recently, Harris. By repeating the earlier exposures with this instrument, the changes in star positions after an interval of more than a quarter of a century can be found by the "blinking" process. Van Biesbroeck has detected many faint proper-motion stars in this way. The same observer has published long series of comet positions obtained photographically with the 24-inch reflector; in order to improve the orbits of these objects it is essential that they be followed over as long an arc as possible. Measures of comets have often been continued for months with the 24-inch reflector after most observers abandoned them because they were too faint. Such extended series are especially valuable in distinguishing between parabolic or slightly hyperbolic orbits and the elliptic ones which indicate periodicity.

The brightnesses of comets and their puzzling fluctuations also constitute studies from these photographic documents.

Stellar Spectroscopy

Otto Struve

ON THE WALL OF THE DIRECTOR'S office hangs an autographed portrait of Sir William Huggins. Once the personal property of G. E. Hale, it was presented by him to the Yerkes Observatory at the time of his departure for Mount Wilson in 1904. Huggins was probably the most famous of the early pioneers in astrophysics. In 1856 he had built a private observatory in the garden of his London residence at Tulse Hill, and had engaged in the study of the spectra of the stars by means of a small visual spectroscope attached to a moderately large refracting telescope. Three years later, Kirchhoff had succeeded in reversing two strong, dark absorption lines of the spectrum of the sun by placing a flame colored by sodium vapor in front of the slit, so that the lines appeared as two yellow emissions on top of the usual background of the continuous spectrum. The intensity of the background spectrum of the sun was reduced by a filter in this experiment. When Kirchhoff removed the filter, allowing full sunlight to fall upon the slit, the two lines were again seen as black absorption features "with an extraordinary degree of clearness." His announcement of the solution of the mystery of the Fraunhofer absorption lines followed shortly thereafter, and it was this announcement which inspired Huggins to write:

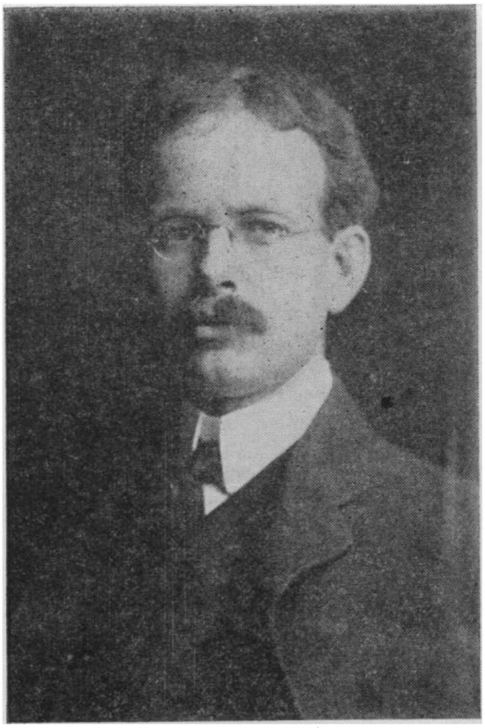
> Here at last presented itself the very order of work for which in an indefinite way I was looking. . . . A feeling as of inspiration seized me: I felt as if I had it now in my power to lift a veil that had never before been lifted; as if a key had been put into my hands which would unlock a door which had been regarded as forever closed to man [from Macpherson's *Makers of astronomy*, Oxford Univ. Press, 1933, p. 167].

During the past 50 years three directors of the Yerkes Observatory have conducted their work under the watchful eyes of Sir William, and I believe that all three have often looked up to his portrait for guidance. My predecessors, Hale and Frost, had known Huggins personally, and his influence is easily discerned in their publications. My own work, though not so intimately connected with that of Huggins, unquestionably resembles his in character. Huggins was filled with the spirit of exploration. When he opened the dome of his observatory and took his seat at the eyepiece of his spectroscope, he entered on a perilous journey to distant worlds where only ingenuity in reading and understanding the records of his instruments could save him from wrong conclusions, and where great perseverance was needed to try again and again to solve those riddles of the universe which would not easily give up their secrets. The major part of the Yerkes Observatory's contributions to stellar spectroscopy has been obtained in a similar spirit of exploration. Our procedure has usually been to examine with the utmost care all stellar spectrograms at our disposal and to try to detect those features which were not already explained by existing theories. Less often our search would be guided by previous theoretical considerations. Having found and described a hitherto unexplained phenomenon, we would next look for related data and then, if possible, measure some recognizable characteristic feature of the new phenomenon as a function of the related characteristic. Our purpose would always be to find a physical explanation. More often than not, the true explanation would escape us time and again, so that the work would have to be laid aside until an advance in a different field would make it tempting to try again.

We have always recognized the importance of long routine programs in astronomy, such as the construction of great catalogues of star positions, of magnitudes or of radial velocities; we have taken some part in programs of this kind, but we must now recognize that our contributions to such large-scale program work have been relatively slight. In stellar spectroscopy we are the successors of Huggins, not of Secchi with his famous catalogue of stellar spectra or of Vogel with his great and systematic work on stellar radial velocities.

When Hale prepared the plans for the Yerkes Observatory, he included in the specifications a stellar spectrograph for the 40-inch telescope. He was primarily interested in the physical study of the sun, but he undoubtedly wanted to supplement his solar investigations with the study of stars of similar characteristics. The outcome of this plan was an important memoir, *The spectra of stars of Secchi's fourth type*, which was published by him, in collaboration with F. Ellerman and J. A. Parkhurst, in 1904, as Part 5 of Volume II of the Publications of the Yerkes Observatory.

Few astronomers nowadays are acquainted with the classification of stellar spectra by Angelo Secchi, who recognized four main classes. Those having strong hydrogen lines were assigned to class I (now designated O, B, and A). Spectra with weak hydrogen and strong lines of elements like Fe I and Fe II, Ca I and Ca II, etc., were assigned to class II (now designated as F, G, and K). The red stars formed classes III (now designated as M) and IV (now designated as N). Hale had been much attracted by the early work of Huggins, Vogel, and others, which had seemed to indicate that Secchi's series of spectral classes represented an evolutionary sequence. The sun belongs to class II. Through the gradual loss of heat it would be expected to become redder. Will it ultimately become a star of class III or of class IV? It was not clear at that time whether classes III and IV represented successive stages of development or two parallel branches. All stars of class IV are fainter than magnitude 5, and little was known concerning their spectra. Hale and his collaborators decided to make use of the great light-gathering power of the 40 inch telescope to obtain spectra of reasonably good definition. The results of the observations, all of which were carried out between January 1898 and November 1902, were exceptionally valuable, and the illustrations which Hale included in his publication rank even now among the finest ever secured. For example, the authors succeeded in photographing the violet region of the spectrum in the neighborhood of Ca II 3933 in the star 19 Piscium—a feat which even today can be duplicated only with very few of the world's largest telescopes. The conclusion was that classes III and IV are parallel sequences, both leading back to stars like the sun. This conclusion has since been confirmed by many independent investigations.



George Ellery Hale, 1863-1938

Edwin Brant Frost, 1865-1935

The old Brashear spectrograph, with which Hale's work on the red stars had been carried out, was in many respects unsatisfactory. Its prism supports were not sufficiently rigid, so that small changes in the flexure of the instrument would take place during the long exposures required for the fainter stars. There was no temperature control, and the dispersion of the prisms could change appreciably during a single exposure. Attempts to use this instrument for the determination of stellar radial velocities were unsuccessful. For example, the well-known standard velocity star ϵ Leonis, as photographed on 17 occasions between February 11 and April 25, 1900, gave velocities ranging from −10 to +13 km./sec. This at first led to the belief that ϵ Leonis varied in radial velocity, but it was afterward shown that the star has an apparently constant radial velocity of about +5 km./sec. Hale pointed out that on many occasions the spectrograph gave excellent results, but it was not dependable and could not compete with instruments used at other observatories.

The greatest advance in perfecting the spectrographic equipment for radial-velocity work had been made a few years earlier by W. W. Campbell at the Lick Observatory. His famous Mills spectrograph was capable of producing spectra with an average dispersion of the order of 10 A./mm. Stars with sharp and strong lines whose laboratory wave lengths were accurately known could be measured with a precision of the order of ±0.1 km./sec. This was an enormous gain over the earlier work of Vogel and Scheiner at Potsdam. It has only recently been surpassed by measurements at the Mount Wilson Observatory on photographs taken with the large, stationary spectrograph at the coudé focus of the 100-inch telescope.

In 1898 Hale obtained a grant from Miss Catherine Bruce, of New York, which enabled him to appoint E. B. Frost, of Dartmouth College, as professor of astrophysics at the Yerkes Observatory and to furnish sufficient funds for the construction of a new spectrograph for accurate radial-velocity work. The instrument made use of three large prisms of Jena flintglass, figured by Brashear in Pittsburgh. The collimator, having an aperture of 51 mm. and a focal length of 1 m., was specially designed by Prof. Hastings to be used in connection with a correcting lens, placed in the cone of rays from the 40-inch objective, in front of the slit, whose purpose it was to convert the visually corrected telescope into one with a color curve having a flat portion in the violet region of the spectrum. Two cameras were provided having focal lengths of 449 and 607 mm., respectively. The mechanical supports were built of strongly reinforced steel, and, following the example of the Lick Observatory, the spectrograph was attached to the telescope near the center of gravity of the former—a procedure which greatly reduced the danger of flexure.

The Bruce spectrograph was placed in operation late in 1901. It has remained in constant use for 46 years, but the optical parts have been changed from time to time, and provisions were added to use it with either one or two prisms. The linear dispersion on the plate is 10 A./mm. at λ 4,500 when used with three prisms and with the longer camera. Tests by Frost and Adams indicated that the precision of their radial-velocity measurements was quite similar to that obtained by Campbell at the Lick Observatory.

Frost's first work with the Bruce spectrograph dealt with the motions of the helium stars. Because many bright representatives of this class are located in the constellation Orion, they were designated by Frost as stars of the Orion type. Perhaps the fact that Hale was concentrating upon stars at the end of the evolutionary sequence, as conceived by Huggins and Vogel, induced Frost to give his attention to those objects which "seem unquestionably to occupy a position very early in the scale of evolution." In the half century which has elapsed since then, our ideas of stellar evolution have undergone many changes. We no longer think of the helium stars as forming the beginning of the cycle and the red stars as forming the end. But in many respects these two groups are still recognized as extreme opposites in temperature and in other physical characteristics.

Together with W. S. Adams, Frost published a paper under the title "Radial Velocities of Twenty Stars Having Spectra of the Orion Type." Although the number of stars was not sufficient to make a solution for the motion of the sun in interstellar space, "the distribution of positive and negative velocities shows clearly the direction of the motion of the sun in space." The average motion of a helium star was found to be surprisingly small—only 7.0 km./sec. It was already known from the work of Campbell and others that the average velocity of the cooler stars is considerably larger. Thus, Frost and Adams brought out the significant fact that the average motions of the stars are not the same for all spectral types. This result has been of fundamental importance in all later investigations concerning the dynamics of the stellar system.

A very puzzling result was stated by the authors in the following short sentence: "...if the sign be regarded, the mean becomes +4.6 km./sec." In other words, after the component of the solar motion had been subtracted from the measured radial velocities, the mean velocity was not zero, or close to zero, but was of the same order of magnitude as the mean velocity taken without regard to sign. The authors had thus, for the first time, recorded the famous K-effect in the motions of the helium stars, which, literally interpreted, means that the system of these stars, as a whole, expands with a velocity of 4.6 km./sec.

In 1910 Frost, in collaboration with J. C. Kapteyn returned to the question of the mean motion of the helium stars. After having discussed the solar motion from the large amount of material collected by Frost, the authors remark:

> ...meanwhile our numbers bring out a somewhat unexpected fact, namely, that the velocity of the sun relative to the stars near the apex is found to be very different from that relative to the stars near the antapex. To show this more clearly, a separate solution was made for the stars for which $\lambda < 90°$ and for which $\lambda > 90°$ (λ is the angular distance of a star from the apex, that is, from the point in the sky towards which the

solar system is moving). We thus find:

Near apex $v = 18.38 \pm 1.40$ km./sec. from 32 stars
Near antapex $v = 28.38 \pm 1.36$ km./sec. from 29 stars
Simple mean $v = 23.38$ .... from 61 stars

The difference is very considerable and cannot well be attributed to accidental error alone.

It would seem that in the direction in which we are moving we are approaching the stars less rapidly than we are receding from the stars located in the opposite direction. This would not be possible if the stars were, on the average, stationary. They must have a systematic motion, and this can best be described as a general expansion in all directions. The nature of this expansion has been the subject of many later investigations. Frost, himself, spent much time and effort in proving that it could not be due to errors in the assumed stellar wave lengths, which were then known with insufficient accuracy. Later workers attributed it to a spurious effect caused by a cluster of helium stars in the Scorpius-Centaurus region, which all move in the same direction. Still others have thought of a gravitational red-shift, a phenomenon which may well be present in the most massive stars of very high temperature whose radii are not particularly large. The problem which was opened by Frost and Kapteyn is still unsolved.

In the course of Frost's radial-velocity work on the stars of early spectral type, many new binaries were discovered. These objects show variable radial velocities, and sometimes their lines are double—corresponding to the opposite motions of the components in a close double-star system. The pages of the *Astrophysical Journal* were virtually swamped with announcements of new binaries. Their number grew so rapidly that Frost was, at times, concerned over the question whether enough stars of constant velocity would be left to provide sufficient material for the statistical study of the motions of the helium and hydrogen stars. He and his associates, therefore, began the laborious task of determining the orbits of some of these binaries. Only in this manner could the average systemic velocity of a close double star be determined.

On May 14, 1902, Frost made a discovery of great importance. On that particular night he obtained two spectrograms of the bright helium star, β Cephei. He had observed it on many previous occasions and had found the velocity to vary as in a spectroscopic binary. But all efforts to find a period within the usual range of a few days to a few weeks had failed. He states in his first announcement concerning β Cephei:

> We had assumed from the first plates that the period would be rather long, but a suspicion to the contrary led me to take two plates on the night of May 14, and during the interval of five and one half hours the velocity changed 14 km., or nearly half of the whole range so far observed.

Such rapid variations in velocity were a sensation in 1902, and Frost diligently continued his observations. Four years later he announced that the period is $4^h34^m11^s$, and that the velocity curve is nearly symmetrical, with a range of 34 km./sec. He tried to determine a set of orbital elements, in the conventional manner, and found that the radius of the projected orbit would be unbelievably small—only 45,000 km. Later investigations at the Yerkes Observatory, including one completed in 1947 by Miss Nancy Roman, show that β Cephei is not a real binary, but a star of other and, in many respects, unique physical properties. We still know little concerning the cause of the variations in radial velocity; perhaps they are produced by some kind of pulsations, as in the Cepheid variables. Another interesting representative of this class of stars, β Canis Majoris, has been investigated by Swings and the writer and more recently by Miss A. Underhill. It shows remarkable, and as yet unexplained, periodic variations in the profiles of the absorption lines (first discovered at the Lick Observatory).

The last years of Frost's administration were clouded by his blindness. He lost the sight of one eye, through the loosening of the retina, while working with the 40-inch telescope. A rapidly growing cataract in the other eye in 1921 ended his scientific work. He retained the directorship until 1932, but he was no longer able to take an active part in the research work of the Observatory.

The original equipment of the Observatory was unquestionably the best that could be obtained at that time. But severe financial restrictions throughout most of Hale's and all of Frost's administrations made it impossible to maintain the equipment on the high level that was required to meet the competition of other institutions. The Yerkes Observatory gradually fell behind, and the work slowly assumed a more routine character. It was at this stage that, through the initiative of President R. M. Hutchins, a new era of development and expansion was started. In 1932 Frost retired, and the writer was appointed to succeed him as the director. At the same time a contract was signed, binding the University of Texas and the University of Chicago for 30 years in the joint operation of a new observatory, to be built in the Davis Mountains of western Texas from the W. J. McDonald bequest to the University of Texas. The new observatory, equipped with an excellent 82-inch reflector and with up-to-date spectrographic equipment, was completed in 1939. Since then, most of the results in stellar spectroscopy have come from material secured with the McDonald telescope. But it is not possible to distinguish between Yerkes and McDonald contributions. They are closely interwoven and should be regarded as the work of a single group of scientists.

Through the perseverance of many careful observers at the 40-inch telescope there had been gradually accumulated, by about 1925, a fine collection of approximately 10,000 photographs of the spectra of nearly 1,000 different stars. Frost had intended to use this material for the determination of the motions of the stars in the line of sight. The spectra of the stars were flanked on both sides by the spectra of a laboratory source, such as that of the electric spark between iron or titanium terminals. The photographs could then be placed in a measuring machine, and the astronomer could determine the slight "Doppler shifts" of the lines of the star as measured with reference to the lines of the comparison source. This work was carried out in two stages: in 1926 we published the results for 360 stars of the helium type (now designated as class B); in 1929, the velocities of 500 hydrogen-type stars (now designated as class A).

More important was the opportunity which the collection of spectrum photographs offered for the study of the intensities and profiles of the lines. Most people have only a hazy idea of the appearance of the absorption lines in a stellar spectrum. Since the spectrum is produced by illuminating a narrow metal slit with the light of the star, we expect to find a continuous band of colored light, crossed by sharp, black lines whose profiles are faithful images of the slit and whose locations on the continuous spectrum correspond to those shades of color which are absorbed by the atoms in the atmosphere of the star. Such a spectrum is actually observed when we examine the light of the sun with a prism or diffraction grating. But not all stars have such spectra. Many have broad and hazy features in the place of the sharp Fraunhofer lines of the sun, and frequently they are not at all black, even near their centers, but are visible only as very slight depressions of intensity in the continuous spectrum.

In the course of my work on the measurement of the Doppler shifts of these hazy features, I was seriously bothered by the question of whether we could really trust the settings which I was making upon the geometrical centers of the broad lines. The results were plausible, but I would have been better satisfied if I could show that the cause of broadening acted symmetrically toward the red and toward the violet sides of the spectrum. Little was then known about the broadening of spectral lines in the laboratory, and next to nothing about their broadening in the stars.

The first task was to examine all cases of broadened absorption lines in order to determine, if possible, whether they originated from one cause or from several. It was at once clear that very strong lines—those which presumably were produced by large concentrations of atoms—are always broad. Such are, for example, the famous calcium lines of the sun, *H* and *K*. But there are many stars in which all lines, both faint and strong, appear broad. In other stars precisely the same lines are sharp and narrow. This phenomenon was highly intriguing. We tried at first to determine whether the stars with broad lines differed systematically in their other characteristics from those with sharp lines, but in nearly all respects the two groups were identical. We suspected a tendency of the broad-lined stars of the hydrogen type (class A) to be intrinsically less luminous than those with narrow lines, but before our discussion was completed, the same result was announced by Adams and Joy in their paper on the absolute-magnitude difference between stars with nebulous and stars with sharp lines. But the phenomenon did not suggest a physical cause of the line broadening, and it has since been shown to be caused, at least in part, by a systematic difference in the classification of the spectra.

The solution to our problem came from an examination of close spectroscopic double stars. Those with very short periods (of the order of one day) always had broad lines, while those of longer periods usually had much narrower lines. The short-period systems undoubtedly consisted of two stars almost in contact. Tidal forces would compel them to rotate as one solid body: the periods of rotation and revolution would be the same. Hence, the broadening should be due to rapid axial rotation. This result was later confirmed in many different ways, and, by analogy, we concluded that single stars also occasionally rotate with enormous speeds. The highest velocity at the equator is of the order of 300 km./sec.; that of the sun, only 2 km./sec.

The discovery of stellar rotation opened the way to other studies. On the one side, it led to studies of the distribution of rotational velocities and their bearing upon the old problems of the origin of double stars and planetary systems. On the other, it raised the question: Are there other spectroscopic phenomena which are correlated with that of axial rotation? One interesting correlation was found at once: the widths of the hydrogen emission lines observed in a small fraction of the helium and hydrogen stars are correlated with the rotational velocities determined from the absorption lines. The conclusion was simple: these stars are surrounded by nebulous envelopes of luminous hydrogen which revolve around them. When the axis is perpendicular to the line of sight, the emission lines and absorption lines are broad; when it is in the line of sight, both types of lines are narrow. However, the absorption lines can be narrow not only because the axis is in the line of sight but also because the star has actually a slow rotation. Such stars have no emission lines. The existence of the radiating nebula depends upon rapid rotation, it being somehow produced as a result of this—most probably through some kind of equatorial escape of gases from the rapidly rotating star. Sometimes, when we observe a rapidly rotating star whose axis is very nearly perpendicular to the line of sight, a thin, but radially extended, gaseous ring is formed which produces a series of very narrow and sharp absorption lines.

Gradually we eliminated those spectroscopic phenomena which are caused by stellar rotation. After this was done, it appeared that there were many stars of class B in which some helium lines were broad and hazy, while others were sharp and narrow. The lines were all relatively weak; hence, the broadening was not that produced by large concentrations of atoms. An examination of laboratory data on the Stark effect showed that all those lines whose Stark splitting in an electric field is pronounced are broad in the helium stars. This type of broadening is well known to physicists and is ascribed by them to the perturbing action which neighboring charged particles—electrons or ions—produce upon the radiating atoms of helium. Such an effect should be large when the pressure is large, because then the perturbing particles are close to the radiating atoms. Upon this theoretical prediction we built a method for determining the pressure in stellar atmospheres. From these we could easily find the luminosities and could decide from the appearance of the helium lines whether a star is a supergiant or one of more moderate luminosity.

There was an interesting consequence of this work on the Stark effect. In the laboratory the presence of electric fields facilitates the appearance of helium lines which are normally forbidden by the selection rules. These lines were actually found in several dwarf stars such as γ Pegasi and τ Scorpii. But another prediction of the Stark effect could not be verified: electrical fields are known in the laboratory to shift some helium lines toward the red side and others toward the violet side of the spectrum. The broadening should thus be one-sided; the lines should be unsymmetrical and their measured positions should give slightly erroneous wave lengths. We noticed early in our investigations that the broadened helium lines were essentially symmetrical, so that any excess of broadening on one side over that on the other could only be an effect of the second order. Many years ago I suggested that this peculiar discrepancy between observation and the statistical theory of Stark broadening is caused by the collisions of particles and radiating helium atoms. The theory of collisional broadening has in the meantime been developed by physicists. But the exact application to stellar atmospheres was lacking until Chandrasekhar made an important theoretical advance which enabled Mrs. M. Kiess-Krogdahl to explain not only the symmetrical appearance of the lines but also their observed profiles and equivalent widths.

Our next concern was that of the strange, broad but often very deep lines in supergiants and a few peculiar stars such as 48 Librae. Rotationally broadened lines have shallow central depressions; lines broadened by large concentrations of atoms (radiation-damping), by Stark effect, or by collisions, all have characteristic wings. The lines in supergiants have bell-shaped profiles, with relatively steep edges. Thermal motions cannot explain them, because the lines are much too broad for the temperatures known to exist in the reversing layers. Our study was complicated by the fact that the resolving power of astronomical spectrographs is not sufficient to bring out this type of broadening except in very few bright stars. After several years of unsuccessful efforts, Elvey and I finally found the explanation: the atmospheres of many supergiant stars are not quiescent, but show strong, turbulent currents, up and down, so that the observed line-profiles have approximately the shape of a Gauss curve, the motions being distributed more or less in a random manner. There have been numerous investigations of this phenomenon since our announcement of it in 1934. One of the most significant was by J. L. Greenstein, who showed that there exist in the observed profiles appreciable departures from the simple Gauss curve. In a few supergiants (α Cygni) and stars with very extended atmospheres (17 Leporis) there is a tendency for the lines to show profiles with two minima of intensity, sometimes of unequal depth. This would suggest that the motions are predominantly in two streams: one rising in the atmosphere, and the other descending. But the line-profiles show that the two streams must be thought of as consisting of turbulent cells of dimensions which are small, relative to the height of the star's atmosphere. There has as yet been found no direct connection between the phenomena of turbulence in stars and in the earth's atmosphere, but the possibility of such a connection is not excluded.

The most recent advance in this field resulted from a comparison of measurements by Miss H. Steel in the spectrum of δ Canis Majoris with others made by me. The conclusion was that the turbulent velocity is a function of height in the reversing layer, increasing with the latter.

The problem of the central intensities of stellar absorption lines has been the subject of several Yerkes investigations, notably by Greenstein. Stars with large rotations or with other forms of mechanical Doppler broadening, such as expansion in novae or nova-like stars, were, of course, excluded. The hot stars have relatively shallow lines, even in supergiants, but Greenstein pointed out that they are not as shallow as theory would have led him to expect.

In a way, our studies of stellar line-profiles were all preparations for the important task of determining the abundances of the chemical elements in the atmospheres of the stars. There are some reasons to believe that these abundances are not the same in all stars, and much of the evidence comes from the Yerkes and McDonald Observatories. Thus, υ Sagittarii, according to Greenstein, has a low abundance of H and a high abundance of He, while Popper has found a helium star without any lines of H whatever. Astronomers at other observatories have been led to similar conclusions. All of these results depend upon our ability to derive the number of absorbing atoms per cubic centimeter from the profile of an absorption line.

The question of the abundances of the chemical elements in the universe constitutes one of the most fundamental problems of all physical science, and it is receiving increased attention at the Yerkes and McDonald Observatories. It is an extremely difficult problem, however, and astrophysics is full of the graves of premature and insufficiently founded theories and observational conclusions. Among the most convincing data are recent results by G. Herzberg from McDonald spectrograms on differences in abundance of the carbon isotopes in different stars. On the other hand, the writer has recently observed a close binary system (UX Monocerotis) in which the hydrogen absorption lines undergo periodic variations in intensity, so that at times they are almost invisible, while at others they are extremely strong. In this case, at least, it would be unsafe to attribute the variations to changes in abundance. It is certain that the real differences of chemical abundance are still, to a large extent, obscured by an unknown phenomenon which affects the line intensities. It will be necessary to identify this phenomenon and explain it before we can succeed with the abundance problem.

After we had derived a reasonably complete understanding of the profiles of stellar absorption lines, it was tempting to apply the new knowledge to certain mysterious stars which had puzzled astronomers since the days of Huggins. Foremost among them was the problem of ϵ Aurigae. A spectroscopic double star with a period of 27 years, this third-magnitude star shows only the lines of one component, and it is from the variable Doppler shift of these lines that the orbit could be determined. The plane of the orbit is in the line of sight, and once every 27 years the principal component of ϵ Aurigae is eclipsed by the other, invisible component. Spectroscopic double stars are not rare: several hundred have been discovered and critically analyzed. But ϵ Aurigae presented a puzzle which would not yield to the conventional methods of analysis. The eclipse was found to be total, so that the disk of the dark, invisible component completely covered that of the bright, visible star. Yet the spectral lines of the latter remained visible throughout the many months of totality. Most of them were greatly strengthened, appearing unsymmetrical during the partial phases of the eclipse. The light curve is of such a character, however, that the invisible, dark component can only be of much lower surface temperature than the principal component and consequently should have other absorption lines, namely, those which are characteristic of low temperature. Observations of ϵ Aurigae were started by Frost almost as soon as the Yerkes Observatory was opened. Several investigations of its spectrum were made at different times by Frost, Struve, and Elvey, but, while much valuable information was obtained, the cardinal question of why the lines of the bright component remained visible during totality remained unanswered. Finally, in 1937, armed with our new knowledge of line formation and with a new theory of the light curve, the problem was solved in a joint investigation by Kuiper, Struve, and B. Strömgren. The invisible, eclipsing star is incredibly large, its diameter being roughly similar to that of the orbit of Saturn. This enormous, cool supergiant is partly transparent, so that the light of the much smaller, bright component of the system shines through it. The asymmetries of the lines are produced by the gases of the cool supergiant, whose axial rotation produces a small relative displacement.

There remained one small but rather puzzling circumstance. The absorption effects in the cool supergiant which give rise to the observed asymmetries of the lines did not influence the strong magnesium line, Mg II 4481. This was unexpected, because from analogy with other, ordinary stellar spectra we should have believed this line to be affected quite as much as the numerous lines of Ti II, Fe II, etc. We started looking for other astronomical spectra which might show a similar weakness of the Mg II line. The outcome was a series of investigations, in which K. Wurm cooperated, on the suppression of lines with excited lower levels which are not metastable, when the field of radiation is of small density, but corresponds in distribution with wave length to a high temperature. The fundamental theoretical idea of this work goes back to a paper by S. Rosseland, published in 1926, and the phenomenon is usually described as that of diluted stellar radiation.

This phenomenon has proved to be a remarkably powerful tool in astrophysics. A layer of gas in front of a radiating stellar photosphere is, in effect, an absorbing screen which reduces the intensity of the transmitted beam in those wave lengths to which the atoms of the screen are tuned. An ordinary absorbing screen absorbs a fixed fraction of the incident light, whether it is placed close to the radiating source or close to the eye of the observer. But the absorbing source of magnesium atoms has the property of absorbing a larger fraction of the incident light if the atoms are near the surface of the star and a smaller fraction if they are far above the surface of the star. The suppression of the magnesium lines in ϵ Aurigae during the total eclipse means that the atoms are very far away from the source of light—the small, bright component which is being eclipsed. This is exactly what we had already deduced from the unsymmetrical lines of titanium, iron, etc. The latter are not sensitive to the dilution effect and always absorb the same fraction of the incident light, no matter what their distance is from the radiating source. If all absorbing atoms—those of magnesium, as well as those of titanium, iron, etc.—are located in the semitransparent, invisible supergiant component, we should be able to determine the distance between the two components from the degree of suppression of the magnesium lines.

The most interesting applications of the theory of the dilution effect have been obtained in the case of the lines of helium. Some have lower levels which are metastable, while other, equally strong lines have excited lower levels which are not metastable but are connected with the ground level of the helium atom by very strong ultraviolet transitions. The former are not affected by the distance of the source, while the latter are suppressed unless the atoms are on the surface of the star itself.

We at once made use of this discovery. In several stars we found the sensitive helium lines to be suppressed by a factor of the order of 100, as compared to the normal intensities of these lines. Since the degree of suppression is proportional to the amount of radiant energy from the light source at the point where the helium atom is located, and since this is inversely proportional to the square of the distance from the star, we were able to conclude that the absorbing screen of helium atoms is located at an average distance of roughly 10 times the radius of the star itself.

This immediately led to the solution of another astronomical puzzle, namely, that of the famous eclipsing binary, β Lyrae. By a strange coincidence, the problem of β Lyrae was discussed at a conference of astronomers in connection with the dedication of the Yerkes Observatory in 1897, but the final solution came in a joint study by Kuiper and Struve in 1941. The system of two giant stars with almost touching surfaces generates a gaseous stream which flows from one component toward the other and is then split into two branches: the one flows around the cooler of the two components and returns ultimately to the place of origin; the other is forced by centrifugal action to leave the system and spirals rapidly outward into space. Gaseous streams produce remarkable absorption effects when observed in front of the luminous body of the hotter component of β Lyrae. When apparently projected upon empty space, they produce strong emission lines in the spectrum.

The recognition of gaseous streams in β Lyrae soon led to the discovery that many other binary systems possess similar streams. During the past four years much effort has been spent at McDonald and at Yerkes, at first in the study of the emission features produced by these streams, and more recently in the study of the corresponding absorption effects. This work is still in progress. A particularly interesting feature of these double-star spectra is the shape of the emission lines of hydrogen, consisting of two separate peaks. As the invisible component of the double star begins to eclipse the brighter component, we observe at first the disappearance of the violet emission peak; then, during total eclipse we often fail to see any trace of emission, while after totality we observe the appearance of the violet peak and the disappearance of the red peak. The emitting atoms of hydrogen form a ring around the bright double-star component which revolves around the latter in the same direction as the orbital revolution.

In 1939, P. Swings came to the Observatory from Belgium to collaborate in the study of another class of peculiar stellar spectra. He intended to remain for one year, but the war intervened and he remained until the middle of 1943. During this interval we devoted most of our attention to an interesting group of objects—those whose spectra have sharp and narrow emission lines of highly-ionized atoms, often including the forbidden nebular types of radiation. Due to Swings' experience in the spectroscopic analysis of laboratory sources we were able to record and identify numerous previously unknown emission lines. Many new results were obtained, and the previously proposed hypothesis of the binary nature of these objects was greatly strengthened.

Another puzzling group of objects was attacked by Swings and Struve with the large coudé spectrograph in a study of α Canum Venaticorum. This star has at times very strong lines of Eu II, Gd II, and other rare earths, but the intensities are variable in a period of about 5 days, so that at certain other times the rare earths are absent or very weak. An exhaustive investigation gave a good description of the phenomena, but served only to eliminate such simple explanations as a periodic change in normal ionization conditions. We found a few suggestive relations, but were unable to account for the extraordinary variations. We next observed another star having variable lines, ϵ Ursae Majoris, but again there was no physical explanation. W. A. Hiltner made a study of β Coronae Borealis in which the rare-earth lines are also unusually strong but in which there are no periodic variations in intensity; no clue to our problem was found. We have a large amount of observational facts for a few stars, and it is disconcerting that no theory is able to account for them. For further progress, more stars with variable lines must be found. This work of discovery was at first undertaken by W. W. Morgan, who in the early 1930's found several new representatives of this almost completely neglected class. A. J. Deutsch has greatly extended the work of discovery and has furnished us with a list of interesting objects and their periods. Whether we now have a broad enough basis of observational data to insure success in our search for a physical theory remains to be seen.

During the past 15 years the 40-inch telescope has been used to good advantage for spectroscopic investigations with instruments of small dispersion. An *Atlas of stellar spectra* by Morgan, Keenan, and Kellman has become the accepted standard for the classification of stars according to their temperatures and pressures. Another atlas consisting of spectrophotometric tracings of coudé plates of 8 bright stars taken at the McDonald Observatory with dispersions between 2 and 14 A./mm. was prepared by Hiltner and Williams and published by the University of Michigan Press. This serves as a valuable source for many astrophysical investigations.

Among the fuzzy-line stellar spectra of the helium type there were many which had sharp and exceedingly narrow lines of ionized calcium. These lines were known to Frost and his co-workers and aroused their interest because all other lines, such as those of He I, Si III, O II, etc., were uniformly broad and hazy. The problem of the sharp calcium lines was brought to a focus when in 1904 J. Hartmann, of Potsdam, announced that these lines remained stationary in the spectroscopic binary δ Orionis, whose other absorption lines showed the characteristic periodic variation in radial velocity as the binary pursued its course along an orbit whose plane is approximately in the line of sight. Hartmann had suggested that the stationary calcium lines are produced by a cloud of calcium atoms in interstellar space and have no relation to the binary system. But this revolutionary hypothesis was not accepted by other astronomers, and several investigations appeared (erroneously, as we now know) to show that the calcium atoms are distributed in the immediate neighborhood of the double-star components. The problem remained in this state until 1926, when A. S. Eddington, in his famous Bakerian Lecture of that year, presented strong theoretical arguments in favor of the existence of an exceedingly tenuous gaseous substratum in interstellar space. Eddington's work led to a simple prediction: the sharp calcium lines must be present in all distant stars, not only in spectroscopic binaries, and their absorption intensities must increase with the distances of the stars. The rich spectrographic material of the helium stars at the Yerkes Observatory offered a tempting invitation to test Eddington's hypothesis. We already knew that the helium stars have exceedingly high intrinsic luminosities—100 or even 1,000 times the candle power of the sun—so that for any given apparent magnitude an average helium star is from 10 to 30 times as far away as one of the solar type.

A preliminary study of the Yerkes collection gave a strong indication that the sharp calcium lines were indeed stronger in the more distant stars, but because of the limited light-gathering power of the Yerkes telescope the range in distance was not sufficiently large to place the result beyond all reasonable doubt. Our telescope was not big enough to photograph the spectra of the fainter and, hence, the more distant stars. In order to supplement the Yerkes material I obtained permission from W. S. Adams to spend several months at the Mount Wilson Observatory and to use the 60-inch reflecting telescope for the observation of the spectra of a selected list of faint helium stars, principally in the constellations Cepheus and Cygnus. I was also permitted to inspect the magnificent collections of stellar spectra at Victoria and at the Lick Observatory. The final result was a complete confirmation of Eddington's hypothesis: interstellar space contains a gaseous medium in which the ionized atoms of calcium—those which produce the observable lines H and K in the violet part of the spectrum—are distributed with a density so low that approximately one calcium ion is found in every 10^8 cc. of space. An interesting by-product of this work was a new method for the determination of the distances of the more remote stars in our galaxy from the measured intensities of the interstellar absorption lines.

In the meantime, principally through the research of H. N. Russell at Princeton, it had become amply clear that hydrogen forms by far the most abundant substance in the stars and nebulae. It seemed strange that the gaseous substratum in interstellar space should consist mostly of calcium. Was it not possible that, because of the very unusual conditions of extremely low pressure, high exciting temperature, and excessively low density of the exciting stellar radiation, the calcium lines would be placed at an advantage in producing absorption lines, while the hydrogen lines, even though produced by an exceedingly abundant species of atoms, would absorb so weakly that its lines would escape detection? There were theoretical reasons to suspect this; but how could we prove it? A simple computation showed that the interstellar hydrogen atoms, if really present in anything like the expected abundance, might produce a faint glow of radiation in the Milky Way, between the stars. There was, however, no spectrograph at our disposal sufficiently powerful to record this feeble hydrogen radiation.

We had a new Schmidt camera of the then unusual focal ratio f/1, which had been made for us by a Chicago amateur telescope maker, as well as a pair of excellent quartz prisms, but there was no suitable collimator. We decided to build a strange, new instrument at the McDonald Observatory. This has since been described in the astrophysical literature as a "nebular spectrograph." A small, clock-driven, equatorial mounting supports on one side a long, narrow, rectangular, plane piece of mirror which serves as the slit, and on the other side the Schmidt camera with quartz prisms, working as an objective-prism instrument. The reflection from the slit-mirror is directed upward along the polar axis to a stationary plane mirror placed higher up on the slope of our mountain. This circular mirror reflects the beam toward the camera, which is focused on the slit mirror at an effective distance of 150 feet. This instrument gave excellent results, and in a short time Elvey and I could announce the existence of vast regions of hydrogen radiation in the Milky Way. The average density of the interstellar hydrogen is about 1 atom/cc.

After the completion of the 82-inch telescope at McDonald in 1939, the nebular spectrograph was dismounted, and the work on interstellar hydrogen radiation was discontinued. In recent years J. L. Greenstein has used the large reflector in a study of the physical properties of those condensations of the interstellar medium which we know as gaseous nebulae.