The Interferometer in Astronomy.¹

By Prof. A. S. EDDINGTON, F.R.S.

TO the naked eye the stars and planets equally appear as points of light. A telescope magnifies the planets into discs, but no telescope is large enough to render visible the disc of a star. We can calculate that a lens or mirror of 20 ft. aperture would be needed to show us even the largest star disc; the construction of such an instrument, if not hopeless, is far distant. We have considerable knowledge as to the size of stars, but until recently it was all found by indirect calculation; no test had made out the image to be other than that of a geometrical point. At the risk of going over familiar ground I must consider briefly the mode by which a telescope forms an image—in particular how it reproduces that detail and contrast of light and darkness which betrays that we are looking at a disc or a double star and not a blur emanating from a single point. This optical performance is called resolving power. Resolving power is not primarily a matter of magnification but of aperture; provided we use an eyepiece of reasonably high power the limit of resolution is determined by the size of aperture of the object-glass.

To create a sharply defined image the telescope must not only bring light where there ought to be light, but it must also bring darkness where there ought to be darkness. The latter task is the more difficult. Light waves in the æther tend to spread in all directions, and the telescope cannot prevent individual wavelets from straying on to parts of the picture where they have no business. But it has this one remedy—for every trespassing wavelet it must send a second wavelet by a slightly longer or shorter route to interfere with the first, and so produce darkness. This is where the utility of a wide aperture arises—by affording a wider difference in route of the individual wavelets, so that those from one part of the object-glass may be retarded relatively to and interfere with those from another part. A small object-glass can furnish light; it takes a big object-glass to furnish darkness.

Recognising that the success of an object-glass in separating double stars and other feats of resolution depends on the production of darkness in the proper place by interference between the waves from different parts of the aperture, Michelson asked himself whether the ordinary circular aperture was necessarily the most efficient for giving the required interference. Any deviation from the circular shape is likely to spoil the definition of the image—to produce wings and fringes. The image will not so closely resemble the object viewed. But, on the other hand, we may be able to sharpen up the tell-tale features. It does not matter how different the image-pattern may be from the object, provided that we are able to read the significance of the pattern. If we cannot reproduce a disc, let us try to produce something which is *distinctive* of a disc.

A little reflection suggests that we ought to increase the resolving power by blocking out the middle of the object-glass and using only two extreme regions on one side and the other. For these regions the differ-

ence of light-path is greatest, and the corresponding wavelets are the first to interfere; they are the most efficient in furnishing the dark contrast needed to outline the image properly.

But if the middle of the object-glass is not going to be used, why trouble to construct it? We are led to the idea of using two widely separated apertures, each involving a comparatively small lens or mirror—after the pattern of a range-finder. That is much easier to construct than a huge lens circumscribing both apertures.

It is one thing to detect a small planetary or nebular disc; it is another thing to make a close measure of its diameter. It is one thing to detect the duplicity of a star; it is another thing to measure the separation of the components. Michelson's first experiments were directed not towards performing feats of resolution beyond what had previously been attained, but towards improving the accuracy of measurement. He applied his method first to measuring the diameters of Jupiter's satellites—discs which are easy to detect, but very difficult to measure trustworthily with an ordinary micrometer. But it is easier to understand the application of the method to measurement of double stars than

FIG. 1.

to the diameters of discs; and I shall therefore speak more particularly of the double-star problem first, although that is not the historical order.

Consider light coming from a distant point and passing through two small apertures, A and B, the rest of the object-glass being blocked out (Fig. 1). From each aperture the light disturbance diverges in all directions, and our problem is to find the nature of the luminous pattern formed in the focal plane, this pattern constituting the image which is viewed and magnified by the eyepiece. At the point P (where, according to geometrical optics, the single point-image ought to appear) we have full illumination because the waves from the two apertures have equal paths, AP and BP, and reinforce one another. A little to one side we have another point of full illumination, Q₁; the paths, AQ₁ and BQ₁, are unequal, but differ by exactly a wave-length, so that the waves again arrive in the right phase to reinforce one another. Similarly we shall have a series of points of full illumination, Q₂, Q₃, etc., where the path-difference amounts to 2, 3, etc., wave-lengths. Intermediately there will be points of darkness where the path-difference is $\frac{1}{2}$, $1\frac{1}{2}$, $2\frac{1}{2}$ wave-lengths, and the waves arrive in opposite phase and

¹ From the presidential address delivered before the Royal Astronomical Society on February 9, on presenting the gold medal of the Society to Prof. A. A. Michelson.

cancel one another. The light-pattern viewed by the eyepiece is thus a line of alternate bright and dark fringes. At first sight it might seem that the fringes would continue of equal brightness to a great distance ; but actually they soon fade away, because in the more oblique directions there is interference, not merely between the two apertures, but between different parts of the same aperture. In fact the fringes appear as fine detail in the midst of the small diffraction disc which would be formed by either of the apertures singly.

Arrange that the two apertures are movable, and widen their distance apart. The points Q_1 , Q_2 , Q_3 now come closer together, that is to say, the fringes contract. Decrease the distance and the fringes spread out. It is a simple matter to find a formula giving the width of the fringes for any given separation of the apertures.

When the object viewed is a double star—two points of light—each point will produce its own line of fringes, and these will be superposed if the double star is a close one. It may happen that the two systems of fringes are in step, in which case the alternate bright and dark spaces will be conspicuous ; but if they are at all out of step the pattern will be blurred. Remembering that we can alter at will the width of the fringes by varying the separation of the apertures, we can adjust them, so that the bright fringes for one component coincide with the dark spaces for the other component. If the two systems are of equal brightness one system will fill the gaps in the other, leaving merely a line of uniform brightness ; if the two components are of unequal brightness the same adjustment will give minimum visibility of the alternation of light and shade. Varying the distance between the apertures this critical position can be fixed with considerable precision ; and for close double stars of not too unequal magnitude the separation is measured in this way much more accurately than with a micrometer.

The disc of a single star or planet is likewise measured by finding a position of the apertures for which the fringes disappear. It is not now a problem of two points producing overlapping fringes, but every point of the circular disc produces a fringe-system, and the effects must be summed. When the diameter of the disc is 1.22 times the width of the fringes (*i.e.* the distance from one bright fringe to the next) the integrated effect is uniform illumination and the fringes disappear altogether. It is not much use trying to see in one's head a result which is more fittingly the subject of algebraic calculation ; but we may notice in a general way that with this ratio the two outer quarters of the disc fall at places where the central half is producing dark spaces. That indicates roughly how the different portions of the disc compensate one another. The observation consists in varying the separation of the aperture until the fringes disappear ; the diameter of the disc is then 1.2 times the fringe-width calculated for that separation.

The possibilities of a method of this kind had been explored to some extent before Michelson took up the problem ; indeed Stéphan in 1874 had attempted unsuccessfully to detect the discs of stars by this means. We owe to Michelson the practical demonstration of its success. His first paper appeared more than thirty years ago in the *Philosophical Magazine* for July 1890.

The next year he followed up the theory by measuring the diameters of the four satellites of Jupiter at the Lick Observatory. The method proved entirely successful, and his measures were afterwards closely confirmed by Hamy at the Paris Observatory in 1899 using the same device. The great value of the method seemed to be proved ; it was thoroughly tested ; and it forthwith lapsed into oblivion.

In 1919 Michelson again took up the matter with energy. He made observations in August with the 40-in. refractor at Yerkes which were found to be encouraging ; and he went on to use first the 60-in. and then the 100-in. at Mount Wilson with the more ambitious design of surpassing the highest resolving power yet reached. At Mount Wilson he had the co-operation first of J. A. Anderson and afterwards of F. G. Pease. A great success was quickly obtained with the double star Capella. Capella is a spectroscopic binary with a period of 104 days. It was known that the distance of its components must nearly approach the limit of visual detection, but attempts to observe it visually had failed. (I may remark that that is a rather controversial statement to make—particularly at the R.A.S.—but the controversy is now ancient history.) With two narrow apertures in the beam from the 100-in. mirror the fringes were observed and then brought to minimum visibility by varying the position angle and separation of the apertures. The changing position angle and distance were traced through the revolution. Anderson's measures, afterwards continued by Merrill, have given a very accurate orbit. The separation of the two components varies from 0.04" to 0.05". From a comparison of this visual orbit with the spectroscopic orbit we find the parallax of Capella and also the mass. The parallax is 0.063", and the components are respectively 4.2 and 3.3 times as massive as the sun. The parallax does not differ much from that given by trigonometrical and spectroscopic determinations ; but these were very rough values, whereas the interferometer parallax is presumably of the highest order of refinement. I suppose that the mass determinations are about the best we have for any star.² But what is especially important is that Capella is the *only giant star* for which we know both the mass and the absolute luminosity.

I may perhaps be allowed to refer to a personal interest in this first big result of Michelson's method. Capella now supplies the chief lacking constant in the radiative theory of stellar equilibrium, for which I had waited five years. It is, I think, generally conceded that the absolute magnitude of a giant star mainly depends on its mass, and theoretical formulæ can be found expressing the law of dependence. But we need to know one pair of corresponding values in order, as it were, to anchor the formulæ. Hitherto that correspondence could only be guessed roughly from statistical knowledge of the average luminosity of giant stars and an estimate of the corresponding average mass based on our general knowledge of the masses of stars (which, unfortunately, relates chiefly to dwarf stars). Having now the exact figures for Capella, we can substitute a precise determination

² The masses of α Centauri, Sirius, and Procyon may have about the same accuracy, but I do not think that any others reach this standard.

instead of the provisional estimate; the change is by no means unimportant, the original estimate having been considerably in error.

Capella would have been slightly beyond the theoretical resolving power of the 100-in. if used in the ordinary way, though an elongation might have been detected. Resolving power was actually gained by blocking out the mischievous central portion of the aperture. But now came the final step—to produce fringes with a greater path-difference than any telescope yet constructed could provide. In 1920 a 20-foot interferometer, designed by Michelson and Pease, was constructed, in which the two interfering apertures could be separated to a distance of 20 ft. This was used in conjunction with the 100-in. mirror, which helped to bring the two beams together to produce their fringes. One might say that Michelson was now employing a 20-foot mirror; only, since he was only intending to use two small areas at its edges, he economically constructed those particular areas and left the rest of the mirror to imagination.

On July 10, 1920, the great 20-foot beam was placed across the telescope. On December 13 success was attained, and the diameter of Betelgeuse was measured. Its interference fringes had totally disappeared when the mirrors were at 10 ft. separation, although the other stars showed them. The deduced diameter was $0.045''$ —about the same size as a halfpenny fifty miles away.

Michelson's visits to Mount Wilson were limited to the summer months, and he was not present when this result was obtained. When he returned in 1921 he found his collaborators much occupied in trying to find some plan of obtaining definite measures of the visibility of the fringes instead of vague judgments. He suggested the plan of using two apertures, one fixed and the other variable; a difference in the size of the apertures reduces the visibility to a definite extent, depending on the ratio of the two apertures. Finally,

a comparison apparatus was constructed with one square aperture of 4 in. and the other a square variable from 4 in. to zero, in order to afford a definite scale of visibility.

In the early trials it took days to find the fringes, but as gradual improvements were made a few hours' work on the first night of a series of observations sufficed; the subsequent settings being made in a few moments.

I need only touch very briefly on later developments. Diameters of Antares, Aldebaran, Arcturus, and β Pegasi have since been measured. But, of course, the discs of most stars are far below the limits for a 20-foot instrument. Prof. Hale is now constructing a 50-foot interferometer, and it is estimated that thirty or forty stars will be within its grasp. There is no need for a large mirror, and the use of the 100-in. in conjunction with the first interferometer was rather a luxury. The 50-foot is of different design, and will not depend on any other telescope. All the diameters of stars measured up to the present confirm very closely the theoretical values that had been predicted for them. The enormous actual size of these stars—the earth's orbit could be placed entirely inside Betelgeuse—is a picturesque feature of the results; but that was a confirmation of facts already established almost beyond doubt.

It is not unlikely that interesting bypaths may be opened up. Considerable fluctuations in the diameter of Betelgeuse have been found, which may or may not be due to varying definition. The star is an irregular variable showing also changes of line-of-sight velocity, and the correlation of varying diameter with these other fluctuations would be of great physical interest if it turns out to be genuine. Michelson has pointed out that it is theoretically possible to determine by the interferometer the distribution of light over the disc—the law of darkening at the limb. That is a conceivable development for the future.

Sunlight and Disease.¹

By Dr. C. W. SALEEBY.

"IN the beginning, God said, Let There Be Light."

In or before the eighth century B.C., Zarathustra, foremost among many sun-worshippers in many ages, taught the cult of the sun and the green leaf and thrift, in place of pillage and murder. In the beginning of medicine, Hippocrates, practising at Cos in the temples of Æsculapius—son of Phœbus Apollo, god of the sun and medicine and music—practised the sun-cure. In the beginning of our era, Galen and Celsus used the sun. In the Dark Ages, by a pitiful misconception, the cult of the sun fell into desuetude as a species of pagan Nature-worship, and ill persons were treated alike in physical and in intellectual night. Tuberculosis and other ills were treated by the Sovereign touch, reputed to cure the "king's evil."

In the second half of the nineteenth century, we find certain heralds of the dawn. In 1856, Florence Nightingale vigorously but vainly protested against the orientation of Netley Hospital, observing that no sunlight could ever enter its wards. In 1876, Sir

Benjamin Ward Richardson praised sunlight in his "Hygeia, The City of Health." In 1877, Downes and Blunt showed that sunlight will kill anthrax bacilli. In many writings at this period, John Ruskin upheld sunlight and declaimed against the "plague-cloud" of smoke above our cities. In 1890, Dr. Theobald Adrian Palm (*nat.* 1848), who still practises medicine at Aylesford, in the Garden of England, showed by the geographical method that lack of sunlight is the chief factor in the causation of rickets, and added an admirable series of recommendations accordingly.² His paper was entirely ignored, and I found it in America, thanks to an American bibliographer. Robert Koch and others showed that sunlight kills tubercle bacilli. In 1893, Niels Finsen began to cure lupus, a form of cutaneous tuberculosis, by the local use of sunlight, and Sir James Crichton-Browne made observations to the same effect in this country. In 1900, on May 1, the London Hospital

¹ From a discourse at the Royal Institution on March 9.

² "The Geographical Distribution and Ætiology of Rickets," *The Practitioner*, October and November 1890.