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THE PAST TWENTY YEARS OF PHYSICAL ASTRONOMY¹

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A COMPLETE survey of the progress of physical astronomy during recent years would be so formidable an undertaking that to attempt to cover the entire field would require a whole series of lectures rather than a single evening. So I shall limit myself to the attempt to trace for you the development of only one or two of the more recent conceptions and methods of modern astrophysics and to show how greatly they have enlarged the views which we held, even as recently as the first ten years of this century. From the standpoint both of the results accomplished and the outlook toward the larger problems of astronomy there probably has never been a period quite comparable to that of the past twenty years.

The underlying cause of this remarkable progress has been the intimate relationship which has developed between physics and astronomy, so that important discoveries in the one science have reacted immediately upon the other and found far-reaching applications almost at once. A quarter of a century ago an immense amount of observational material had been collected in our physical laboratories and observatories to the interpretation of which the key was almost entirely lacking. We could hardly hope to understand the behavior of matter in the distant stars when the mechanism of the light given out by a candle flame was still quite unknown to us. So in astronomy, as in physics, a great new field was opened up by the fundamental discoveries of Rutherford, Bohr and many others on the structure of matter and the nature of radiation.

It is a commonplace to say that all our primary knowledge of stars is derived from the light which they give out, where the term *light* is used in a general way to include both visible light and invisible radiation, such as heat or X-rays. From a star's light we can measure its position, its slow movement across the sky, its brightness and its distance, but we can do a great deal more. By analyzing its light we can study its individuality, which is defined almost as uniquely by the faint rays of light which reach us as is the personality of a friend by the actions of his daily life. The main problem of physical astronomy,

¹ Address given in San Francisco on April 16, on the occasion of the presentation of the Bruce medal by the Astronomical Society of the Pacific.

accordingly, is to interpret the inscriptions which we find contained in these stellar records, which we call the spectrum.

To an observer who looks at the stars on a clear night the differences of color are very noticeable. Betelgeuse is red, Sirius is blue-white. If these stars are looked at through a piece of red glass, Betelgeuse still looks bright while Sirius becomes comparatively faint; through blue glass, on the other hand, Betelgeuse is very faint and Sirius remains bright. This means simply that most of the light of Betelgeuse is red light and that of Sirius blue light. If, instead of using colored screens, we look at the stars through a glass prism we obtain all the colors at once drawn out into a band which is known as the spectrum. Red lies at one end and violet at the other, with yellow, green and blue lying between. The red portion of the spectrum of Betelgeuse is very bright and the blue faint, while in Sirius the reverse is the case. We are all familiar with the fact that the color of the filament in the bulb of an electric lamp is red when the voltage is low, and quickly turns to white when the voltage becomes normal. If we should look at its spectrum we should see mainly red light when the filament first begins to glow, and much more blue light as the temperature rises. Hence we can reason directly that the temperature of Betelgeuse is low and that of Sirius very much higher because its blue light is so intense. Actually, the temperature of Betelgeuse is about 3,000° Centigrade (5,400° Fahrenheit) and that of Sirius is about 10,000° Centigrade.

We see then that the band of colored red light which we call the continuous spectrum gives us valuable information regarding physical conditions in the stars. Of much greater importance, however, is the network of dark lines which crosses the continuous spectrum, and which we see when a narrow slit is used in front of our glass prism. A spectrum of lines is formed whenever we heat a gas to the point at which it sends out light. For example, if we look with our prism at one of the long horizontal mercury lamps, used so extensively in the illumination of manufacturing plants, we see a number of colored bright lines. The most intense of these is a green line which is responsible for the rather ghostly color of the light, but there are other lines colored blue, yellow and red. Together these lines form the characteristic spectrum of mercury vapor. In the same way, if we pass an electric current between the ends of two iron rods and form an electric arc, the hot iron vapor gives us some two thousand bright lines, colored according to their position in the spectrum, which are characteristic of iron, and of iron alone. So each element has its own groups of spectral lines which distinguish it uniquely from every other element.

If we now compare directly the lines of the different elements with the dark lines which cross the continuous spectrum of the sun or of most of the stars, we find immediate evidence for the presence of the great majority of the elements in their atmospheres. The lines are dark as seen against the brilliant background, instead of bright as in our laboratory sources, but in number, position and intensity the correspondence is almost perfect. This gives us a means of analyzing the composition of the sun or of the most distant stars which we can observe with our spectroscope. The latest studies of the sun made in this way give definite evidence of the presence of fifty-seven of the elements known to the chemist on the earth. Six have been added to the number within the past few months, and there can be little doubt that all the others are present as well, our failure to observe them being due to physical conditions present in the sun which prevent their spectral lines from appearing with sufficient intensity.

This method of analyzing spectra in a qualitative way has been known for many years. So, too, has the extremely important fact that the spectral lines are displaced by small amounts when the source of light and the observer are approaching or receding from one another. If a star, or the edge of the sun due to its rotation, is approaching us more waves of light reach us in a second than if there were no relative motion. Hence the length of the waves is shortened slightly, and the spectral lines are shifted a trifle from their normal positions toward the violet end of the spectrum. Similarly, if a star is receding from us the displacement is toward the red end of the spectrum. The quantities to be measured are small, but they can be determined with remarkably high precision, and from them we can obtain the motions of the stars toward or away from the earth. This forms one of the most fruitful fields of investigation in all astronomy, for the results derived from it enable us to find at what rate our sun is moving in space, how the motions of the stars in our system are related, and how even the enormously distant universes of stars, the spiral nebulae, are moving with respect to us and to one another. The Lick Observatory was one of the pioneers in this type of research and has maintained its leading position in the accuracy with which it has carried on these difficult and exacting observations. The most recent publication of the Lick Observatory by Dr. Campbell with the collaboration of Dr. Moore forms a landmark in this field, and bears remarkable testimony to the skill and resourcefulness of these two eminent members of our society.

The situation at the beginning of the century as regards the interpretation of spectral lines, how they originate and what information they can give us con-

cerning physical conditions in the sun and stars was much less satisfactory. We knew almost nothing about how an atom gives out light, and the different lines of the spectrum were necessarily classed together in most of our investigations. One important difference, however, had been recognized by Sir Norman Lockyer between some of the lines produced in the electric arc and the electric spark. In the spark spectrum of different elements certain lines were found to be much more intense than in the spectrum given by the arc, and these lines, to which Lockyer gave the name "enhanced," he considered as due to a modified form of the element arising from some sort of decomposition of the atom produced by the high temperature of the spark. In this hypothesis modern research has shown that he was substantially correct.

About 1905 a few studies were commenced which began to throw light upon the differences in behavior among different spectral lines. One of these was made at the Mount Wilson Observatory, and I should like to describe it in some detail, partly because it is of interest historically, but more because it illustrates the extent of the applications which a comparatively simple research may come to acquire. It is one more illustration, so frequent in scientific work, of the old Biblical story of how Saul went out to seek his father's asses and found a kingdom.

One of the earliest photographs of the spectrum of a sun-spot was obtained at Mount Wilson in 1905, nearly all observations before that time having been visual. Now the principal difference between the spectrum of a sun-spot and that of the general surface of the sun consists in the marked change in the relative intensities of great numbers of lines, some being weakened in the spot spectrum and others greatly strengthened. In many cases lines barely visible in the solar spectrum become very prominent in the spot. Many of the weakened lines we soon recognized as being enhanced lines, that is, lines stronger in the spectrum of the spark than of the arc, but we had no adequate explanation to account for the behavior of the strengthened lines. The attempt to find such an explanation was the object of an investigation begun at Mount Wilson a little more than twenty years ago.

As a working hypothesis we made the assumption that the temperature of sun-spots is below that of the general surface of the sun. Our problem, then, was to see whether we could duplicate under conditions of varying temperature in the physical laboratory the observed behavior of the spectral lines in sun-spots. For this purpose we used the iron arc, the supply of electric power on Mount Wilson being at that time quite inadequate for an electric furnace. The method used was to pass a powerful current through the arc

and photograph the spectrum: then to reduce the current to as low an amount as possible and on the same plate to photograph the spectrum again. Since the amounts of energy passing through the arc were very different in the two cases it could fairly be assumed that the temperatures were also different. Later we simplified the method by magnifying greater the image of the arc and comparing the spectrum of the outer cooler flame with that of the hotter core near the iron poles.

The study of the photographs at once led to definite results. It was found that many iron lines were relatively much more intense in the flame than in the core of the arc, and that these were without exception just the lines which were strengthened in the spectrum of sun-spots. On the other hand, lines unaffected in different portions of the arc remained essentially unchanged in sun-spots. So we were able to classify the iron spectrum into groups of high and low-temperature lines, and to make an accurate comparison with the corresponding lines in the sun-spot spectrum, which showed remarkably good agreement. Soon afterward some experiments made in Pasadena with an electric furnace of temporary construction showed that the results obtained with the arc were definitely to be ascribed to the effects of temperature, and not to any electrical phenomena present in the arc. Finally, conclusive evidence for the low temperature of sun-spots was afforded by the discovery of the presence of bands in the spectrum, due to the existence of compounds which can exist only at reduced temperatures.

A few years later, when the Pasadena laboratory was completed, a thorough investigation of the spectra of many elements was carried out by Dr. King, and the lines were arranged in classes according to their behavior under known conditions of temperature. These results have confirmed and extended the earlier work at Mount Wilson, and have proved of immense value to all modern investigators who have analyzed spectra and studied the internal structure of the atom.

You will readily see that the discovery of the temperature classification of spectral lines meant much more than a means of interpreting the behavior of lines in the sun-spot spectrum. It formed essentially a new method of attack upon the physical problems of the sun and stars, especially as it was soon supplemented by other results showing the behavior of spectral lines under varying conditions of density and pressure. A partial breach had been in the hitherto almost impenetrable wall surrounding the interpretation of the spectrum.

The fundamental discoveries necessary to the adequate explanation of these results of observation came in the years following 1911 from the physical labora-

tories of Europe. Sir Ernest Rutherford first suggested that an atom of matter is an electrical structure built up out of natural units of positive and negative electricity. The positive charge is concentrated into an exceedingly minute nucleus; the negative charge extends over a relatively much larger region which, however, is only about one one hundred millionth of an inch in diameter. For a dozen years following the work of Bohr, every one thought of the electrons, the units of negative electricity, as describing tiny orbits around the nucleus, like planets around the sun. Now, since Schrödinger has developed his complicated but very successful "wave-theory," we are much less dogmatic about the exact position and motion of the negative electricity. We know, however, that under increasingly violent disturbance the negative charge can be split off from the atom, one natural unit at a time, to escape as free electrons; and we have good reason to believe that some of these unit charges are held very close to the nucleus and firmly bound, while others are near the outside of the atom and much more loosely held. The number of electrons outside the nucleus ranges from one for the simplest atom, hydrogen, and two for the next, helium, to twenty-six for iron, eighty-two for lead, and ninety-two for the heaviest known atom, uranium. A great many of the properties of atoms can be explained by means of a structure of successive shells of electrons. The laws of atomic structure fix the maximum number of electrons which can go into any one shell, so that a heavy atom like one of iron or lead contains several complete shells of electrons and an incompletely filled one on the outside.

Our immediate interest in the atom is concerned with the way in which it gives out or absorbs light. In an atom in its ordinary or normal state all the electrons are as close to the nucleus, which attracts them strongly, as the laws of atomic structure permit them to be. It is possible, however, by various means to raise one or two electrons into new positions which without serious error we may think of as farther from the nucleus. In this condition, known as an "excited" state, the atom is loaded with energy. If left to itself it will usually change back into a less excited state after something like a hundred millionth part of a second, and to do so it has to unload some of its energy, which is given out in the form of light. By a law of nature which appears to be one of the most fundamental that human science has yet discovered, but which remains utterly unexplained, the number of vibrations a second in the emitted light is exactly proportional to the amount of energy which the atom unloads. If this light is observed with a spectroscope we see a sharp line in a position in the spectrum defined accurately by the energy unloaded by the

atoms which produced it. Since even the simpler atoms have dozens of excited states and the more complex several hundred—Dr. Russell has found 364 excited states in the case of the neutral titanium atom—the intricate character of the spectrum of many of the elements is easily understood.

In all these excited states the atom retains all its electrons, but it is possible through more violent disturbance, electrical or otherwise, to remove an electron completely. The atom is then called ionized and can exist in many different excited states. Changes between these states produce a whole new spectrum of lines, not one of which except by chance coincides with a line of the neutral atom. There is abundant evidence to show that the enhanced lines of the various elements come from ionized atoms with one electron missing, and the ordinary are lines from neutral atoms with all their electrons present. Lockyer's bold hypothesis that the atoms giving the enhanced lines are partly decomposed is, therefore, substantially true, only it is a different kind of decomposition from that known to the chemist. It has been found possible to remove not only one, but two, three, or even more electrons from the atom. In these states, however, the energy emitted is usually so great that the resulting spectral lines lie far in the ultra-violet, where we could not observe them in the stars, or even in the sun.

With one more word we shall be ready to apply our knowledge. The spectra of the sun and stars show dark lines. This means that light has been absorbed by the reversal of the process already described. An atom can pick up energy from light passing by it and become excited, rising from a state of lower to one of higher energy: but it can do this only if the number of waves per second in the light is exactly sufficient to furnish the necessary energy for the change. Hence atoms of a given kind absorb a definite set of sharp spectral lines, identical in position with those which they emit. Any particular atom, however, can not absorb all the lines of the spectrum, but only such as correspond to a transition from its particular state to some other, and can absorb only one of these at once. So when we find thousands of absorption lines in the spectrum of iron, we realize that among the trillions of atoms present in the iron vapor thousands of different processes are occurring. The work of the last five or six years has gone so far in the interpretation of complex spectra that we can take almost any line in a stellar spectrum and say not only what sort of atom produced it, but also, so far as energy transitions go, just what the atom was doing at that time.

Suppose now that we have a long tubular electric furnace in our laboratory and pass white light through it. Inside our furnace is a bit of metallic

sodium. At a low temperature, far below a red heat, the sodium begins to vaporize, and in the spectrum of the light which has come through the vapor we find the familiar pair of dark lines in the yellow, as well as others in the ultra-violet. But if we heat our furnace to 2,000° Centigrade we shall find new absorption lines appearing in the orange, the green and the blue, no trace of which could be obtained with the cooler vapor.

The reason is not far to seek. In the cooler vapor practically all the atoms are in the normal state of lowest energy. Such atoms can absorb some of the spectral lines, but not all; and though by this absorption they are raised to excited states each one falls back again so soon that the number of atoms per million which are excited at any given instant is very small. But as we heat our gas hotter and hotter the collisions of its atoms become violent, and as a result a small but steadily increasing fraction of the atoms will be raised to the excited states and absorb other lines.

We see now why the lines belong to different temperature classes and just what these classes mean. The low-temperature lines are absorbed by atoms in unexcited or mildly excited states; the high-temperature lines by highly excited atoms. We see, too, what the relatively great strength of the low-temperature lines in the spectra of sun-spots means. There are more unexcited atoms in the sun's atmosphere above a spot than elsewhere, and this means that the atmosphere there is cooler.

This is not all, however. At a sufficiently high temperature the collisions between the atoms of a gas become so violent as to knock electrons completely off from some atoms and the gas becomes partially ionized. The process is self-limited, since the wandering free electrons will sooner or later meet with other ionized atoms and recombine with them. But the hotter the gas the more numerous will be the ionized atoms and the fewer the neutral atoms. At the temperature of the sun elements which require less energy for the removal of an electron, like calcium or scandium, are very considerably ionized; those which require more, like iron and silicon, are much less ionized. So the enhanced lines of calcium are strong and those of iron relatively weak. Above sun-spots, where the gas is cooler and the proportion of the neutral atoms is greater, the arc lines therefore become stronger, especially for the more easily ionized elements, and the enhanced lines weaker, especially for the elements which are hard to ionize. The combination of these principles affords a detailed and complete explanation of the peculiarities of the sun-spot spectrum which have so long been extremely puzzling.

There is another factor in the process of ionization which is of equal importance in the study of the sun and stars. Let us suppose that we have a mass of gas at a given high temperature. If it is dense the atoms and electrons will be close together, and the chances of their meeting and recombining will be good. But if the gas is allowed to expand and become rarefied the chances of recombination become steadily less. The percentage of atoms which are ionized increases therefore as the pressure diminishes.

This solves a solar puzzle of long standing. At the time of a total eclipse of the sun we can observe its upper atmosphere, the chromosphere, and measure the heights to which the different spectral lines extend. We then find that the enhanced lines of the different elements rise to a much greater height than the low-temperature lines. For example, the H and K enhanced lines of calcium reach a height of seven thousand miles and the blue low-temperature line λ 4227 a height of only three thousand miles. Since the top of the chromosphere should be cooler, if anything, than the bottom, we should expect the low-temperature line to be stronger at the top. The difficulty was solved by Saha, the Indian physicist, in 1920. Though the temperature is probably about the same throughout the depth of the chromosphere, the pressure and density must be far lower at the top than at the bottom. In the lower regions some neutral calcium atoms are present and give the low-temperature line; in the upper regions all atoms are ionized and the line due to the neutral atoms disappears.

One immediate application of this modern theory is to the spectra of the stars. We have every reason to believe that there are no great differences in the composition of the heavenly bodies, and that all the elements recognized upon the earth are present in them. Why, then, do we not see in their spectra the lines of all these elements? The answer is a very simple one. The sun and the stars are too hot or too cold, too rare or too dense to show all the lines at the same time. As we have seen, it takes much more energy to rob some elements of their electrons than it does others. A sun-spot and the red stars are comparatively cool, and the temperature is high enough to bring out strongly only those lines of the elements which require little energy for their excitation. So the low-temperature lines are strong and the lines of ionized elements are weak. At the higher temperature of the general surface of the sun the ionized lines become stronger. When we come to the hottest stars the elements become completely ionized, the lines due to the normal atom disappear and we have a spectrum consisting solely of lines due to very

highly excited atoms. The spectra of the hottest stars, accordingly, are very simple, consisting of lines of ionized helium, doubly and triply ionized oxygen, nitrogen and one or two other elements. It would be quite possible to conceive of a star so hot that it had no lines at all, at least in the part of the spectrum we can observe. The temperatures of the hottest stars we know are certainly upward of $30,000^{\circ}$ Centigrade ($54,000^{\circ}$ Fahrenheit), and may in some cases run as high as $100,000^{\circ}$ Centigrade. At somewhat lower temperatures the normal helium lines begin to appear, then the lines of the ionized metals, such as iron, calcium and many others, and finally those due to the neutral atom of these elements. The spectra of the cooler stars, therefore, such as our sun, Arcturus, or Betelgeuse, with temperatures ranging from $6,000^{\circ}$ to $3,000^{\circ}$, are very complex and rich in lines, the normal atom of iron alone contributing about two thousand lines to the observable part of the spectrum. Hydrogen is the only element to show lines in the spectra of practically all the stars, affording strong evidence of its extreme abundance throughout all space.

If we know the temperature and pressure of a gas the degree to which an element is ionized can be pretty accurately calculated. As we have already seen, the temperatures of the sun and the stars can be determined from such considerations as the color of their light, and by utilizing our knowledge of the intensities of the enhanced lines we can derive the pressures in the stellar atmospheres. In this way we find that the pressure in the sun's atmosphere is not more than one ten-thousandth part of the earth's atmosphere, and that, though it is many hundreds of miles deep, the whole quantity of gas in it is not more than would be contained in a layer of common air a foot or two thick. This is a very remarkable conclusion, but it is confirmed fully by the fact that a layer of gas in the laboratory an inch thick, and by no means all composed of metallic vapor, will give absorption lines stronger than those in the solar spectrum.

The question may fairly be asked why, if the sun's atmosphere is so very tenuous, we see a sharp edge and do not see down deeper into its interior. Ionization and the free electrons produced by it again give the answer. An ordinary gas, like atmospheric air, scatters a little of the light which passes through it, so that distant mountains, even in the clearest weather, are seen through a bluish haze. Various investigations have shown that an ionized gas acts in the same way, but many thousands of times more strongly, and that the haziness increases very rapidly with the density. Consequently, the sun's atmosphere, even at its very low density, becomes filled with an "electron haze," which prevents us from seeing deeply. Such

a great flood of energy is flowing through it from the far interior of the sun that this haze appears intensely luminous and gives us the brilliant visible surface.

Recently we have commenced at Mount Wilson an attempt to determine the relative amounts of the various elements in the atmospheres of the sun and stars. For this purpose groups of related lines called "multiplets" are used, in the production of which it is possible to calculate from theory the relative numbers of atoms involved. On comparing the intensities of these lines in the solar spectrum we find that fully a million times as many atoms are active in producing the strongest lines as in giving one which is barely visible.

Using the same principles in the case of several of the brighter stars whose spectra can be photographed on a very large scale, we find that the amount of vapor of iron, titanium and similar metals in the atmospheres of the great red stars Betelgeuse and Antares is something like one hundred times greater per square mile of surface than for the sun. Most of the stars which have been studied so far are, in reality, far brighter than the sun, and have very extensive atmospheres. Procyon, the only star roughly comparable in brightness to the sun, has about the same amount of atmosphere. In the redder stars the low-temperature lines are much stronger, in comparison with the high-temperature lines, than in the sun. When the corresponding numbers of atoms are found, a fairly simple calculation gives the temperatures of the star's atmosphere. The resulting values range from $3,000^{\circ}$ for Betelgeuse to $9,900^{\circ}$ for Sirius and are in excellent agreement with those found from the color of the light.

The enhanced lines of iron and titanium, due to the ionized atoms, are also stronger in Betelgeuse and Antares than in the sun. In view of the much lower temperature we might expect them to be weaker; and it appears that they must be produced in a region of very low pressure; in other words, in the very extensive chromospheres. The hydrogen lines, which are absorbed only by hydrogen in a highly excited state, might be expected to be weaker in these cool red stars. They are actually stronger than in the sun and appear also to arise in the chromosphere. This apparently chaotic set of facts is brought into intelligible order by the modern theory of stellar atmospheres.

Two things determine the equilibrium of a star's atmosphere, the force of gravity and the amount of heat which flows outward per square mile of its surface. The former controls the rate at which pressure increases in the deeper layers, while the latter fixes the temperature of the visible surface and also provides an upward radiation pressure which holds up

the atmosphere against gravity and makes it far more extensive even in the sun than it would otherwise be. When gravity at the surface is small the pressure and density in the atmosphere are low and the electron haze is thin. We, therefore, see down through more material, and the total quantity of atmosphere above a given area of the surface is large. At the same time, owing to the lower pressure, the gas is more highly ionized than in the sun, and the enhanced lines are relatively stronger. Radiation pressure, moreover, is stronger in comparison with gravity and can support a more extensive atmosphere in which ionization is high. This still further strengthens the enhanced lines, and also those of hydrogen, which, having the lightest atoms, is easily supported.

The special characteristics which are thus broadly outlined are exactly those of the giant stars, while the much fainter dwarfs show the opposite peculiarities. But why should low surface gravity be associated with great brightness in a star? The answer comes from the famous work of Professor Eddington, which shows that the brightness of a star depends mainly on its mass and increases very rapidly as this increases. For stars of the same mass but different sizes both gravity and radiation pressure diminish as the diameter increases, but in the same proportion, and it can be shown from this that the extent of atmosphere will be a good deal the same for all. But for stars of different mass, whatever their size, the radiation pressure increases much faster than does gravity, and the massive stars should have much more extensive atmospheres and chromospheres than the less massive stars.

This brings us at once to the last application which I shall attempt to make of our theory, that to the determination of the intrinsic brightness and distances of stars. Stars may appear bright to us because they are intrinsically very luminous or because they are very near. For example, the two stars Procyon and Betelgeuse appear in the sky of nearly the same brightness. We know, however, that Betelgeuse is very much farther away, and that if they were at the same distance Betelgeuse would appear at least one thousand times as bright as Procyon. We might then say that if the intrinsic brightness or candlepower of Procyon is 1, that of Betelgeuse is 1,000.

It was nearly fifteen years ago that we made our first attempts at Mount Wilson to learn whether the intrinsic brightness of a star had any influence on its spectrum, the work being a direct outgrowth of our study of the sun-spot spectrum and the temperature classification of spectral lines. Knowing from direct measurement the distances and hence the intrinsic brightness of many stars, we could compare directly the spectrum of a very luminous or giant star with

that of an intrinsically faint or dwarf star of nearly the same temperature. This showed at once that many of the enhanced lines and those due to hydrogen were very strong in the giants and weak in the dwarfs, while the behavior of other lines, mainly low-temperature lines, was just the reverse. With the aid of stars of known brightness it then proved comparatively simple to establish a relationship which would give us the intrinsic brightness of a star as soon as the relative intensities of these lines were known. The distance is obtained at once from an easy calculation based on the intrinsic brightness, as compared with the apparent brightness in the sky.

The method has two very considerable advantages. It is rapid, since a single photograph of spectrum will yield a value of the intrinsic brightness and distance of a star; and it is applicable to stars whose distances are so great that the usual direct method of measurement can not be used. The nearest star to us is at a distance of twenty-five million million miles, and most of even the brighter stars are from ten to one hundred times farther away. As seen at these greater distances the earth's orbit becomes almost vanishingly small. In the spectroscopic method, however, the intrinsic brightness of a star can be determined equally well whatever its distance. Hence the method has been used extensively at several observatories during recent years, and has nearly tripled the number of stars for which we know the distance.

A very interesting result of this increase in our knowledge of the real brightness of the stars is the extraordinary range which we find. There is a faint star recently observed by van Maanen which gives out only one fifty thousandth part the light of our sun; on the other hand, the bright southern star Canopus is at least ten thousand times as luminous as our sun, and there are doubtless other stars still brighter or fainter than those which have been observed. So we have a range of at least five hundred million, and probably one thousand million, in the quantity of light which the stars are pouring out.

The spectral differences between giant and dwarf stars and the spectroscopic method of deriving the real brightness of the stars find a satisfactory explanation in the theory we have been discussing. Eddington has shown that the intrinsic brightness of a star is directly related to its mass and increases with it. As we have already seen, the more massive a star is, the more extensive is the atmosphere which it can support by the outward pressure of its radiation. Such an extensive atmosphere of low density favors the ionization of the atoms and we should expect to find the enhanced lines strong. On the other hand dwarf stars of small mass would have shallow atmospheres, and we should expect the enhanced lines to be weak and

those due to the normal atom strong. This is in agreement with observation. Our spectroscopic method of finding the real brightness of stars appears, therefore, in the main to be a method of finding their masses. The immense size of such stars as Antares, with a diameter of about two hundred million miles, affords excellent direct evidence for the existence of the extensive atmospheres predicted by our theory.

I realize fully that in this very condensed statement it has not been possible to touch on some of the most interesting developments of modern physical astronomy, such, for example, as the processes which maintain a star's energy, and the source of supply of its enormous radiation. Yet the conception of how modern physics interprets the spectrum and modern astronomy applies it, and how largely both sciences are based upon the ultimate structure of matter and the nature of radiation, is a most illuminating and inspiring one, however inadequately I have been able to bring it before your minds this evening.

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MOUNT WILSON OBSERVATORY

CHARLES HENRY GILBERT

DR. CHARLES H. GILBERT was born on December 5, 1859, at Rockford, Illinois, his parents removing later to Indianapolis. He died suddenly at Palo Alto, on April 20, 1928, from a paralytic stroke. His father, Edward Gilbert, came early from Bohemia, becoming an insurance and realty agent and a pillar of the Congregational Church of Oscar McCulloch, widely known as a philanthropist and as a liberal Christian. His mother, Sarah Bean, still vigorous and competent at the age of ninety-three, is a typical representative of the Massachusetts Puritans at their best, and America has no better stock.

Charles was a graduate of the Indianapolis high school, where he found his first scholarly inspiration under Herbert Edson Copeland, a brilliant young naturalist, one of the ablest Cornell has ever sent out, but who died untimely from a fall into White River in January, 1877. From Indianapolis, Copeland transferred him to his intimate friend, the writer, who had become professor of zoology in Butler University at Irvington, then a suburb of Indianapolis. Gilbert took from the University of Indiana in 1883 the degree of Ph.D., the river fishes being his specialty. He had followed Dr. Jordan to the University of Indiana, where he became instructor and later professor in zoology. With the exception of four years as professor at the University of Cincinnati, he was continuously associated with Dr. Jordan, from 1877 to 1928, in Butler University, Indiana University and Stanford University, where he became emeritus professor in 1925.

In 1877, Dr. Gilbert had joined Dr. Jordan in a fish survey of the state of Georgia, a line of research not attempted before. In 1879 he was appointed by Professor Baird as secretary to Dr. Jordan's exploration of the fish fauna of the Pacific Coast, a research occupying most of 1880, and which Gilbert extended to Mazatlán and Panama. For many years the papers of "Jordan and Gilbert" were the most prolific in American ichthyology, their most extended paper being a descriptive "Synopsis of the Fishes of North America" in 1882.

From 1880 to 1928 Dr. Gilbert retained connection with the Fish Commission (later the Bureau of Fisheries). Since the first serious study of the Pacific salmon, by Jordan and Gilbert in 1880, he devoted his scientific work to the five American species of these fishes, until he came to know more of their character and habits than all other men taken together. The demonstration that their individual ages are recorded in their scales is largely his work, though others have made fruitful efforts at the same problem. The clue to his conclusions rests in the fact that in migratory fishes, the rings of growth recorded in the scales are larger and more wide-set during their well-fed life in the sea.

In nearly all the expeditions of Dr. Jordan to various parts of the world, Dr. Gilbert took an active part, as well as conducting others to Alaska, Hawaii, Japan and Panama. The ascent of the Matterhorn in 1881, with Dr. Jordan, Dr. M. B. Anderson and three students, was made at Dr. Gilbert's suggestion. In this adventure he was struck in the face by the fall of a great rock. This kept him, with Jordan, W. W. Spangler and two guides, one the famous Jean Baptiste ("John the Baptist") Aymonod, near the summit all night. His steel-rimmed Derby hat and careful ministrations by his comrades saved his life.

In 1909 Dr. Gilbert assisted the International Fisheries Commission in its salmon investigations, and for the last five summers he devoted himself almost wholly to salmon problems in Alaska.

In 1882 Gilbert was married to a fellow student, Julia Hughes, also interested in zoology and a member of the Matterhorn party. She died in November, 1915. During her life in Palo Alto she was a notable leader in favor of civic betterment. He left three children—Carl Gilbert, an attorney in Santa Fe; Ruth (Mrs. Percy B. Baker), of Atlanta, and Winifred (Mrs. Carl F. Braun), of Pasadena. All these are graduates of Stanford University.

Dr. Gilbert, one of the pioneers of the Stanford faculty, was a man of versatile genius. He had talent as musician and linguist, though his writings and lectures he confined rigidly to aspects of his chosen