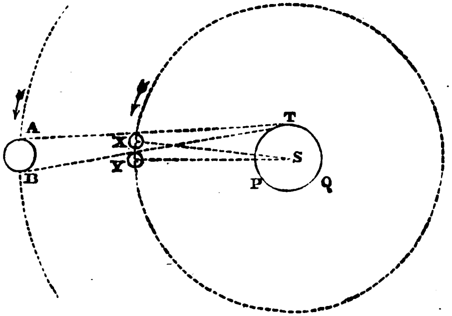
FIG. 26.



We shall endeavour to simplify the statement of this method by leaving out several of the details which complicate its application in practice.

The planet Venus on certain rare occasions comes between the earth and the sun, and is then seen by an observer upon the earth like a black spot upon the face of the sun. Thus, suppose the circle C A B (fig. 26) to represent the apparent disk of the sun, the planet Venus appears to enter on the disk of the sun at A, and then moving across the sun in a direction which is indicated by the dotted line A B, leaves the sun at B. The time occupied in the passage of Venus across the sun may be about four hours. When Venus is just completely inside the sun, as shown in the figure, where the circle expressing the edge of Venus just touches internally the circle expressing the edge of the sun, Venus is said to be at first internal contact. We shall now show how, by observing the time at which first internal contact takes place, the distance of the sun from the earth is to be determined. Let P Q T (fig. 27) denote the sun, of which the centre is S. Let

FIG. 27.



A B denote the earth, and let X and Y denote two positions of the planet Venus. Suppose we draw A T a common tangent to the sun and the earth, and also the common tangent B T, touching the earth in B and the sun in a point so close to T as to be undistinguishable therefrom. The circle through A B denotes the orbit of the earth; and the circle through

X Y denotes the orbit of Venus, and the arrows indicate the directions in which the earth and Venus are moving. Now, as Venus is moving much faster than the earth, it follows that Venus will overtake the earth, and thus at a certain time will arrive in the position X. (It will be seen that we are assuming for the present the orbits of the earth and Venus to lie in the same plane.) Now, what will be the ap pearance of Venus when it is at X, as viewed from the station A on the earth? The observer at A will just be able to see Venus at first internal contact, and having previously regulated his clock accurately, he will be able to note the moment at which Venus occupies the position X.

We have already pointed out (§ 53) the artifice by which we may suppose the earth to be at rest in its orbit, while the movements of Venus relative to the earth remain unaltered. In fact, if the earth were at rest, and if the periodic time of Venus in its orbit were 584 days; then the appearances of Venus with reference to the sun, and as seen from the earth, would be the same as they actually are when the earth is moving round the sun in 365 days, and Venus in 224 days. We shall then suppose that the earth is at rest in its orbit, and that Venus is moving with the slower motion just referred to.

Let us now suppose that Venus moves on until it reaches the position Y. To the observer at B Venus will now be visible at first internal contact. It is, therefore, clear that A is the spot on the earth at which the internal contact is first seen, and that B is the spot on the earth where the internal contact is last seen. A slight correction will have to be made here on account of the motion of revolution of the earth upon its axis, for during the time occupied by Venus in passing from X to Y the earth will have turned through an angle which is quite appreciable. Consequently the real point, B, on the earth's surface, where the internal contact is last seen, will be slightly different from what it would have been if the earth had not rotated on its axis after the first internal contact had been observed from A. Astronomers, however, know how to allow for this difference, and we shall not here consider it further.

We shall therefore suppose that expeditions are sent to the two stations A and B (of course as a matter of fact, they can only be sent to the places nearest A and B which are suitable from geographical considerations), and that at each of these two stations the moment of first internal contact is observed. We may also suppose that a telegraph wire is laid from A to B, so that at the instant of contact, as seen at A, a telegraphic signal is despatched to B. The observer at B then notes the arrival of this signal on his clock, and when he himself sees the contact at a time also marked by his own clock, he is able with the greatest precision to determine the interval of time between the two contacts.

We have thus learned the time which Venus takes in passing from the position X to the position Y. But we also know (§ 53) that the entire time which Venus requires for performing a revolution round the sun (relatively to the earth) is 584 days; hence if we assume that Venus moves uniformly, we can by a simple sum of proportion find the angle X S Y.

Now the radius T S is small compared with the distance S X. We may, therefore, with sufficient accuracy for our present purpose suppose that the angle X T Y is equal to the angle X S Y.

We may now consider the problem to be solved, for the distance A B being very nearly equal to the diameter of the earth is therefore known. Also the angle A T B is known, and therefore the distance A T from the sun to the earth is known.

§ 69. **Distance of the Sun from the Earth.**—The most recent determinations make the sun's mean distance from the earth equal to

149,000,000 kilometres.

The actual distance, however, varies between 147,000,000 kilometres in winter and 151,000,000 kilometres in summer.

By means of carefully executed measurements it is found that the average angle which the diameter of the sun subtends at the eye is 1924″.

We are hence able to find the true diameter of the sun, for knowing the distance O A (fig. 2, § 2), and the angle A O B, we are enabled to find the distance A B. The diameter of the sun as thus determined is

1,390,000 kilometres.

CHAPTER XIII.

PARALLAX OF THE FIXED STARS.

§ 70. **The Fixed Stars.**—Great as is the distance of the sun from the earth, it is small compared with the distances of some of the fixed stars. It is true that we only know the distances of a very few of these bodies, but there is good reason to believe that the great majority of them are even more distant from us than those of which we do know the distance.

It may be well for us here to glance for a moment at the rank which the fixed stars occupy among the other bodies which are found in the universe. Our sun is not only the source of light and heat to the planets, but it is also the centre around which they revolve, and its mass so overwhelmingly exceeds that of all the planets and their moons taken together that the planetary system is merely a minute adjunct to the sun. From a distance, less than the distance of any of the fixed stars, the planets would have become quite invisible though the sun might still be seen as a brilliant object.

Astronomers are however led to the belief, that although the sun is to us *on the earth* vastly more important than any of the other bodies in the universe, yet this importance is due rather to the comparative nearness of the sun to the earth than to the real pre-eminence of the sun among the other bodies of the universe.

An examination of the countless myriads of those bodies with which the heaven is bespangled, and which, in order to distinguish them from the planets, we call the *fixed stars*, has taught us that, like our sun, they are bodies which shine by their own light and heat, and that their apparent minuteness is only due to the vast distances by which they are separated from us. When proper allowance has been made for the effect of this distance, it is found that some of these stars are, to say the least, as bright and large as our sun, and thus we are led to the conception that our sun is really only one of the host of stars which are so plentifully found even in the most remote regions of the heavens to which the power of the telescope can penetrate.

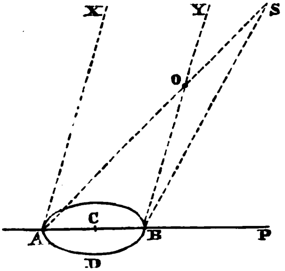
We thus see that the measurement of the distance of a fixed star is an entirely different problem from the measurement of the distance of the sun. We were able in effecting this measurement to make use of the diameter of the earth as a base line. We shall however find that a far larger base line is required for the celestial measurements now to be undertaken.

§ 71. **Annual Parallax of a Star.**—We shall here only give an outline of the method which has been adopted by astronomers, for the actual application of the method, as in the case of the determination of the sun's distance, is complicated by a number of circumstances which, though highly important for the astronomer, need not be entered upon in a work which aims merely at explaining the principles.

It is easy to conceive that the apparent angular distance between a star and the centre of the sun can be measured by suitable observations. In fact if the right ascension and declination of the centre of the sun and the star be determined in the usual way, then the angle could be calculated by spherical trigonometry; or indeed, we might suppose the positions of the star and the sun to be plotted upon a globe, and the angle between the two positions measured in the usual way. Now, supposing this angle to have been measured at a suitable epoch of the year and the measurement to have been repeated precisely half a year afterwards, we should then have the means of finding the distance of the star.

For suppose (fig. 28) that S represents the position of the star, and A D B be the orbit of the earth; then when the earth is at A, we measure the angle S A B. Six months afterwards, when the earth is at B, we can measure the angle S B A. The distance A B is double the distance of the sun from the earth, hence in the triangle S A B we know the base A B, and the two base angles, and hence the triangle is determined and the sides A S and B S are known. The angle which the radius of the earth's orbit subtends at a star is called the *annual parallax* of the star.

Fig. 28.



§ 72. **Impracticability of this Method.**—The stars are, however, so excessively remote from us that the angle S A P differs from the angle S B P by only an exceedingly minute quantity. This being so, a minute error in the measurement of one of the angles might cause a very large error in the distance of the star concluded from such measurement. Now there is one source of error which even the greatest care cannot entirely obviate, and that is the refraction of the atmosphere. It is true that we can calculate and allow for the grossest part of this error; but even when this allowance has been made as well as our knowledge will permit, there are still outstanding small irregularities which would prevent the measurement of the angles being made with the required precision.

§ 73. **Determination of the Difference of the Parallax of two Stars.**—We are therefore obliged to resort to a somewhat modified method. Suppose that there is another star which, *on the celestial sphere,* appears pretty close to S, but which is *very much more distant* from us than S. Let A X and B Y (fig. 28) be lines drawn from A and B in the direction of this very distant star. Finally, we shall suppose that this auxiliary star is so exceedingly remote that the lines A X and B Y are practically parallel. We now measure the angle X A S between the two stars when the earth is at A; and then measure the angle Y B S between the two stars when the earth is at B. Now it is true that both of these angles are also affected by refraction, but if the two stars are *apparently very close together on the celestial sphere* the effect of refraction on the relative positions of the two stars is insignificant. The apparent place of each star is of course slightly different from the real place on account of refraction, but the two stars being close together (on the celestial sphere) undergo very nearly equal displacements by refraction, and the small difference in the relative position and the angular distance, which refraction is able to produce, is susceptible of being computed with the utmost precision.

We shall now show how these observations will enable us to compute the distance A S. Since A X is parallel to B Y, the angle Y O S is equal to the angle X A S, but the angle Y O S is equal to the sum of the angles O S B and O B S, and therefore the angle A S B is equal to the difference between the angles X A S and Y B S. It follows that the angle A S B is determined by taking the difference between the two measurements of the angular distance of the stars corrected for refraction.

The angle S A B can then be measured, and even if a minute error in the determination of this angle should arise from the uncertainty of the refraction, it would produce an inappreciable effect upon the distance required. We are therefore enabled, since A B is known, to construct the triangle S A B, and thus the distance S A is determined.

§ 74. **The Proper Motion of the Stars.**—To determine the distance of a fixed star by this method it is therefore necessary to have another star adjoining it on the celestial sphere, the distance of which is very much greater. The question here arises, how are we to know which of two apparently adjacent stars is farther off than the other? There is really no way of making sure of this before the actual observations have been made. There are, however, some *a priori* considerations which enable us to make a coarse guess as to whether a star is comparatively near us.

It is most probable, in fact it is practically certain, that every one of the stars is actually in motion. The relative places of the stars on the heavens are thus gradually changing. These changes, however, take place with such extreme slowness, that even in the lapse of centuries the forms of the constellations and the general appearance of the heavens have not appreciably altered. Even when the places of the stars have been determined with the utmost accuracy which meridian observations will permit, we do not find in the *great majority of stars* any perceptible change of position from one year to another. There are, however, a limited number of stars possessing an amount of *proper motion* (as it is called) which is quite appreciable in accurate observations. Now the fact of our seeing this proper motion and being able to measure it is a presumption that those stars which possess the proper motion are probably nearer to us than others in which no proper motion has been detected. This is the presumption which has chiefly guided those astronomers who have hitherto devoted their attention to the measurement of the distances of the stars from the earth. If, in the immediate vicinity of a star which has a large proper motion, a minute star be visible which has not that proper motion, it may be presumed that the former of these stars is nearer to us than the latter, and that the apparent contiguity of the two stars on the surface of the celestial sphere is only due to one of the stars lying near the line of sight directed towards the other.

§ 75. **Distances of the Stars.**—The distances of several stars have been determined in this way. Of these distances none are less than 200,000 times the distance of the earth from the sun. From so vast a distance as this the earth's orbit only appears about the same size as a halfpenny would do at a distance of two and a half kilometres!

CHAPTER XIV.

THE PRECESSION OF THE EQUINOXES.

§ 76. **Alterations in the Right Ascensions of Stars.** We have already explained the general method by which the right ascension of a star may be determined (§ 23). Let us suppose that this operation is repeated for the same star at widely separated intervals of time; to give definiteness we state here the mean right ascension of Sirius at four different dates:

Mean Right Ascension of Sirius.

	h	m	s
Jan. 1, 1847 . .	6	38	25
Jan. 1, 1857 . .	6	38	51
Jan. 1, 1867 . .	6	39	17
Jan. 1, 1877 . .	6	39	44

We thus see that on the four dates here given, which are separated by intervals of ten years, the mean right ascensions of the star Sirius have perceptibly altered. It will also be observed that the changes in the right ascension take place uniformly at the rate of about 2·65 seconds of time per annum. In the course of centuries this change becomes very marked, even to the coarsest methods of observing, and consequently we find that this phenomenon was known to the ancient astronomers.

§ 77. **Precession of the Equinoxes.**—Now let us state exactly what the phenomenon is. On January 1, 1847, the vernal equinox crossed the meridian $6^h\ 38^m\ 25^s$ before the star Sirius. On January 1, 1877, the vernal equinox crossed the meridian $6^h\ 39^m\ 44^s$ before Sirius. It is therefore obvious that the vernal equinox and Sirius are further apart now than they were thirty years ago. Compared with Sirius the vernal equinox now comes on the meridian a little earlier than it did thirty years ago, and thus the phenomenon in question has come to be known as the 'Precession of the Equinoxes.'

We have selected the star Sirius merely as an example; had *any* star been chosen we should have equally found that relatively to that star the vernal equinox was continually changing its position.

§ 78. **The Ecliptic is at rest.**—We are thus led to the belief that the positions of the equinoxes on the celestial sphere are in a state of continual change. Now as the equinoxes are the intersections of the ecliptic and the equator, it follows that one if not both of these circles must be continually changing its place upon the surface of the heavens.

It is, however, easy to show that of these two circles the ecliptic at all events has no perceptible motion. If we could see the stars surrounding the sun in the heavens, we should find, for example, that every 23rd of May the sun passed between the

Pleiades and Hyades, that every 21st of August it passed exceedingly close to Regulus (α Leonis), and that on every 15th of October it passed a little above Spica (α Virginis). The track of the sun among the stars is thus invariable, and hence to account for the motion of the vernal equinox we must suppose that the ecliptic is at rest and that the equator is in motion.

§ 79. **Motion of the Celestial Pole.**—By observations of a star at widely separated intervals it has been found that the polar distance is changing, as well as the right ascension. Thus for the dates already given we have for the polar distances of Sirius :—

Date.	Mean Polar Distance of Sirius.
Jan. 1, 1847	106° 30′ 37″
„ 1857	106° 31′ 24″
„ 1867	106° 32′ 11″
„ 1877	106° 32′ 56″

We thus see that the angular distance from Sirius to the north pole is steadily increasing at the rate of about 4″·6 annually. It follows that either the north pole or Sirius must be in motion on the surface of the heavens. If we make the same observations for any other star we find a similar change, and hence we see that there is a relative motion between every star in the heavens and the north pole. Now, shall we say that the stars are moving relatively to the pole, or the pole moving relatively to the stars? If we reflect that the stars have next to no relative motion among themselves, it is obviously more natural for us to suppose that the pole is actually moving among the stars.

To this conclusion also the observations of the changes in right ascension would have conducted us, for if the equator be in motion among the stars (as we have seen it is), then it is a necessary consequence that the pole, which is merely the point on the celestial sphere 90° from the equator, must be in motion also.

We are thus led to inquire into the nature of the motion of the pole which will be adequate for the purpose of explaining the changes of right ascension and declination of the heavenly bodies to which we have adverted.

§ 80. **The Obliquity of the Ecliptic.**—The first point to be considered is the inclination of the ecliptic to the equator. To determine the *obliquity of the ecliptic*, as this inclination is called, it is only necessary to observe the greatest declination of the sun on Midsummer-day, and this declination is the required obliquity. We shall here give the obliquity of the ecliptic as determined by this method in the years already referred to.

Date.	Obliquity of Ecliptic.
June 21, 1847 . .	23° 27′ 23″·56
„ 1857 . .	23° 27′ 37″·12
„ 1867 . .	23° 27′ 13″·85
„ 1877 . .	23° 27′ 26″·51

Now, though it would not be correct to say that the obliquity was absolutely constant, yet the changes in its value are extremely small. In fact the mean of the four values just given is

$$23^\circ \quad 27' \quad 25''\cdot26$$

and the difference between this quantity and the greatest or least of the four observed values is only about one seven thousandth part of the total amount.

§ 81. **Motion of the Pole among the Stars.**—We are thus led to the conclusion that whatever be the motion of the equator among the stars it constantly preserves the same inclination to the ecliptic.

Let P denote the pole of the celestial equator, and let T denote the pole of the ecliptic. Then, since the ecliptic remains fixed among the stars it follows that the place of T among the stars does not change. Now, since the angle between two planes is equal to the angle between the perpendiculars to those planes drawn through a point upon the line of intersection, it is evident that the obliquity of the ecliptic is equal to the angular distance of the poles P and T. Hence, since we have seen that the obliquity of the ecliptic remains constant, it follows that the arc P T must remain constant, and that therefore P can only move in a small circle on the celestial sphere of which T is the pole.

We have now only to ascertain the velocity with which P moves round in its small circle.

By a comparison of ancient observations with modern observations the rate at which this motion is performed has been determined with great accuracy It is found that the arc T P sweeps through an angle of 50″·26 annually, and from this it is easy to calculate that, for P to complete a whole revolution round T, a period of nearly 26,000 years is necessary.

The consequences of this continual change in the position of the pole are very remarkable. The polar star, at present of such importance to astronomers, was not always so near the pole as to be convenient for the many purposes to which it is now applied. Thirteen thousand years ago it was distant from the pole by more than 40°, and in thirteen thousand years more it will again be separated by the same distance.

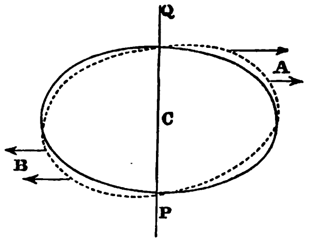
§ 82. **The Pole of the Earth.**—It should be observed that although the pole in the heavens is moving about among the stars in the way we have described, yet that the axis about which the earth rotates appears to be rigidly fixed in the earth. In fact (so far as observations have hitherto gone), we might suppose a rigid axis driven through the earth, and the earth to be spinning round this axis once in every sidereal day. This axis (of course carrying the earth with it) traces out a right circular cone, of which a perpendicular to the plane of the ecliptic is the axis, and the time occupied in the description of this cone is 26,000 years.

It can be shown from dynamical principles that the actual pole of the earth *might* be revolving *on the earth itself* in a small circle in a period of 306 days; or to put the matter more plainly, if a line were drawn from the centre of the earth to the celestial pole, and if the point in which this cuts the surface of the earth were marked each day by a peg, then the positions of the pegs might not always be the same;

but all the pegs might lie upon a circle, such that the peg corresponding to the 307th day would be in the same place as that belonging to the first day. Observations have been specially directed to this point, and it has been shown that even if such a motion of the pole on the earth exists, the circle which it describes can hardly be a dozen metres in diameter.

§ 83. **Permanency of an Axis of Rotation.**—We shall now consider the mechanical cause of this very remarkable phenomenon. If a body (of the same shape as the earth) be set spinning about its polar axis, then the body will continue for ever to spin about this axis, and the direction of the axis will continue for ever parallel to itself. In fig. 29 let P Q represent the axis about which the earth is spinning, then, by the symmetry of the figure it is obvious that the centrifugal forces on all the parts of the earth will neutralise each other. If, however, from any cause the position of the earth be slightly deranged so that it occupies the place indicated by the dotted lines, then the centrifugal force acting upon the protuberant portions will obviously have the effect of tending to restore the earth to its original position. It follows that the motion of the earth is stable when spinning about its polar axis.

FIG. 29.



In the annual path of the earth around the sun, the axis of the earth (subject only to the small effect of precession) remains constantly parallel to itself. A familiar illustration of the same permanency of an axis of rotation is presented by the humming top, which will stand up straight when it is spinning, though it will not do so when at rest.

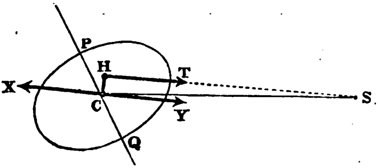
§ 84. **Cause of the Precession of the Equinoxes.** There is however a disturbing cause in action which deranges the motion of the earth around its axis from the simple character it would otherwise have. This disturbing cause is due to the attraction of the sun and the moon upon the protuberant portions at the earth's equator.

To explain this, we have to make use of a theorem in mechanics which we cannot demonstrate in this volume, but the truth of which will perhaps be admitted. If the earth be rotating round its polar axis, then that rotation will not be disturbed by any force which passes through the centre of gravity of the earth. In fact, so far as the mere rotation of the earth upon its axis is concerned, we might regard the centre of gravity as a fixed point, and then the force which passed through the centre of gravity could be neutralised by the reaction of the fixed point.

Now if the earth were a perfect homogeneous sphere, the attraction of the sun or the moon would be a force passing through the centre of the sphere, and so would leave the rotation unaffected. Or, even if the earth were not a perfect sphere, or not homogeneous, still if the attracting body were so far off that all points of the earth might be considered as practically at the same distance from the attracting body, in this case also the attraction would be a force passing through the centre of gravity of the earth. The sun and the moon, however, are both so comparatively near the earth that we are not entitled to make this supposition, and, consequently, neither the attraction of the sun nor of the moon passes through the earth's centre. To this is due the phenomenon of the Precession of the Equinoxes.

Let P Q (fig. 30) represent the axis of the earth, and let S be the position of the attracting body. Then, since the attraction varies inversely as the square of the distance, it follows that the portion of the earth turned towards the attracting body will be acted upon

FIG. 30.

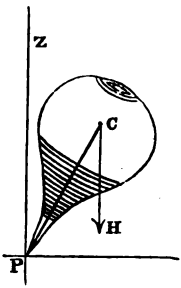


by a greater force than the portion on the remote side, and, consequently, the total attraction will be directed along the line H S, which passes above the centre of gravity of the earth C. Let H T represent the magnitude of this force, both in intensity and in direction. Through the centre C draw a line X Y parallel to H T, and let us suppose that equal and opposite forces C X and C Y are applied at the centre C, each of these forces being equal to H T. The force C Y may now be left out of view, for as it acts through the centre of gravity, it can have no effect upon the rotation of the earth around its axis. Thus the effect of the attracting body upon the earth may, so far as the rotation of the earth is concerned, be represented by the pair of equal parallel and opposite forces H T and C X. Such a pair form what is known in mechanics as a *couple.*

It would seem as if the immediate effect of this couple would be to turn the earth so as to bring its polar axis C P perpendicular to the line C S, or (supposing the sun to be the attracting body under consideration) to bring the plane of the equator to coincide with the plane of the ecliptic. The effect of the couple is, however, so entirely modified by the fact that the earth is in a state of rapid rotation, that paradoxical as it may appear, the real effect of the couple is not to move C P in the plane of the paper, but to make C P move perpendicularly to the plane of the paper.

§ 85. **Illustration of the Pegtop.**—In explanation of this apparent paradox, we may remark that in a miniature form every schoolboy is already acquainted with a precisely analogous phenomenon in the motion of a common pegtop. In fig. 31 the line P Z is vertical, P C is the axis of the pegtop, and C is the centre of gravity of the pegtop. Now, if the pegtop *when not spinning* were placed in the position represented in the figure, the force of gravity acting along C H would immediately cause it to tumble over, the line C P moving in the plane of the paper. But when the pegtop is in a state of very rapid rotation, the circumstances are entirely different.

FIG. 31.



Every one has observed that the axis C P, so far from falling in the plane of the paper, commences to move perpendicularly to the plane of the paper, and will, in fact, describe a right circular cone around P Z as an axis. It is undoubtedly true that after a time the angle Z P C begins to increase, and that before long the pegtop really does tumble down, but this is solely due to the influence of disturbing forces, viz. friction at the point and the resistance of the air, and that if these forces could be evaded, the speed with which the pegtop spins would be undiminished; and so long as that speed remained unaltered, so long would the axis of the pegtop continue to describe the right circular cone around the line P Z.

Assuming that what holds good in the case of the pegtop holds good in the colossal case of the earth itself, we should expect to find that the axis P C, instead of moving towards S and thus diminishing the obliquity of the ecliptic, would move perpendicularly to the plane of the paper and thus not alter the obliquity of the ecliptic at all. The axis of the earth would then describe a right circular cone of which the axis is perpendicular to the plane of the ecliptic, and this is actually the motion which the precession of the equinoxes requires.

§ 86. **Precession due to both Sun and Moon.**—The precession of the equinoxes is due to the action of both the sun and the moon. Owing, however, to the proximity of the moon its effect is greater than that of the sun. In fact of the total amount, about one-third is due to the sun and the remainder to the moon.

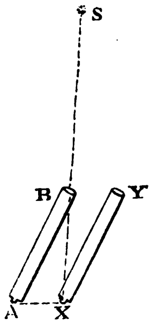
CHAPTER XV.

THE ABERRATION OF LIGHT.

§ 87. **The Aberration of Light.**—The discovery of the aberration of light, by Bradley, is one of the most interesting episodes in the history of science. In the hope of detecting the existence of annual parallax in the star γ Draconis, Bradley had observed the zenith distance of the star on all available opportunities for an entire year. These observations revealed an apparent movement in the star, entirely different from the movement which would be produced by the annual parallax for which Bradley was in search. It was not until after this apparent motion had been detected and examined in several stars, that Bradley was enabled by a happy conjecture to give it a satisfactory explanation. Bradley found that the apparent movements of the stars which he had discovered were an immediate consequence of the fact that the velocity with which light travels, though exceedingly great, is still not incomparably greater than the velocity with which the earth moves in its orbit round the sun. The phenomenon thus revealed is called the aberration of light. This discovery, though it relates to magnitudes so exceedingly small as to be perceptible only in very accurate measurements, is yet of so delicate and so beautiful a character that it must undoubtedly rank among the very greatest discoveries which have yet been made in astronomy.

§ 88. **Explanation of the Aberration of Light.**—Let S, fig. 32, represent a star to which a telescope is to be directed. If the telescope be at rest, it is obvious that the telescope should be pointed along the ray X S which comes from the star. If, however, the telescope be in motion a little consideration will show us that, when the star is seen, the telescope must generally not be pointed exactly at the star but in a somewhat different direction. Let us suppose that the telescope will move from the position marked A B to the position X Y in the same time as the light from the star travels from B to X. Then it is plain that, for us to see the star, the telescope must be pointed in the way shown in the figure. For the star can only be seen when rays of light from the star enter the eye of the observer. The telescope must therefore be so placed that the rays which enter the object glass of the telescope can come out of the eye piece. When the telescope is in the position A B the light enters the telescope through the object glass at B; the motion of the telescope is then sufficient to enable the light to pass down the tube of the telescope without being lost against the sides, and when the telescope reaches the position X Y the light emerges from the eye piece at X, and enters the eye of the observer.

FIG. 32.



If, therefore, the observer, who, of course, shares the same motion as the telescope, observes the position of the star, he will see the star in the direction X Y in which the telescope is pointed, and, therefore, he will judge erroneously of the position of the star to an extent which is measured by the angle between the direction S X of the rays which come from the star and the direction X Y in which the telescope is pointed.

§ 89. **Determination of the Velocity of Light.**— It is an exceedingly interesting consequence of the discovery of the aberration of light that we are enabled to deduce from astronomical observations the velocity with which light travels through space. The movement of the telescope to which we have referred arises from the annual motion of the earth around the sun. This annual motion takes place at the average rate of 29 kilometres per second, and consequently, 29 kilometres per second is the velocity with which the telescope is carried along. Now it is evident that while the telescope is carried over the distance A X, the light must travel through the distance B X, and hence we see that the velocity of the earth is to the velocity of light in the ratio which A X bears to B X. If, therefore, we could in any way find the angles of the triangle B A X, we should know the ratio which the velocity of light bears to the velocity of the earth in its orbit, and as the latter is known, the velocity of light would be determined.

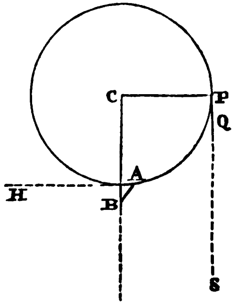
Of these, the angle B A X is immediately known; for as the earth is moving in the ecliptic (for the present we may suppose the orbit to be circular) and in a direction perpendicular to the line drawn from earth to the sun, the earth must at any moment be moving towards that point on the ecliptic which is 90°

from the sun. Therefore the point in the heavens towards which the earth is moving on any given day is determined. The line A X, which indicates the direction of the motion of the telescope, is therefore directed to a point upon the heavens which is known. The angle B A X is therefore known, for it is merely the angular distance between the point in the heavens to which the telescope is pointing, and the point on the ecliptic which is 90° from the sun.

The angle A B X can also be determined by means of observations, and to show the principle of the method by which this is obtained we shall suppose a very simple case.

Let C (fig. 33) represent the sun, and P the position of the earth in its orbit. Let P Q be the direction of the telescope, which is pointed precisely to that point of the heavens towards which the earth is moving and which is, of course, a point on the ecliptic 90° from the sun. Let us suppose that there is a star, situated in the direction indicated by the line P S. In a quarter of a year after the earth was at P it will have reached the position A, and the telescope is again pointed to the same star. Now if it were not for aberration the star would be seen in that point of the ecliptic which was 180° from the sun, along the direction C B. Owing, however, to aberration, the telescope must be pointed

FIG. 33.



in a somewhat different direction, A B. It follows that the angle C B A will be equal to the difference between 180° and the angle which the star makes with the sun, and hence the angle C B A is known. This angle C B A is the difference between the real direction of the star and the direction in which the telescope is pointed. Of course, it will not generally happen that a star will be so opportunely situated as in the case we have supposed; but the illustration will serve to exemplify the statement, that by suitable observations *at different seasons of the year* the angle A B X (fig. 32) between the real and apparent direction of the star can be determined. Thus two angles of the triangle B A X are known, and thus the species of the triangle is known, and the velocity of light can be determined.

§ 90. **Other Determinations of the Velocity of Light.**—Another method by which the velocity of light may be determined, and which is indeed the way in which that velocity was first discovered, is presented by the phenomena of Jupiter's satellites. The planet Jupiter is attended by a very beautiful system of four moons. These moons are constantly being eclipsed by passing into the shadow of Jupiter. To see these eclipses only a small telescope is required, and they have consequently been much observed ever since the first discovery of the satellites of Jupiter by Galileo. From these observations the movements of the satellites have become so well known that it is possible to predict the occurrence of the eclipses, and the times at which they will commence and terminate. After many comparisons between these predictions and the actual observations certain discrepancies were brought to light, the cause of which was not at first manifest. It was, however, noticed that the eclipses occurred earlier than was expected when the earth was in that part of its orbit near Jupiter, and later than was expected when the earth was distant from Jupiter. This suggested the explanation that the velocity of light was not indefinitely great, and that thus, when we were near to Jupiter, we received tidings of the occurrence of an eclipse with less delay than when we were further off.

The velocity of light has also been determined by means of actual experiments on the earth, and the results of these experiments agree in a remarkable way with the results deduced from aberration, and from the eclipses of Jupiter's satellites.

The velocity of light, according to recent elaborate researches, is 300,400 kilometres per second.

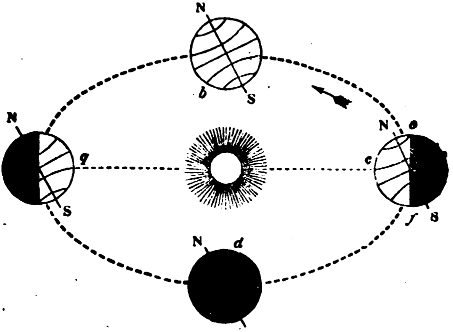
CHAPTER XVI.

THE SEASONS.

§ 91. **Changes of the Seasons.**—Let fig. 34 represent the path of the earth around the sun. We do not attempt in this figure to represent the earth and the sun to scale. Let N S be the direction of the axis about which the earth rotates, then in each of the four positions in which the earth is shown the direction N S will be parallel.

Let us first consider the earth in the position *c*. The north pole of the earth at N will then be turned towards the sun, and consequently at or near the north pole there will be continual daylight. This is shown a little more fully in fig. 35 (p. 114). All the region inside the small circle *e d* (fig. 35) will be in constant daylight because the revolution of the earth about the axis N S cannot bring a place within this circle into the dark hemisphere. This circle, *e d*, is called the Arctic Circle, and it will thus be seen

FIG. 34.

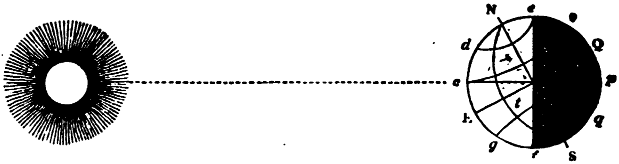


that during the Arctic summer all places within the Arctic Circle enjoy perpetual day.

If the centre of the earth be joined to the centre of the sun, the joining line will cut the surface of the earth in the point *c* (fig. 35). The circle *c v* will also be of importance. When the earth has the position shown in the figure, the sun will be vertically over head at the point *c*. This circle is called the tropic of Cancer, and the sun can never be vertically overhead in any place which lies north of the tropic of Cancer.

Let us now draw a plane through the centre of the earth perpendicular to the polar axis N S. This plane will cut the surface of the earth in a circle, E Q, which is called the *equator.* Since half this circle will lie in the illuminated hemisphere and half in the dark hemisphere, it follows that the day and night at the equator will be of equal length. At all places between the equator and the Arctic Circle there will be both daylight and darkness in every revolution of the earth, but as the portion of the earth which lies between these boundaries is more in the illuminated hemisphere than in the dark hemisphere, it follows

FIG. 35.



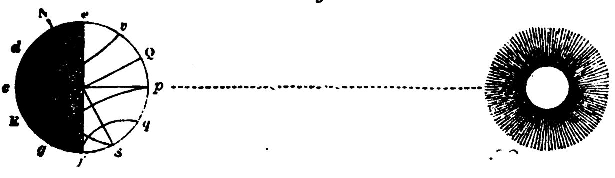
that the day will be longer than the night. On the southern hemisphere of the earth, i.e. the hemisphere between the south pole and the equator, we draw the circles *f q* and *g p* precisely similar to the Arctic Circle and the tropic of Cancer in the northern; these circles are called respectively the Antarctic Circle and the tropic of Capricorn. At any place between the equator and Antarctic Circle the night is longer than the day, while at any place between the Antarctic Circle and the south pole there is perpetual night.

We have thus described the way in which the sun's light and heat are received by the different regions of the earth when the earth is in that part of its orbit denoted by *c* (fig. 34). Let us now see how this corresponds to the seasons.

Suppose the earth and sun to occupy the relative positions shown in fig. 35, then, as we have seen, the sun shines continually in the Arctic regions, while in the Antarctic regions the sun is not seen at all. Hence we have summer in the Arctic regions and winter in the Antarctic regions. Between the equator and the Arctic Circle the day is longer than the night, while between the equator and the Antarctic Circle the night is longer than the day. The warmth received from the sun is also very much greater in the northern hemisphere than in the southern hemisphere. The reason of this is that the sun shines much more perpendicularly on the earth between E and *d* than it does between E and *f*. Thus, throughout the whole of the northern hemisphere we have summer, and throughout the whole of the southern hemisphere we have winter.

Let us now suppose the case when the earth is in the position of fig. 36. The condition of the two

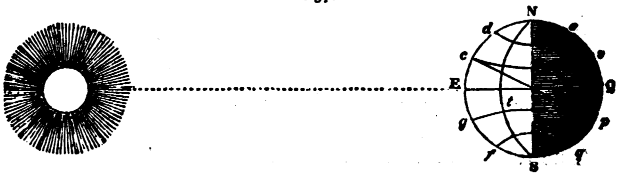
36.



hemispheres is reversed. The Arctic Circle is in perpetual darkness, the Antarctic Circle is in perpetual sunshine. Winter reigns over the entire northern hemisphere, while summer prevails throughout the southern hemisphere.

Finally, when the earth is at the intermediate positions we have the condition of spring or autumn, for now, as we see by fig. 37, the axis of the earth is perpendicular to the line joining the centre of the earth to the sun. Hence it is evident that, in this

FIG. 37.



case, day and night are of equal length all over the globe. We thus see that by the revolution of the earth about the sun, combined with the rotation of the earth about its axis and the constant inclination of the earth's axis to the plane of the ecliptic, the changes of the seasons are produced.

CHAPTER XVII.

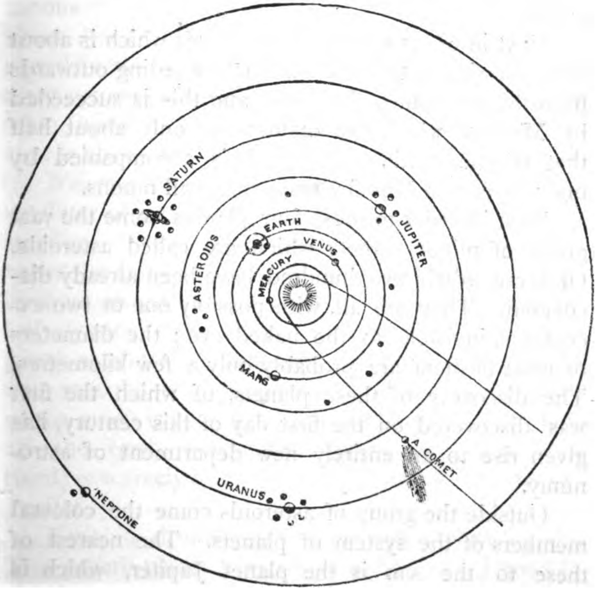
THE SOLAR SYSTEM.

§ 92. **The Solar System.**—By the expression *solar system* we are to understand the group of celestial bodies which consists of the sun himself, the planets and their satellites, and the comets. To these should, perhaps, be added a vast host of minute bodies which, when they come into our atmosphere, produce the well-known phenomena of the shooting stars.

All the bodies we have mentioned form one isolated group in the universe. The most prominent member of the group is, of course, the sun, which far exceeds in dimensions all the other bodies of the solar system taken together.

In fig. 38 we give a general sketch of the relations

FIG. 38.



of the different members of the solar system. It is, however, not possible to represent conveniently in a figure the real proportions of the orbits.

§ 93. **The Planets.**—In the centre we have the sun, round which all the other bodies circulate. The planet, so far as we know at present, which is nearest to the sun is Mercury, to the motions of which we have already referred (§ 54). Mercury is so extremely close to the sun that the intensity of the radiation of heat from the sun must be seven times greater on Mercury than on the earth. The diameter of Mercury is somewhat less than half the diameter of the earth.

Next in order comes Venus (§ 46) which is about the same size as the earth. Then proceeding outwards from the sun comes the earth, and this is succeeded by Mars, of which the diameter is only about half that of the earth. The earth is accompanied by one moon, and Mars by two very small moons.

Next in order to these four planets come the vast group of minor planets which are called asteroids. Of these nearly two hundred have been already discovered. They are all, with possibly one or two exceptions, invisible to the naked eye; the diameters of most of them are probably only a few kilometres. The discovery of these planets, of which the first was discovered on the first day of this century, has given rise to an entirely new department of astronomy.

Outside the group of asteroids come the colossal members of the system of planets. The nearest of these to the sun is the planet Jupiter, which is much the largest of all. The diameter of Jupiter is more than ten times as great as the diameter of the earth, while the diameter of the orbit in which

Jupiter moves around the sun is five times the diameter of the orbit of the earth.

The time occupied by Jupiter in completing one revolution about the sun is about twelve years. Notwithstanding the vast size of Jupiter his rotation upon his axis is performed more rapidly than the corresponding rotation of the earth, the period being scarcely ten hours. Jupiter is attended by no less than four moons or satellites. The nearest of these moons to Jupiter is only distant from him by six times his radius. This satellite moves completely round Jupiter in less than two days. The fourth or the most distant satellite is about four or five times as far from Jupiter as the first satellite, and its time of revotion is about sixteen days.

We may thus contrast the circumstances of the satellites of Jupiter with the circumstances of our own satellite. The moon is distant from us by about sixty times the earth's radius, and the time of its revolution is about 27·3 days. We thus see that our moon is relatively much more distant from us than any of Jupiter's satellites are from him. There is also another very remarkable point of contrast, for while the mass of the moon is about one ninetieth part of the mass of the earth, the largest satellite of Jupiter (the third) is scarcely a ten-thousandth part of the mass of Jupiter.

Next in distance from the sun comes Saturn. This superb planet, which is second only to Jupiter in size, is in some respects the most remarkable object in the solar system. In addition to a retinue of no less than eight satellites, Saturn is attended by a ring or rather series of rings, which is probably without a parallel in the solar system.

Next after Saturn comes the much fainter object Uranus. This, though visible to the naked eye, was not recognised as a planet before Sir William Herschel's discovery of it in 1781. Sir William Herschel supposed that Uranus possessed six satellites. Subsequent observation indicates the existence of four of these satellites, but that of the remaining two must be regarded as extremely doubtful.

The outermost known planet of our system is called Neptune. This planet is attended by one satellite.

Figure 38 also shows a portion of the parabolic orbit of a comet.

CHAPTER XVIII.

THE FIXED STARS.

§ 94. **Magnitudes of the Stars.**—On a clear night the heaven is seen to be bespangled with a vast multitude of minute points of light. Astronomers are in the habit of calling these objects the *fixed stars*, for the purpose of distinguishing them from the planets. The fixed stars maintain their *relative* positions unchanged from year to year, while the positions of the planets are (as we have seen) incessantly changing. It is, however, to be observed that the planets which can be *easily* seen with the unaided eye are only five in number (viz. Mercury, Venus, Mars, Jupiter, Saturn). Uranus can be seen like a very faint star, and one or two of the remaining planets have occasionally been detected by sharp vision. It is thus evident that out of the multitude of celestial objects visible to the unaided eye every clear night by far the largest part consists of what we call the fixed stars.

The first feature connected with the stars to which we shall direct attention is their very different degrees of brightness. Astronomers have divided the stars into different groups corresponding to their brightness. Thus, about twenty of the brightest stars are said to be of the *first magnitude.* Among these we may mention Sirius (the brightest star in the heavens), Vega, Capella, Aldebaran, Rigel, Arcturus, Spica, and Betelgueze.

Next in order to these come the stars of the second magnitude. Of these we may mention as examples the four brightest stars in the constellation of Ursa Major (the Great Bear).

§ 95. **Numbers of the Stars.** — Argelander has computed the number of stars of each of the different magnitudes with the results here given.

1st	20	4th	425	7th	13,000
2nd	65	5th	1,100	8th	40,000
3rd	190	6th	3,200	9th	142,000

It will thus be noticed that the numbers of the stars of each magnitude increases with very great rapidity as the brightness diminishes. Thus, though there are but twenty stars of the first magnitude, there are 142,000 stars of the ninth magnitude.

Of these stars, however, only a comparatively small number are visible to the unaided eye; even the stars of the 6th magnitude are faint, and it requires very good vision to perceive stars of the 7th magnitude without the assistance of a telescope. The number of stars which can be seen with the unaided eye in England may be estimated as about 3,000.

It is hardly possible to estimate the numbers of stars whose magnitudes are lower than the 9th. This partly arises from their prodigious numbers, and partly from some uncertainty in the estimation of these magnitudes. Argelander has, however, published a series of maps of the stars in the Northern Hemisphere. These maps include all stars from the brightest down to a magnitude intermediate between the 9th and the 10th, and upwards of 300,000 stars are recorded upon these maps. The still smaller stars are as yet uncounted. In fact, every increase in telescopic power serves to render visible countless myriads of stars which an inferior power would not show at all.

§ 96. **The Milky Way.**—The prodigious richness of the heavens in the smaller classes of stars is well illustrated by the nature of the Milky Way. The Milky Way is an irregular band of faint luminosity, which encircles the whole heavens. The telescope shows that this faint luminosity really arises from myriads of minute stars, which, though individually so faint as to be invisible to the naked eye, yet by their countless numbers, produce the appearance with which, doubtless, everyone is familiar.

§ 97. **Clusters of Stars.**—The stars are very irregularly distributed over the surface of the heavens.

This is, indeed, sufficiently obvious to the unaided eye, and it is confirmed by the telescope. In certain places we have a dense aggregation of stars of so marked a character as to make it almost certain that the group must be in some way connected together, and that, consequently, the aggregation is real, and not only apparent, as it might be if the stars were really only accidentally near to the same line of sight, and, consequently, appeared to be densely crowded together, when, in reality, they might be at vast distances apart.

Of such a group we have a very well known example in the group called the Pleiades, which we have already mentioned (§ 8). Most persons can see six stars in the Pleiades without difficulty, but with unusually acute vision more can be detected. With the slightest instrumental aid, however, the number is very greatly increased, and the group is seen to consist of perhaps 100 stars.

Another illustration of such a group is an object in the constellation Cancer known as the Præsepe, or the Beehive. To the unaided eye this is merely a dullish spot on the sky, not well seen unless the night is very clear. A telescope shows, however, that this dullish spot is really an aggregation of perhaps 60 small stars.

By far the most splendid object of this kind in the northern hemisphere is the cluster in the Sword-handle of Perseus. We have here two groups of stars close together, and, when seen in a good telescope, the multitudes of these stars, and their intrinsic brightness, form a most superb spectacle.

§ 98. **Globular Clusters.**—The objects known as *star-clusters* are exceedingly numerous. Among them are several which are remarkable telescopic objects, not for the brightness (even in the telescope) of the individual stars composing the star cluster, but for the vast numbers in which the stars are present, and for the closeness with which they lie together. These objects are often known as *globular clusters*, because the stars forming them seem to lie within a globular portion of space, and they frequently appear to be much more densely compacted together towards the centre of the globe. In fact, at the centre of one of these splendid objects it is in some cases almost impossible to discriminate the individual stars, so closely is their light blended. As Sir John Herschel says, 'It would be a vain task to attempt to count the stars in one of these globular clusters. They are not to be reckoned by hundreds, and on a rough calculation grounded on the apparent intervals between them at the borders and the angular diameter of the whole group, it would appear that many clusters of this description must contain at least five thousand stars compacted and wedged together in a round space whose angular diameter does not exceed eight or ten minutes, that is to say, in an area not more than a tenth part of that covered by the moon.'

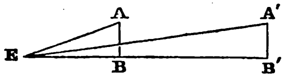
The most remarkable of these objects in the northern hemisphere is the globular cluster in Hercules (Right ascension $16^{h}\ 37^{m}$. Declination $+ 36^{\circ}\ 43$). To the unaided eye or in a small telescope this looks like a dull nebulous spot, and it requires a good telescope to exhibit it adequately.

§ 99. **Telescopic Appearance of a Star.**—The appearance of a star in a telescope differs in a most marked manner from the appearance of one of the larger planets. In the case of the planet we can see what is called the 'disk,' we can actually observe that the planet appears circular and that it is presumably a globe with an appreciable diameter. In most cases too we can discern markings upon the globe of the planet of which drawings may be made. Indeed, as we have already mentioned (§ 52), we can see in the planet Venus changes precisely analogous to the phases of the moon, thus proving, of course, that the planet possesses an appreciable disk. By increasing the magnifying power of the telescope the size of the disk can be increased, though, of course, at the expense of its intrinsic brightness.

Widely different, however, is the telescopic appearance of a fixed star. Even the most powerful telescope only shows a star as a little point of light. By increasing the optical power of the telescope the brilliancy of the radiation from this point can be increased, but no augmentation of the magnifying power has hitherto sufficed to show any appreciable 'disk' in the great majority of the fixed stars which have been examined. How is this to be explained? The answer is to be sought not in the real minuteness of the stars but in the vast distances at which they are situated. In order to form some estimate of the real diameter which the stars do subtend at the eye, let us suppose that our sun were to be moved away from us to a distance comparable with that by which we are separated from those stars which are nearest to us.

For this purpose the sun would have to be transferred to a distance not less than 200,000 times as far as his present distance from the earth. Let A B (fig. 39), denote the diameter of the sun, and let E be the position of the earth.

FIG. 39.



Then as we have already seen (§ 2), the circular measure of the angle which the sun subtends at the earth is practically equal to A B ÷ E B. Now suppose the sun be transferred to the position indicated by A′ B′ then the angle which he would subtend in the new position is A′ B′ ÷ E B′.

Hence the ratio of the angles which the apparent diameter of the sun subtends at the eye at the two different distances is

$$\frac{A\,B}{E\,B} \div \frac{A'\,B'}{E\,B'}$$

but as the *real* diameter of the sun is the same in both cases, we must have

$$A\,B = A'\,B'$$

and hence the ratio just written becomes

$$\frac{E\,B'}{E\,B}$$

Hence we infer that the angle which the sun's diameter subtends at the eye varies inversely as his distance from the observer.

If, therefore, the sun were to be carried away from us to a distance 200,000 times greater than his present distance, the angle which his diameter at present subtends would be diminished to the 200,000th part of what it is at present. Assuming as we may do for rough purposes that the sun's apparent diameter is half a degree, it follows that the apparent diameter when translated to the distance of a star would be expressed in seconds by the fraction

$$\frac{1800}{200000} = 0''\cdot009.$$

In other words, the sun's diameter would then subtend an angle less than the hundredth part of a single second.

It is at present, at all events, quite out of the question to suppose that a quantity so minute as this could be detected even by the best instruments. Even were it ten times as great it would be barely appreciable, nor unless it were at least fifty times as great would it be possible to measure it with any approach to precision.

It is, therefore, clear that we cannot infer from the minute apparent size of the stars in the telescope anything with respect to their actual dimensions.

§ 100. **Variable Stars.**—We have mentioned the mode of classifying stars by their magnitudes; we have now to add that there are some stars to which this method cannot be applied. These are called *variable* stars, inasmuch as their brightness is not constant, as that of the majority of stars appears to be. There are some hundreds of stars in the heavens the brightness of which is now known to change. It would be difficult here to describe in detail the different classes of the variable stars, so we shall merely give a brief account of a few of the most remarkable.

In the constellation Perseus is a bright star Algol (Right ascension $3^h\ 0^m$. Declination $+40^\circ\ 27'$). Owing to the convenient situation of this star it may be seen every night in the northern hemisphere. Algol is usually of the second magnitude, but in a period of between two and three days, or more accurately in a period of $2^d\ 20^h\ 48^m\ 55^s$ it goes through a most remarkable cycle of changes. These changes commence by a gradual diminution of the brightness of the star from the second magnitude down to the fourth in a period of three or four hours. At the fourth magnitude the star remains for twenty minutes, and then begins to increase in brightness again until after another interval of three or four hours it regains the second magnitude. At the second magnitude it continues for a period of about $2^d\ 13^h$, when the same series of changes commences anew.

Another very remarkable star belonging to the class of variables is o Ceti or Mira (Right ascension $2^h\ 13^m$. Declination $-3^\circ\ 34'$). The period of the changes of this star is $331^d\ 8^h$. For about five months of this time the star is quite invisible, it then gradually increases in brightness until it becomes nearly of the second magnitude. After remaining at its greatest brightness for some time it again gradually sinks down to invisibility.

§ 101. **Proper Motion of Stars.**—We have hitherto frequently used the expression 'fixed stars;' we have now to introduce a qualification which must be made as to the use of the word *fixed* with reference to the stars. Compared with the planets, the places of which are continually changing upon the surface of the celestial sphere, the stars may, no doubt, be termed fixed, but when accurate observations of the places of the stars made at widely distant intervals of time are compared together it is found that to some of the stars the adjective *fixed* cannot be literally applied, as it is undoubtedly true that they are moving. It is true that the great majority of what are called fixed stars do not appear to have any discernible motion, and, even those which move most rapidly, when viewed from the vast distances by which they are separated from the earth, appear to traverse but a very minute arc of the heavens in the course of a year. The most rapidly moving star does not move over an arc on the celestial sphere of 10″ per annum. A motion so slow as this is unappreciable without very refined observations. The moon has a diameter which subtends at the eye an angle which we may roughly estimate at half a degree, and to move over a space equal to the diameter of the moon on the surface of the heavens would require a couple of centuries even for the most rapidly moving star.

We have already had occasion to discriminate between real motion and apparent motion (§ 46), and are therefore naturally tempted to inquire whether the motions of the stars which we have been considering are real, or whether they can be explained as merely apparent motions. Now where must we look for the cause of the apparent motion? It is manifest that the annual motion of the earth around the sun could not possibly explain the appearances which have been observed. The annual motion of the earth around the sun would have an effect which must be clearly periodic in its nature. In fact, it would be merely the annual parallax which we have already considered (§ 71). The motions which we have to explain are not (so far as we know at present) of a periodical character; for the stars which possess this motion usually appear to move continually along great circles.

§ 102. **Motion of the Sun through Space.**—It was therefore suggested by Sir W. Herschel that possibly a portion of the proper motions of the stars could be explained by the supposition that the sun, carrying with it its retinue of planets, and all the other bodies forming the solar system, was actually moving in space. On this supposition, it is clear that those stars which were sufficiently near to us must have an apparent proper motion. If the motion of the sun were directed along a straight line towards a certain point of the heavens, then the apparent place of a star at that point would be unaffected by the motion of the sun; but all other stars would spread away from that point just as when you are travelling along a straight road the objects on each side of the road appear to spread away, as it were, from the point towards which your journey was directed.

It was found by Sir W. Herschel that a considerable portion of the observed proper motions of the stars could be explained by the supposition that the sun was moving towards a point in the heavens near to the star λ Herculis. The investigations of other astronomers have tended to confirm this very remarkable deduction as to the sun's motion in space, and have led them to conclude that the sun is moving towards a point of the heavens which (considering the difficulty of the investigation) is exceedingly close to the point determined by Sir W. Herschel. The right ascension of the point thus determined is $17^h\ 8^m$, and its declination is $+ 35°$.

Not only has the direction in which the sun moves been determined, but the same series of observations serve to determine the velocity of the motion. It is found that in one year the sun probably moves through a space equal to 1·623 radii of the orbit of the earth around the sun.

We thus see that the real motion of the earth in space is of a very complicated character; for though it describes an ellipse about the sun in the focus, yet the sun is itself in constant motion, and consequently the real motion of the earth is a composite movement, partly arising from its own proper motion around the sun, and partly arising from the fact that as a member of the solar system, the earth partakes of the motion of the solar system in space.

§ 103. **Real Proper Motion of the Stars.**—It should, however, be observed that after every possible allowance has been made for the effect of the motion of the solar system there remain still outstanding certain portions of the proper motions of the stars, which are only to be explained by the fact that the stars in question really are in actual movement.

Nor, if we reflect for a moment, is there much in the last conclusion to cause surprise? The first law of motion combined with the most elementary notions of probabilities will show us how exceedingly improbable *rest* really is. Among all the possible kinds of motion, infinitely various both in regard to velocity and in regard to direction, there is no one which is not *à priori* just as probable as another; there is no one which is not *à priori* just as probable as *rest.* Hence even if there were no causes tending to produce change from an initial state of things it would be infinitely improbable that any body in the universe was absolutely at rest. But even if a body were originally at rest it could not remain so. Distant as the stars are from the sun, and from each other, they must still, so far as we know at present, act upon each other. It is true that these forces acting across such vast distances may be slender, but great or small they are incompatible with rest, and hence we may be assured that every particle in the universe (with, it is conceivable, one exception) is in motion.

We are thus led to believe that the fact that proper motion has only been detected in comparatively few stars is to be attributed, not to the actual absence of proper motion, but rather to the circumstance that the stars are so exceedingly far off that, viewed from this distance, the motions appear so small that they have not hitherto been detected. It can hardly be doubted that could we compare the places of stars now with the places of the same stars 1,000 years ago most of them would be found to have changed. Unfortunately, however, the birth of accurate astronomical observation is so recent that we have no means of making this comparison, for the ancient observations which have been handed down to us are not sufficiently accurate to afford trustworthy results.

§ 104. **Double Stars.**—We have already alluded to the occasional close proximity in which stars are found on the celestial sphere. In many cases we have the phenomenon which is known as a *double star.* Two stars are frequently found which appear to be so exceedingly close together, that the angular distance by which the stars are separated is less than one second of arc, and an exceedingly good telescope is required to 'divide' such an object, which, when viewed in an inferior instrument, would appear to consist only of a single star. The great majority of double stars known at present are, however, not nearly so close together. About 10,000 objects have now been discovered which are included under the term double stars, though it must be added that the components of many of these are at a considerable distance apart.

We shall here briefly describe a few of the most remarkable of these very interesting objects.

§ 105. **Castor as a Binary Star.**—One of the finest double stars in the heavens is Castor (α Geminorum). (Right ascension 7^h 26^m. Declination $+ 32°$ $17'$.) Viewed by the unaided eye the two stars together resemble but a single star, but in a moderately good telescope it is seen that what appears like one star is really two separate stars. The angular distance at which these two stars are separated is about five seconds. One of the stars is of the third magnitude, and the other is somewhat less. The reason why the unaided eye cannot distinguish the separate components is their great proximity. An angle of five seconds is about the same angle as that which is subtended by the diameter of a penny at a distance of about 1,200 metres, and is therefore quite inappreciable without instrumental aid. The question now arises whether the propinquity of the two stars forming Castor is apparent or real. This propinquity might be explained by the supposition that the two stars were really close together compared with the distance by which they are separated from us. Or, it could equally be explained by supposing that the two stars, though really far apart, yet appeared so nearly in the same line of vision that, when projected on the surface of the heavens, they seemed to be close together. It cannot be doubted that in the case of many of the double stars, especially those in which the components appear tolerably distant, the propinquity is only apparent and arises from the two stars being near the same line of vision. But it is also undoubtedly true that, in the case of very many of the double stars, especially among those belonging to the class which includes Castor, the two stars are really at about the same distance from us, and therefore, as compared with that distance, they are really close together.

Many double stars of this description exhibit a phenomenon of the greatest possible interest. If we imagine a great circle to be drawn from one of the two component stars to the north pole of the celestial sphere, then the angle between this great circle and the great circle which joins the two stars is termed the *position angle* of the double star. By an ingenious instrument called a *micrometer*, which is attached to the eye-end of a telescope mounted equatorially, it is possible to measure both the position angle of the two components of a double star, and also the *distance* of the two stars expressed in seconds of arc. When observations made in this way are compared with similar observations of the same double star, made after an interval of some years, it is found in many cases that there is a decided change both in the distance and in the angle of position. In the case of the double star Castor, at present under consideration, it is true that the movement is very slow. It is, however, undoubted that in the course of some centuries [1] one of the components will revolve completely around the other.

§ 106. **Motion of a Binary Star.**—The theory of gravitation affords us the explanation of these changes. We have seen how in the case of the sun and the planets each planet describes around the sun an orbit of which the figure is an ellipse, with the sun in one focus, while the law according to which the velocity changes is defined by the fact that equal areas must be swept out in equal times. The circumstances presented by the sun and a planet (the earth, for example) are somewhat peculiar, and Kepler's laws must be stated somewhat differently before they can be applied with strict generality to the motion of a *binary star* (as one of the moving double stars is termed). In the case of the sun and the earth we have a comparatively minute body moving around a very large body. In fact, as the mass of the sun is more than

[1] The periods assigned for the time of revolution of Castor vary from 232 years (Mädler) to 996 years (Thiele).

300,000 times greater than the mass of the earth, we may neglect the mass of the earth in comparison with the mass of the sun. Thus, in speaking of Kepler's laws as applied to the motion of a planet around the sun, we often regard the centre of the sun as a fixed point, and attribute all the motion which is observed to the planet.

It is manifest, however, that some modification of Kepler's laws is necessary before we can apply them to the case of most of the binary stars. In the case of Castor, though the two components are not exactly equal, yet they are so nearly so that it would obviously be absurd to regard even the larger of them as a fixed point while the whole orbital motion was performed round it by the other. The fact of the matter is, that *both the components* are in motion, each under the influence of the attraction of the other, and that what we actually observe and measure is only the relative motion of the components.

It would lead us beyond the limits of this book to endeavour to prove the more generalised conception of Kepler's laws which we shall now enunciate. Let us suppose the case of a binary star so far removed from the influence of other stars or celestial bodies that their attraction may be regarded as insensible. Then each of the two components of the binary star is acted upon by the attraction of the other component, but by no other force. We suppose a straight line A B to be drawn connecting the centres of the stars, and we divide this line into two parts, A G and B G, in the proportions of the masses of the two stars, so that the point of division G lies between the two stars and nearer to that star, A, which has the greater mass. The point G thus determined is the *centre of inertia* of the two stars. Now, it can be proved that however the stars A and B may move in consequence of their mutual attractions, the point G will either remain at rest or will move uniformly in a straight line. It can be shown that each of the stars A and B will move in an elliptic orbit around the point G as the focus, and that each star will describe equal areas in equal times.

It can also be shown that, although both of the stars are in motion, yet the relative motion of one star about the other, *i.e.*, the motion of the star B about the star A as it would be seen by an observer who was stationed on A, is precisely the same as if the mass of the star A were augmented by the mass of the star B, and as if A were then at rest and B moved round it just as a planet does around the sun. To this apparent motion of B around A, Kepler's laws will strictly apply. The orbit of B is an ellipse of which A is one of the foci, and the radius vector drawn from A to B will sweep out equal areas in equal times.

It is natural to inquire whether these theoretical anticipations with respect to the motions of the binary stars are borne out by observation. We have no reason to expect that we shall actually see motions of the simple character which we have described. It is to be recollected that the plane in which the orbit is described may be inclined *in any way* to the surface of the celestial sphere. Consequently the orbit which we shall see will only be the projection of the real orbit upon a plane which is perpendicular to the line joining the binary star to the eye. We have therefore to consider what modifications the orbit may undergo by projection. It can be shown that if the original orbit be elliptic, the projected orbit will be elliptic also; but it also appears that though the star A was the focus of the original orbit, it would not be the focus of the projected orbit. The law of the description of equal areas in equal times would hold equally true both in the original orbit and in the projected orbit.

By a comparison of observations made at different times it is possible to plot down the actual position of the star B with respect to the star A, at the corresponding dates. It is found that in the case of several binary stars the orbit thus formed is elliptic, and it is possible, by a consideration of the position of the point A in this ellipse, to determine the position of the true orbit with reference to the celestial sphere and the various circumstances connected with the motion.

In this way the true orbits of several of the most remarkable among the binary stars have been determined. Of these stars the most rapid in its movements appears to be 42 Comæ Berenices, which accomplishes its revolution in a period of 25·7 years. The two components of this star are exceedingly close together, the greatest distance being about one second of arc. There is very great difficulty in making accurate measurements of a double star so close as this one. Consequently more reliance may be placed upon the determination of the orbits of other binary stars, the components of which are farther apart than those of

42 Comæ Berenices. Among these we may mention a very remarkable binary star ξ Ursæ Majoris. The distance of the two components of this star varies from one second of arc to three seconds. The first recorded observation of the distance and position angle of this star was by Sir W. Herschel in 1781, and since that date it has been repeatedly observed. From a comparison of all the measurements which have been made it appears that the periodic time of the revolution of one component of ξ Ursæ about the other is 60 years, and it is exceedingly improbable that this could be erroneous to the extent of a single year. Thus this star has been observed through more than one entire revolution.

§ 107. **Dimensions of the Orbit of a Binary Star.**—In the determination of the size of a binary star all we can generally ascertain is, of course, the diameter of the orbit as measured in seconds of arc. Actually to determine the number of kilometres in the diameter of the orbit, it would be further necessary for us to know the distance at which the binary star is from the earth. This distance is, in the great majority of cases, entirely unknown to us at present. There are, however, one or two exceptions. Of these we shall mention 61 Cygni.

The angular distance[1] at which these stars are separated is about 15·5 seconds of arc. As this distance has changed but very little since the star was first examined in 1781, and as the position angle has changed by 50° or more, it would seem that the

[1] Sir John Herschel, *Outlines of Astronomy.*

orbit of one component of 61 Cygni about the other is circular, and that the plane of the orbit is very nearly perpendicular to the line joining the eye to the star. Now, the annual parallax of this star has been ascertained to be $0''\cdot348$, that is to say, the radius of the earth's orbit, viewed from the distance of 61 Cygni, subtends an angle of $0''\cdot348$. It therefore follows that the real distance between the two components of 61 Cygni must exceed the distance of the earth from the sun in the same proportion as $15''\cdot5$ exceed $0''\cdot348$. It follows that the distance of the components of 61 Cygni must be 44·54 times greater than the distance of the earth from the sun. Thus the orbit, which one of the components of 61 Cygni describes about the other, is larger than the orbit which is described around the sun by the outermost planet of the solar system.

§ 108. **Determination of the Mass of a Binary Star.**—When we know the diameter of the orbit of a binary star and its periodic time we are able to compute the sum of the masses of the two component stars. This is an exceedingly interesting subject, inasmuch as it affords us a method of comparing the importance of the stars, as far as mass is concerned, with the importance of our sun.

Let us first consider what the periodic time of a planet would be if it revolved round the sun in an orbit of which the radius were 44·54 times that of the earth's orbit. According to Kepler's third law, the square of the periodic time is proportional to the cube of the distance; consequently, since the earth revolves around the sun in one year, it follows that a planet such as we have supposed would revolve around the sun in a period of time which was equal to the square root of the cube of 44·54 i.e. to 297 years very nearly.

According to the latest results it would appear that the periodic time of the revolution of one of the components of 61 Cygni about the other is 452 years, i.e. the velocity with which the motion takes place is less than it would be if the mass of 61 Cygni equalled the mass of the sun.

We shall now show how the ratio of the mass of the sun (augmented, it should in strictness be said, by the mass of the earth) to the two components of 61 Cygni, taken together, can be ascertained. For this we require the following principle, which for the present we shall take for granted.

If two bodies, A and B, are revolving in consequence of their mutual attractions, then the sum of the masses is inversely proportional to the square of the periodic time, supposing the mean distance of A and B to remain unaltered:

It therefore appears that the following proportion is true:

$$\frac{\textit{Mass of Sun and Earth}}{\textit{Mass of } 61 \textit{ Cygni}} = \left(\frac{452}{297}\right)^2.$$

It follows from this that if we regard the mass of our sun as 1, the mass of 61 Cygni is 0·432.

Now, though it is true that subsequent observations may necessitate corrections in these results, yet we may be pretty confident that the two components of 61 Cygni have a mass which is at all events comparable with the mass of our sun. The most uncertain part of the data is the annual parallax of 61 Cygni.

§ 109. **Colours of Double Stars.**—One of the most pleasing and remarkable phenomena presented by double stars are the beautiful colours which they often present. The effect is occasionally heightened by the circumstance that the colours of the two components are frequently not only different but are contrasted in a marked manner. Conspicuous among these objects is a very beautiful double star γ Andromedæ. The two components of this star are orange and greenish blue. Attentive examination with a powerful telescope shows also that the greenish blue component consists of two exceedingly small stars close together. While considering this subject it should be remarked that isolated stars of a more or less reddish hue are tolerably common in the heavens, the catalogues containing some four or five hundred stars of this character. Among those visible to the naked eye perhaps the most conspicuous is the bright star α Orionis. Stars of a greenish or bluish hue are much less common, and it is very remarkable that, with very few exceptions, a star of this colour is not found isolated, but always occurs as one of the two components of a 'double star.'

CHAPTER XIX.

NEBULÆ.

§ 110. **Nebulæ.**—There are a great number and variety of objects in the heavens which are known under the general term of 'Nebulæ.' The great majority of these objects are invisible to the naked eye, but with the aid of powerful telescopes some thousands of such objects have been already discovered. Of these objects, which for convenience are grouped together, many are undoubtedly mere clusters of stars such as those of which we have already given some account. It is, nevertheless, tolerably certain that many of the objects termed nebulæ are not to be considered as mere clusters of stars, though their real nature has, as yet, been only partially determined.

§ 111. **Classification of Nebulæ.**—The following analysis[1] of the different objects, which are generally classed under the name of nebulæ, has been made by Sir William Herschel, to whom the discovery of a vast number of nebulæ is due :—

1. Clusters of stars, in which the stars are clearly distinguishable ; these are again divided into globular and irregular clusters.
2. Resolvable nebulæ, or such as excite a suspicion that they consist of stars, and which any increase of the optical power of the telescope may be expected to resolve into distinct stars.
3. Nebulæ, properly so called, in which there is no appearance whatever of stars, which again have been subdivided into subordinate ones, according to their brightness and size.
4. Planetary nebulæ.
5. Stellar nebulæ.
6. Nebulous stars.

[1] Sir John Herschel's *Outlines of Astronomy.*

The first of these classes is that which we have already described (§§ 97, 98); the resolvable nebulæ, which form the second class, are to be regarded as clusters of stars, which are either too remote from us, or the individual stars of which are too faint to enable them to be distinguished. Among the most remarkable objects at present under consideration are the oval nebulæ. They are of all degrees of eccentricity, some being nearly circular, while others are so elongated as to form what have been called 'rays.' The finest object of this class is the well-known nebula in the girdle of Andromeda. This object is just visible to the naked eye as a dullish spot on the heavens. Viewed in a powerful telescope it is seen to be a nebula about $2\frac{1}{2}°$ in length, and $1°$ in breadth. It thus occupies a region on the heavens five times as long and twice as broad as the diameter of the full moon. The marginal portions are faint, but the brightness gradually increases towards the centre, which consists of a bright nucleus. This nebula has never actually been resolved, though it is seen to contain such a multitude of minute stars that there can be little doubt that with suitable instrumental power, it would be completely resolved.

Among the rarest, and indeed the most remarkable, nebulæ are those which are known under the name of the 'Annular Nebulæ.' The most conspicuous of these is to be found in the constellation Lyra; it consists of a luminous ring; but (as Sir John Herschel remarks) the central vacuity is not quite dark, but is filled in with faint nebulæ, 'like a gauze stretched over a hoop.'

Planetary Nebulæ are very curious objects ; they derive their name from the fact that, viewed in a good telescope they appear to have a sharply defined more or less circular disc, immediately suggesting the appearance presented by a planet. These objects are generally of a bluish or greenish hue. Their apparent diameter is small ; the largest of them is situated in Ursa Major, and the area it occupies on the heavens is less than one hundredth part of the area occupied by the full moon. Still the intrinsic dimensions of the object must be great indeed. If it were situated at a distance from us not greater than that of 61 Cygni, the diameter of the globe which it occupies would be seven times greater than the diameter of the orbit of the outermost planet of our system.

Among the class of Stellar Nebulæ one of the most superb objects visible in the heavens must be included. The object to which we refer is the great nebula in the Sword-handle of the constellation of Orion. The star θ Orionis consists of four pretty bright stars close together, while in a good telescope at least two others are visible, the whole presenting the almost unique spectacle of a sextuple star. But around this star, and extending to vast distances on all sides of it is the great nebula in Orion. The most remarkable feature of this nebula is the complexity of detail which it exhibits. The light is of a slightly bluish hue, and under the great power of Lord Rosse's telescope portions of it are seen to be undoubtedly composed of stars. Perhaps it would be more correct to say that portions of it *contain* stars ; for, as we shall presently show, there is good reason to believe that in this nebula, as well as in some others, a part of the light which we receive is due to glowing gas.

The last of the different kinds of nebulæ to which we shall allude is the class of objects known as nebulous stars. By a 'nebulous star' we are to understand a star surrounded by a luminous haze, which is, however, generally so faint as only to be visible in powerful instruments.

CHAPTER XX.

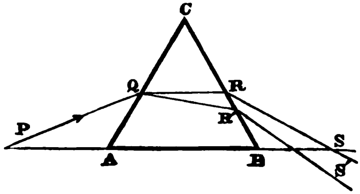
SPECTRUM ANALYSIS.

§ 112. **Composition of Light.**—We shall now give some account of a very remarkable method which has recently been applied with great success to the examination of the heavenly bodies. This method is termed *spectrum analysis.* The peculiar feature of spectrum analysis is, that with the assistance of a telescope it actually gives us information as to the nature of the elementary substances which are present in some of the celestial bodies. To explain how this is accomplished it will be necessary for us to describe briefly some properties of light.

A ray of ordinary sunlight consists in reality of a number of rays of different colours blended together. The 'white' colour of ordinary sunlight is due to the joint effect of the several different rays. We have, however, the means of separating the constituent rays of a beam of light and examining them individually. This is due to the circumstance that the amount of bending which a ray of light undergoes when it passes through a prism varies with the colour of the light.

§ 113. **Construction of the Spectroscope.**—Suppose A B C, fig. 40, to represent a prism of flint glass. If a ray of ordinary white light travelling along the direction P Q falls upon the prism at Q, it is bent by refraction so that the direction in which it traverses the prism is different from the direction in which it was moving when it first encountered the prism. The

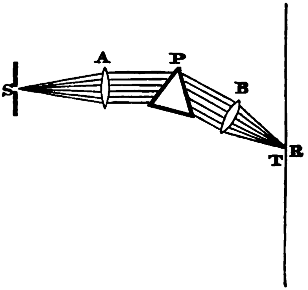
FIG. 40.



amount of the bending is, however, dependent upon the colour of the light. In a beam of white light we have blended together the seven well-known prismatic colours, viz., red, orange, yellow, green, blue, indigo, violet. We shall trace the course of the first of these and the last. The red light is the least bent; it travels along (let us suppose) the direction Q R until it meets the second surface of the prism at R; it is then again bent at emergence, and finally travels along the direction R S. On the other hand, the violet portion of the incident beam, which originally travelled along the direction P Q, is more bent at each refraction than the red rays. Consequently after the first refraction it assumes the direction Q R′, and after the second refraction, the direction R′ S′. The intermediate rays of orange, yellow, green, blue, and indigo, after passing the prism, are found to be more refracted than the red rays, and less refracted than the violet rays; they are, therefore, found in the interval between the lines R S and R′ S′.

We have therefore, in the prism, a means of decomposing a ray of light and examining the different constituents of which it is made. We shall now show how this is practically applied in the instrument known as the *spectroscope*. The principle of this instrument may be explained by reference to fig. 41. At S is a narrow slit, which is supposed to be perpendicular to the plane of the paper. Through this slit a thin line of light passes, and it is this thin line of light which is to be examined in the spectroscope. After passing through S, the light diverges until it falls upon an achromatic lens placed at A. This lens is to be so placed that the distance A S is equal to the focal length of the lens; it therefore follows that the beam diverging from S, will, after refraction through the lens A, emerge as a beam of which all the constituent rays are parallel.

FIG. 41.



Let us now for a moment fix our attention upon the rays of some particular colour. Suppose, for example, the *red rays*. The parallel beam of red rays will fall upon the prism P. Now, since each of these rays has the same colour, it will, on passing through the prism, be deflected through the same angle, and therefore, the beam which consisted of parallel rays before incidence upon the prism will consist of parallel rays after refraction through the prism, the only difference being that the entire system of parallel rays will be bent from the direction which they had before. In this condition the rays will fall upon the achromatic lens B, which will bring them to a focus at a point R, where we shall suppose a suitable screen to be placed. Thus the red rays which pass through the slit at S will form a red image of the slit upon the screen at R.

But what will be the case with the violet constituents of the light which passes through S? The violet rays will fall upon the lens A, and will emerge as a parallel beam (for we have supposed the lenses A and B to be both achromatic), the parallel violet beam will then fall upon P, and it will emerge from P also as a beam of parallel rays. It will, however, be *more deflected* than the beam of red rays, but still not so much so as to prevent it falling upon the lens B, which will make it converge so as to form an image at T near to the red image at R, but somewhat below it.

Now let us suppose the slit at S to be exceedingly narrow, and let us suppose that the beam of light which originally passed through S contained rays of *every degree* of refrangibility from the extreme red to the extreme violet. We should then have on the screen an indefinitely great number of images of the slit in different hues, and these images would be so exceedingly close together that the appearance presented would be a band of light equal in width to the length of the image of the slit, and extending from R to T. This band, the colour of which gradually changes from red at R to violet at T, is known as the *prismatic spectrum.* Instead of the screen the eye itself may be employed to receive the light which emerges from the lens B, so that the spectrum is impressed upon the retina. For the more delicate purposes of spectrum analysis this plan is always adopted.

Suppose, now, that the light which was being examined consisted only of rays of certain special refrangibilities, the spectrum which would be produced would then only show images of the slit corresponding to the particular rays which were present in the beam. Consequently, the spectrum would be 'interrupted,' and the character of the spectrum would reveal the nature of the light of which the beam was composed.

This may be made to give us most valuable information with reference to the nature of the source from which the light emanates. We do not here attempt to enter into the matter further than is necessary to show how the method can be applied astronomically. When the light from some of the nebulæ (especially those of a bluish hue) was examined in the spectroscope it was found by Huggins that by far the greater portion of the light is concentrated into two or three bright lines. This proves that a great portion of the light from nebulæ of this particular character consists of rays possessing the special refrangibilities corresponding to the observed rays.

We have thus an accurate means of comparing the light which comes from the nebulæ with the light from other sources. If a glass tube contain a small quantity of gas, and if a galvanic current be passed through the tube (we do not here attempt to enter into details) the gas inside the tube may be raised to a temperature so exceedingly high that it will become luminous, and the light which emanates from it can be examined by means of the spectroscope. It is found that each different kind of gas yields light which in the spectrum forms lines of so marked a character as to make the spectrum characteristic ot the gas. It has thus been discovered by Huggins that the light from several of the nebulæ brings evidence that in some of these distant objects substances are present with which we are familiar on the earth. He has thus found that there is excellent reason to believe that several of the nebulæ are at least partially composed of glowing gaseous material, and that among their constituents are to be found hydrogen and nitrogen, which are both elements of much importance on the earth.

Spectrum analysis has also been applied with success to the examination of the light from the sun as well as from the fixed stars. To consider this application it would, however, be necessary for us to enter more extensively into the subject than our space admits. Suffice it to say, that it has been ascertained, by the aid of spectrum analysis, that the majority of the fixed stars are probably bodies of the same general character as our sun, but with individual peculiarities, and that in the sun and in several of the stars we have been able to ascertain the existence of several elementary substances which are present on the earth.

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