Heat from the Stars

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ILLUSTRATIONS FROM PHOTOGRAPHS

LIGHT is the most universal of all languages. Its messages reach us with equal facility from the depths of the universe and from the electrons whirling in the nearest atom. Like the hieroglyphics of the Egyptians, its tones are silent, but, unlike them, it tells of the present as well as of the past. Its daily reports from the most distant stars were despatched millions of years ago, but within the limits of the solar system its slowest deliveries are completed within a few minutes, and on earth within small fractions of a second. The new knowledge that it brings is of the most varied character, ranging from the constitution of matter to the structure of the universe. Recently it has told us much of the evolution of the stars, whose life-cycles we are at last beginning to comprehend.

A few years ago Russell advanced his now famous theory of giant and dwarf stars. Starting from the early conceptions of Lane and Ritter, but developing them in the light of modern discoveries, he sketched for us the extraordinary characteristics of early stellar life. Nebulæ we had previously pictured as vast regions of space filled with faintly glowing rarefied gases, and stars were supposed to condense out of them. No one imagined, however, that a fully formed star like Betelgeuse, which marks the right shoulder of Orion, could actually be a gaseous sphere 300,000,000 miles in diameter, so highly rarefied that its average density is far less than that of the air we breathe. To test this theory and to prove beyond doubt the tremendous rise in temperature and decrease in diameter which it indicated for the successive stages of stellar life, has taxed the capacities of our ablest astronomers and best-equipped observatories. Fortunately, we are in the midst of a period of rapid progress, in which new instruments and methods are keeping pace with the demands of new theories. Some of these have been described in previous articles. But other vital steps remained to be taken, one of which was to measure with precision the radiant energy of the stars, and especially to determine the relative proportions of the visible and invisible rays emitted by the cooler ones.

VARIETIES OF RADIATION

It was in 1666 that Newton made the first analysis of sunlight with a prism. After him more than a century elapsed before Sir William Herschel took the next step. Fig. 1, from Herschel's paper in the "Philosophical Transactions of the Royal Society" for 1800, shows the simple but effective means employed by him to supplement the limited powers of the eye. The spectrum of sunlight, formed by a prism on the white surface of a table, was visible through the well-known range from violet to red. But at these limits it seemed to stop. A thermometer, exposed to the violet, showed a slight heating effect, but no sign of radiation was found beyond these visible rays. At successive points toward the red the thermometer rose higher and higher, but at this end of the visible spectrum the heating effect did not cease. On the contrary, the exposed thermometer continued to give higher readings after it had been moved entirely beyond the range of the red. In other words, the maximum heating effect of the sun's rays when analyzed by a prism seemed to lie in an invisible region beyond the red, since known as the infra-red. Herschel rightly concluded that light and radiant heat are identical, their observed effects simply depending upon the powers of the receiving instrument. The human eye responds only to the rays from red to violet, while his thermometer detected not only these rays but also others, which are less refracted by the prism. Later he gave further evidence of this identity, by proving that the invisible heat rays can be reflected, and also refracted by concave mirrors or lenses, in the same way as light rays. We are all familiar with such invisible heat rays, which are given by a stove long before it is heated to redness.

This first step into the invisible having been taken, within a year Ritter discovered the existence of ultra-violet rays, beyond the visible violet, by their effect in blackening silver chloride. Then followed, in 1802, the great advance of Thomas Young—the first measurement of the wave-lengths of light of various colors. He found that the difference between red and violet is merely a difference in wave-length, the waves of the former being about half again as long as those of the latter. A simple experiment will make this difference clear.

Take a long piece of rope and fasten one end to a post. Hold the other end in the hand, with the rope drawn nearly taut, and vibrate it up and down. It is easy to make waves run along the rope from the hand to the post. If the hand is moved quickly, the waves will be short. If more slowly, the waves will be longer. In the case of violet light the vibration frequency is high and the waves are very short. For yellow light the frequency is lower and the wave-length greater (about $\frac{1}{50000}$ inch). Toward the red and in the infra-red the wave-length continues to increase, as Fig. 2 illustrates. The extent of the spectrum has grown with the development of new and more sensitive instruments and the discovery of radiations, such as the X-rays, which were at first supposed to be utterly unlike the rays of light. Now we recognize no distinction, except that of wave-length and the diverse effect on our receiving instruments, as we pass from the shortest known radiations of radium through the ultra-violet into the visible spectrum, and then beyond its red end into the immense range of increasing wave-lengths which finally culminates in the longest radio waves.

The illustration (Fig. 2) is due to the late Ernest Fox Nichols, who presented it in connection with a paper read before the National Academy of Sciences as the last act of his life. Just as he concluded its presentation, after having described his success in producing the only type of waves previously undiscovered in this long sequence, he quietly sank to the platform and died. Such a passing, under the dome of the Academy's superb new building, dedicated on the previous day by the President of the United States to science and research, was the fitting culmination of a life devoted to the increase of knowledge. To Nichols, as we shall see in the course of this article, we owe some of the most important advances in the study of radiation and the first successful measures of the heat of the stars.

HEAT FROM THE STARS

Sir William Huggins, the great pioneer in astrophysics, was the first to attempt to measure the heat radiation of the stars. His discoveries with the spectroscope had taught him the advantage of utilizing laboratory instruments in the observatory, and he accordingly attached a delicate thermocouple (a junction of two metals very sensitive to radiant heat, see page 56) to his 8-inch telescope in 1869. Some of the brightest stars, when focussed on the thermocouple, seemed to give indications of heat radiation, but their accidental origin became evident twenty years later when Boys failed to detect stellar heat with far more sensitive instruments.

Thus matters stood in 1898, with no evidence of success after several serious attempts to measure the heat radiation of stars. The Yerkes Observatory had just been completed, and Nichols was developing the radiometer which, in the special form given it later, served so successfully in the classic investigations of Nichols and Hull on the pressure of light. It was already beautifully adapted for refined radiation measures, and as it greatly surpassed the best previous devices for this purpose, I invited Nichols to try it at the Yerkes Observatory during the summer of 1898 for the detection of stellar heat.

The special radiometer which he built for the purpose was an instrument of extreme sensitiveness. Its delicate mica vanes, suspended in a vacuum, received the star's image, given by a 24-inch concave mirror, after reflection from the mirror of a clock-driven heliostat mounted between the north and south domes of the observatory. By moving the heliostat means of testing, and also of measuring the loss of heat caused by absorption in the earth's atmosphere, were afforded by the observation of standard candles

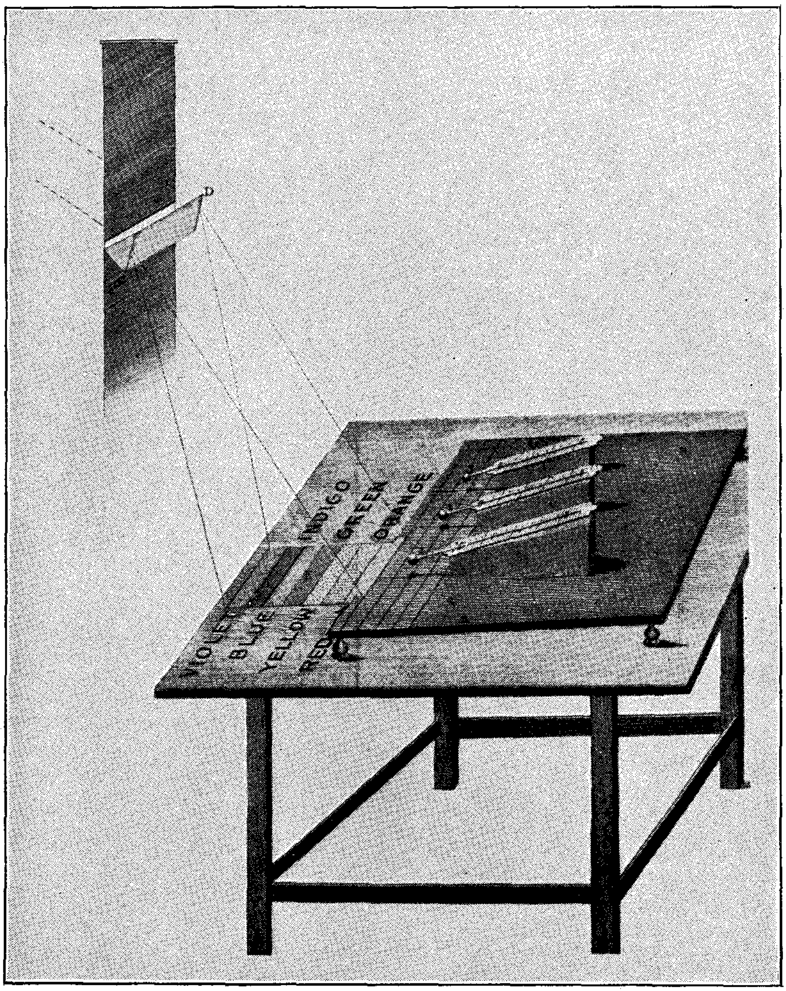

FIG. 1. Herschel's discovery of the invisible infra-red rays.

The infra-red portion of the solar spectrum, which cannot be seen by the eye, was detected by means of its heating effect on thermometers set at various points beyond the red end of the visible spectrum.

mirror, the star's image could be thrown on or off the vanes, and the resulting deflection could be measured by observing through a small auxiliary telescope the image of an illuminated scale reflected from a minute mirror attached below the radiometer vanes.

A standard candle, at a distance of about 27 feet, was used to test the sensitiveness of the radiometer. Additional mounted in tents at distances of 2,000 feet and 4,500 feet respectively. To give an idea of the sensitiveness of the apparatus, it may be said that the average deflection for a candle in the nearer tent, 2,000 feet away, was 67 millimetres (the apparent motion of the scale in the auxiliary telescope). One evening Doctor St. John, who was in this tent, extinguished the candle and placed his head in front of the candle-box when the signal to expose was given. The observed deflection, due to the heat radiation of his head at a distance of 2,000 feet, was 25 millimetres, repeatedly checked! In fact, the sensitiveness of the apparatus was so great that, if there were no loss due to the absorption of the intervening air, the number of candles in a group at a distance of about sixteen miles could be determined from the average of a series of measures. The radiometer employed was found to be twelve times as sensitive as the radiomicrometer of Professor Boys, and this advantage, combined with the increase in diameter of the concave mirror from 16 inches to 24 inches, sufficed to make possible the first successful measures of stellar heat.

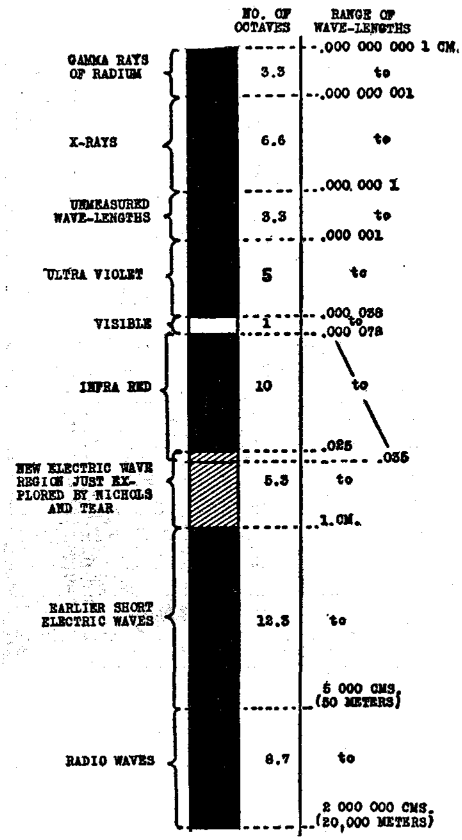

FIG. 2. Chart of the complete spectrum, showing the new electric wave region just explored by Nichols and Tear.

The entire length of the visible spectrum, from red to violet, is comprised in the narrow white region just above the middle of the chart. The immense range of the complete spectrum is thus apparent.

The average deflection produced by the bright star Arcturus, combining the observations of 1898 with those made with somewhat improved apparatus in 1900, was 1.08 *millimetres*. Vega, a star of equal brightness but bluer in color, gave an average deflection of 0.52 millimetres. Allowing for their difference in altitude, which involves a difference in atmospheric absorption, Nichols found that the total radiation of Arcturus was 2.2 times that of Vega. As these stars are of equal brightness to the eye, this means that Arcturus sends us more invisible rays from the infra-red region. This result, as Nichols pointed out, may be accounted for by the fact, now abundantly confirmed, that Arcturus, though of lower temperature than Vega, and therefore sending us a greater proportion of the longer wave-lengths, is so much greater in diameter as to give us about twice as much total radiation.

The pioneer results of Nichols, who also succeeded in measuring the heat radiation of Jupiter and Saturn, opened a new and very important field of astrophysical research. They pointed to the existence of comparatively cool stars whose radiation might be chiefly of the invisible sort and they hinted at the possibility of determining a star's diameter from a study of its heat radiation. Both of these possibilities have now been realized.

THE WORK OF PFUND AND COBLENTZ

I wish that time and space permitted me to describe in these pages the whole progress of modern astronomy. All I can hope to do, however, is to tell of some of the principal advances of my associates, with such historical background as to render their significance clear. But before passing on to recent work at Mount Wilson a word must be said of the important progress achieved by Pfund and Coblentz, who perfected the thermocouple, and applied it with marked success to the measurement of stellar heat.

The thermocouple is based upon a discovery made by Seebeck in 1822. He found that if two different metals fixed in contact are at different temperatures, an electric current is produced. Nobili, who had devised a sensitive galvanometer for the study of feeble currents, applied the thermocouple, with its aid, to the measurement of small temperature changes. In 1895 the Russian physicist Lebedew found that a thermocouple made of iron and the alloy constantan was more sensitive in a vacuum than at atmospheric pressure. Pfund made effective use of this principle in 1913 at the Allegheny Observatory, where he was very successful in measuring stellar heat radiation with a 30-inch reflecting telescope.

A year later Coblentz, of the Bureau of Standards, made another important advance at the Lick Observatory, where his improved vacuum thermocouple, employed with the 36-inch Crossley reflector, enabled him to measure the heat radiation of 105 stars. The variation of the heat radiation with the spectral type of the star, indicated by the results of Nichols for Arcturus and Vega, was beautifully shown by his results, which reached stars as faint as magnitude 6.7, just beyond the range of the naked eye. His most important conclusion is that "red stars emit 2 to 3 times as much total radiation as blue stars of the same photometric magnitude." In 1921, following up at Flagstaff some experiments begun at Mount Hamilton, Coblentz studied the relative proportions of radiations of different wave-lengths by means of absorbing filters, and thus obtained estimates of the temperatures of 16 bright stars.

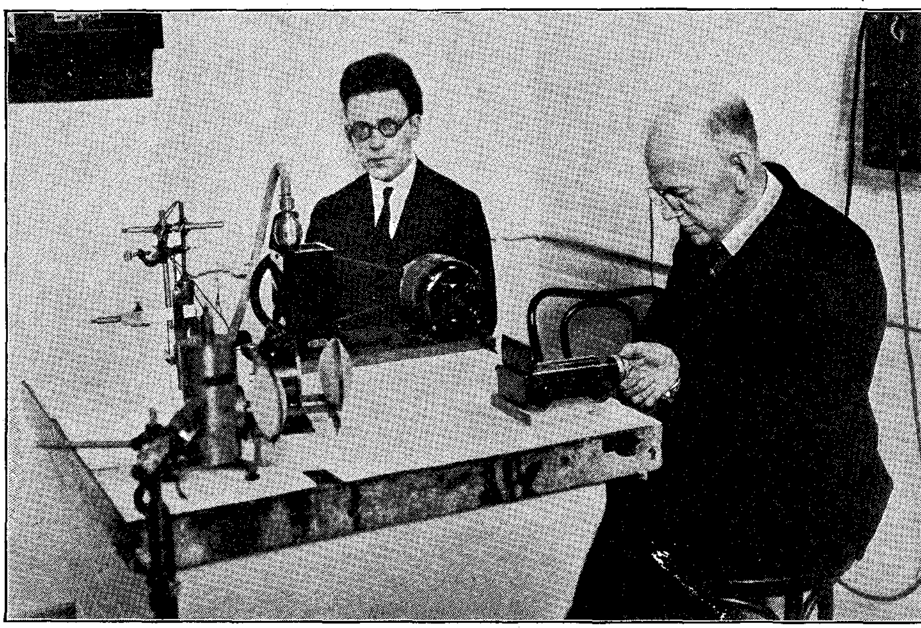

FIG. 3. Ernest Fox Nichols and his assistant, Doctor Tear.
The apparatus shown is that used in the exploration of the new electric wave region indicated in Fig. 2.

OBSERVATIONS WITH THE 100-INCH HOOKER TELESCOPE

The Hooker telescope on Mount Wilson* is admirably adapted for the measurement of stellar heat. Its concave mirror, 100 inches in diameter, collects more than seventeen times as much light as the 24-inch mirror used by Nichols at the Yerkes Observatory, and its optical and mechanical perfection permit observations to be made with far greater ease and certainty than was possible with the apparatus then available. It is astonishing to realize, however, that Pettit and Nicholson, using with this telescope improved vacuum thermocouples of their own construction, have been able to measure the heat radiation of one star as faint as the thirteenth magnitude—not far above the limit of visibility in Herschel's 20-foot telescope! Moreover,

*Described in "The New Heavens," p. 18.

with a star of the type of X Cygni at minimum brightness (see below), it would be possible to reach five magnitudes fainter.

When employed for the measurement of the heat radiation of stars, the thermocouple is mounted at the upper end of the tube of the Hooker telescope, in the focus of the 100-inch mirror. The deflections of the galvanometer produced by the star's heat are recorded photographically, and under favorable conditions they can be measured with extremely small errors. As the atmosphere forms only a thin shell around the earth, its absorption decreases rapidly from low to high altitudes. This means that as a star rises from the eastern horizon toward the meridian, it constantly appears to grow brighter. The sensitivity of the thermocouple is so great that in the case of bright stars at low altitudes the resulting change in brightness in one minute can be detected. Thus under such circumstances the limit of precision in the measurements is set by the difficulty of correcting for the exact loss due to absorption by our atmosphere.

The thousands of observations made with this apparatus by Pettit and Nicholson during the last three years have led to many important conclusions. In harmony with the results of Nichols and Coblentz, the proportion of radiations of great wave-length (infra-red) emitted by the stars is found to increase with their spectral type. That is to say, the redder the star the greater the proportion of invisible heat radiation it sends us. In the case of red variable stars like Omicron Ceti this effect is surprisingly large. Thus at its minimum brightness, when beyond the reach of a telescope less than 3 inches in aperture, this variable sends us 1,300 times as much heat as a white star (type A_0) of the same brightness. As the variable is so faint visually, it will be seen how great a proportion of invisible infra-red radiation it must emit at such times. But Omicron Ceti is outdone by X Cygni, a variable star ranging from the fourth to the fourteenth magnitude. Observations show that while to the eye X Cygni is 10,000 times as bright at maximum as at minimum, the total radiation as measured with a thermocouple undergoes a variation of only 1.7 times. At minimum brightness X Cygni emits 50,000 times as much heat as a white (A_0) star of the same magnitude. Its diameter must therefore be enormous. The possibilities of the thermocouple used with the 100-inch telescope, which is sensitive enough to detect the heat of a candle 100 miles away if there were no loss due to absorption by the intervening atmosphere, are well illustrated by these results.

RECENT ADVANCES BY ABBOT

The success of Abbot's studies of the solar spectrum on Mount Wilson led to a trial of the bolometer (another instrument for measuring feeble heat radiation) for similar investigations of the spectra of bright stars. In his preliminary observations with the 100-inch telescope in 1923 he succeeded in making an approximate examination of ten stellar spectra. But the bolometer proved to be hardly adequate for this difficult task, and a Nichols radiometer was chosen to replace it. This delicate instrument, built under Doctor Nichols's direction by Doctor Tear, has proved to be a marvel of efficiency. Retaining the great steadiness necessary for measures of precision, it is nevertheless fully fifteen times as sensitive as the stellar radiometer used at the Yerkes Observatory. Combining with this the advantages to be expected from the large aperture and stable mounting of the telescope, the altitude and clear sky of Mount Wilson, and certain minor instrumental improvements, a thousandfold gain in effective sensitiveness appeared probable. In spite of the great weakening of the radiation caused by dispersing the star image into a spectrum, Abbot believed that energy curves showing the intensity of radiation in various parts of the spectrum might be obtained for some of the brighter stars.

Observations were made of nine bright stars in October, 1923. The resulting energy curves, after correction for the absorption of the earth's atmosphere and the utilization of certain visual observations of the brightness of these spectra in the visible region, are shown in Fig. 8. This illustration, for the sake of economizing space, contains two sets of curves, one (to the left) referred to the horizontal wave-length scale at the bottom of the figure, the other referred to the scale four squares above it. In both cases the infra-red region is on the right, the visible spectrum extending only from 0.4 to about 0.8.

The height of the curve measures the mum intensity has a simple and definite meaning, of the greatest interest. Take a bar of iron and heat it in the fire. It gets very hot long before it begins to emit dull-red light. Finally, when greatly heated,

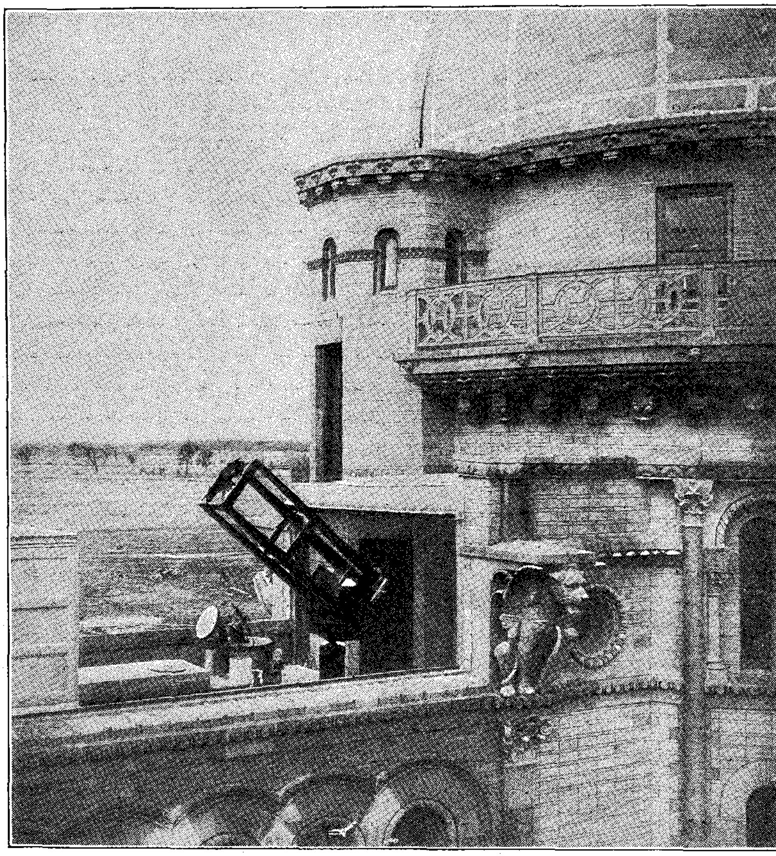

FIG. 4. Heliostat room of the Yerkes Observatory, where Nichols made the first measurements of stellar heat.

Light from the stars was reflected by the circular heliostat mirror to a concave mirror which formed the stellar image on the radiometer vane. (The larger instrument above the heliostat was not employed for this work.)

intensity of the radiation at the corresponding point in the spectrum. It will be seen at once that the maximum, which is in the ultra-violet, far beyond the violet limit of the visible spectrum in the case of the bright bluish-white star Rigel in the constellation of Orion, moves steadily toward the right in the following stellar sequence: Rigel, Vega, Sirius, Procyon, the Sun, Capella, Aldebaran, Beta Pegasi, Betelgeuse, and Alpha Herculis. In the last four stars the most intense point in the spectrum is beyond the red limit, in the infra-red.

This change in the position of maxi-

it becomes "white hot." During the heating the point of maximum intensity in its spectrum, at first far out in the infra-red, steadily advances from the invisible infra-red toward the visible red and then on toward the violet.

The corresponding differences found by Abbot in the stars, and confirmed by other observers in a different way, may be similarly interpreted. Along the route from Alpha Herculis to Rigel the surface temperature steadily rises from about 2,500° to about 16,000° C. (see Fig. 8), and the color changes from red to bluish-white. We are thus observing, with the

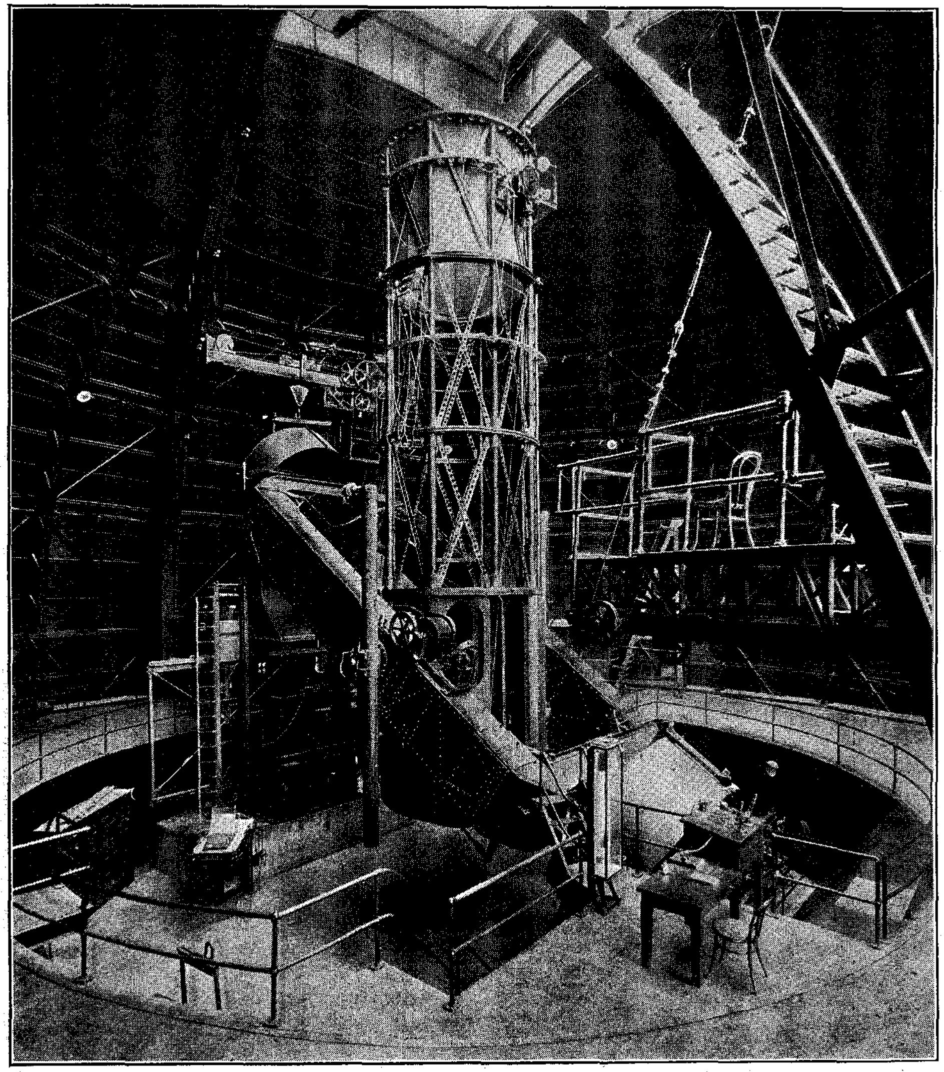

FIG. 5. The 100-inch Hooker telescope used by Nicholson and Pettit, and also by Abbot, for the measurement of stellar heat.

aid of a new device, the predicted progress of stellar evolution.

These results are not given by Abbot as final, but they are at least approximately correct, and they certainly represent great progress in astrophysical research. Making due allowance for the necessity of future revision when additional measures become available, Abbot has also deduced provisional diameters of these stars from his measures (supplemented by the visual observations of Wilsing and his associates and the photographic observations of Rosenberg), with results that are in most cases of the same order of magnitude as the interferometer measures of Michelson and Pease* and the theoretical determinations of Russell. Sirius and Procyon are found to be of about the same size as the sun, while the other stars observed range from twice to 500 times the sun's diameter. Let us see how these new results harmonize with the latest theories of stellar evolution.

THE LIFE HISTORY OF A STAR

Great advances in our knowledge of stellar evolution, made within the past

*See the chapter on "Giant Stars" in "The New Heavens."

year, now enable us to sketch more precisely the life history of a star. We see it in its extreme youth as an enormously distended mass of gas, sometimes exceeding 300,000,000 miles in diameter. The diameter, shown by the Michelson interferometer to be more than 300 times that of the sun.

Such a star radiates much heat, slowly decreases in diameter, and increases in

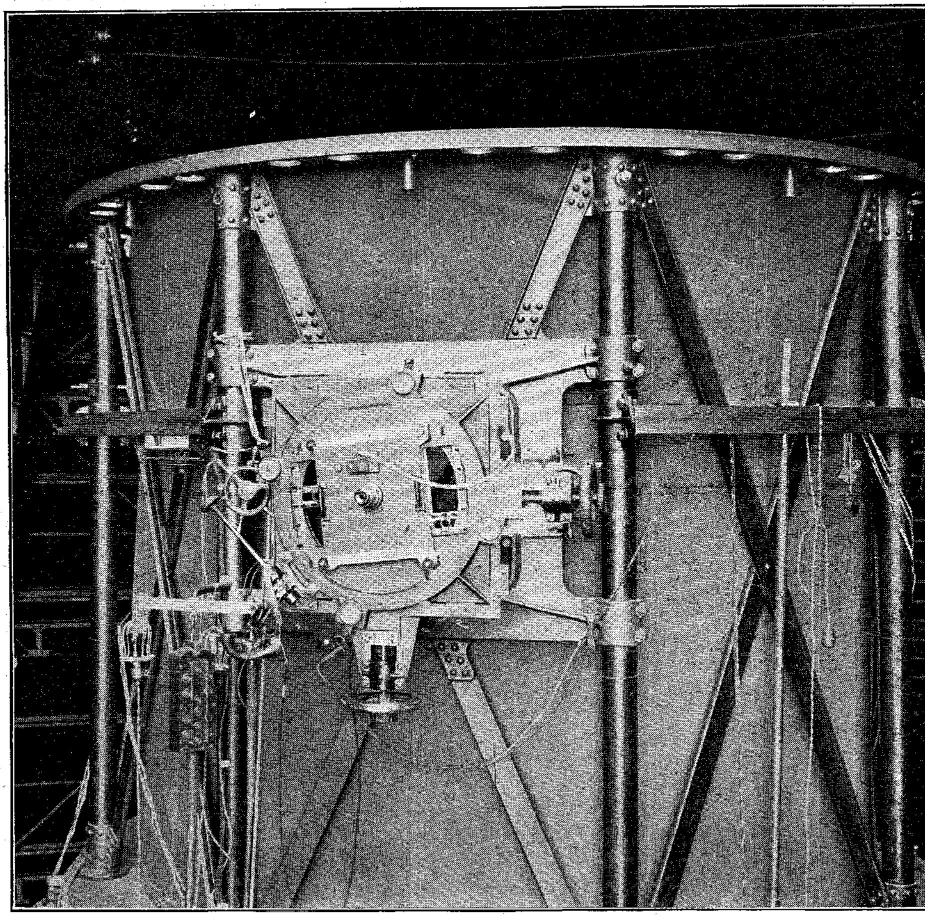

FIG. 6. Upper end of the tube of the Hooker telescope with thermocouple attached.

surface temperature of this red giant is comparatively low, ranging from 2,500° to 3,000° C., and the density of its outer parts is so slight as to be comparable with that of the residual gas in a vacuum tube, from which most of the contents have been pumped. At the centre of the star, however, the pressure must attain thousands of tons and the temperature two or three million degrees. The well-known red star Betelgeuse in Orion is an excellent example of this early stage of stellar life. Although its surface brightness is comparatively low, its great total brightness is accounted for by its immense density. These changes are accompanied by a steady rise in temperature, which becomes greater and greater as the star changes in color from red through yellow to white. The surface temperature of the white stars may exceed 20,000° C., and their central temperature may reach 30,000,000°. After the maximum surface temperature is attained the surface temperature begins to fall, but the central temperature may remain nearly constant for a long period. The color meanwhile changes from white through yellow to red, so that at one end of the scale we have huge expanded red giants and near the other small condensed dwarfs, also comparatively cool at the surface but with internal temperatures of many millions of degrees and enormous internal pressures. The sun, which is an early dwarf star, has a surface temperature of about 6,000° C., and a central temperature perhaps as great as 30,000,000° C. Thus far the history of stellar life does not differ greatly from Russell's theory, but some new and surprising modifications of the theory have recently become necessary.

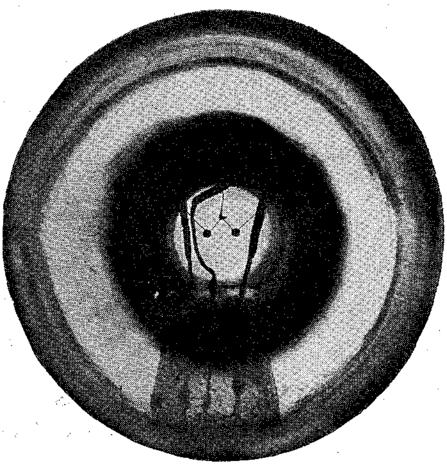

FIG. 7. The junctions of the vacuum thermocouple, as seen through the eye-piece.

Galvanometer deflections in opposite directions are obtained by setting the star first on one junction and then on the other.

STRIPPED ATOMS IN THE STARS

We are becoming accustomed to think of atoms no longer as fixed entities but as planetary systems, in which from one (hydrogen) to ninety-six (uranium) negative electrons whirl in their orbits about a central positive nucleus. With the aid of his "hot spark," taken in a high vacuum, Millikan has just been able to strip the seven outer electrons from their orbits in the atoms of chlorine and other elements, thus reducing these atomic systems to simpler forms. A cosmic counterpart of the modern physicist would be some Titan, operating upon the solar system, hurling into space first Neptune, then Uranus, Saturn, Jupiter, Mars, the earth, and Venus, as he brought more and more powerful thunderbolts to bear upon the planets.

The spectra of the sun and stars plainly reveal the existence of similar phenomena. In the great flames or prominences which rise thousands of miles above the sun's surface, the calcium atoms are shown by the spectroscope to have lost one electron, torn from the outermost orbit. In the atmosphere of the hottest stars the loss of from two to four electrons changes the spectra of the metals so completely that all of their lines in the visible and accessible ultra-violet regions disappear, while the remaining lines, in the extreme ultra-violet, are completely shielded from our view by the absorption of their light in the earth's atmosphere. In the hottest stars only the lines of certain elements whose atoms are less easily disrupted are found in the regions open to our study.

The highest temperature attained in the atmospheres of the stars does not greatly exceed 20,000° C., whereas 300,000° C. would be needed to accomplish the effects of Millikan's most powerful sparks. Within the stars, as we have seen, the temperature rises to many millions of degrees. Under such conditions the lighter atoms must lose all their electrons, and be reduced to completely stripped nuclei, resembling the sun deprived of all the planets. The heavier elements may still retain a few of their inner electrons.

A dense body is one in which the atoms are closely packed together. In ordinary matter, with its electrons intact, this process of crowding cannot go very far, even under great pressures. The orbits of the electrons are widely separated and the outer orbit acts like an impassable boundary which cannot be broken down by any pressures attainable in the laboratory. Platinum, the densest substance we know on earth, is only 21.5 times as dense as water. But when the atoms are stripped of all or most of their electrons, as they are within the hottest stars, the gravitational pressures of hundreds of millions of tons per square inch may crowd the electrons and protons much closer together, and thus produce densities up to 100,000 times that of water.

The faint companion of Sirius is a case in point. It is one of the exceptional white dwarfs (most dwarf stars are red), of small diameter, great surface brightness, and enormous internal temperature. If Eddington's calculations are correct, its density must be about 50,000

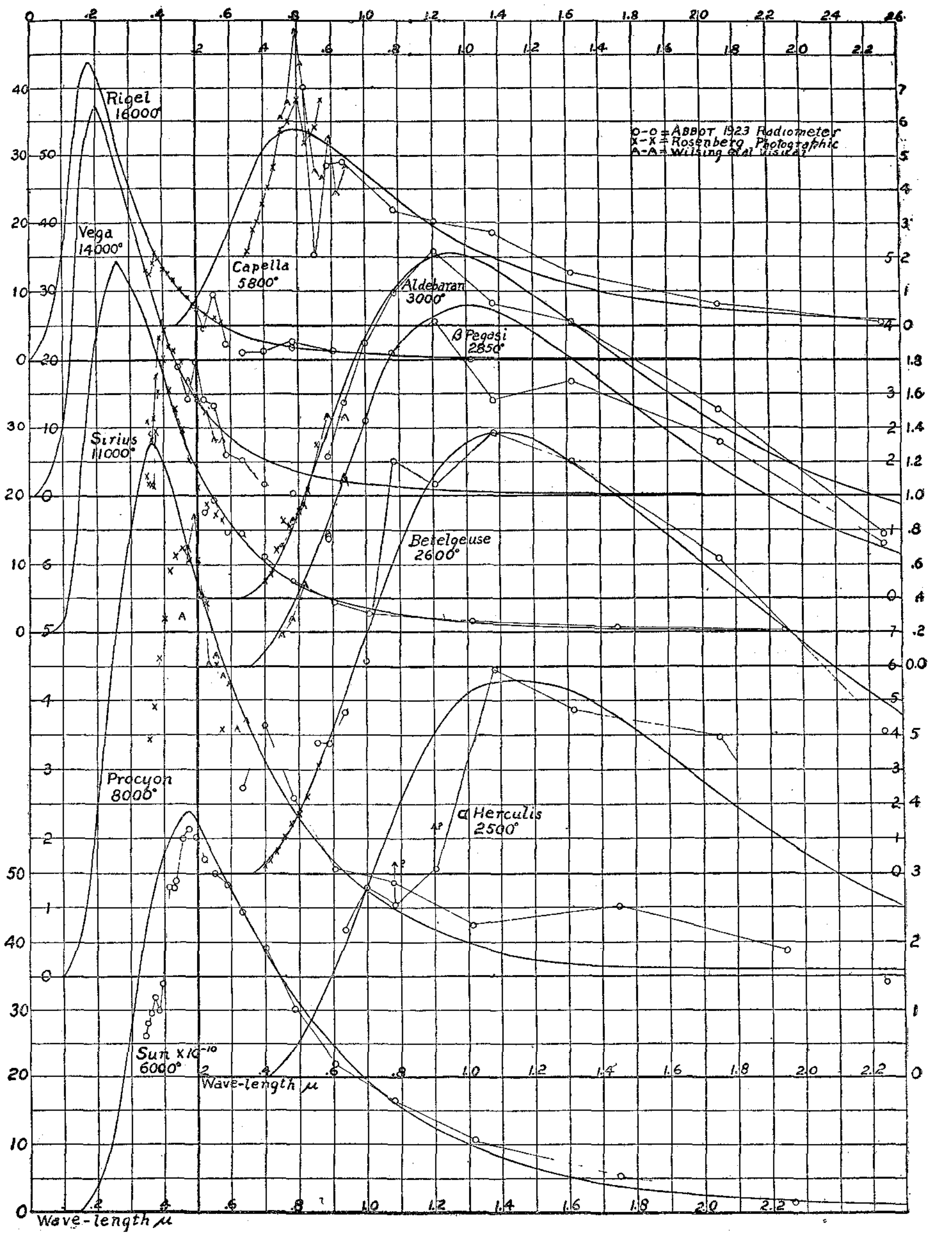

FIG. 8. Abbot's energy curves of stellar spectra.

The height of the curve measures the intensity of the radiation at the corresponding point in the spectrum. The maximum of intensity, far in the ultra-violet for the very hot star Rigel, moves steadily toward the red in stars of lower and lower temperature.

times that of water. With such a density the lines in the spectrum ought to be greatly displaced toward the red, according to Einstein's theory of relativity. It is very difficult to photograph separately the spectrum of this faint object, because of the close proximity of Sirius, the brightest star in the sky. With the aid of the 100-inch Hooker telescope on Mount Wilson, Doctor Adams is at work on the spectrum of the companion, and it is probable that he will be able to determine whether this shift of the lines occurs. If his results confirm Eddington's prediction, we shall have every reason to believe that in this strange celestial object a density about 50,000 times that of water, enormously transcending anything known on earth, has actually been attained.*

Until recently it has been supposed that the compressibility of a condensing star would rapidly decrease when the density began to approach that of water. But Eddington has shown that stellar atoms, reduced as they are by the loss of electrons, may have only about $\frac{1}{100000}$ of the bulk of ordinary atoms. The substance of a star may then continue to act like a perfect gas, of high compressibility, until a density greater than 10,000 times that of water is reached.

THE SLOW REDUCTION OF STELLAR MASS

Three years ago Seares found from a study of over a thousand stars of various spectral types that their masses showed a progressive decrease with increasing age, the dwarfs being of much smaller mass than the giants. He accordingly suggested the possibility that the mass may decrease with loss of energy by radiation. Eddington, who has recently investigated this question, has come to a similar conclusion. He suggests that a star may gradually lose mass by burning itself away through the liberation of subatomic energy. Jeans believes that this might result from the falling together of positive and negative electric charges and their consequent annihilation, their energy being transformed into radiation. In any event, Jeans holds that a star's development must involve a steady decrease of mass. The rate of transformation of mass into radiation is fixed by the theory of relativity, which states that when a given mass is destroyed, the energy set free is equal to this mass multiplied by the square of the velocity of light. Knowing the energy radiated by the sun, Jeans calculates that the sun must consequently be losing mass at the rate of 4,200,000 tons per second. Some of the giant stars of large mass must be decreasing at 10,000 times this rate. Thus it seems probable that we must give up the old idea that a star's mass is constant, and substitute the conclusion that the red dwarf stars, after ages of copious radiation, are so reduced in substance that their faintness is fully accounted for in this way.

The exceptional white dwarfs, in Russell's view, represent the last stage of stellar life, when the remaining material is so "intractable" that it requires an enormous internal temperature to transform it. The central temperature would therefore rise far above 30,000,000° C., and the surface temperature would return to that of the white stars or perhaps to an even higher level.

This remarkable conception of stellar development has been made possible by the powerful resources of modern physics, both experimental and mathematical. But theories are made to be tested, and without adequate means of observation their value would be lost. Thus we must depend in the final analysis upon the capacities of our instruments, which have now been augmented by the devices described in this article. In measuring the heat radiation of a star we are measuring the outpouring of its energy as it burns up its substance and passes through the various stages of its life.

In the work of the future, measures of stellar heat radiation will play an increasingly important part. We therefore owe a debt of gratitude to Ernest Fox Nichols, who not only was the first to measure the heat radiation of a star but who also devised and perfected the radiometer which in Abbot's hands has given us the last word on the subject. We are still more deeply indebted to him for his unwavering devotion to scientific research, to which he returned again and again in spite of all obstacles and in defiance of a mortal disease. Twice drawn into administrative work, and at last permanently incapacitated by a serious organic affection, he adhered to his determination to renew research in his favorite field of radiation. Many a man of science will envy the sudden close of his life, at the very moment when his latest discoveries had made complete the long sweep of the spectrum. To men like Nichols, with a heart devoted to the most fundamental interests of mankind and a mind therefore concerned before all else with the advancement of truth, science owes its rise to its present heights and the world its escape from mediæval ignorance.

* Since this article was put in type Adams has confirmed the prediction of Eddington.

A Florentine Face

BY BERNICE KENYON
Author of "Songs of Unrest"

ILLUSTRATIONS BY HARRY TOWNSEND

"DON'T believe them. They never tell the truth."

In plain English, the words sounded straight against his mind, without the intermediary process of translation; therefore they had a singular force, and captured his attention. He traced their direction—some tables down and to the right across the dining-room. From his lonely vantage-point he saw two people, a man and a woman; the man faced him, and had, now that he noticed it, one of the strangest faces in the world. High domed brow, shrewd eyes, and satyric mouth, very little color at all, but wrinkles indicative of cruel humor. Julian Henderson, watching, put his age at fifty, and wondered why the face seemed so familiar here in Italy, where he knew no one. Then it dawned on him—it was the face of a famous drawing of Machiavelli's "Prince."

"Don't believe them, I say. They never tell the truth." The repeated sentence brought up a second time against Julian's attention. To what part of a conversation, he wondered, did it apply? But what followed was less distinct, and he could not make it out. Well, it really didn't matter, and it was no affair of his; still, English was pleasant to hear.

In that dining-room of the Casino Hotel, in Rapallo, were some three hundred people, of whom about two hundred and fifty were wealthy Germans, and the rest a bad assortment of French, English, Italians, and Americans. Julian felt more alone than ever before in his life. It was impossible to be interested in his American countrymen here represented, and the English were not much better. He wondered what brought all these people together. Italy was no place to come for rest or diversion. One's very mind shrivelled in the cold Riviera wind, and with it all pleasant sentiment and fellow-feeling. The best one could do was sit and look on at the rest of the dreadful hotel guests until, from disillusion and persistent hardness, one's face grew to look like that of Machiavelli's "Prince" over yonder.

Julian Henderson himself made a striking, dark, clean-cut figure in that room full of rotund Germans. They had no style, no apparent breeding or culture. Still, they appeared to be enjoying life, while he could not shake off a persistent uneasy sadness. Yet he didn't envy them their jollity, for somehow, at that moment, it seemed to him obscene. They laughed without humor, heavily, and with their mouths full. In their harsh Teutonic chatter, the softer voices speaking French or English were lost and confounded; he could no longer hear distinguishable words.

To forget for a moment the unpleasantness of the surrounding scene, he pulled a letter out of his pocket, and began to read:

"Villa Paraggi, Paraggi, Italy.

"My dear," (it began). "The happiness that you give me is not given to many women. It is more than I can express to you in words. It takes immense courage to do what you have done. And because you make me so very happy, I can wish much good to the whole world—I can even wish that your ex-wife may enjoy her new freedom as much as I shall enjoy yours.

"But I am writing like a fool. What I want to say is come—come immediately. This villa which I have lived in so long, with a fair amount of content, seems suddenly empty, waiting for you, though you have never seen it. At last I find some