Mr. Finch. I was impressed by the agreement of the American and Australian observations. Has Stoyko published any recent results?

Mr. Smith. No, but Mme. Stoyko recently compared earlier results from the northern and southern hemispheres. A paper on the German results mentions a reduction in amplitude.

Dr. Whitrow. Would the melting of polar ice have any effect?

The Astronomer Royal. This effect was considered but found to be insignificant. Ocean currents were also considered.

Dr. Gething. Has any attempt been made to determine $\Delta\alpha_a$ errors of N30 from the discrepancies between the fluctuations observed at the different observatories?

Mr. Smith. It would be far too uncertain to attempt to correct a star catalogue by this method.

Dr. Hunter. Is it possible to make a prediction of the variation?

Mr. Smith. It is necessary to attempt prediction for current work but this is liable to some uncertainty.

Mr. Gold. The mechanism which must be responsible for setting up the free nutation might be thought to be the same as that responsible for the fluctuation in the length of the day. If that were so we might ask the meteorologists to explain both at one go.

The President. We must offer our hearty thanks to Mr. Smith and Mr. Tucker for presenting this paper. The meeting is now adjourned until 1953 May 8.

MEETING OF THE ROYAL ASTRONOMICAL SOCIETY

Friday, 1953 May 8, at $16^h\ 30^m$

Professor H. Dingle *vice* Dr. J. Jackson, *President*, in the Chair

Secretaries, A. Hunter
Flora M. McBain

The Minutes of the Ordinary Meeting of 1953 April 10 were read, confirmed and signed. *Professor H. Dingle*, acting on behalf of the President, Dr. J. Jackson, for the first part of the meeting, then called on *Mr. P. A. O'Brien* to give an account of his paper on "The distribution of radiation across the solar disk at metre wavelengths".

Mr. O'Brien. Measurements have been made at Cambridge of the distribution of radio "brightness" across the solar disk at wavelengths of 1·4, 3·7 and 7·9 metres, for which the radiation originates entirely in the corona. The distributions are very sensitive to changes in electron density and temperature and so one might hope to derive from them something like a model corona.

The method used is in effect the radio analogue of Michelson's stellar interferometer. Two comparatively small aerials are arranged as an interferometer so that the separation between the aerials may be varied. As the separation increases the lobe width of the interference pattern decreases to a size comparable with the Sun's diameter, and the amplitude of the recorded sinusoidal pattern decreases accordingly. The projection of the interferometer axis on the Sun's disk may be arranged to pass through the centre of the disk at an angle α to the equatorial plane. The projection of the axial plane of the interferometer (the plane perpendicular to the interferometer axis) then makes an angle α with the Sun's axis of rotation. If we now imagine the distribution of brightness over the disk to be integrated in narrow strips parallel to the axial plane, a "strip" or projected distribution is obtained corresponding to the particular value of α used. It can be shown that the projected distribution is given simply by the Fourier transform of the experimental curve relating the amplitude of the interference pattern to the increase in aerial separation. Such a distribution gives no indication of how the brightness varies in a direction perpendicular to the interferometer axis, and if results are obtained only for a single value of α, it is convenient to assume that the brightness is distributed over the disk with circular symmetry. The radial distribution of brightness is then given by a Fourier-Bessel transform of the experimental curve. This assumption was made in earlier work done in 1949 by Stanier at a wavelength of 60 cms, and by Machin in 1950 at a wavelength of 3·7 metres.

In the present work the possibility of radio asymmetry in the corona was also investigated by varying α. The first four experiments, carried out as far as possible at times of low sunspot activity, extended from October 1951 to May 1952. Each lasted an average of nine days and were carried out for values of α of 2°, 15°, 19° and 53° at a wavelength of 1·4 metres. The results indicated that any variation in the projected distribution as α changed was being partially masked by temporal variations for a fixed value of α. Observations were therefore made at a large number of aerial separations for values of α from approximately 0° to 90° on one day over a period of nine hours. Assuming symmetry about the solar axis an analysis of the results showed that the shape of the Sun was approximately elliptical, the radius at which the brightness temperature was reduced to half its central value being about 25 per cent greater at the equator than in the polar direction. A second similar experiment gave approximately the same result.

Considering only those projected distributions for values of α near 0°, the results of the six experiments extending over a period of eight months, showed that the half width of the distribution gradually decreased with time by about 25 per cent.

The asymmetry could not be investigated at the 3·7 and 7·9 metre wavelengths, but the results of several experiments over a period of about a year indicated definite temporal variations of the distribution, as found at 1·4 metres.

In attempting to derive a model corona the results for all three wavelengths were averaged and smoothed, circularly symmetrical distributions derived. These showed clearly the increase in size of the emitting disk with increasing wavelength. The brightness temperature was reduced to 10 per cent of its central value at 1·6, 2·2 and 2·8 solar radii for the wavelengths 1·4, 3·7 and 7·9 metres, respectively.

These smoothed experimental curves have been used in theoretical work by C. J. Bell. They differ appreciably from the usual theoretically derived distributions based on the Allen—van de Hulst electron density and isothermal coronas, the main discrepancy being the very much greater radial extent of the radiation found experimentally. It was not possible to resolve this discrepancy by supposing the temperature to vary with height in the corona, and a new model corona was therefore derived entirely from the radio observations. The electron density thus deduced does not differ from the Allen—van de Hulst values by more than a factor 2 or 3 out to a radius of about 3R⊙ and thereafter decreases very much more slowly with increasing radius. The electron temperature falls rather rapidly from about 1 million degrees in the lower corona, varying approximately as the inverse cube of the radius.

Professor Dingle. I invite discussion on this interesting work.

Rev. P. J. Treanor. What was the width of the lobes of the interference pattern?

Mr. O'Brien. The smallest lobe-width corresponds to an aerial separation of about 100 wavelengths and is therefore about $\frac{1}{8}^\circ$.

Rev. Treanor. Since this is about a quarter of the solar diameter would it not have been worth while applying a correction?

Mr. O'Brien. It is not possible to apply a correction for this finite resolving power. The distribution is given uniquely by the experimental curve of amplitude against aerial separation. The finite resolving power blurs out the detail of the distribution, but more refined observations can only be made by increasing the maximum aerial separation.

Dr. H. Bondi. In connection with the previous point, it would be interesting to know how experimental errors are reflected in the Fourier transforms.

Mr. O'Brien. The Fourier transform itself is insensitive to the distribution; the main error arises in determining the temperature at the centre of the disk, on account of influences far out from the centre.

Professor Dingle. I must now close this discussion and ask you to return your thanks to Mr. O'Brien for his contribution.

The Chair was then resumed by *Dr. J. Jackson.*

The President. I have great pleasure in welcoming our George Darwin Lecturer, *Dr. Edwin P. Hubble,* this evening. He obviously needs no further introduction from me, and I therefore now ask him to deliver his lecture.

Dr. Hubble. I propose to discuss the law of red shifts—one of the two known characteristics of the explorable universe. It is important that this law should be formulated as an empirical relation between observed data out to the limit of the greatest telescope. Ultimately when a definitive formulation has been achieved, the number of competing interpretations will be reduced to a minimum. The path towards such a formulation is now clear and the investigations are under way at Mount Wilson and Palomar.

There are three phases in the history; the discovery phase, which ended in 1928/9, the rapid extension to the limit of the 100-inch in 1929/36, and the current attempts to reach the limit of the 200-inch, with the definitive formulation, which began about two years ago.

The discovery emerged from a combination of distances, derived at Mount Wilson, with radial velocities of about 46 nebulae, of which Slipher had contributed 42, including the first to be measured (– 300 km/

sec for M 31). The list was completely dominated by large positive velocities, ranging up to +1800 km/sec for NGC 584.

Attempts were made, from 1916 onward, to derive the solar motion with respect to the nebulae, but the general recession proved intractable. Then, in 1918, Wirtz attempted to "save the phenomena" by introducing a constant K term in the equations. The device improved the results, but not enough to render them acceptable. It did however suggest that the next logical step would be to replace the constant K with rK a term which varied with the distances of the individual nebulae. Various solutions in the early and middle twenties, using apparent luminosities and angular diameters as measures of relative distances, failed only because these criteria were not sufficiently accurate to give individual distances over the relatively short range of radial velocities. The problem was finally solved when the brightest stars in late type spirals were established as suitable distance indicators, and were calibrated by Cepheids in a few of the nearest nebulae. This new development started in 1923/4, when Cepheids found in M 31 and M 33 identified them as extra galactic systems, indicated their distances and showed that the upper limit of the brightest stars could be used as a distance criterion. When in 1928 this was applied to the nebulae with measured velocities, the law of the red shifts was established out as far as the Virgo cluster, about 7 million light years, as an approximately linear relation, the velocities of recession increasing by about 500 km/sec per million parsecs.

The second phase was a Mount Wilson project, and lasted from 1928 to 1936. Mr. Humason assembled spectra of nebulae, and I attempted to estimate their distance. Attention was concentrated on clusters, because their brightest members could be regarded as distance indicators, and because the great clusters are dominated by the concentrated and hence most easily observed elliptical nebulae.

After checking his technique by reobserving some of Slipher's nebulae, Humason marched with giant strides from cluster to cluster to the limit of the 100-inch, reached when apparent velocities of 40,000 km/sec were recorded in the Boötes cluster, and in Ursa Major No. II, and readable spectra could not be obtained in the Hydra cluster (now known to have shifts half as great again). Spectra of field nebulae were also assembled in large numbers, and furnished an account of red shifts in the nearer, more conspicuous nebulae of all types.

When the second phase ended, the law of red shifts appeared to be linear out to approximately 250 million light years, the velocities increasing at the rate of 530 km/sec per million parsecs. The solar motion was largely accounted for by galactic rotation. It was established that the law did not operate within the local group. Magnitude-velocity relations could be used to calibrate all the relations in terms of brightest stars. Assuming $M_{pg} = -6 \cdot 35$ for Brightest Stars, the corresponding values for Field Nebulae and Fifth Nebulae in clusters were $-15 \cdot 20$ and $-16 \cdot 45$ respectively.

Towards the end of the second phase, Mayall began assembling spectra with a very fine U.V. spectrograph on the 36-inch Crossley at Mount Hamilton. He paid special attention to systems of low surface brightness for which his instrument was fully as efficient as the larger telescopes. He now has a list of about 280 nebular velocities, which include 100 of Humason's 570. These data furnish a wealth of information, the discussion of which must await publication, but they refine and confirm previous results, and in particular establish the order of precision of the measures (p.e. < 30 km/sec) and of the dispersions among the nebulae. These range from 60 km/sec among 11 members of the local group to perhaps 1200 km/sec for the Corona Borealis cluster, the dispersion increasing steadily with compactness. From these results it becomes evident that the uncertainties in the law are entirely those of distances, and the difficulties are therefore largely those of photometry. This was the situation when the 200-inch and its accessories came into action. The current programme has two parts, the extension of the observed range, and the revision of the distance scale. The first part is straightforward, once suitable clusters are found. During the first season, (1950/51) Humason obtained spectra in three clusters beyond the limit reached by the 100-inch. They gave velocities of the order of 50,000, 54,000, and 61,000 km/sec, the last being the Hydra cluster. Out to these limits, groups of clusters at successive intervals to furnish mean points for the correlation curve can be selected from plates with the 48-inch Schmidt reflector.

Beyond 60,000 km/sec, possible cases suggested by the 48-inch are being checked with the larger telescopes, and apart from these we must rely on chance finds. Humason has now observed groups of three clusters at 25,000, 40,000, and 50,000 km/sec, representing both galactic hemispheres, and two clusters at about 58,000 km/sec to group with Hydra. He is confident that larger velocities, at least up to a quarter of the velocity of light, can be recorded when such clusters have been located.

The second part of the programme deals with the revision of the distance scale. For this, the unit of distance has to be revised, faint magnitude sequences set up in selected areas, nebular magnitudes measured and corrected for the effects of red-shifts, and the possibility of errors arising from internebular obscuration and evolutional changes in luminosity during the travel time of the light examined.

That the unit of distance requires re-examination can be seen from a study of M 31; novae and globular clusters in M 31 have long been known to be fainter with respect to the Classical Cepheids than is the case in our own system. This discrepancy was emphasized when Baade resolved the body of M 31 and recognized it as a Type II population, the brightest stars of which are known to be comparable with those in the globular clusters. A two-fold programme was finally adopted to clarify the situation. One project is a study of M 31 with the 200-inch to establish the relative luminosities of all the brighter elements (the distance indicators) in the stellar stsyem, including the Classical Cepheids of Type I and the globular clusters and brightest stars in the Type II population, as well as the Cepheids of the kind known to belong to Type II. These so-called W Virginis Cepheids are important because of the possibility that the discrepancy might reflect a systematic difference between the period-luminosity relations in the two populations. This project is being undertaken by Baade, and is still under way. The second project, carried out by Sandage, Arp, Baum and others under the general supervision of Baade, is nearing completion. This has been to extend the colour-magnitude arrays for globular clusters down to very faint limits on the main sequence, and superposing them on the arrays for the local stars. Final results still await the establishing of very faint photometric standards, but provisional results indicate that the current values for the mean magnitude $M_{pg} = 0^m{\cdot}0$, of cluster-type variables is of the proper order, and cannot be changed by more than a few tenths at most. Thus the current estimates for the brightest stars in globular clusters are also confirmed. This indicates that the Classical Cepheids in M 31 are nearly $1^m{\cdot}5$ brighter than previously supposed; Thackeray has found a similar discrepancy between Classical Cepheids and cluster types in the Small Magellanic Cloud. Thus Shapley's calibration for the Classical Cepheids in the Galactic System, which has been used for 35 years, appears to be in error by nearly $1^m{\cdot}5$. Our current estimates of absolute distances must therefore be nearly doubled.

The standards for magnitudes and colours were established up to about $m_{pg} = 18^m{\cdot}5$ by Stebbins and Whitford in three of nine selected areas. They are now being extended by Baum up to 19^m in all the areas, and up to 21^m in some of them. This will provide standards for all clusters in which red-shifts have already been measured, and the programme should soon extend to the faintest clusters in which red-shifts *can* be measured.

The measurement of total magnitude has been undertaken by Stebbins and Whitford, Pettit and others, photoelectrically, and by Bigay and Holmberg with photographic techniques. In these programmes it is hoped to reduce errors to not more than about $0^m{\cdot}1$ either way.

The effect of red-shifts, whatever their interpretation, is to reduce the energy of each light quantum received, unless the fundamental relation $E\lambda = constant$ is rejected. Bolometric magnitudes are simply reduced by the factors $(1 + d\lambda/\lambda)$, but since red-shifts change the energy-wavelength distribution of the light received, the effects on measured magnitude are selective. The actual energy distribution must therefore be known in order to compare the energy received through the wavelength "windows" in the atmosphere, telescopes and measuring devices, with the energy that would have passed through in the absence of a red-shift. The 6-colour measurements of Stebbins and Whitford in 1947 provided for the first time an energy curve, reduced to no atmosphere, for the elliptical nebula M 32. Since elliptical nebulae are remarkably homogeneous in spectral type and colour this curve can be applied directly to all elliptical nebulae. The curve has a maximum in the yellow and is steeper on the blue than on the red side. It follows that the red-shifts affect photographic magnitudes most, while corrections to photovisual magnitudes are smaller and more reliable. Red magnitudes are changed by less than $0^m{\cdot}1$ for red shifts up to 0·3, and the corrections should be very reliable. The yellow magnitudes, however, offer the most reliable results at the moment, because enough red measures are not yet available.

The favoured red shift-magnitude relation at the moment is

$$\log c\frac{d\lambda}{\lambda} = 0{\cdot}2\, m_{pv} + 1{\cdot}16 \quad \text{(10th nebula)}$$

As more clusters are observed the residuals should offer a critical test of the presence of internebular absorption; where spectra have not yet been recorded, colours offer an approximate criterion. There are, at present, no indications of absorption in the directions examined.

From a comparison of the above relation with a similar correlation for the brightest stars in nearby nebulae the M_{pv} of the 10th nebula seems to be of the order of $-17^{m}\cdot4$ on the old scale and a little less than $-18^{m}\cdot9$ on the new. The few results available from novae and globular clusters in members of the Virgo cluster appear to be consistent with this.

These magnitudes however have not been corrected for effects of recession, as they must be if red-shifts are interpreted as Doppler shifts. The corrections range up to a maximum of $0^{m}\cdot2$ for the Hydra cluster, and if the uncorrected data do define a linear relation, the corrected data would lead to a non-linear relation in the sense of an accelerated expansion. There is as yet insufficient data to discriminate between the alternatives of uniform and accelerated expansion, but a decelerated expansion seems unlikely. A definitive formulation of the law of red-shifts should be available however before long, out to distances of about 900 million light years (new scale of distances). The implications of the law may be traced out to nearly double that distance by its effect on the distribution of nebulae in depth.

The "age of the Universe" is likely to be between 3,500 and 4,000 million years, and thus comparable with the age of rock in the crust of the Earth. Thus if red-shifts do measure the expansion of the Universe, we may be able to gather reliable information over a quarter of its history since expansion began, and some information over nearly half of the history.

The President. I was at Greenwich when this great work was in its earlier stages, and I have been quite absorbed by this account of its development. By the way in which Fellows have received this lecture it is obvious that it has made a great impression on them also. We therefore give you, Dr. Hubble, our warmest thanks for your lecture, and we extend our good wishes for your future work.

The meeting then adjourned until 1953 July 22 in Newcastle.