I

RECENT ADVANCES IN STELLAR ASTRONOMY[1]

THE LIGHT OF THE STARS

THE study of the stars is the oldest of the sciences: yet it rests on the slenderest physical basis. Were our atmosphere always cloudy—instead of about half the time—human affairs, and most of human science, would go on very much the same. We could see nothing of the great universe beyond the clouds; yet the light of the Sun and Moon would penetrate them, and their attraction would still set the tides in motion, and reasoning from these data, we might deduce a good deal about the Sun and Moon. But the very existence of the stars would be unsuspected, for it is only by their light that we know them, and this light is far too feeble to pierce the clouds.

How feeble, indeed, it is, is one of the things which most of us fail to realize. The light even of Sirius—the brightest of the stars—is equal to that of a 25-candle lamp a mile away. Ordinary artificial light, such as is commonly used to read by, is a million times brighter, and full sunlight is ten thousand times stronger still. It is only because of the amazing range of adaptation of the human eye—which incomparably surpasses that of any instrument which has ever been constructed—that we can see the stars at

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[1] A course of three lectures delivered by Professor Henry Norris Russell, Ph.D., of Princeton University, in the Physics Amphitheatre of the Rice Institute, January 26, 27, and 28, 1922.

all, and yet escape being blinded by the glare of day. But our eyes do better than merely to detect the almost infinitesimal quantities of energy which the stars send us: they give us very good reports regarding their relative amounts.

Almost from time immemorial, the stars have been classified according to their apparent brightness, and the system of describing this which is still used is well over two thousand years old. Since the days of Hipparchus the brightest of them have been called "stars of the first magnitude," those decidedly fainter, "of the second magnitude," and so on to the sixth magnitude—the faintest visible to the unaided eye. When accurate measures of starlight began to be made, about the middle of the nineteenth century, it was found that a 2nd magnitude star sent us about 2½ times as much light as one of the 3rd magnitude, the latter again 2½ times the light of a 4th magnitude star, and so on—a difference of five magnitudes corresponding to a light ratio of 100. With this principle as guide, the scale of magnitudes can be extended to the faintest stars visible with the telescope, which in the case of the hundred-inch instrument at Mount Wilson are of about the 21st magnitude, and backward to bright objects, for which the numbers expressing the magnitudes are negative, so that the magnitude of Venus is about —4; of the full Moon —12.5; and of the Sun —26.7.

We are not confined, however, to visual observations, when we measure the brightness of the stars. The intensity of the image on a photograph, if properly standardized, serves as well, and the photographic magnitudes which are thus derived give us much more than a mere check upon our previous results. The eye is sensitive primarily to green and yellow light (red and blue, for equal energy, making but a relatively weak impression) so that our visual magnitudes are substantially measurements of the stars with yellow-green light. The ordinary plate on the other hand is influenced almost entirely by violet light.

It is, therefore, not surprising that the stellar magnitudes determined in the two ways often disagree. Red stars photograph relatively faint, and bluish ones bright. This has been known since the first stellar photographs were made, but its full importance was recognized much more recently. In this difference between the visual and photographic magnitudes we have a way of measuring the color of a star's light—for which reason it is called the *color-index*. The results are in excellent agreement with the direct estimates of color by visual observation, but have two great advantages—first, that we can assign to them a definite physical meaning, and second, that they are more trustworthy, for the eye is a rather poor judge of color in objects as faint as the stars. Indeed, by using an isochromatic plate, with a "color screen" to cut off the violet light and let through the green and yellow, we may get "photovisual" magnitudes which are substantially equivalent to the usual determinations, and in some cases better—notably for very faint stars, where the behavior of the eye has annoying peculiarities. By either method we find that sunlight is near the middle of the range of starlight colors. Stars like Vega, or, even more, those in the belt of Orion, are much bluer, while those like Arcturus, and especially Antares, are much redder. But the colors of the stars lie between definite limits, which may be described as corresponding to the emission of three times as much violet light, in proportion to the yellow, as in the Sun's case, and again one-third as much violet light. Between these limits all shades of color are found in nearly equal abundance;

but only about one star in a thousand is redder than the limit, and it is doubtful if any known star is bluer.[1]

Terrestrial sources of light, on the same scale, are found to be very red. All but a few of the whitest of them, such as the carbon arc or the gas-filled tungsten lamp, are redder than the reddest of the ordinary types of stars, and even the exceptions are much redder than the Sun. Our instinctive standards for estimating color, in fact, are quite different for the stars and for artificial light. A commonplace, though modern, illustration of this is the "daylight" incandescent lamp, which is carefully adjusted to give light of the color of sunlight, but, if seen among other lamps at night, looks blue.

So far, however, we have been talking only about the apparent brightness of the stars—the light which we get from them. What of their real brightness—the light which they send out? To determine this we must know the distances of the stars—and this opens up a long and difficult chapter of practical astronomy.

The first rational estimate of the distance of a star was reached from photometric considerations, and by no less distinguished a philosopher than Newton. He proved, first, that the stars do not shine by reflected sunlight—for they show no perceptible disks in the telescope and therefore they could not reflect light enough to account for their observed brightness. They must, therefore, be self-luminous like the Sun. Now Sirius looks rather fainter than Jupiter. From this fact, by ingenious but thoroughly sound reasoning, Newton showed that, if Sirius was really as bright as the Sun, its distance must be fully 100,000 times as great as that which separates the Earth and Sun. We know now that the actual distance is five times greater;

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[1] Except the nuclei of certain nebulæ, which may not be ordinary stars.

but this determination, made by methods impracticable in Newton's day, detracts in no wise from the credit which admittedly he deserves for giving the first correct estimate of the order of magnitude of the remoteness of the stars.

It is well-nigh a century since Bessel determined the parallax and distance of 61 Cygni—applying principles essentially similar to those of the range-finders which are used with modern artillery. Slowly at first, then faster, the technique of observation improved, and now, by taking a dozen or so of photographs with one of our larger telescopes we can measure the distance of a star a million times as far away as the Sun, and be more likely than not to get it right within five per cent. There are not many stars as near as this—only a few score, among the millions which the telescope reveals—and for the remote ones the percentage error of our measures increases in proportion to their distance. But, up to ten million times the Sun's distance, the results of direct measures of parallax are still of value—particularly if we can take the average of three or four determinations by good observers.

To describe these enormous distances with convenience, we need a new unit of measurement. Astronomers are coming very generally to adopt the distance at which the parallax of a star would be one second of arc. The word *parsec* has been coined to denote this distance—which is 206,000 times the Earth's distance from the Sun, or, in common units, 19 millions of millions of miles. It may also be defined as equal to 3.26 light-years—the latter unit being the distance which light travels in a year. No known star lies within one parsec of the Sun. Two stellar systems are nearer than two parsecs, and there are probably three or four hundred nearer than ten parsecs—the majority still awaiting observation. Our direct meaures of parallax are fairly good up to thirty, or even to fifty parsecs.

When we can get a star's distance, it is very easy to calculate its real brightness, and the range in the values is enormous. The faintest star so far known, is an eleventh magnitude star, discovered by Innes, which is a distant companion of the first magnitude star Alpha Centauri—two degrees away from it, but moving in the sky at the same rate, so that the two probably form one great system. Its parallax is slightly greater than that of the bright star, which makes it the nearest known object in the heavens (1.3 parsecs) and its real brightness is but one ten-thousandth part that of the Sun. It is only visible because it happens to be so near us. Alpha Centauri itself is just about as bright as the Sun, but our next nearest neighbor in space—another faint star discovered by Barnard—gives out about 1/2700 of the Sun's light.

Sirius (also a near neighbor, at 2.7 parsecs) is 25 times as bright as the Sun—and so our list might go on almost indefinitely, for there are more than a thousand stars for which direct measures of parallax have been made, but many of the brightest stars in the sky have parallaxes too small to measure in this way. All that our measures indicate is that their distances are greater than 50 parsecs, and probably than 100, and that their real brightness in some cases must be more than a thousand times the Sun's.

With such an enormous range of values to deal with, it is obviously desirable to have some simple method of expressing the real brightness of a star, as convenient as the stellar magnitude is for the apparent brightness. Kapteyn met the need by inventing the "absolute magnitude" which is simply the magnitude that the star would appear to have if it were brought to a standard distance—which he chose as 10 parsecs. On this scale the absolute magnitude of the Sun is +4.8, that of a star 100 times fainter would be +9.8, that of Innes's star is +15; while a star 100 times brighter than the Sun would have an absolute magnitude of –0.2 (which is approximately the case for Arcturus or Vega). Still brighter stars, with negative absolute magnitudes, exist; but to obtain any accurate notion of their brightness we need some more powerful method of measuring distance.

One such method has developed from the discovery of a number of "moving clusters" of stars. All the members of each of these clusters are moving together in space—in parallel directions and at the same rate—though their proper motions in the sky appear, on account of perspective, to converge towards a definite vanishing point. When we know this point, and measure with the spectroscope the rate at which the stars of the cluster are receding from us (or perhaps approaching, in which case their proper motions diverge from a common point)—it becomes a simple matter of geometry to calculate the parallax and distance of every star in the cluster. The first of these clusters to be fully investigated (in a classical paper by Lewis Boss) is the Hyades group in the constellation Taurus, which contains about a hundred stars forming a roughly globular group about ten parsecs in diameter, with its centre forty parsecs from the Sun, and ranging in luminosity from fifty times the Sun's light to one-tenth of its brightness.

Of more immediate interest to us is a huge group in the southern sky studied by Kapteyn, and containing most of the brighter stars in Scorpius, Centaurus and the Southern Cross. The proper motions of these stars are small and their distances great, averaging about 100 parsecs. Two of them are of the first magnitude, and much excel in luminosity any of the stars which we have previously mentioned, Beta Centauri possessing a luminosity 2,500 times the Sun's while Antares (Alpha Scorpii) exceeds the Sun's light a little more than three thousand fold. There are many other stars in this cluster which are several hundred times brighter than the Sun.

Another similar star group comprises most of the conspicuous stars in Orion, and many in Canis Major. This group is even farther off, but it is difficult to estimate its distance with precision, for it is moving almost straight away from us, so that the stars seem to stand almost still in the sky. The majority of the stars appear to be at distances of between 150 and 200 parsecs. Among these are the three stars of Orion's belt, which average about 4,500 times as bright as the Sun, and the still brighter Rigel, in the southern part of the constellation, which appears to give out some 13,000 times the Sun's light and be the brightest star at present known. Two other stars of the first magnitude, Canopus and Alpha Cygni, are also known to be exceedingly remote, but we cannot yet measure their distances. One or both may be as luminous as Rigel, or even brighter.

We have, therefore, among the stars a range in real luminosity of at least a hundred million fold. The physical interpretation of such great differences must obviously be of prime importance. But before we can discuss it intelligently we must analyze the light of the stars more thoroughly. We can do this best by photographing their spectra. For those visible to the naked eye this can be done in considerable detail; and the brighter telescopic stars, down to the ninth or tenth magnitude, are accessible with lower dispersion. Years of study at Harvard, mainly by E. C. Pickering, Mrs. Fleming and Miss Cannon, have culminated in the classification of the spectra of more than 200,000 stars.

The familiar, but nevertheless amazing, result of these researches is that all but a minute fraction of these can be placed in one or another of six spectral classes, which, during the progress of the work, came, by the law of survival of the fittest in nomenclature, to be designated by the arbitrary letters B, A, F, G, K, and M. What is still more noteworthy is that these six classes grade into one another imperceptibly, so that they form parts of a single sequence (in the order named above). The transition from any type to the next always takes place through the same intermediate stages (illustrated, of course, by different stars) so that we may adopt the familiar decimal classification, and call a star half way between B and A, for example, B5A, or simply B5.

This linear sequence of types finds room for more than 99 per cent. of the stars. The exceptions can almost all be placed in three additional classes—denoted by the letters O, R and N—of which the first evidently belongs at the head of the list, before B, and is connected with it by intergrades, while the other two form a sort of side-chain branching from the main sequence near K.

Spectra near the head of this sequence show mainly the lines of the permanent gases—hydrogen, helium, oxygen and nitrogen. As we pass on from B to A the helium lines disappear, and lines of the metals come in —at first those lines which show in the laboratory only, or chiefly, in the spectrum of the electric spark. Farther on, in Class F, the arc lines of the metals appear, and in

Class G, (to which the Sun belongs) they are predominant, while the spark lines become weaker as do also the lines of hydrogen. This change continues into Class K, and the flame lines of the metals, (produced in a flame, or an electric furnace, at relatively low temperature) become conspicuous. Finally, in Class M, heavy absorption bands appear, which have been identified as due to the presence in the star's atmosphere of the vapor of titanium oxide. Another set of bands, produced by compounds of carbon, is prominent in Classes R and N.

What physical or chemical conditions are there behind this succession of types? Are the atmospheres of the various stars really as different in chemical composition as their spectra appear to indicate? This is a tempting hypothesis at first sight: but there are weighty objections to it.

First of all, the sequence of spectra is linear. In passing from a given type to those which closely resemble it, we have practically only two lines to follow—up or down the series. It seems an inevitable deduction from this that the spectrum of a star might be described in mathematical language, as a function of a single variable. Now the chemical constitution of an atmosphere is a function of many variables. For all that we know, the amounts of helium, oxygen, iron, hydrogen, and other elements in it may vary independently. If variations of this sort lay behind the spectral differences, there is no apparent reason why the lines of different elements should always show so definite a relation between their behavior—or, indeed, any conspicuous relation at all.

Moreover, we know of pairs of stars, so close that no telescope can separate them, whose duplicity is known only because one component of the system eclipses the other at regular intervals. In some such cases two stars, separated by hardly more than their own diameter, have spectra differing as widely as A and K. The stars of such a pair have doubtless been formed out of the same original mass, and it is quite incredible that practically all the hydrogen has segregated in one component, and practically all the metals in the other.

No: we must look to some difference in the physical conditions of the stars' atmospheres to explain the differences in their spectra, and to differences in some *one* important particular. There is no doubt at present that this condition is the *temperature* of the atmosphere and of the star's surface below it. Practically sufficient evidence of this is found in the colors of the stars. Those which are "early" in the spectral sequence—of Classes O, B and A—are conspicuously white or bluish; stars of Class F are yellowish; and of Class G yellow, like the Sun; those of Class K reddish, and of Class M red—as are also those of Class R, while the N-stars are the reddest in the sky, and the only ones which are found beyond the limits of color mentioned earlier, which correspond approximately to Classes B and M.

It has long been realized that the behavior of the line-absorption in stellar spectra is in general agreement with this hypothesis, on which the B-stars are the hottest, and the M-stars the coldest of those in the main sequence. But the full interpretation of the results has come only very recently, since the processes by which spectra are produced have begun to be understood. The great astrophysical importance of these considerations was pointed out, a year or two ago, by Dr. Saha, Professor at Calcutta, and much of what follows is borrowed from his discussions.

It is now generally accepted that the atoms of the various chemical elements are complicated structures, consisting of a very minute and heavy nucleus, carrying a positive electrical charge, surrounded (at a great distance in comparison with its own size) by electrons, in numbers just sufficient to neutralize the charge on the nucleus (so far as its action on things outside the atom is concerned), and arranged in some sort of successive rings, layers, or shells—each much larger than the last—though even the outermost is perhaps a hundred-millionth of an inch in diameter. These electrons are probably not at rest, but in motion; and there appear to be certain possible *steady states* of motion, in which they can continue to move for long intervals, if not indefinitely. While this happens, the atom neither emits nor absorbs radiation; but if one of the electrons is shifted from one of these steady states to another, radiation takes place. If the electron has less energy in the new position than in the old, the balance is liberated in the form of monochromatic radiation—a train of waves of a definite rate, or frequency, of vibration. If the change is in the other direction, the energy necessary to effect it is absorbed. In either case, the frequency of the radiation is exactly proportional to the amount of energy involved in the change of state on the part of the electron—the factor of proportionality being the "quantum constant" h, which keeps cropping up in all sorts of physical problems, but whose real nature still evades our analysis.

When the energy change is large, the vibrations are very rapid. For example, if one of the innermost electrons, close to the nucleus, is shifted to an outer level, and falls back again, we get radiations of very short wave length—X-rays, in fact. But if one of the outermost electrons of all is shifted, the attraction of the nucleus upon it is relatively small, and is modified, too, by that of the other electrons—less work is done, and the corresponding waves are long enough to be called light.

There are many of these possible states, and still more ways in which a shift from one to another may take place. This explains why the spectrum of a given element may contain a great number of lines. Each individual atom at a given instant probably absorbs or emits but one kind of light—a single line—but while one change is going on in one atom, different changes are happening in others, giving different lines, and so the mass of gas as a whole absorbs or emits them all.

In a gas at low temperature—or at least at the lowest temperature at which the element in question can be vaporized—almost all the atoms will have their outer electrons in the state corresponding to the smallest content of energy. When light is passed through this gas the spectral lines corresponding to a shift of the electron from this position to those others which (so to speak) can be directly reached from it, will be absorbed. In a hotter gas, where the atoms collide with each other more violently and increase their stores of internal energy, the light will find some of them with their electrons already in the "higher" positions of greater energy content, and the shifting of these electrons to still higher energy levels will cause the absorption of additional lines. At first there will be relatively few atoms in these other states, and the new lines will be faint. But as the temperature is raised still more, the proportion of atoms which are thus stimulated by collision will rise, and the new lines will increase in intensity, compared with the "ultimate" lines which at first appeared alone.

This reasoning furnishes a beautiful explanation ot the manner in which an element such as iron shows relatively few lines when heated just to its boiling point in an electric furnace, more lines when the furnace is heated several hundred degrees hotter, and still more when the atoms are subjected to the much more intense excitation of the electric arc.

But this is not the whole story. If the first and most easily movable electron—of which alone we have been speaking so far—receives a sufficient supply of energy, it may be pulled clear away from the atom, leaving a positively charged, or "ionized" residue. Then the game begins again, a second electron being shifted, stage by stage, and at last removed. During this process the energy-steps are quite different (and, in general, greater) so that we get an entirely new set of spectral lines, usually with more rapid vibrations, and shorter wave-lengths. For some atoms, such as sodium, the second electron is exceedingly hard to get off, and the corresponding radiations are of such short wave-length that they can only be observed with special apparatus. In others, as magnesium, a second electron comes off fairly easily—about twice as hard as the first—giving lines in the visible spectrum and the ultra-violet. These are the characteristic spark lines—or "enhanced" lines, as Sir Norman Lockyer called them, because, even when present in the arc spectrum, they are strengthened in the spark. For magnesium, the third electron is very hard to get away, and the lines corresponding to its removal are difficult to observe. In some other atoms, such as silicon, a third or even a fourth electron may be removed with the production of visible radiation; but, even then, a state is finally reached in which only radiations of too short wave-length to be detected by ordinary means are produced by further stripping of the electrons from the atom. The amount of work which is required to remove an electron from an atom may also be measured by electrical means in a suitably designed vacuum tube, as well as by the spectroscopic processes previously described. Combining the information that we get in the two ways, we know that some elements, like sodium and potassium, are easily ionized, others, like magnesium and zinc, with more difficulty, while the permanent gases, hydrogen, oxygen and nitrogen, are much harder to ionize, and helium hardest of all.

We can now understand what happens in the atmospheres of the stars. In the red stars, where the surface temperature is lowest, the atoms are subjected to a relatively mild stimulus, and the "ultimate," or "furnace" lines of the metals are prominent, with the arc lines of the same substances present, but fainter. For hydrogen, whose ultimate lines lie in the ultra-violet, the only accessible lines belong to a "subordinate series," absorbed only by atoms in which the electrons have already suffered one shift; and at this temperature very few of the hydrogen atoms undergo this internal change, so that the hydrogen lines are weak, and those of the other permanent gases, which are still harder to excite, are absent. As the temperature rises to that of the Sun, the lines of oxygen begin to appear. The arc lines of the metals grow stronger. Some of the metallic atoms lose one electron and are in a position to absorb the enhanced lines. For other elements, such as potassium, which have no enhanced lines in the accessible region, the lines of the neutral atoms gradually fade out, with nothing to replace them. By the time that we reach the F type, the arc lines of the metals are getting fainter, though the enhanced lines remain, while the hydrogen lines get stronger and stronger. Farther on, in the A type (Sirius) the metallic lines all become weak and just beyond, in Class B9 the lines of helium appear—to strengthen with rising temperature, till at the top, in Class B0, practically all the metallic lines are gone, the hydrogen lines are fainter and we have the helium lines, the enhanced lines of oxygen and nitrogen, and even traces of the enhanced lines of helium. In the atmosphere of such a star—which must be exceedingly hot—the atoms of the metals have almost all lost two, or possibly three, electrons, and very few or none are left in a condition to absorb any lines in the visible spectrum or the nearer ultra-violet. Though the hydrogen atoms are harder to ionize, most of them have lost their one electron, leaving much fewer to produce the line absorption than in the case of the cooler stars of Class A. The oxygen and nitrogen atoms have lost an electron, and even helium—the hardest nut of all to crack—is beginning to yield.

We obtain thus a clear and consistent picture of the processes which underlie the spectral sequence. All that needs further to be said concerns the bands which appear in the spectra of the reddest stars. These are known (in many cases at least) to be produced by compounds. When an electron can be removed from a molecule, containing several atoms held together by those forces which we ordinarily call "chemical affinity," the energy changes are again quite different, and very complex, so that an enormous number of lines are produced, grouped into bands in the spectrum. At the temperature of the M-stars, this happens for the titanium oxide vapor in the atmosphere. But at the higher temperature of Class K the violence of collisions with other atoms is too much for these molecules: they break apart into their constituent atoms, and are dissociated. The bands disappear, while the lines of titanium are reinforced, the oxygen, meanwhile, going as it were into hiding and requiring a much more violent stimulus to rout it out. But why should the other red stars of the R and N types show a different set of bands, and why should these and the bands characteristic of the M-stars never be found together? Curtiss has given a beautiful explanation. Both sets of bands are due to compounds—one to a metallic oxide—the other to some compound of carbon. It is very likely indeed that these two are chemically incompatible, and incapable of existing together. When the carbon is in excess it takes away the oxygen from the titanium—as it does from iron-ore in the blast furnace. When the oxygen is in excess it combines with all the carbon—getting it into some form in which it does not produce the characteristic bands—and what is left over combines with titanium. So here, at a temperature low enough for the chemical compounds to form, we have a real chemistry of the stars—not merely physics—and our first distinction seems to be the old familiar one between an oxidizing and a reducing atmosphere.

We might now reasonably expect to find that the hottest stars were the brightest, and the cooler stars fainter, but the facts are against us. Among the stars of enormous luminosity of which we have already spoken, those in Orion's belt are of Class B0, at the top of the scale; but Alpha Cygni is of Class A2, Canopus of Class F, and Antares actually of Class M, at the other end of the series. A general study of the relations between the spectral types of the stars and their absolute magnitudes is therefore of importance. The material required for the elucidation of the real relationship was first provided, a dozen years or so ago, by the investigation of the spectra of faint stars at Harvard; and, as soon as this became available the main features of the situation were pointed out, independently, by Hertzsprung and myself. If we group the stars according to their spectra, we find that those of Class B are always bright. Among the long list studied by Kapteyn, those of Class B2 or "earlier" are almost all brighter than the absolute magnitude zero, that is, more than 100 times more luminous than the Sun. The "later" B's average fainter, and some of the A's come down to less than ten times the Sun's light. In Class F some stars come down to two or three times the Sun's light, yet Canopus, which belongs to this class, is enormously bright. So the list continues, the lower limit of brightness growing steadily fainter, by about two magnitudes from each class to the next, while there is no indication of a change in the upper limit. As far as Class G the stars seem to be distributed all through the range of brightness in which they occur; but in Class K, there appears a division into two groups—brighter and fainter—which in Class M has become very sharp and definite. There are few, if any, stars of this spectral type which are comparable with the Sun in brightness, while there are many whose light is from 20 to 100 times the Sun's, and others with a brightness of from 1/50 to 1/500 that of the Sun.

Combining all these results, we find that practically all the stars fall into one or other of two great divisions. In the first of these the brightness is very much the same, whatever the spectral type, and averages about fifty times that of the Sun: in the other the brightness falls off very rapidly with increasing redness, stars of Class G averaging about as bright as the Sun, and those of Class M a hundred times fainter. Hertzsprung has called these by the happily chosen names of "giant" and "dwarf" stars. The members of either group show a dispersion in brightness of a magnitude or so on either side of the mean—and more in scattering instances—so that the two groups are really separated only in Classes K and M. Even in Class K, a few stragglers occupy an intermediate position, and in Class G the brighter dwarfs and the fainter giants overlap. In Class F the two are much intermingled, and in Classes A and B there is no real distribution. Almost all known stars belong to one or other of these divisions. The few enormously luminous stars, such as Rigel and Antares, may be regarded as scattering giants, much brighter than the average. There are, however, a very few white stars of very low luminosity—the faint companions to Sirius and to Omicron Eridani, and one or two others—which fall definitely outside the scheme, and present an unsolved riddle.

The recognition of the giant and dwarf stars helps to clear up a number of puzzling things—particularly some connected with apparent contradictions in the properties of the "average star" of some given kind. For example, it is certain that a large majority of all the stars in a given region of space (say within twenty parsecs of the Sun) are dwarfs—most of them faint and red. Yet, among the stars brighter than the sixth magnitude, the large majority are giants—as is shown both by direct measures of parallax, and by the study of their proper motions. This is really simple enough. When we make a list of the stars visible to the naked eye, we include only those dwarfs which lie very near us, for, since they are intrinsically faint, the remoter ones are invisible to us.

But the giant stars, being far brighter, can be seen at great distances. We are fishing for them in much wider waters, and naturally we catch more. The most striking instance is afforded by the M stars. Here the dwarfs are so faint that not one of them is visible to the naked eye, though three of the four nearest stars belong to this class, and our naked-eye list is composed exclusively of giant M's, though there are probably more than a hundred dwarf M's which are nearer us than any of these giants. Among the K-stars, only a few of the nearest dwarfs are visible to the unaided eye, while the proportion among the G's is larger. We are therefore dealing with complex mixtures, composed of giants and dwarfs in different proportions for the different spectral types, and the average parallax, proper motion, or what not, of the stars selected in this curious way may be very far indeed from representing the average of the stars of the same type in a given region of space. Indeed, different methods of selection—for example, the rejection of the stars of large proper motion—may greatly change the relative proportion of giants and dwarfs in our mixture, and therefore the calculated characteristics of the "average star." Much care is necessary in interpreting such averages, for the effects of this "involuntary selection" are often far-reaching and unexpected.

One would naturally expect that these great differences in absolute magnitude, among stars of the same spectral class, would be associated with differences in the spectra themselves. From what has already been said, no large differences can be anticipated; but smaller differences exist, and are of much importance. Here again Hertzsprung was the first in the field—pointing out, as long ago as 1905, that certain stars, in whose spectra Miss Maury, at

Harvard, had noticed that the lines were exceptionally narrow and sharp, were much superior in absolute magnitude to the general run of stars.

The greatest advance, however, was made eight or ten years later by Adams and Kohlschütter. By this time reliable information was at hand regarding the absolute magnitudes of a large number of stars. Photographing the spectra of a selected list of these with the same instrument, and comparing the plates, the Mount Wilson investigators were able to detect many small differences which had escaped earlier notice. Certain lines were stronger in the giant stars, and others in the dwarfs. What is more, the relative intensities of certain pairs of such lines (one of each kind) was found to vary in a regular manner with the absolute magnitude. When the law of this variation had once been determined, with the aid of a dozen or so stars of a given spectral class for which the parallaxes and absolute magnitudes were known, it became possible to take the spectrum of any other star of this class, examine the lines in question, and find from their relative intensity what is the star's absolute magnitude—in other words, how bright it really is. Knowing this, and the star's apparent brightness, we can immediately calculate its distance and parallax.

In this way the way opened for the determination of "spectroscopic parallaxes." The method is surprisingly accurate—the average error of a determination of parallax being about twenty per cent.—and very rapid in practice, since it takes much less time to get the two or three spectrograms which are sufficient for the purpose than to take and measure the dozen or fifteen plates which are required for a determination by the direct or "trigonometric" method. Moreover, since the probable error is a fixed percentage of the parallax, the spectroscopic method is much superior to the other in accuracy for faint stars at great distances, where the parallax is smaller than the errors of observation by the direct method. For the nearest stars, on the other hand, the trigonometric method is the more precise. The most serious limitation of the new method is that, as developed at present, it is available only for stars of spectrum more advanced than A8. Some recent work by Lindblad at Mount Wilson, however, indicates that, by the use of other spectral lines and somewhat different methods the A-stars may be included. As, thanks to Kapteyn, we already know a great deal about the B-stars, this will fill the last serious gap in our information.

Two thousand stellar parallaxes have been determined at Mount Wilson by this method during the past five years, and the work goes on actively. Shapley at Harvard is just beginning investigations of the same sort, using the unique collection of photographs accumulated by Pickering's untiring energy. It is not too much to hope that, within a very few years more, we shall know the distances of all the stars of Class F and redder, which are visible to the naked eye, and perhaps of many fainter ones. If Lindblad's methods fulfil their promise, and Kapteyn's investigations on the B-stars continue, we may arrive before long at a very good idea of the distances and distribution in space of all the stars which can be seen without a telescope.

The results so far obtained confirm completely the existence of the giant and dwarf stars, and their characteristic properties, and give us information about the very brightest stars that we could hardly have hoped to obtain otherwise. In all the spectral classes there are some stars a thousand times as bright as the Sun, or even brighter. These all show the narrow sharp lines noticed by Miss Maury, and are often called c-stars, following her notation. The average parallax of these stars can be obtained with considerable accuracy from their proper motions, taking into account the apparent drift produced by the Sun's motion in space, so that the spectroscopic parallaxes have here another firm point of support. Some of these c-stars are variable in a highly distinctive fashion, known as Cepheid variation, from the star Delta Cephei. The changes in brightness are continuous, with a regular period of a few days or weeks, and are accompanied by changes in color and spectrum—the star being redder, and further advanced in spectral type, at minimum. Whenever we find a star that varies in this fashion we can be morally certain that it is several hundred times brighter than the Sun.

Now a large number of faint stars which vary in brightness in exactly this way occur in the Magellanic Clouds—those remarkable patches, like outlying fragments of the Milky Way, which lie near the south pole of the heavens. They must be all at substantially the same distance from us. Miss Leavitt, at Harvard, found some years ago that there is an extraordinarily exact connection between the average brightness of these stars and their periods—those of longer period being the brighter. It is extremely probable that this relation holds true also among the nearer Cepheid variables which have already been mentioned. If this is so we can determine the absolute magnitude of such a variable, and hence its distance, from a mere knowledge of its period. Following this line, Shapley has determined the distances of more than a hundred isolated Cepheid variables, some of which are as much as five thousand times as bright as the Sun. Their distances range from sixty parsecs (for the Pole-star, which shows a slight variation of this type) to more than five thousand parsecs in a few instances. But these are not the greatest distances that can be measured by this very powerful photometric method. Shapley derives a distance for the Smaller Magellanic Cloud, of 19,000 parsecs. More recently Seares, working on similar principles, but utilizing our knowledge of the absolute magnitudes of blue stars (whose color indicates that they are of Class B) has estimated that the star clouds in the Milky Way itself lie at distances ranging from 6,000 to 15,000 parsecs.

Even these distances are surpassed by those of the great globular clusters of stars, which have been the object of one of Shapley's most striking investigations. From a study of the Cepheid variables which appear in these clusters, and by a most ingenious combination of other data, he has succeeded in obtaining reliable estimates of the distances of all the known objects of this type, 69 in all. These clusters are extraordinarily similar in size and constitution. The denser central portion of any one is some 10 parsecs in diameter, while the outlying stragglers extend to a distance of more than 50 parsecs in all directions. Within this region there are at least 40,000 stars brighter than the Sun, and probably a still greater number of fainter ones. The brightest stars, which are almost all red giants, average about 1,000 times the Sun's luminosity.

The nearest of these gigantic systems—which is visible to the naked eye in southern latitudes as a hazy star, Omega Centauri—is 6,500 parsecs away, while the remotest of them is at the enormous distance of 65,000 parsecs, or more than 200,000 light years. They are scattered somewhat irregularly through a somewhat oval region, symmetrical about the plane of the Milky Way, and almost 100,000 parsecs in maximum extent. The centre of this region is by no means near the sun—as is obvious from the fact that most of the globular clusters are found in one hemisphere of the heavens, and hardly any in the other—but is distant about 13,000 parsecs, in the direction of the constellation Sagittarius. It appears, therefore, that we are very far indeed from being at the centre of the universe. Astronomers, like others, used to think so, and were confirmed in their belief by the fact that the number of stars visible to the naked eye, and even in a small telescope, is substantially the same in all regions near the Milky Way (though smaller, of course, near its poles). This means that such stars are distributed around us almost uniformly in all directions in the galactic plane. But we now believe, with good reason, that the cause of this is that practically all the stars visible with a small telescope lie within relatively small distances—two or three thousand parsecs—which do not reach out to the boundaries of the universe of stars. It is only when we consider very faint stars, which are much more remote, that the real eccentricity of distribution becomes apparent. In other terms, we used to suppose that our soundings of the depths of stellar space gave us the same results in all directions: but what they really recorded was "no bottom." It is only with the longer measuring line afforded by modern photometric methods of determining distance that we strike bottom at last. This expansion of our conceptions of the extent and magnitude of the stellar universe is one of the most remarkable of all the advances of modern Sidereal Astronomy.