Measurement of the Distances of the Stars.

[Concluded from p. 254.]

The next attempt to which I wish to refer is the one made by Sir William Herschel. In a paper communicated by him to the Royal Society in December 1781, he reviews the serious difficulties involved in determining the parallax of a star by comparing its zenith distance at different times of the year. Especially there is the uncertainty introduced by the refraction of light, and—in addition—as the angular distances of stars from the zenith are changed by precession, nutation, and aberration, any errors in the calculated amount of these changes will all affect the results. He proposed, therefore, to examine with his big telescope the bright stars and see which of them had faint stars near them. The bright stars, he said, are probably much nearer than the faint stars; and if the parallax does not even amount to 1″ the case is by no means desperate. With a large telescope of very great perfection it should be possible to detect changes in the angular distance of two neighbouring stars. By this differential method the difficulties inherent in the method of zenith distances will be eliminated. Herschel made a great survey to find suitable stars, and in this way was led to the discovery of double stars—*i. e.*, of pairs of stars which are physically connected and revolve around one another. This was a most important discovery, but as the two components of a double star are practically at the same distance from us they do not serve to determine parallax, for which we need one star to serve as a distant mark.

For another forty years persistent efforts were made without success. Piazzi, in Italy, thought he had detected parallax in Sirius and a number of other bright stars, but the changes he detected in the zenith distances were unquestionably due to errors introduced by uncertainty in refraction, or slight changes in the position of his instruments in the course of the year. Dr. Brinkley, in Dublin, made a gallant effort and took the greatest pains. He thought he had succeeded, and for many years there was a controversy between him and Pond as to whether his results were reliable. The state of knowledge of the distances of the fixed stars in 1823 is summed up accurately by Pond in the *Philosophical Transactions*:—

> "The History of annual parallax appears to me to be this: in proportion as instruments have been imperfect in their construction, they have misled observers into the belief of the existence of sensible parallax. This has happened in Italy to astronomers of the very first reputation. The Dublin instrument is superior to any of a similar construction on the Continent; and accordingly it shows a much less parallax than the Italian astronomers imagined they had detected. Conceiving that I have established, beyond a doubt, that the Greenwich instrument approaches still nearer to perfection, I can come to no other conclusion than that this is the reason why it discovers no parallax at all."

Besides these and other efforts to find parallax in the zenith distances of stars, attempts were also made to detect changes in the time at which the stars cross the meridian, to see if they are slightly before their time at one period of the year and slightly after it at another. But these, too, were unsuccessful, even in the hands of astronomers like Bessel and Struve. The best were some observations of circumpolar stars made by Struve in Dorpat between 1814 and 1821. The following table shows some of the results at which he arrived:—

Polaris and ε Urs. Maj.	$\pi + 0{\cdot}053\pi' = +{}''{\cdot}075 \pm {}''{\cdot}034$
ε Urs. Maj. and α Cass.	$\pi + 0{\cdot}962\pi' = -{\cdot}136 \pm {\cdot}110$
ζ Urs. Maj. and δ Cass.	$\pi + 1{\cdot}099\pi' = +{\cdot}175 \pm {\cdot}127$
η Urs. Min. and α Persei	$\pi + 0{\cdot}402\pi' = +{\cdot}305 \pm {\cdot}071$
Capella and β Drac.	$\pi + 1{\cdot}147\pi' = +{\cdot}134 \pm {\cdot}139$
β Aurig. and γ Drac.	$\pi + 1{\cdot}138\pi' = +{\cdot}020 \pm {\cdot}117$

This table has the merit of not looking wildly impossible in the present state of our knowledge. It has the disadvantage of not giving a definite parallax to each star. For example, it is impossible to say how much of the 0″·134 is to be given to Capella and how much to β Draconis. Further, the probable errors, though really small, are nearly as large as the quantities determined.

Struve and Bessel therefore attempted the problem by the differential method recommended by Herschel. It had now become easier to carry out. The method of mounting telescopes equatorially had been devised, so that the telescope was always kept pointing to the same part of the sky by clockwork-driven mechanism. Struve chose the bright star α Lyræ, and measured its distance from a faint star about 40″ away on 96 nights between November 1835 and August 1838. In the focal plane of his telescope he had what is called a position micrometer. The micrometer contains two parallel spider-threads stretched on frames, and the frames are movable by screws till the stars are bisected by the threads: the distance apart of the threads is known by the readings of the screw-heads. He found that α Lyræ had a parallax 0″·262 with a probable error ±0″·025.

Bessel chose the star 61 Cygni as a likely star to be near the Sun, and therefore to have appreciable parallax. 61 Cygni is not nearly so bright as α Lyræ, but has a very great angular movement or proper-motion among the stars. Bessel used an instrument called a heliometer. Like Struve's telescope, it was mounted so that it could be driven by clock-work to point always at the same star. The object-glass of Bessel's telescope was made by the great optician Fraunhofer, with the intention of cutting it in halves. Fraunhofer died before the time came to carry out this delicate operation, but it was successfully accomplished after his death.

Delicate mechanism was provided for turning the glass, and also for moving the two halves relatively to each other; the amount of movement being very accurately measured by screws. Each half gives a perfect image of any object which is examined, but the two images are shifted by an amount equal to the distance one half of the lens is moved along the other. Thus when a bright star and faint star are looked at, one half of the object-glass can be made to give images S and *s*, and the other half S′ and *s*′. By moving the screw exactly the right amount *s*′ can be made to coincide with S, and the reading of the screw gives a measure of the angular distance between the two stars. Bessel made observations on 98 nights extending from August 1837 to September 1838. The following table, taken from a report by Main (*Mem. R. A. S.* vol. xii. p. 29), shows how closely the mean of the observations for each month accords with the supposition that the star has the parallax 0″·369:—

Mean date.	Observed Displacement.	Effect of parallax 0″·369.	Mean date.	Observed Displacement.	Effect of parallax 0″·369.
1837. Aug. 23	+0″·197	+0″·212	1838. Feb. 5	−0″·223	−0″·266
Sept. 14	+0·100	+0·100	May 14	+0·245	+0·238
Oct. 12	+0·040	−0·057	June 19	+0·360	+0·332
Nov. 22	−0·214	−0·258	July 13	+0·216	+0·332
Dec. 21	−0·322	−0·317	Aug. 19	+0·151	+0·227
1838. Jan. 14	−0·376	−0·318	Sept. 19	+0·040	+0·073

Simultaneously with these determinations of the distance of α Lyræ and 61 Cygni, the distance of α Centauri, one of the brightest of the southern stars, was found by Henderson from observations of zenith distance made by him at the Cape between April 1832 and May 1833. He learned, just before the termination of his residence at the Cape, that this star had a very large proper-motion. Suspecting a possible parallax, he examined the observations when he had taken up his new office of Astronomer Royal for Scotland, and found a parallax amounting to 0″·92. He did not, however, publish his results till he found that they were confirmed by the right ascensions. In a communication to the Royal Astronomical Society in December 1838, he states that it is probable that the star has a parallax of 1″·0.

The great and difficult problem which had occupied astronomers for many generations was thus solved for three separate stars in 1838:—

	Parallax.	Distance.	Modern observations.	
			Parallax.	Distance.
a Centauri (Henderson)......	1″·0	200,000	0″·750	270,000
61 Cygni (Bessel)	0·314	640,000	·285	700,000
a Lyræ (Struve)	0·262	760,000	·10	2,000,000

(The unit of distance is that from the Earth to the Sun.)

Henderson's observation is interesting because *a* Centauri is, so far as we yet know, the nearest of all the stars to us. But by far the most valuable of these observations is Bessel's. The heliometer, which he devised, proved itself to be by far the most serviceable instrument for determining stellar parallax till the application of photography for this purpose.

The somewhat dramatic manner in which the distances of three stars were determined in the same year, after several centuries of failures, may have led to the hope that the range of many more stars would soon be found. This was not the case, however. Each star had to be measured separately, and involved many nights of observations. The quantities to be measured were so small that they taxed the resources of the best instruments and best observers. In 1843 Peters published the parallaxes of half a dozen stars determined with the vertical circle at Pulkovo, but the parallax of only one of these, Polaris, was obtained with much accuracy. With Bessel's heliometer, Schlüter and Wickmann measured the distance of Gr. 1830, the star which had the largest known proper-motion. In the sixties, Auwers with the same instrument determined the parallax of several quick-moving stars, and also of the bright star Procyon. With the Bonn heliometer, Krueger in the sixties measured the distance of three stars, and Winnecke of two more. Other observations were made, amongst others, by Maclear, Otto Struve, Brünnow, and Ball; but as these observers had not such suitable instruments, their results were not of the same high standard of value. A generous estimate would place the number of stars whose distances had been satisfactorily determined before 1880 at not more than twenty. In the eighties, progress became more rapid. Gill, the Astronomer Royal for the Cape, in conjunction with a young American astronomer, Elkin, determined with great accuracy, though with only a small 4-inch heliometer, the distance of nine stars of the Southern Hemisphere. These stars included *a* Centauri and the bright stars Sirius and Canopus. These results were communicated to the Royal Astronomical Society in 1884. The work of Gill and Elkin did not stop there. After some years, a very fine 7-inch heliometer was obtained at the Cape, and with it, between 1888 and 1898, the parallaxes of 17 stars were determined by Gill and his assistants with very great accuracy. The stars observed at the Cape consisted of the brightest stars of the Southern Hemisphere and of the stars with the greatest proper-motions. The results were remarkable. The stars with large proper-motions were nearly always comparatively near—say, within one million times the Sun's distance. On the other hand, some of the very brightest stars, particularly Canopus, the brightest star in the sky after Sirius, were at vastly greater distances.

Meanwhile, Elkin, who had been appointed Director of the Yale Observatory in 1884, carried out with a 6-inch heliometer, between the years 1885 and 1892, a determination of the distances of the ten brightest stars of the Northern Hemisphere. After these were finished, the Yale observers, Elkin, Chase, and Smith, embarked on the ambitious programme of the determination of the distances of 163 stars of the Northern Hemisphere which show large proper-motion. They have added 41 southern stars to these, and 35 stars of special interest. The results of all these observations were published in 1912. They have not, in most cases, the high accuracy of the Cape Observations, but, nevertheless, are of good accuracy and appear to be free from any considerable systematic error.

A third important series of observations was made by Peter with a 6-inch heliometer at Leipzig. These were commenced about 1890, and continued till the death of Prof. Peter in 1911. The parallaxes of 20 stars were determined with the same high accuracy as the Cape Observations. Observations with the heliometer require both skill and industry. To secure the needful accuracy measures must be made in four different positions of the instrument, so that possible small systematic errors may be eliminated by reversal. Great care is required in the adjustments of the instrument, particularly in the accurate determination of the scale-value at different temperatures.

The possibility of obtaining satisfactory results with less labour was considered by Kapteyn, in view of the successful determination of the parallax of Gr. 34 by Auwers. From 1885 to 1887 he made observations with the transit-circle at Leiden of 15 stars for the purposes of determining parallax. The observation consisted in observing the times when the star whose parallax was sought and two or three neighbouring stars crossed the meridian. Observations are made at the two most favourable epochs—say, every night in March and every night in September—to determine whether the star has changed its position relatively to its neighbours in the interval. The difficulties are two-fold. The purely accidental error of observations of transits is considerable as compared with the small quantity which is sought. Besides this, the star whose parallax is required is probably brighter than the comparison stars, and special precautions are required to guard against personal errors of the observer.

In questions of this kind the only satisfactory way is to judge by the results. From observations made on 50 nights, values of the parallax are obtained not nearly so accurate as the best heliometer observations, but still of considerable accuracy. Finally, the parallaxes of four of the stars which had been previously determined by measures with a heliometer showed satisfactory agreement.

This method has been employed by Jost at Heidelburg, very extensively by Flint at the Washburn Observatory of the University of Wisconsin, and is now being tried at the Cape by Voûte, a pupil of Kapteyn. It appears to me that this method can never give results of the highest accuracy, but that it may be of use in a preliminary search for stars of large parallax. The argument of the facility of the method compared with the heliometer has, however, lost much of its force; for, as I hope to show next, the highest accuracy attainable with the heliometer can be secured much more easily with a photographic telescope.

The application of photography to the determination of stellar parallax was first made by Pritchard in Oxford between 1887 and 1889. He took a large number of photographs and measured on them the angular distance of the star which he was considering from four of its neighbours. In this way he determined the parallax of five stars. He began this work late in life, and it was left for others to develop the photographic method and find what accuracy could be attained with it. At first sight it seems very easy, but experience shows that there are a number of small errors which can creep in and vitiate the results, unless care is taken to avoid them.

It has gradually become clear that with a few simple precautions and contrivances, a greater accuracy can be reached in the determination of parallax by photography and with much less trouble than by any other method. Between 1895 and 1905, several astronomers succeeded in obtaining from a few plates results as accurate as could be obtained from many nights' observations with the heliometer by the most skilled observers. In the last five years a large number of determinations have been made. In 1910 Schlesinger published the parallaxes of 25 stars from photographs taken with the 40-inch refractor of the Yerkes Observatory, and in 1911 Russell published the parallaxes of 40 stars from photographs taken by Hinks and himself at Cambridge. The opinion expressed by Gill on these observations (*M. N.* vol. lxii. p. 325) was that, but for the wonderful precision of the Yerkes observations, the Cambridge results would have been regarded as of the highest class. The facility with which the

Yerkes results are obtainable is expressed very tersely by Schlesinger—"the number of stellar parallaxes that can be determined per annum will in the long run be about equal to the number of clear nights available for the work." With the heliometer at least ten times as much time would have been required. During the last year two further instalments of the results of the Yerkes Observatory have been published by Slocum and Mitchell, giving the parallaxes of over 50 stars. It might be thought that the high accuracy attained by them is largely attributable to the great length of the telescope. From experience at Greenwich, I do not think this is the case, and believe that similar results are obtainable with telescopes of shorter focal length. As several observatories are now occupied with this work, we may expect that the number of stars whose distances are fairly well known will soon amount to thousands, as compared with 3 in 1838, about 20 in 1880, about 60 in 1900, and now perhaps 200.

The stars whose distances have been measured have generally been specially selected on account of their brightness or large proper-motion. Each star has been examined individually. Kapteyn has suggested that instead of examining stars singly in this way, photography gives an opportunity of examining all the stars in a small area of the sky simultaneously and picking out the near ones. The method has been tried by Kapteyn and others—among them Dr. Rambaut of Oxford. The idea is very attractive, because it examines the average star and not the bright star or star of larger proper-motion. It is liable, however, to some errors of systematic character, especially as regards stars of different magnitudes. Comparison of the results so obtained with those found otherwise will demonstrate whether these errors can be kept sufficiently small by great care in taking the photographs. Till this is done no opinion can be expressed on the success of this experiment, which is worth careful trial.

The question may be asked, how near must a star be to us for its distance to be measurable? I think we may say 10 million times the Sun's distance. This corresponds to the small angle $0''\cdot02$ for the parallax. If a star's parallax amounts to this, there are, I believe, several observatories where it could be detected with reasonable security, though we shall know more certainly by the comparison of the results of different observatories when they accumulate.

You will readily imagine that an accurate knowledge of the distances of many stars will be of great service to astronomy. There are ample data to determine the positions, velocities, luminosities, and masses of many stars if only the distances can be found. Thus we know the distance of Sirius, and we are able to say that it is travelling in a certain direction with a velocity of so many miles per second: that it gives out 48 times as much light as the Sun, but is only $2\frac{1}{2}$ times as massive. The collection and classification of particulars of this kind is certain to give many interesting and perhaps surprising results. But it is not my purpose to deal with this to-night. The task I set before myself in this lecture was to give an idea of the difficulties which astronomers have gradually surmounted, and the extent to which they have succeeded in measuring the distances of the stars.

F. W. Dyson.

CORRESPONDENCE.

To the Editors of 'The Observatory.'

The Age of the Earth.

Gentlemen,—

In the June number of the *Observatory* a very interesting difficulty is pointed out, arising from the assumption of a comparatively short life (some 20 million years) for the Sun. It is suggested that this would entail some 50 novæ a year to maintain a stellar system of 10^9 stars. It is urged that this is statistically improbable, and that, if it did occur, it could not escape observation.

This difficulty is perhaps not quite insuperable. Firstly, the 20 million years were obtained simply by dividing the Sun's gravitational energy $\frac{3}{5}m^2/r$ by the present rate of emission $5{\cdot}31\,(10)^{-5}T^4 4\pi r^2$, T being the effective temperature. This gives the upper limit for the time during which the Earth can have been in its present state, which was the problem examined in the letter to which the note referred. In reality, of course, neither T nor r are constant. Thus the real age is probably considerably greater, for it must contain long periods during which T was much smaller than it is now. It is possible that the 50 novæ per year might be reduced to 5 or 10 by taking this into account. It must be conceded that even this smaller number of new stars could scarcely pass unnoticed, even though the more distant ones might not reach a greater magnitude than 9 or 10.

The statistical improbability of collision arises, of course, from the assumption that there are no dark stars. If the stellar system has existed for a longer period than the life of a single star, however, there must be many such.

The strongest evidence against a short age of the Sun and Earth appears to be that adduced by Prof. Strutt. He found that minerals which contain radioactive substances contain a certain amount of helium. As the amount of helium produced in unit time by each unit mass of the radio-active material is known, a minimum estimate of the time since which the mineral has existed may be obtained. This method seems to be confirmed wherever a test is possible. Thus, all minerals of the same geological epoch