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*"To the solid ground
Of Nature trusts the mind which builds for aye."*—WORDSWORTH.

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Scientific Worthies.

XLIV.—ALBERT ABRAHAM MICHELSON.

THE co-operation of members of the English-speaking race is heartily welcome in many departments of human activity, some of them presumably more important even than the pursuit of science. But to us who are engaged in that study, the brilliant results obtained of late years in the United States, and the friendly co-operation existing between that country and the different parts of the British Empire, are a suitable subject of felicitation; and I am privileged to write an article in appreciation of the work of one of the most distinguished physicists in the world, the circumstances of whose normal life I understand to be as follows :

Albert Abraham Michelson was born in Strelno, Poland, on December 19, 1852. In 1854 his parents migrated to the United States. After emerging from High School in San Francisco, young Michelson was appointed to the Naval Academy, from which he graduated in 1873, and two years later became instructor in physics and chemistry under Admiral Sampson, continuing this work until 1879. After a year in the Nautical Almanac Office at Washington, Michelson, now an ensign, went abroad for further study at the Universities of Berlin and Heidelberg, and at the Collège de France and the École Polytechnique in Paris. Upon his return to the United States in 1883 he became professor of physics in the Case School of Applied Science, Cleveland, Ohio; whence, after six years, he was called to Clark University, where he remained as professor until 1892, when the University of Chicago opened its doors. Prof. Michelson went to this new institution as professor of physics and head of the department, a position which he still holds. In June 1925 he was honoured by being appointed to the first of the Distinguished Service Professorships made possible by the new development programme of the University.

It was while he was at Cleveland that Prof. Michelson

collaborated with Prof. Morley in their joint experiment; and it may have been for the purpose of that experiment that he invented his particular form of interferometer, with the to-and-fro beams at right angles. Later, he applied it in Paris to the determination of the metre, with an estimated accuracy of about one part in two million.

During the World War, Prof. Michelson re-entered the Naval Service with the rank of Lieutenant-Commander, giving his entire time to seeking new devices for naval use, especially a range-finder, which became part of the U.S. Navy Equipment.

So recently as 1924 he undertook a very accurate determination of the velocity of light, using Mount Wilson and San Antonio, 22 miles apart, as the stations. It is believed that he intends to continue this with a base-line 90 miles long, so as to obtain this great fundamental constant with extreme accuracy.

A Nobel Prize was awarded to Prof. Michelson in 1907, the first American to get one for science; and the Copley Medal, the most distinguished honour of the Royal Society of London, was awarded him in the same year.

The gold medal of the Royal Astronomical Society was presented to Prof. Michelson on February 9, 1923; and the compact exposition of the reasons for that award, by the president, Prof. Eddington, on that occasion will be found in *NATURE*, vol. **111**, p. 240.

As an expounder of scientific progress it is interesting to read Michelson's address given as retiring president of the American Association for the Advancement of Science, which fortunately has been reproduced in *NATURE* of January 11, 1912 (vol. 88, p. 362). It covers a lot of ground and the work of many people; and one characteristic of it is the slight emphasis on his own name in connexion with his own work.

Let us see if we can obtain some idea, not indeed of the whole scope of his work, but of some of the salient and outstanding features of it.

Michelson has touched on many departments of physics, but in optics, the highest optics, he excels. In this subject he can be regarded as the most fertile and brilliant disciple of the late Lord Rayleigh, for his inventions are based on a thorough assimilation of the principles of diffraction, interference, and resolving power; and his great practical achievements are the outcome of this knowledge. In this appreciation a reminder of some of the salient features of that work must be appropriate. But his papers cover far more than general principles; they enter into minute details, as is always necessary when theory has to be translated into experiment and instrumental construction. He has been happy in having at his command the possibilities of equipment provided by enlightened citizens of the United States of America; he has been aided by the singular skill of some instrument-makers both in the States and in Great Britain; but without a thorough grasp of theory his ingenious designs would have been impossible.

Michelson seems to have a special instinct for all

phenomena connected with the interference of light, with a taste for exact measurement surpassed by none in this particular region. The interferometer with which he began became in his hands much more than an interferometer. He applied it to the determination of the standard metre in terms of the wave-length of light, with exact results which will enable remote posterity millions of years hence to reconstruct, if they want to, the standard measures in vogue at this day. He applied it also to analyse the complex structure of spectrum lines, and with remarkable completeness to determine the shape and size of invisible objects, such as to ordinary vision, however much aided by telescopic power, will probably remain mere points of light. *NATURE* is read by many other than physicists, and a rough general idea of how these things were accomplished may be welcomed.

The kind of interferometer dependent on the use of a semi-transparent plate was begun so long ago as 1859 by Fizeau, who thus split a beam of light into two halves, and with the aid of auxiliary silvered mirrors sent the beams round a circuit along identical paths in opposite directions, so as to become reunited at their point of separation. Thus, by alternate concurrences and oppositions of phase, the illumination was redistributed into bands of remarkable brilliance, which bands would shift in position if any cause accelerated one of the half beams and retarded the other.

Michelson modified this arrangement by altering the angle of the auxiliary mirrors, and setting them perpendicular to the light, so as not to send the two beams round a contour, but to reflect each back upon itself. Each half-beam then makes a to-and-fro journey along its own path, the interference fringes being produced, as before, when the beams reunite at their point of initial separation at the end of their independent journeys. The accidents which can happen to such separated beams are of a different character from those operative in the Fizeau arrangement, and it becomes a different instrument.

If we begin with the two paths equal, noting the position of the fringes by a micrometric device, and then gradually lengthen one of the paths by making its perpendicular mirror retreat, the bands will shift so as to interchange bright for dark when the mirror has retreated a quarter-wave length—which, of course, is an exceedingly small amount. If, by a screw motion, we make the mirror gradually move backwards, an eye at the micrometer will see the bands sailing or floating past, in such a way that their passage can be counted; and we can thereby determine how many wave-lengths the mirror has retreated. We might thus cautiously move it back a centimetre, or even a decimetre, and might then, by ingenious devices and different standard

gauges of length, gradually extend the range virtually to as much as a metre: thus counting with extreme precision, and to a small fraction, the number of waves in that length,—using, of course, very homogeneous light, such as is given by a line in the spectrum of cadmium or mercury, or other monatomic substance emitting a simple kind of light.

Now suppose the source of light is not simple: suppose instead of being a single line, it is a double one. Then what will be the effect? The wave-length of the two lines is slightly different. With some adjustments the interference bands may agree in position, so that they are clear and plainly visible: with other adjustments the bright parts of one set may overlap or be superposed upon the dark parts of the other; thus restoring a uniform illumination, and making the bands disappear. A further adjustment in the same direction will cause them to reappear again, and so on periodically. By studying these variations of visibility, and plotting a curve to represent them, after the manner of Rayleigh (see his “Investigations in Optics,” *Phil. Mag.*, 1879 and 1880, or Paper Number 62, in vol. i. of his “Collected Scientific Papers”), the nature of the source can be specified with precision, and the relative intensity of the components of the double or multiple source ascertained.

Perhaps the easiest way of getting a general idea of the process is to employ a very simple interference instrument, such as two parallel slits in a card, mounted in a tube like a taper-holder, to which the eye is applied, and then look at a fine line of light like a luminous hair. Interference bands will be seen, caused by the meeting and overlapping of the beams which have come through the two slits. (Lord Rayleigh describes such an easily-made and popular instrument in vol. iv. of the “Collected Papers,” p. 76.) Now imagine the source of light shifted parallel to itself, through a distance which when multiplied by a reducing fraction (the ratio of the distance between the slits to their distance from the source) will equal half a wave-length of light. The bands will now look the same as before, but the bright bands will be in the dark bands’ places; thus indicating the amount which corresponds to a half wave-length shift. Next, imagine a precisely similar source placed in the original position, and look at the two together. Each will give its own set of bands, but no bands will be visible, because the bright parts of the one will blot out the dark parts of the other. Separate the two sources a little more, or bring them a little nearer together, and in either case the bands will reappear.

We may next proceed to consider what happens when, instead of the two simple sources of light, a square or oblong patch of light is looked at, filling up

the space between the two positions. The thing is now becoming a little more complicated, and a numerical factor will have to be introduced depending on the shape of the source of light. It need not be an oblong; it might be a triangular patch, or a circular disc, or any other simple shape. Michelson made a serious study of what would happen for all manner of luminous apertures, and found that a numerical factor could be introduced appropriate to each simple shape, and drew the visibility curve to be expected under the various conditions. This paper will be found in the *Phil. Mag.* for April 1891; and in September 1892 his later paper applied the curves to determine the peculiarities of spectrum lines employed as the source of light.

Before that, however, Michelson had realised that on Rayleigh’s principles the resolving power of a telescope could be indefinitely increased by using it to form, not an ordinary image of an object, but the diffraction or interference pattern of such an object.

An early paper by Lord Rayleigh on “The Resolving Power of Spectroscopes,” in which the main theory is given, is in the *Phil. Mag.* for March 1874. (See also vol. i. of “Collected Papers,” pp. 216, 420, and 424.)

Early in the century that remarkable genius, Thomas Young, had devised what he called an “eriometer” for measuring the size even of very minute granules by their diffraction pattern,—for example, the rings of the halo formed by such a substance as lycopodium. Rayleigh suggested an extension of this method in his “Encyclopædia Britannica” article, “Wave Theory,” where he gave the theory of different apertures, and refers to previous workers in France and elsewhere. (Paper Number 148 in vol. iii. of “Collected Papers.”)

Michelson pursued the subject into great detail; and in a magnificent paper in the *Phil. Mag.* of July 1890 he suggested the application of interference methods to astronomy. He knew well that the resolving power of a telescope depended on the diameter of its aperture, and that the formation of an image was essentially an interference phenomenon; the minuteness of a point image, and therefore the clearness of definition, depending on the size of the object-glass. But he pointed out that if the aperture was limited to slits at opposite edges—so that no actual image anything like the object would be formed, but only the interference bands which the beams from the two slits could produce—a study of those bands would enable us to infer about the source of light very much more than we could get by looking at its image. For example, suppose it was a close double star, and suppose the slits over the object-glass were movable, so that they could be approached nearer together, or separated the whole distance of the aperture apart. A gradual separation of the slits would now cause the fringes to go through

periods of visibility and invisibility; and the first disappearance of the fringes would tell us that the distance apart of the two components of the star (multiplied by the distance between the slits and divided by the distance of the star) would equal half a wave-length of light. The two components might be far too near together ever to be seen separately, and yet we could infer that the star was a double one; and by further attention to the visibility curve we could infer the relative brightness of the two components and their position relative to our line of sight.

Furthermore, if, instead of looking at a star, we turned the slit-provided telescope on a planet with a disc too small for ordinary measurement, the size of that disc could be estimated from the behaviour of the interference fringes produced by its light in a suitable interferometer, or by the telescope converted into one.

Michelson begins this 1890 paper thus:

"In a recent paper on 'Measurement by Light-waves' it was shown that the limitation of the effective portions of an objective to the extreme ends of a diameter converted the instrument into a refractometer; and although definition and resolution are thereby sacrificed, the accuracy may be increased ten to fifty fold.

"The simplest way of effecting this in the case of a telescope is to provide the cap of the objective with two slits adjustable in width and distance apart. If such a combination be focussed on a star, then, instead of an image of the star, there will be a series of coloured interference-bands with white centre, the bands being arranged at equal distances apart and parallel to the two slits. The position of the central white fringe can be marked from ten to fifty times as accurately as can the centre of the telescopic image of the star.

"One of the most promising applications of the method is the measurement of the angular magnitudes of small sources of light."

Michelson further realises, even at this early date, that by this method the virtual aperture of a telescope may be immensely increased by supplementing it by a pair of receiving mirrors beyond the object-glass, catching the light at 45° , and sending it towards the object-glass, where it is caught by two other mirrors, and sent down towards the eye. The interference-fringes now formed will be as if the two slits were separated by the whole distance of the outer mirrors apart. He then says that, by means of a right-and-left-hand screw, the mirrors are to be separated until the fringes disappear; when the angular diameter of the planet, if its disc is circular and uniformly illuminated, will be the ratio of a wave-length of light to the distance between the mirrors, multiplied by the numerical factor 1.22. This factor, it is interesting to note, was obtained by Sir G. B. Airy so long ago as 1834 (*Camb. Phil. Trans.*) as the appropriate number for a uniformly illuminated

disc, when he was considering the resolving power of a telescope as dependent on the diameter of its object-glass. (See also Rayleigh, vol. i. p. 416.)

Michelson then goes on:

"The chief object of the method proposed is the measurement of the apparent size of minute telescopic objects, such as planetoids, satellites, and possibly star discs, and also double stars too close to be resolved in the most powerful telescope. . . . It would appear that a one-inch glass may be made to do the work now required of a ten-inch."

In view of the extraordinary and sensational interest which has been aroused by the recent application of this method by Michelson himself, with the aid of collaborators at Mount Wilson Observatory, Pasadena, California, and with the hundred-inch telescope established there, it may be interesting to quote here part of the conclusion of this paper of Michelson's of date 1890:

"(1) Interference phenomena produced under appropriate conditions from light emanating from a source of finite magnitude become indistinct as the size increases, finally vanishing when the angle subtended by the source is equal to the smallest angle which an equivalent telescope can resolve, multiplied by a constant factor depending on the shape and distribution of light in the source and on the order of the disappearance.

"(2) The vanishing of the fringes can ordinarily be determined with such accuracy that single readings give results from fifty to one hundred times as accurate as can be obtained with a telescope of equal aperture."

Then, after a few more clauses, comes this remarkable anticipation:

"If among the nearer fixed stars there is any as large as our sun, it would subtend an angle of about one hundredth of a second of arc; and the corresponding distance required to observe this small angle is ten metres, a distance which, while utterly out of question as regards the diameter of a telescope-objective, is still perfectly feasible with a refractometer. There is, however, no inherent improbability of stars presenting a much larger angle than this; and the possibility of gaining some positive knowledge of the real size of these distant luminaries would more than repay the time, care, and patience which it would be necessary to bestow on such a work."

There seemed little hope at that time, and certainly no reasoned expectation, that any stars, except perhaps some of the very nearest, could have discs big enough for perception and measurement even by this virtual telescope of thirty feet aperture. But in the course of the quarter of the present century through which we have lived, mathematical astronomers have been busy. When the history of recent stellar astronomy comes to be written, some living names such as H. N. Russell, Shapley, Eddington, and Jeans will shine as stars of the first magnitude. The possibility of giant stars—so named by Hertzsprung—has come above our mental

horizon; and Eddington made the notable prediction that a star like Betelgeuse must be in a highly rarefied state at a tremendously high temperature, and that it would be swollen out by the pressure of light to a size almost comparable with the dimensions of a solar system, although it could not contain very much more matter than, say, two or five times our sun. His argument, in brief, is that the spectrum of a young red star like Betelgeuse shows that it cannot be radiating furiously. Why then is it so conspicuous an object to our vision? It can only be because it is of enormous size, its density perhaps a thousand times less than atmospheric air. By utilisation of the data available in the light of his theory of stellar constitution, Eddington made an estimate of the diameter of the star.

So with great skill Michelson and his collaborators got the interferometer to work. After many preliminary adjustments, on December 13, 1920, Dr. F. G. Pease at Mount Wilson, with Michelson's apparatus, measured the diameter of a star for the first time, using Betelgeuse for the purpose. The interference-fringes formed by the star were observed, the object mirrors were gradually separated, and it must have been a joyful moment when, as they grew farther and farther and farther apart, the fringes at the eye end became less distinct and ultimately disappeared. The distance apart of the mirrors now, multiplied by the proper fraction, gave the angular dimensions of the star—a thing which had never before been observed in the history of the world. An estimate of the star's distance gave its actual diameter, and confirmed Eddington's prediction!

Other stars have since been measured, and the giant stars well deserve their name. Moreover, an instrument has been put in the hands of posterity to the power of which we can scarcely set a limit in investigating utterly invisible details, both about the heavenly bodies and about atoms, by the new and powerful method of analysing the radiation which they emit.

The form of instrument adapted to the heavens is, however, not applicable to the atoms. The spectrum of atomic radiation is formed by a grating; and Rayleigh showed (see "Collected Papers," page 427, vol. i.) that the power of a prism spectroscope is expressed approximately by the number of centimetres of available thickness of glass, which is one form of saying that, to get high definition or separating power, we must use interference depending on a great number of wave-lengths retardation. The resolving power of a grating depends on its total aperture, which must always be limited to inches, since accuracy of ruling over the whole breadth is essential; but one can have retardation gratings, where the interference is caused, not merely by extra distance due to angular slope of path, but by the

retarding effect of a dense substance, such as gelatine or something transparent, instead of by the successive obliterations or dark spaces of the grating. There would seem to be no particular advantage in that; but Michelson perceived that the retardation principle might be employed so as to make a grating which combined with its own effect the resolving power of a prism. A slab of glass a centimetre or more thick might be used to give the necessary lag in phase of many thousand wave-lengths, and thereby secure a definition and resolving power unthought of before.

So Michelson designed the Echelon spectroscope, consisting of thick slabs of glass, each protruding a millimetre or so beyond the other—a staircase spectroscope. When he brought this out in 1898 in the *Astrophysical Journal*, vol. 8, p. 37 (see also *Am. J. Sci.* and *Camb. Phil. Trans.* for 1898-99), it seemed as if such an instrument could scarcely be constructed, or, if it were constructed, that the number of slabs must be very few. But I understand that the skill of Messrs. Adam Hilger has sufficed to construct an Echelon with so many as fifty slabs; and this, or some similar Echelon, is now a regular instrument in the examination of the minute structure of spectrum lines. Naturally it cannot cover a great range of the spectrum; it has to be fed with light of a nearly definite refrangibility, and then it analyses the light, as a high-power microscope analyses a small range of visible structure.

The striking thing about all these instruments is that they give us, by inference, information about the invisible; and further developments are to be expected. For example, in connexion with stellar variation Prof. Shapley had proposed a theory of periodic pulsation, which would enable a single star to vary without an eclipsing companion; and this hypothesis was taken up by Eddington for the case of the Cepheid variables.

Subsequent repetition of the Mount Wilson interferometer-measurements on Betelgeuse, after an interval, seems to show that variations in diameter actually occur; and probably by this time much more information has been obtained than can here be summarised. But it illustrates the power of the instrument to confirm the indications of theory.

Before leaving this part of the subject it may be interesting to refer physicists to Paper 199 in vol. iv. of Rayleigh's "Collected Papers," also in *Phil. Mag.* for November 1892, in the form of a letter from Lord Rayleigh to Prof. Michelson about the interference bands of nearly homogeneous light.

I will only add further that Michelson has applied his instrument to examination of the Zeeman phenomenon, with inferences about the multiple character of many of the lines, as recorded in his paper on "Radiation in a Magnetic Field" (*Phil. Mag.* for July 1897 and April 1898).

References to Michelson's earlier papers on this subject are :

A general theory of interference-fringes in a refractometer, in *Phil. Mag.* for April 1882; a mathematical paper on the visibility of interference-fringes in the focus of a telescope, in *Phil. Mag.* for March 1891; on the application of interference methods to spectroscopic measurement, in *Phil. Mag.* for September 1892.

Now I find that I have omitted all reference to what is the popularly best-known work of Michelson, the application of his interferometer to determine if possible the motion of the earth through the ether. The speed expected was of the order one-ten-thousandth of the velocity of light; but since the journey of the light in the instrument is a to-and-fro journey—one half-beam going as nearly as possible with and against the hypothetical stream of ether, while the other half-beam goes at right angles to that direction—the amount to be measured was not one-ten-thousandth but the square of that quantity; that is to say, the observer had to measure one part in a hundred million—no easy matter. The apparatus has been so often described, and the theory so often given, that there is no need to say much about it. The interferometer was mounted on a stone slab floating in mercury, and the whole observation conducted with great care. The result was zero; and that zero was used afterwards as the corner-stone of the great and beautiful edifice of relativity.

That so extensive a structure should have been initiated by a zero result is philosophically curious, and shows great faith in the trustworthiness of the experimenters, Michelson and Morley. I am told that Morley, before he died, was rather overawed by the consequences deduced from that experiment, and was anxious that it should be repeated with still greater care, and under many conditions, some of which were indicated in their early paper (*Phil. Mag.*, December 1887), entitled "On the Relative Motion of the Earth and the Luminiferous Æther," by Albert A. Michelson and Edward W. Morley. For even then they suggested, on page 459, that perhaps at moderate distances above the level of the sea, or at the top of an isolated mountain peak, the relative motion might be perceptible.

Such repetition has, as we know, lately been attempted, with results which at present seem too unlikely to be credited; but as Prof. Miller's experiments are *sub judice*, I will say no more about them. I know that Michelson agrees with me (or did in 1920) that there was nothing in the original Michelson-Morley zero result to justify a denial of the existence of the ether; nor is a positive result necessary to re-establish it. The theory of relativity (so called) has led to a search for *absolute* conditions, independent of accidents of motion, the same for all observers;

and this search for the absolute will continue, being justified by its brilliant success, quite apart from the corner-stone which is still part of the structure. On the whole, the theory rather tends to strengthen our philosophic conviction of the ether as an integral and absolute ingredient in the universe, although, for purposes of calculation and attainment of results, it—like many other things—can be safely ignored.

I append references to such papers as were published in the *Phil. Mag.* on other subjects, for the convenience of any who would like to look at them:

"Note on an Air-Thermometer" (September 1882); "A Method for Determining the Rate of Tuning-Forks" (February 1883); "On the Relative Motion of the Earth and the Luminiferous Æther"—the first Michelson and Morley paper (December 1887); "On a Method of making the Wave-length of Sodium Light the Actual and Practical Standard of Length" (December 1887); "A New Harmonic Analyser"—Michelson and S. W. Stratton (January 1898); "The Velocity of Light" (March 1902); "The Relative Motion of Earth and Æther" (December 1904); a short mathematical paper on "Diffraction" (April 1905); "On Metallic Colouring in Birds and Insects" (April 1911).

OLIVER LODGE.

Discovery and Dialectics.

Science and Scientists in the Nineteenth Century. By the Rev. Robert H. Murray. Pp. xvii + 450. (London: The Sheldon Press; New York and Toronto: The Macmillan Co., 1925.) 12s. 6d. net.

DR. MURRAY, who is rector of Broughton and is distinguished as a historical writer, says: "In a sense my book forms an assault upon science, or to put it more correctly, upon the preconceptions that lie at its base far more than most F.R.S.s are aware." It is therefore permissible that a review of it in this journal should be, in a sense, a reply; for the book is very well written, it is interesting to read, and its data are culled from a wide range of the annals of men of science themselves; hence what one must call its misconceptions are likely to impress themselves upon a fairly wide public. On the other hand, there is a great deal in it from which scientific readers cannot fail to draw a very salutary lesson.

The virtue of the book lies in the emphatic warning, well hammered home by numberless examples, against pooh-poohing new ideas. The treatments of Jenner, J. Y. Simpson, Lyell, Joule, Darwin, Pasteur, and Lister by their contemporaries, together with less familiar and more briefly handled cases, are adduced in evidence of the futility of—may one coin a word?—Pooh-poomposity and the shut mind. It is a most valuable sermon on personal faults. Dr. Murray deplors the spending of time and energy which is exacted from discoverers by their need to silence hostile