universe it is as important as that of the law of gravitation. Professor Hale spoke of the possible evolution of a nebula into a star. In its contraction it developed heat energy in conformity with the principle of the conservation of energy. Helmholtz first applied this principle to contracting suns about sixty years ago, and his work was followed by that of Kelvin, Lane, and Ritter. This work shows us that if our own Sun has no other important source of heat, it cannot have supplied the Earth with heat for more than about 20,000,000 years. On the same basis, the Sun will not give the Earth heat more than about 10,000,000 years in the future.

These figures were derived on the basis that the Sun has no other important sources of heat than that produced by its own contraction. But physicists and chemists have recently found that some atoms break up into their constituent parts, and that in the process an enormous amount of energy is liberated. Possibly the sub-atomic energies are important sources for maintaining the heat of the stars. At any rate, most geologists believe, on the basis of geological evidence, that the Earth is many tens of millions of years, if not hundreds of millions, old, and astrophysicists are generally willing to admit that the life of a star is many times 20,000,000 of years. And if this is true, we may reasonably infer that the Earth will exist and be suitable for the abode of life for tens of millions of years in the future.

So we see that mathematical astronomy for the last fifty years has not been devoted to applying the law of gravitation to current celestial phenomena, for that had been done with almost complete success a half century earlier, but to a rigorous testing of the fundamental laws and principles on the basis of which we shall unfold and come to understand the evolution of the universe from infinity to infinity.

ADDRESS BY PROFESSOR GEORGE E. HALE.

SOME REFLECTIONS ON THE PROGRESS OF ASTROPHYSICS.

The great national edition of the works of Galileo, published by the Italian Government under the skilled and devoted editorship of Professor Favaro, contains a page of unique interest in the archives of astronomy. Reproduced in facsimile from Galileo's note-book, the hasty sketches and rapid notes made during his first telescopic observations of Jupiter lie before us. Copernicus had already published his great work on the revolutions of the heavenly bodies, and Galileo, with a mind singularly free from the medieval prejudices of the day, had accepted the heliocentric view, and had become its chief exponent. But the true conception of Jupiter's system of satellites dawned slowly,
and in the few notes made from night to night we can trace its development in Galileo’s mind. First regarded as stars, whose changing configurations must result from the motion of Jupiter, the satellites were gradually perceived to belong to a wonderful system revolving about Jupiter as the planets revolve about the Sun. This splendid illustration of the views of Copernicus marked the downfall of the Ptolemaic system and the beginning of modern astronomy.

Of this new era, which arose from the invention of the telescope, it is not within my province to speak. But we must realize how the astrophysics of the last half century is deeply rooted in a more remote past. When Galileo discovered spots on the Sun he opened to investigation the problems of solar physics. In the same century Newton decomposed sunlight into its primary colors, though he failed to detect the dark lines of the solar spectrum. These were first seen by Wollaston and accurately mapped by Fraunhofer in the year of Waterloo. But although Fraunhofer discovered similar lines in the spectra of certain stars, and even detected the coincidence of the double yellow line of sodium in a flame with the double dark line which he called D in the solar spectrum, the significance of these observations was not perceived until 1858.

It is a remarkable fact that firm foundations for the study of both organic and inorganic evolution were laid in this same year. The Origin of Species, presenting a vast mass of evidence in support of the theory that new species originate by natural selection, raised the biological world out of the systematism of Linnaeus into the stimulating atmosphere of the Darwinian period. At the same moment the study of the evolution of the Sun and stars was made possible by Kirchoff’s law of selective absorption and his identification of the dark lines of the solar spectrum with the lines of the chemical elements in the flame and spark. It became as easy to determine the chemical composition of the solar atmosphere as to analyse a common substance by the ordinary processes of the chemist. Sodium, iron, calcium, hydrogen, in fact nearly all terrestrial elements, were found in the Sun and soon afterward in stars. If a new star blazed out in the Milky Way, its chemical constituents were seen to be of the very kind most familiar to us on the Earth. Thus a marvelous unity, embracing the most remote objects of the universe, was at length perceived. And the instrument that revealed it furnished also the means of tracing the life histories of the stars.

Secchi, Rutherfurd, Huggins, and Draper were the pioneers in this new field. The diverse spectra of the stars were at once recognized as indications of physical development. Huggins’ discovery of the gaseous nature of certain nebulæ was taken to point to a source of material
from which stars might be formed. And thus was set on foot that splendid campaign, rendered possible by the effective use of the objective prism and the modern slit spectrograph, powerfully supplemented by the photographic plate, which has carried us well on the way toward a perception of the course of stellar evolution.

I cannot attempt to trace the tactics, or even the broader elements of strategy, in this great attack on the celestial hosts. Nor may I pause to show how one unit in the stellar ranks, placed as an outpost at the center of the solar system, has been subjected to the varied assault to which his proximity exposes him. The time at my command may be better devoted to a brief survey of some of the larger results achieved and a glance at the means which have made them possible.

So few are the principal types into which the stars may be resolved that Fraunhofer himself detected most of them. Disregarding certain special groups, and confining our attention to the more pronounced marks of distinction, we find that more than a hundred thousand spectra photographed at Harvard belong to the following classes: white stars, in which the lines of helium are conspicuous; stars, also white, in which hydrogen plays the leading role, while traces of the metals begin to appear; yellowish stars, like the Sun, in which the hydrogen lines, less conspicuous than before, are accompanied by thousands of lines due to metallic vapors; and orange or red stars, in which the still fainter hydrogen and stronger metallic lines are accompanied by bands characteristic of titanium oxide. These classes stand in an unbroken sequence, passing over by slow and barely perceptible changes from one to another, and marking out a line of development in which some single variable must undeniably play the dominant part. The differences in the spectra, indicated by the greater or lesser prominence of one or another element, cannot mean fundamental differences in chemical composition. This might be proved in several ways, but is perhaps most clearly illustrated by the recently discovered fact that certain variable stars, of the Cepheid class, undergo a regular variation in spectral type in the space of a few hours, showing at the same time corresponding fluctuations in brightness and in temperature. Again, we know that the spectrum of a sunspot, a cooler region on the Sun, closely resembles that of a red star, which is essentially a cooler Sun.

Temperature, then, is the main source of the observed differences in stellar spectra. The white helium stars attain temperatures of perhaps 20,000° C, the white hydrogen stars may exceed 10,000°, the yellowish stars like our Sun measure about 6,000°, while the red stars range from 2,000° to 3000°, thus falling within the limits attained by our electric arcs and furnaces. With these and certain laboratory devices
we may test this temperature hypothesis, and prove its general validity beyond any reasonable doubt.

Thus in the gradations and sequence of their spectrum lines, in color differences corresponding with the shift of the maximum brightness in the spectrum toward the red with lowering temperature, and in other respects no less remarkable, the stars fall into an ordered series. Only recently has it been shown by Kapteyn, Campbell, and Boss that the speeds with which the stars are moving through space also vary in the same sequence; a condition so unexpected and so fundamental that it taxes existing means of interpretation.

At this point astronomy and astrophysics have joined hands in pushing forward the study of stellar evolution. The stars vary enormously in mass, in density, and in surface brightness, and if we are to discuss intelligently the differences in their spectra we must reduce them as nearly as may be to a common basis. A long step in this direction has been taken by classifying stars, not merely on the indications of their apparent brightness, but in terms of their actual brightness—the brightness they would have if they were all brought to the same distance from the Earth. To do this we must know their exact parallaxes, few of which have been determined until recently with the necessary precision. Fortunately a strong group of astronomers, including the director of the Dearborn Observatory, is cooperating most effectively in the photographic measurement of stellar distances. The number of parallaxes already determined has sufficed to yield some remarkable conclusions, when coupled by Hertzsprung and Russell with the results of spectroscopic and photometric investigations.

The first of these is that the white stars greatly exceed the Sun in actual brightness, while the very faint stars are invariably red. Moreover, there appear to be two great classes of stars: those of extreme brightness, which have been called giants and those of lesser brightness called dwarfs, of which our Sun is a typical example. In the case of the red stars these classes are sharply separated into two groups, between which there seem to be no stars of intermediate brightness.

We may not pursue in their interesting details the conclusions and speculations to which this new conception of stellar classification has given rise. Some of them require the support of further observations before they can be finally accepted, but recent work strongly confirms the view that a point of inflection is likely to enter the time-honored path of stellar evolution. Lockyer, on other grounds, suggested long ago that the curve of development should have both ascending and descending branches, and advanced spectroscopic evidence in support of his conclusion. But his reasoning and results differ in many respects from Russell's.
According to Russell, the red giant stars of great diameter, low density, and low temperature, represent the early stage of sidereal life. Contraction following radiation of heat would give rise to denser and hotter stars, culminating in the intensely hot white stars of the helium class. Further contraction, attended by a reduction of temperature, would result in the dense dwarf stars, which occupy the declining slope of the curve of stellar development.

Whatever our predilections, we must welcome most cordially the new light which has been thrown on our central problem, even if we cling to the classic idea that the white stars are young while the red stars, irrespective of their absolute brightness, represent the period of decline. This older and more widely accepted view has the advantage of affording an unbroken transition from nebular to stellar spectra, which is lacking if we begin our sequence with Russell's red giants. Yet Adams has recently shown that for spectroscopic reasons the red stars should be divided into two groups and the progress of research may soon be expected to provide a reliable means of distinguishing between the old and new views.

Time fails me to show how the spectrope has extended Bessel's "astronomy of the invisible" into a larger realm, and revealed a new department of double star astronomy, now connected without essential discontinuity with the classic field to which the Dearborn telescope, in the hands of Burnham, Hough, and Fox, has made so many contributions. Nor may I enter the great domain of star-streaming, which belongs primarily to astronomy, though the last wide extension of its boundaries has come from the work of the spectrope. The old barriers between the physical and the structural problems have broken down, and the old and new astronomy are working together in the closest harmony. Adams has just demonstrated, for example, a simple means of determining a star's distance from a knowledge of its apparent brightness and the ratios of the intensities of certain lines in its spectrum. Founded upon the indispensable parallax measures, which will ultimately extend both its range and its precision, the new method should prove a powerful ally in the further study of both the structure and the evolution of stellar systems.

Turning now to the instrumental side, we observe great changes in the observatory equipment during the last half-century. Telescopes have grown in size and in perfection, while their indispensable auxiliary, the photographic plate, has increased their efficiency a hundred-fold. The spectrope, no longer the simple aid of the chemical laboratory, has taken its rightful place beside the telescope as an instrument of the most diversified possibilities and of the widest usefulness. No longer limited to the determination of chemical composition of flames
and suns, it tells us in no uncertain tones of the motions, temperatures, pressures, magnetic properties, life history, and even the distances of the heavenly bodies. As a result of its growth and refinement the qualitative period of spectroscopy, once a reproach, has given place to an era of measurements which cannot be surpassed for precision in the entire range of science. Brought into closer contact with the physicist and chemist, the astrophysicist has profited without limit by their marvelous progress, and adapted their devices to his special needs. Thus the observatory has received from the laboratory scores of auxiliaries and methods, which have led its investigations into unimagined fields. The bolometer and radiometer, the perfected thermopile and the radiomicrometer, have given us precise measure of the solar radiation and detected its fluctuations, determined the heat of stars beyond the vision of the naked eye, and mapped the vast region of the infra-red spectrum where neither eye nor sensitive plate is of any avail. Selenium and photo-electric cells have proved stars to be variable which were formerly supposed to shine with unchanging light. The recognition of the electron and the rise of modern physics have been reflected in the work of the observatory. The phenomenon of Zeeman, showing the remarkable resolution of spectrum lines under the influence of a magnetic field, is now known to have been seen—though not interpreted—by the solar physicist long before it was detected in the laboratory. The relationship of hydrogen and helium, the effect of an electric field on radiation, and even the principle of relativity are applied or tested in the observatory while yet a novelty in the laboratory or the study of the mathematician. Thus by the use of many new agencies, the astrophysics of yesterday has become the new and broader subject of to-day.

But it is neither in multiplied resources nor in the construction of larger telescopes that we perceive the most significant advance of the half-century. The greatest difference between the present and the past lies in the broadened outlook of the investigator. No longer groping in the dark, or confining his attention to some minute specialty pursued without reference to a larger view, he has widened his horizon and entered into harmonious cooperation with others in his field. Thus the capacity of any single instrument has been multiplied twice, first by the use of the photographic plate or other auxiliary method, and again by the coordination of effort which does away with useless duplication. I have heard the great geologist Suess, a man of the widest interests and richest imagination, describe a certain astronomer as "one of those who busy themselves with those vermin of the skies—minor planets and comets." He did not mean that asteroids and comets, which have played such an important part in the larger prob-
lems of our solar system, are not worthy of study. What he objected to was the haphazard way in which they are sometimes observed. It is worth while to record, even without purpose, without reason, and without hope, the position of a chance asteroid or a passing comet. But it is far better to mix intelligence with industry, to plan observations in harmony with some central idea, to cooperate with others in pursuit of some large end. Thus each record may be greatly enhanced in value, and given a better chance of holding a permanent place in the archives of research.

Such is the change which has come over the spirit of the observatory. The accumulation of data is no longer pursued blindly, but is based upon an intelligent plan. Such vast problems as the structure of the universe or the evolution of the stars are now attacked in a sane manner that progress has multiplied by leaps and bounds. And this is because of a freer and better use of the scientific imagination, acting under the inspiration which we owe in no small measure to Lyell and to Darwin and to others of their time. The theory of evolution is no longer bounded by the limits of the nebular hypothesis or the principle of natural selection. Rising out of these great conceptions, it has expanded into a vast and sweeping vision which embraces all nature. From the whirling electrons in the minute solar system of the atom to the globular star clusters, the spiral nebulae, and the great star streams of the sidereal world is now but a step. Without break of continuity, we study the nature of the electron and the composition of nebulae, the constitution of the atom and the formation of the stars, the organization of complex matter and the evolution of the Earth. We watch with Lyell and Suess, and others of our own day, the development of the Earth's face and the ebb and flow of molten and of aqueous tides. Deep below the Cambrian rocks, embedded in those great sedimentary deposits which filtered during slow millions of years through the depths of prehistoric seas, we find the first signs of life. We isolate the unit of the biologist, and as we marvel at the complexity of the cell as contrasted with the electron, we admire the patience and perseverance which has brought order out of chaos in the intricate mazes of organic existence. We watch the rise of strange life forms, their transformations and effacements, the long intervals of stagnation and repose, the renewed appearance of life in other aspects, graceful and grotesque, gigantic and inconceivably minute. Surveying with Darwin the wide extent of the dead and living world, we perceive the play of a single principle in thousands of diverse organic forms, and see it restore the continuity of that evolutionary progress which is more easily traced among the simpler elements of inorganic nature. We observe the modern biologist, applying the experimental method and producing in
his laboratory the variations and mutations which have occurred so often in the history of terrestrial life. We follow the prolific researches of the anthropologist, see him restore the missing links, and trace the marvelous advance which has developed man out of the low intelligence of the anthropoid world. Finally, we see the crude efforts of the first artist endeavoring to express his conceptions, the gathering together of peoples, and the rise of the earliest civilizations. And as we survey the long process of evolution, in its unbroken manifestation from electron to star, from Earth to man, we feel the impulse which has taught us no longer to be content with the limited view point of the specialist, but in whatever we do, howsoever restricted our field, to look out toward the widest expanses of nature and profit in our researches by the clarifying and inspiring example which has been set for us by the leaders of modern thought. Let me close with the words of the great geologist Suess* one of these leaders now unhappily lost to us:

"What a memorable half century we have lived through! During this time, under the influence of increasing knowledge of nature, all human conceptions of the Earth have changed. It is remarkable, however, to see how often the single inquirer, bent upon the object of his quest, fails to comprehend the broader aspects of a problem by whose details he is fettered, just as the stone-cutter clinging to a facade, cannot see the splendor of the structure on which he himself is engaged. And yet there is a special charm in geological studies precisely on account of the extraordinary range of accommodation that is demanded of the eye, of the same eye which now examines the disintegration of quartz in a thin slide under the microscope, now sweeps over snowy mountain peaks, over dark precipitous cliffs and verdant vales, and with commanding glance reads their structure in the features of the landscape. But not less is the demand on the adjusting powers of the mind. From the most subtle conclusions derived from an ingenious experiment the geologist must be able to lift the mental eye over hill and valley into the most distant parts of the universe. There the glowing spectra of nebulae teach him that even now the great processes of world making are not yet ended. With the aid of instruments he can daily witness the greatest eruptions of superheated gases emanating from the body of our Sun. Photography spreads before him the pictures of the desolate crater-fields of the Moon.

"Returning to his Earth he now perceives that the sum total of life's phenomena not only forms a single phenomenon, but that it is also

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