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593RD ORDINARY GENERAL MEETING,

HELD IN THE CONFERENCE HALL, THE CENTRAL HALL, WESTMINSTER, ON MONDAY, JUNE 18TH, 1917,

AT 4.30 P.M.

THE RIGHT HON. THE EARL OF HALSBURY, F.R.S., PRESIDENT OF THE INSTITUTE, TOOK THE CHAIR.

The Minutes of the preceding Meeting were read and confirmed.

The SECRETARY announced the election of Mr. J. Gilbert Dale, F.R.G.S., as a Member of the Institute.

The PRESIDENT introduced Sir FRANK W. DYSON, the Astronomer Royal, and asked him to deliver the Annual Address.

ANNUAL ADDRESS.

THE DISTANCES OF THE STARS. By Sir FRANK W. DYSON, M.A., F.R.S., Astronomer Royal.

THE American astronomer, Simon Newcomb, places at the head of a chapter of his book on the stars a quotation from Kant: "Two things ever fill my mind with new and increasing admiration and awe, the oftener and longer I reflect on them—the star-strewn sky above me and the moral law within me." A parallel passage might be taken from the Psalmist, "The heavens declare the glory of God," and later in the same psalm, "The law of the Lord is perfect, converting the soul." A being who could look at the stars without awe and wonder would surely be of extraordinarily limited intelligence. But he who watches them in their courses from night to night cannot fail to be struck by a sense of the mystery which surrounds them. This is increased with the increase of our knowledge, and therefore I think it fitting for me to take as the subject for my address to-night "The Distances of the Stars," for the distance is one of the most important facts we can discover about a star, and is the key to the discovery of several others.

Now the stars are bodies like the sun; the sun is, in fact, the star about which we know most. We know how large it is, that it has a diameter of 865,000 miles—we know how dense it is, that its density is, in the mean, something like that of water—we know how hot it is, say 7000° C. near the surface and increasing greatly as we penetrate inwards—we know that it consists, at any rate near the surface, of many chemical elements with which we are familiar on the earth, all in a gaseous condition owing to the high temperature—we know that it rotates on its axis in twenty-five days, that a number of planets, including the earth, revolve around it, and that it is moving through space at the rate of twelve miles a second.

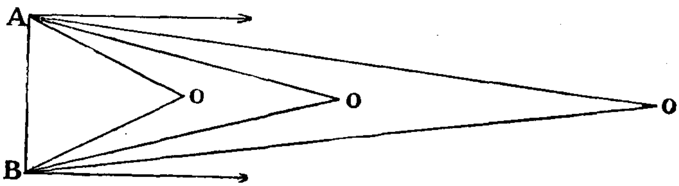
Now when we look at the stars they are simply points of light in the sky: we have no notion whatever of their distances. They are all so small that they have no perceptible disc, such as the sun has. When we look at them with a telescope, however large, they still remain the merest points. If you will admit that they are bodies like the sun and comparable with it in size, you will see that they must be at a very much greater distance. I suppose that our largest telescopes would show the sun with a disc of sensible size if it were twenty or thirty thousand times as far away. But it is begging the question to begin by assuming that the stars are like the sun, and we will show how their distances are found with no assumptions except those of elementary geometry.

I dare say you are familiar with the method used by surveyors in finding the distances of inaccessible objects. They take two points, A and B, and measure carefully the distance from A to B, and then measure, by an instrument called a theodolite, the two angles, O A B and O B A. When this is done it is easy to calculate the distances O A and O B by a branch of elementary mathematics called trigonometry. There is nothing at all mysterious or difficult about it; suppose that A B is 1 mile, and on a sheet of paper we put down $a\ b = 1$ inch and draw the angles at a and b equal to those at A and B, then $o\ a$, $o\ b$ will give us the distances we require in the scale of an inch to a mile.

This same method can be easily applied to determine the distance of the moon. If the moon is observed simultaneously from two places on the earth, let us say the observatories at Greenwich and the Cape, one angle corresponding to that at A is measured at Greenwich, another corresponding to B is measured at the Cape, and the distance A B represents the length of the straight line joining Greenwich to the Cape. In practice, if one wishes to obtain an accurate result there are a number of minutiæ to be attended to, but the general principle is simplicity itself.

If we try to measure the distance of the sun in this way, we can do it, but not very accurately, for the distance of the sun is so great compared to the distance between Greenwich and the Cape that the unavoidable errors in measuring our angles would seriously vitiate the results; we might get a result within perhaps 5 per cent. of the truth.

But if we tried to measure the distance of a star in this way we should come to grief entirely, for the unavoidable errors in measuring the angles would be a million times as great as the small angle A O B on which the distance essentially depends. The fact is that the base-line between Greenwich and the Cape is so short compared with the distance of the star that the star appears to be in the same direction as seen from both places.



Thus we cannot measure the distance of a star by using two places on the earth as the ends of a base line, the earth is so incomparably small compared with the distance we wish to determine.

The problem of measuring the distances of the stars took on a new aspect when it was shown that the earth moved round the sun. Copernicus, in his book, *De Revolutionibus*, published in 1543, showed that the movements of the planets in the sky and the annual recurrence of the seasons were more simply explained if it were admitted that the earth travelled round the sun each year. It was of course a great effort of imagination to conceive of the earth moving in this way, and his views were not readily admitted. They were, however, reinforced very powerfully by Galileo after the discovery of the telescope; among other things he actually saw Jupiter's moons revolving around Jupiter. He removed many of the difficulties in the way of accepting the Copernican system, and in 1632 established the fact that the earth moved round the sun. There was, however, one real difficulty which he did not remove, and that was one connected with the distances of the stars. His opponents said: If the earth moves round the sun, then at opposite times of the year, say in January and July, it will be in such widely different positions that the stars ought to have quite different aspects. You can illustrate this for yourselves very easily from any point where you have a view of objects at different distances. If you change your position by a few yards the nearer objects are seen projected differently against the more distant landscape. In the slide on the screen, for example, there are shown two rough views of Edinburgh from different parts of the grounds of the observatory, which is, say, about two miles away. For example, in the picture on top the chimney in front is shown to the right of the spire of St. Giles' Cathedral and in the picture below it appears to the left. Again the Grange Church spire appears to the right of the Castle in one picture, and to the left in the other. Surely, said the opponents of the Copernican system, we ought to see similar effects among the stars: the stars nearest to us ought to shift their positions relatively to more distant ones. This was perfectly sound argument: it admitted of only one reply, namely, that the stars are at such great distances that these changes of position are too small to be perceived by us. We have all grown up with the idea of the great distances of the stars, and perhaps do not fully perceive how great this difficulty was to the astronomers of the 17th century. They were convinced that Galileo and Copernicus were right, but for two centuries they looked in vain before they found the changes for which they were in search. This is not surprising, for the nearest star, we know now, is more than 250,000 times as far away as the sun. Suppose ourselves at King's Cross Station, and let us represent the distance from the earth to the sun by half of the distance between the railway lines. That is, supposing we are looking northwards, in January we look along the line nearer to the platform and in July along the line further from the platform. If instead of being parallel the lines met somewhere between Grantham and Doncaster, we should have drawn to scale the lines from the earth to the nearest star as seen by us from two opposite sides of the sun. Perhaps it is not surprising that it took astronomers and instrument makers two centuries before they could measure angles with sufficient accuracy.

Another way of looking at the matter may show you what a difficult task was in front of astronomers. The diameter of the sun is 30′. The nearest star to us is at such a great distance that the change of its position amounts to only $\frac{1}{1200}$ part of this. Before any attempt could be successful, it was necessary that astronomical instruments should be improved to such an extent that this small angle could be appreciated and measured.

Before the invention of the telescope, such a thing was quite impossible. The greatest of astronomical observers before its invention, Tycho Brahe, could measure angles of about 1′. Of course, he did not know how very distant the stars were. He tried, but could find no trace of movement, and even concluded that the earth did not go round the sun. But the telescope has increased our faculty of vision in at least three ways. It not only enables us to see fainter objects, but it also magnifies the small angles we have to measure, and thus makes it possible to measure with far greater accuracy. Further, it made possible a method of sighting vastly superior to anything that had been available before its invention. And so after the time of Galileo, when astronomers were convinced that the earth did travel round the sun, they tried with more and more persistence to discover the movement in the stars which would be a consequence of such a movement. Hooke, a contemporary of Newton and Wren, fixed a long telescope, 36 feet long, in a vertical position and examined a star called γ Draconis, which passes near the zenith in the latitude of London. The idea was excellent, because it got rid of the troublesome, and at that time uncertain, effect of the refraction of light by our atmosphere. But Hooke did not succeed.

A great Danish astronomer, Römer of Copenhagen, made an attempt to find the distances of the two night stars, Sirius and Vega. He found a change in the relative positions of these stars in the spring and the autumn amounting to 1′ of arc. He was delighted with his success and published it in a dissertation called "Copernicus Triumphans." But he was wrong, and probably the error arose from small irregularities of his clock, which was not compensated for changes of temperature. Consequently he made errors in his determination of the times at which Sirius and Vega were observed to be due south.

The next attempt to which I will refer was made by Bradley at Wanstead about 1750. He fixed his telescope in a vertical position as Hooke had done, and observed γ Draconis at the times when it passed the meridian. By means of a plumb line he determined the vertical, and with his long telescope measured how far γ Draconis was south of the zenith. The instrument he used, called a zenith section, is still preserved at Greenwich. He watched γ Draconis from day to day for a year, and found a real movement. But it was in the opposite direction to what he anticipated. However, he succeeded in explaining the movement. It was due to the fact that though light travels very fast, it is only 10,000 times as fast as the earth's velocity round the sun. As a consequence of this the light of a star does not seem to come to us always from exactly the same direction. This is easily illustrated by the familiar example of how an umbrella is held in a shower of rain. Suppose the rain to be coming straight down but if you are walking north you point your umbrella a little to the north, if east a little to the east, because your movement in combination with that of the raindrops makes them appear to come in a direction slightly diverted from their true one. Thus a star is not seen in its true direction, but in one slightly diverted towards that in which the earth is moving. This was not the discovery for which Bradley was working, but it gave a method of measuring the velocity of light, and more than that, it vindicated the Copernican theory in another manner, for it showed that the earth was moving round the sun.

Another great astronomer, William Herschel, made a systematic search for the evidence of the nearness of some of the stars. With his great telescope he searched for stars which seemed to be near together; he then used the following argument: here are two stars which appear to be close together, but one may be much further away than the other; it is in fact very likely that the brighter star will be nearer to us than the fainter star. If I have both these stars in my telescope at the same time, and measure the angular distance between them, I may hope to find that the nearer star changes its distance slightly from the further star, due to the fact that the movement of the earth round the sun sometimes brings the near star more into line with the further star than at others. And with my big telescope the matter would not be desperate, even if the nearer star were as much as 200,000 times the distance of the sun from us. The argument was perfectly sound, but he did not find any stars so near. He was rewarded by finding in the sky double stars, which circulated round one another. For example, Castor consists of two close stars which revolve round one another, though it takes hundreds of years for them to complete a revolution. Many other attempts were made by astronomers, and, curiously enough, success was achieved almost simultaneously about the year 1833 by Henderson at the Cape Observatory, Struve at the National Observatory of Russia at Pulkowa, and Bessel at the Observatory at Königsberg. Henderson found the distance of the star *a* Centauri, one of the brightest stars in the southern constellations. This star is 250,000 times as far away as the sun. Struve found the distance of the bright star Vega. This star is about 600,000 times as far as the sun.

Bessel found the distance of 61 Cygni, a star which is not very bright, but which was known to be moving rapidly across the sky, and therefore presumably near. In many ways the most interesting of these observations was that made by Bessel, because he devised a specially delicate instrument, which was very suitable for these refined measurements. This instrument, called a heliometer, was used with marked success by other astronomers, and notably by Sir David Gill, a former Hon. Correspondent of the Victoria Institute. It would be out of place for me to enter into the numerous precautions which have to be taken if reliable results are to be obtained. Industry and skill and a real genius for avoiding the many errors which instruments are heir to, must be combined in the person of one astronomer. Perhaps I may tell you a story about Sir David Gill. He had been lecturing on this subject, and in order to explain the small angles we had to measure, compared them to the angle which a threepenny bit would subtend at the distance of a mile. A brother Scot, in proposing a vote of thanks to the lecturer, said there could be no doubt of his nationality, for no one but a Scotsman would take any notice of a threepenny bit a mile distant.

A great simplification in measuring the distances of stars was brought about by the introduction of photography to astronomical observations, but it must not be supposed that the task is easy: great care is necessary to avoid small errors which would vitiate the results. Nevertheless, there are at the present time seven or eight observatories with large photographic telescopes where this work is successfully carried on. It is quite possible with a dozen good photographs taken at suitable times to measure the distance of a star if it is nearer to us than 5 million times the sun's distance—that is to say, between 400 and 500 million million miles away from us.

I have gone into this at length because it seems to me important to give an idea of the methods employed, as well as of the results obtained. The principle underlying the method is simplicity itself, but the successful application of the principle has been beset by many difficulties. The measurement of these small angles has been made possible by the genius of the engineers who have designed and executed the delicate movements of the telescopes, the opticians who have made the large and perfect lenses, and the chemists who have shown us how to obtain by photography a permanent impression of the light sent us by the stars. In these different ways our human faculties have been so greatly extended that we are able to measure these great distances in the same way as an artillery officer in France can locate and range an enemy position.

It is, however, only a few of the nearer stars whose distances have been measured by astronomers: the number does not amount to more than a few hundreds. No doubt there are still many stars—say one or two thousand—within measurable distance of us, that is to say, within 500 million million miles, whose distances will probably be, but have not yet been determined. But these are only a few of the myriads of the stars we see with our telescopes. Other methods are being employed, and very successfully, for determining their distances. I shall not speak about these, but will rather tell you something more about the stars which are nearest to us. I will confine myself to the stars which are not further than a million times the distance of the sun from us—that is, roughly, stars within 100 million million miles of us. There are about twenty stars known to be within this limit of distance, and if we consider only those stars which are not less than 100 times as faint as can be seen with the naked eye, it is probable that there are still ten or fifteen more to be discovered. Let us consider, then, a huge sphere whose radius is one million times the distance from us to the sun. Suppose we make a model of this sphere and let us take a globe the size of the earth for our model. On this scale a star of the same diameter as the sun would be as big as a tennis ball. Imagine, then, from 30 to 40 tennis balls equally scattered inside the earth; this gives a picture of how near the stars are to one another. This gives us a good idea of the great distances between the stars.

These stars which are nearest to the earth differ a great deal in their magnitudes or brightness as seen by us. Thus Sirius, the brightest star in the sky, is one of them, and the very bright star Procyon is another, and α Centauri, the nearest of all the stars to us, is one of the brightest in the southern constellations. Others are fairly bright stars visible to the naked eye, but, on the other hand, a large proportion are faint and only visible with telescopic aid. From some of these stars we receive only $\frac{1}{100}$ of the light which Sirius gives us, and from some less than $\frac{1}{10000}$. These great differences are partly caused by difference of distances, but to a greater extent by intrinsic differences in the amount of light given out by the stars.

When the distances of stars are known we are able to tell how far the difference in their apparent magnitude is due to differences of distance and how far to real differences in intrinsic brightness.

The principle is very simple. If a body is moved to twice the distance, we receive a quarter as much light from it. If one candle at a distance of one foot gives one just sufficient light to read by, then a 100 candle-power lamp at a distance of 10 feet will be needed—and a 10,000 candle-power lamp at a distance of 100 feet would be equally serviceable. If the distance of a star is known, and the amount of light it gives us is also known, an easy calculation tells how much light it would give if it were no further away than the sun. We call this the luminosity of the star, and just as a candle is taken as a standard for comparing terrestrial lights, so the sun is taken as a standard of luminosity, and a luminosity of 5, say, means that a star gives out 5 times as much light as the sun.

Calculation shows us that Sirius is 48 times as luminous as the sun, Procyon about 10 times, and α Centauri about twice as luminous. Some of the stars are relatively very faint and give out only $\frac{1}{100}$ or less of the light emitted by the sun.

There is one very interesting feature apparent among the nearer stars, that the blue stars in our list are more luminous than the red ones. If the stars—I mean those twenty near ones and not all the stars in the sky—are arranged according to colour, the luminosity progressively diminishes as we go from blue to red.

Now the colour of a star is a very important feature. Most stars are so faint that we can hardly detect their colour. But if we look at the brighter stars we see that Sirius is blue, Arcturus yellow, Aldebaran red. These differences of colour mean differences of temperature. I will not enter into the proof of this. It depends on the knowledge derived from spectroscopic observations of the stars. The blue stars are at a temperature of, say, 10,000° Centigrade, the yellow ones, like the sun, at a temperature of 7500°, and the red ones, like Aldebaran, at a temperature of 4000°. We all know what a difference there is in the brightness of an electric light when it is over-incandescced and when it only has enough current to make the filament at red heat. We attribute the differences in the luminosities of these stars very largely to the fact that they are at a different temperature. No doubt there may be a considerable difference in size, but perhaps the most important difference is the difference in the brightness of their surfaces consequent on the difference of their temperatures.

One remarkable feature in these near stars is that no less than 8 out of 20 are double stars; for example, Sirius is a double star. The bright star we see has a very faint companion which can only be detected by a very large telescope. These two stars revolve round one another in about 50 years. Procyon has a faint companion which gives only $\frac{1}{4000}$ as much light, and these go round one another in 40 years. η Cassiopeiæ has a companion about 60 times as faint as itself, and they go round one another in 230 years. The companion of α Centauri is very bright, and they revolve about one another in 81 years.

When we know the distances of these stars from us we are able to calculate their distances from their companions, and we find that the distance of Sirius from its companion is 21 times the distance of the earth from the sun, that of Procyon 15, of α Centauri 23 times, and so on. We can use this knowledge to find out another very important fact about the stars, for the time which stars take to revolve about one another depends on their distance apart and the strength of the pull which their mutual gravitation exercises. This pull is proportional to the masses of the stars, and in this way we find that the mass of Sirius is $3\frac{1}{2}$ times that of the sun, that of α Centauri twice, and of some of the other stars something at least as great as $\frac{1}{7}$ of the mass of the sun, and so we establish the fact that these stars, at any rate, are not very different from the sun in the quantity of matter that they contain.

When we know the distance we can also determine something about the rate at which the stars are moving. If we know the distance of an aeroplane which is flying perpendicularly to the line joining us to it, the measurement of its change of angular position at once enables its velocity to be determined. In the same way the knowledge of the distance of a star gives us means to find in part the star's velocity. As the spectroscope enables us to determine how fast a star is approaching or receding from us, we are enabled to determine completely the velocities of a number of stars. We find, then, that these are quite comparable with the velocity of the sun, which is moving with a velocity of 11 or 12 miles per second in the direction of the bright star α Lyræ.

These are various particulars in which the stars resemble the sun. They are, roughly speaking, of the same kind of mass, their luminosity varies a good deal, and the velocities with which they travel are quite comparable with that of the sun, may be a little more or a little less. One other thing in which they resemble the sun, though I shall give you no detail of this, is that they consist of the same chemical elements. I have gone through these particulars in order that you may see the general lines of argument of the proof that the stars are bodies like the sun. The sun is bright and presents a disc of measurable size to us. If these stars of which we have spoken could be brought to the same distance they would present measurable discs, in some cases a little larger and in some a little smaller than the sun, but we should not find any enormous disparity. And so we conclude that the sun is just one of the stars of quite average dimensions, bigger and brighter than some but less and fainter than others. We have only found, as you perceive, a very limited number of things about the stars, their sizes, masses, surface temperatures and luminosities. There are many other things we should like to find: for instance, "Have these suns systems of planets revolving round them?" To this we can at present give no answer; but we should presume that they may have. You may ask, "Are we to suppose that these planets have life upon them?" The answer is, that we do not know, and can only guess by the analogy of our own earth and the sun.

I have confined myself to what we can discover about the nearest of the stars. There are means, partly depending on what we learn in this way, and partly on somewhat more complicated applications of geometry and physics, but still simple in principle, by which our knowledge is extended to great distances in space. We find that there are many millions of bodies which are in the main like the sun. Most of the stars we see form a great assembly which extends to two or three hundred times the distance of which I have been speaking in the direction perpendicular to the Milky Way, and to 1000 times this distance when we come to the plane of the Milky Way. We can even go beyond this, and we find clusters of stars far removed from that continuous assemblage of which our sun is a unit. Recent work by Hertzsprung, Shapley and others places the small Magellanic cloud at a distance 3000, the cluster of ω Centauri 700, and the cluster in Hercules 7000—if we take one million times the distance of the earth from the sun as our unit. This last cluster probably contains 50,000 stars brighter than the sun and many more less brilliant.

My lecture has been devoted to the attempt to give in general terms some idea of the principles which guide astronomers and the methods they employ rather than a statement of the results they have obtained. It seems to me that the mere statement of a scientific discovery is of little value without some idea of the means which have been employed to obtain it. It is, of course, quite impossible for anyone but an expert to follow all the details, just as it is only the expert who has studied a problem in all its bearings who will be able to surmount the difficulties and find the true solution. But it is possible to follow the general lines of a scientist's thought. In astronomy, and particularly the part with which I have been dealing to-night, only very simple principles of geometry and physics are necessary. The difficulty is in the application, the great accuracy necessary because of the smallness of the quantities to be measured. There is nothing at all mysterious about the methods employed.

The results are indeed such as to fill thoughtful minds with wonder. We find myriads of bodies essentially like the sun in constitution, scattered about in space at wide distances from one another. The few things we know about them are merely their sizes, temperatures, densities, and some other general features of their physical constitution. A wide region for speculation is opened; but on this I will not enter.

We have been told that "the undevout astronomer is mad." Whatever his religious beliefs may be, he cannot fail to look at the skies with wonder and awe, and the more so as little by little a few facts are gleaned about the stars around us.

The Conference Hall was filled by a large audience that followed the Address, which was illustrated by numerous lantern slides, with deep attention.

At its close the PRESIDENT expressed the great obligation under which the Astronomer Royal had placed the Institute, and a vote of thanks, proposed by Mr. MAUNDER and seconded by the Rev. Prebendary FOX, was carried by acclamation.

Dr. SCHOFIELD then moved a vote of thanks to the Chairman, which was seconded and put to the Meeting by Professor LANGHORNE ORCHARD, and the Meeting adjourned at 6 p.m.