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THE EVOLUTION OF SOLAR STARS.[1]

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THE contemplation of our solar system, in which a number of planets move around the Sun in the same direction, and nearly the same plane, gave rise to the idea that our Sun has gradually condensed from a nebulous mass. This idea was confirmed by the discoveries of the telescope, which enabled men to see nebulous masses suspended in the sky, some spread out irregularly, some in spiral forms with denser portions, and some of globular shape, with a starlike nucleus in the center. It was clearly a tempting subject to astronomers and others to speculate on the gradual formation of the stars out of the original nebulous chaos. No wonder, then, that the interest which had been aroused by Kant and Laplace, when they formed their celebrated Nebular Hypothesis, has been growing steadily, especially since the spectroscope gave us the means of studying the material out of which the stars are formed.

The readers of this JOURNAL must all be familiar with the main facts of stellar spectroscopy and the general idea of stellar

[1] Read before the *Royal Philosophical Society of Glasgow*, November 6, 1901. Revised for publication in the ASTROPHYSICAL JOURNAL, January 1903.

evolution which these facts have suggested. Everyone recognizes that some kind of evolution is clearly indicated by the manner in which star spectra classify themselves into groups which, though distinct, are yet connected with each other by intermediate types. But while agreeing on a general process of evolution, there is still a good deal of room for differences of opinion on the life-histories of particular stars. One of the important questions which may be raised is this: Does each star or, at any rate, the great majority of them, pass through each of the stages of a uniform evolution? Has, for instance, our Sun at one time given a spectrum identical with that of *α Leonis?* Further, are we justified in concluding that all stars are made up of the same chemical elements in the same proportion? And lastly, admitting a uniform evolution, what is the meaning, as the star grows older, of the gradual displacement of the hydrogen in its atmosphere, first by calcium, and ultimately by iron and other metals?

Before we enter into a fuller discussion of these points, I shall briefly review the methods of experimental investigation which are at our disposal. The simple spectroscopic analysis, which only tells us of the presence of an element, is now complicated, but improved, by the observed fact that spectra are found to vary according to the experimental conditions. If we volatilize a metal by a powerful spark, it sends out waves which are different from those which are seen with a weak spark; and if we replace the spark by the voltaic arc, which volatilizes more material, but is probably at a lower temperature, or by the oxyhydrogen flame, distinct differences due to the different condition of the luminous vapor generally appear in the spectra. Opinions are not quite concordant as to the cause of these differences, how far they depend on temperature simply, and how far pressure and density may affect them; or whether, finally, the dissociating power of high electric tension may alone be sufficient to explain the observed facts. The metallic absorption in the solar spectrum seems roughly to correspond to that of our electric arc, while, according to Sir Norman Lockyer, the metallic lines seen in the groups of stars intermediate between the helium and solar spectrum, correspond more closely to the spectra observed in our strongest spark discharges.

In addition to the changes which are produced by temperature and density, we have an effect due to pressure, which consists in a slight lengthening of the waves sent out by the molecules. This effect, which was discovered by Messrs. Mohler and Humphreys, allows us to determine that the pressure to which the vapors in the Sun are subjected is somewhere between two and seven atmospheres.

The investigation of thermal radiation forms another avenue through which we may approach the all-important question of the surface temperature of the stars. It is only quite recently that Mr. E. F. Nichols has succeeded in comparing the total heat radiation of some of the brightest stars. *Vega* and *Arcturus* judged by the eye have the same magnitude, which means that the same amount of that radiation which affects our eyes reaches us from each of these two stars. But when measured by an instrument which is sensitive to all radiation, *Arcturus* is found to have more than double the intensity. As the proportion of total radiation to luminous radiation diminishes with rising temperature, this would indicate a lower temperature for *Arcturus*, and confirm the conclusion, arrived at on other grounds, that the hydrogen stars have a higher surface temperature than the solar stars. Without actual measurements, we may derive the same result from an inspection of the ultra-violet region of the spectrum. This region is made up of rays which are too short to affect our retina, but which produce a photographic effect, and ought to be stronger and more extended, the higher the temperature of the radiating body. We find that in general the hydrogen stars are those which are richest in this ultra-violet light.

These different lines of argument, all leading to the same result, justify us in saying that the surface temperature of the hydrogen stars is higher than that of the solar stars. An extension of the same reasoning leads to the belief that the helium stars have a temperature which is higher still.

The outward appearance and internal constitution of the stars is not solely defined by the temperature of their surface, and we are in some cases in possession of important information concerning their size, mass, and density. Doppler's principle has received important applications, and will probably yield further results. It might, *e. g.*, give us some indications whether any star is near the point at which instability sets in owing to centrifugal force.

Were a star to revolve around an axis which does not point toward the Earth, and with sufficient velocity to be near the point at which it could throw off a planet or break up into two stars, we could not fail to notice it by the broadening of its lines; but at present there seems little hope that we shall ever witness so interesting an event as the formation of a double star out of one rotating body.[1] Yet there are several cases of double stars where the two bodies must be nearly in contact with each other, and some of these must have been formed, not so very long ago, by the splitting up of a single rotating mass.

Passing on to the light thrown by theoretical investigations on the constitution of stars and other systems, I must notice in the first place those researches which refer to the internal state of gaseous masses condensing under the action of gravitational forces. A mass of gas sufficiently great to collect into a globular body will be denser at the center than near the surface, because the whole weight of the outer layer will cause pressure, and therefore increased density of the central portions. As regards the temperature, we might suppose, in the first place, that there is no difference throughout the mass; but even if this were the case at any one time, it could not long remain so. If the gas be warmer than the surrounding space, radiation will take place, accompanied necessarily by a lowering of temperature in some parts, and consequently the setting up of ascending or descending convection currents. These convection currents will ultimately establish a distribution of temperature which is

[1] (Note added February 1903.) Is it possible that the phenomena of so-called new stars may be due to the sudden violent disturbance produced by the formation of a double star? In such a splitting up, gases which are enormously hotter than the surface gases must suddenly be brought to the surface.

not uniform, and has been named by Lord Kelvin the "convective equilibrium."

If a star is a mass of gas in a state of convective equilibrium, its temperature must increase downward. The rate of increase depends to a great extent on the internal constitution of the molecules. At places where the gravitational attraction is the same, the increase of temperature with depth is proportional to the molecular weight multiplied by a number which is 0.4 in the case of gases like mercury vapor, containing one atom in each molecule, and about 0.3 in the case of gases which contain two atoms in a molecule. But as it is exceedingly likely that at the temperature of the stars all molecules are monatomic like mercury vapor, we may base our calculations on that assumption. The investigations of Homer Lane, Ritter, and Lord Kelvin allow us to solve the problem of the distribution of temperature and density within a star, assuming the interior to behave like a perfect gas in a state of convective equilibrium. Lane was the first to see the importance of a conclusion, which may appear paradoxical at first sight, but which is based on strict mathematical reasoning. According to him, a star, while it radiates heat into space, does not cool, but actually becomes hotter, and this is due to the fact that the contraction, which accompanies the loss of heat, is accompanied by an evolution of heat which more than compensates for the loss. We may imagine radiation to take place chiefly from the outside, and there would no doubt be a lowering of the temperature in these outer layers, if all convection currents were artificially stopped. But at the same time the contraction of the outer shell, inclosing the deeper layers, would cause a rise in temperature in the inside, and consequently a disturbance of the thermal equilibrium. This could be re-established only by convection currents, which would supply the lost heat to the outer layers. Calculation shows that the temperature of the center of a star increases in the same proportion as the diameter of a star diminishes; but it must be clearly understood that all these conclusions are based on the supposition that the whole mass of the star behaves like a perfect gas, a supposition which fails to be true at the surface of a star, and also near its center, but probably holds very nearly in the intermediate layers.

If a star contained only perfect gases, its surface would be formed where the absolute zero of temperature is reached. But the metallic vapors which to a great extent compose the stars condense into a liquid at a temperature of more than 1,000° above the absolute zero, and we must therefore imagine the boundary of the stars to be formed, not at the zero of temperature, but at the place where a cloud-like condensation of vapors takes place, the temperature of these clouds being probably somewhere between 4,000° and 20,000° C. This formation of clouds, though it precludes us from applying Lane's results to the outer layers of stars, does not affect his calculations as to their internal constitution, which probably give us a good representation of the state of a star from the photosphere down to considerable depths. Ultimately, and especially in the case of stars which are already advanced in their condensation, the equations will fail, because when the molecules of a gas become as near to each other as they are in liquids, molecular forces come into play, which prevent the gases from behaving in the ideal manner of a perfect gas. The molecular forces diminish the compressibility, and ultimately the heat which is generated by compression will fail to compensate for the heat lost by radiation. When that period has been reached the star will begin to cool, pass into the liquid state, and soon cease to be luminous.

The questions which meet us when we try to interpret stellar spectra will be more easily understood after we have examined more closely what happens on the surface of the Sun. We may, in the first place, inquire with advantage whether our knowledge of the constitution of that body supplies us any arguments for or against the theory of convective equilibrium, as presented to us by Lane and Ritter. I have calculated, chiefly from the data supplied by Ritter, the density, the pressure, and the temperature of the inside of a star having the same mass and size as the Sun, and behaving like a perfect gas in a state of convective equilibrium. The numbers are given in the accompanying table.

A simple calculation allows us to extend the results to a period of time when the Sun had a larger diameter. The first column of the table defines the position of the different layers in terms of the fraction obtained by dividing the distance of any layer from the center, by the distance of the uppermost layer. The second column gives the density, and the third the pressure in megadynes per square centimeter, that unit being very nearly equal to our atmosphere. The last column shows the temperature, which depends, however, on the nature of the gas; the numbers given apply to hydrogen, assuming it to retain its biatomic constitution, and should in other cases be multiplied by the molecular weight. Thus assuming the whole of the inside of the Sun to be made up of hydrogen split up into monatomic elements, the temperature at the center would be 12,000,000 degrees. If made up entirely of monatomic iron, the temperature would have fifty-six times that value. To apply the table to a previous period in which the diameter of the Sun was, *e.g.*, twice as great, we should have to divide the second column by 8, which is the cube of 2, the third column by 16, which is the fourth power of 2, and our fourth column by 2. It is a curious fact, which is not perhaps without significance, that the central density of the Sun, as calculated on the assumption of its being a perfect gas, is only very little in excess of the density which, according to the most careful recent estimate, is to be ascribed to the central portion of the Earth, and again that that estimate is very little in excess of the density of solid iron.

GASEOUS SPHERE IN CONVECTIVE EQUILIBRIUM.

Total mass = mass of Sun = 2×10^{33} grams.
a = molecular weight compared to hydrogen.
R = radius of sphere.
  = $700{,}000/\beta$ kilometers,
    where β is a factor which is equal to unity in the case of the Sun.
r = distance from center.
$x = r/R$.
Mean density = $1.406/\beta^3$.

x	$\beta^3 \times$ Density	$\beta^4 \times$ Pressure in Dynes per Square Centimeter	Temperature
0	8.44	8.65×10^{15}	$24.60 \times 10^6 \times \alpha/\beta$
0.1	8.17	8.19	24.06
0.2	7.39	6.93	22.51
0.3	6.23	5.21	20.07
0.4	4.88	3.47	17.07
0.5	3.54	2.03	13.77
0.6	2.33	1.01	10.43
0.7	1.36	0.41	7.28
0.8	0.65	0.12	4.45
0.9	0.20	0.017	2.02
1.0	0.00	0.00	0.00

If it is allowable to imagine the Sun to consist chiefly of iron vapor, that vapor, when above the so-called critical temperature, might be expected to follow the laws of a gaseous compressibility until the density is nearly equal to that of liquid iron, and, whatever the temperature, we shall not be able to compress gaseous iron to a density greater than that of solid iron. It is also allowable to conclude from this reasoning that the distribution of density in the interior of the Sun is not very much different from that indicated in the table, being probably rather less in the central portions, and hence rather greater in the outer portions of the solar mass.

Though the distribution of density and pressure in the interior of a star is probably fairly well represented by the table, the temperature almost certainly is considerably less through the greater portion of the mass. The failure of our equations in this respect is due to diminished compressibility, and also to our having left all effects of radiation and conduction of heat out of consideration. The effects of conduction will be most marked where, owing to increased density and diminished gravitational attraction, the convection current becomes less effective, as for instance near the center of the star. The effects of radiation will be most marked near the surface, and especially in those portions of the star which lie above the cloudy condensations which we have considered to make up its surface. Gases like hydrogen will reach to some height above the surface, and form an atmosphere around the main body of the star. Were it allowable to neglect radiation altogether, these gases would be in convective equilibrium and rapidly diminish in temperature as they rise above the surface; they could not in fact rise much above the surface before they would be reduced to the zero of temperature.[1] The fall in temperature with altitude above the surface of the Sun is, according to calculation, $26 \times a$ degrees centigrade per kilometer, where a is, as before, the molecular weight. Thus for monatomic iron vapor the diminution in temperature would be 73,000° C. for each 100 kilometers.

It may not be unnecessary to say a few words as to the evidence we possess that the convection currents which play so important a part in the theoretical investigation actually exist in the Sun. The surface radiates an amount of heat into space of which we can form a very fair estimate by measuring the quantity which reaches the Earth. The number so obtained is 1,340,000,000 calories per square meter of the solar surface, the unit of heat being the amount necessary to raise one gram of water through one degree. We obtain an idea of what that number means if we imagine the Sun to be surrounded by a shell of ice; the heat supplied by radiation could melt in each minute a layer of ice fifty-eight feet thick. Or, expressing it with Lord Kelvin in terms of power, we may say that the solar surface does work by radiation equivalent to 131,000 horse-power for each square meter of his surface. The heat thus lost by radiation must be supplied from the inside of the Sun, otherwise the solar surface would cool down in a fraction of a second to a temperature at which it would cease to be luminous. If the heat is carried from the inside to the outside by convection alone, the velocity of the currents of vapor must be very great. Taking the pressure of the vapor near the surface to be one atmosphere, we may say that all the heat contained in a layer having a thick-

[1] (Note added February 1903.) Unless radiation can by itself alone establish a state of equilibrium, convection currents must still take place, and be the predominant factor in the distribution of temperature. Professor Sampson has tried to establish a state of temperature for the case of radiation alone, but his distribution is unstable. As far as my present results go, radiation cannot seriously affect the temperature distribution in the inside of the Sun, unless the material composing it is very much more transparent than we have a right to expect.

ness of 370 meters is lost by radiation in each second of time, and this number does not depend on the nature of the vapor or on its temperature. A layer of that thickness would have to be replaced by convection in every second if the temperature of the surface is to be maintained. From this I calculate that if the difference in pressure between the descending and ascending currents is one atmosphere, the velocity of the convection currents must be 616 meters per second, or about 1,000 miles per hour. These up-and-down draughts of vapor must take place with the calculated velocity, unless an appreciable portion of the heat is supplied from the inside in some other way, as for instance, by radiation. It is difficult to form an estimate as to how far radiation can help to keep up the temperature of the surface. I have made some calculations on that point which, though they have yielded interesting results, cannot at present be expressed in definite numbers. It is sufficient for the present argument to maintain that, even if radiation takes a prominent part in the determination of the distribution of temperature, we cannot escape the conclusion that convection currents must bring about a continuous interchange of matter between the inside and outside of the Sun. This theoretical conclusion is amply confirmed by observation, as is shown by the violent motion observed in the chromosphere and prominences.

In the solar eclipse which was observed in the West Indies in the year 1896 one of these prominences reached to a distance of 140,000 miles. This is by no means the greatest height that has been observed, a prominence being photographed in 1895 by means of an ingenious method due to Professor Hale, which reached to a distance of 281,000 miles from the Sun's limb. The rapidity with which these prominences appear to rise and change their appearance is not perhaps a conclusive proof that the gases which they contain move with great velocity, for these gases are quite possibly always present, and the prominence may only be a sudden lighting up of the gas, or the rapid transmission of an effect, which does not actually require the transmission of a material body. But the tangential velocities observed at the limb of the Sun within the chromosphere have not at present been explained in a satisfactory way except by assuming that there is an actual motion of hydrogen and of the other gases which form the chromosphere. This tangential motion is far more violent than anything which is required for the convection currents necessary to maintain the temperature of the solar surface. Professor C. A. Young, of Princeton University, states that a velocity of a hundred miles a second is often exceeded, and that twice this velocity is occasionally reached. There can hardly be a doubt as to the facts, but their explanation seems to me more difficult than has been generally recognized. Professor Young says on this point:[1]

> It would seem that thus we might explain how the upper surface of the hydrogen atmosphere is tormented by the uprush from below, and how gaseous masses thrown up from beneath should, in the prominences, present the appearances which have been described. Nor would it be strange if veritable explosions should occur in the quasi pipes or channels through which the vapors rise when, under the varying circumstances of pressure and temperature, the mingled gases reach their point of combination; explosions which should fairly account for such phenomena as those represented in Figs. 69 and 70, where clouds of hydrogen when thrown to an elevation of more than 200,000 miles with a velocity which must have exceeded, at first, 200 miles per second, and very probably taking into account the resistance of the solar atmosphere, may, as Mr. Proctor has shown, have exceeded 500—a velocity sufficient to hurl a dense material entirely clear of the Sun's attraction, and send it out into space, never to return.

My doubt as to the correctness of the above explanation is based on the fact that the highest velocity that a gas can reach when forced to move by differences of pressure is equal to the velocity of sound in the gas, where, of course, the temperature of the gas has to be taken into account in calculating the speed of sound waves. In order that a velocity of 100 miles a second may be possible in monatomic hydrogen, it is necessary that the temperature of the gas should be more than two million degrees, for in no other way can the velocity of sound in hydrogen reach so high a value.[2] On the other hand, if at a temperature of

[1] *The Sun*, p. 207.

[2] The velocity of sound may for violent disturbances be greater than that calculated by the ordinary formula, but there is reason to believe that the calculated velocity cannot be exceeded many times.

(Note added February 1903.) Since the above was written, Professor Julius, of

10,000 C., at which we may imagine the solar surface to be, a gas can rush out under the action of a pressure, however great, with a speed of 100 miles a second, the mass of its molecules must be over 200 times less than the mass of the hydrogen atom such as we know it. Sir Norman Lockyer has recently expressed the opinion[1] that the true spectrum of hydrogen such as is seen in the prominences is due, not to the hydrogen atom as we know it, but to a much smaller one, derived from it by dissociation, and he has estimated this smaller atom to have a mass about sixty times smaller than the hydrogen atom. If this view were accepted the difficulty would disappear, and the observed high velocities might be explained by internal pressure. But there is a difficulty in believing such small masses to be capable of emitting visible radiations.

Leaving out of account for the present the possibility of such a great subdivision of atoms, there are, to my mind, only three courses open to us. We may, in the first place, deny the necessity of admitting the existence of velocities as great as those I have named. As regards radial motion outward from the Sun, the evidence in favor of the reality of these velocities is not perhaps conclusive.[2] But the tangential velocities at the limb of the

Utrecht, has made the ingenious suggestion that many of the appearances we observe on the Sun's limb are not real, but are due to an optical illusion, produced by anomalous dispersion. I do not think that, so far, the efforts to account for prominences in this way have been successful, but at present I only wish to point out that the explanation does not get rid of the difficulty which has been pointed out in the text, for the rapid change in appearance, which indicates apparently a large radial velocity, would, according to Professor Julius, still be accounted for by the propagation of some disturbance, though not by a projection of matter. But the velocity of sound is the limiting velocity for the propagation of any disturbance, whether of matter itself or of any arrangement of matter, and, therefore, a large observed velocity is equally fatal to the theory of anomalous dispersion and to the older theory.

[1] *Inorganic Evolution*, p. 182.

[2] (Note added February 1903.) Professor Hale (*Astronomy and Astro-Physics*, **2**, 611 and 917) has described a remarkable outburst on the Sun's surface, the vapors produced by the outburst quickly covering a small portion of the Sun's disk, and obscuring two Sun-spots and a number of faculæ.

After the outburst, however, it was found that no permanent change in the appearance of Sun-spots and faculæ had taken place, and Professor Hale concludes from this that the obscuring vapors must therefore have been well above the layer of spots and faculæ. The velocities of those vapors during the outburst must have been very large indeed.

Sun, which are velocities parallel to the solar surface, have been observed to be as great as the radial velocities, and these must be real unless some other cause may produce displacements of spectroscopic lines. One such cause recently discovered, and already mentioned, is pressure, which increases the wave-length. Other effects might be thought of, which may act in the same direction, but it is much more difficult to imagine any cause which can produce a *shortening* of wave-length. As far as I can judge from the published accounts and drawings, a great tangential velocity at the Sun's limb is as often observed to take place *toward* us as *away* from us; hence, even if two causes may act, one shortening and the other lengthening the waves, it does not seem probable that the two causes would act with equal frequency and to an equal extent in both directions. For the present we are forced to admit only known effects, and hence we are forced to recognize the reality of the great velocities which have been deduced from the observations.

Various attempts have been made to account for a number of phenomena which are observed on the solar surface by electrical actions, such attempts being based on the supposition that the Sun as a whole is a highly charged electrified body. But we know that no body at the temperature of the solar surface could permanently retain an electric charge. If there is therefore a permanent electric force, there must also be a permanent electromotive force tending to drive negative electricity from the inside to the outside, or *vice versa*. There is nothing improbable in such a supposition, as the phenomena of atmospheric electricity show. The surface of the Earth is charged with negative electricity, and though we know that every burning fire, and every wave of the sea breaking into spray, tends to dissipate that charge, it yet is permanent, and remains without apparent diminution. We conclude that some cause, upon which meteorologists and physicists are not yet agreed, exists, which tends to bring the dissipated electricity back to the Earth, and we are confirmed in this conclusion by the fact that falling drops of rain are more frequently charged negatively than positively.

We are therefore quite at liberty to admit a high charge of electricity at the surface of the Sun, which probably does not, however, exert any electric force, except near its surface; the outside being screened by opposite electrification. The only way which occurs to me as possibly causing an appreciable electric force at a distance greater than the solar diameter would be to suppose the existence of highly eccentric meteoric swarms, which, passing near the Sun, would carry the neutralizing charge out into space. The streamers of the solar corona might be due to electric discharges between such retreating swarms and the Sun.

If the Sun is a highly charged electrified body, velocities like those observed in the atmosphere are possible, if these velocities are radial, *i. e.*, from the center of the Sun or toward it, but I am unable to satisfy myself that the observed tangential velocities can be explained by electric action. There remains only one way of accounting for these velocities, and that is to conclude that they are either directly due to meteoric matter circulating around the Sun, or indirectly to meteoric matter falling into the Sun, and locally generating a temperature sufficiently high to allow of molecular velocities of 200 miles per second. The velocity of a piece of matter circulating around the Sun and close to its surface in a circular orbit is about 270 miles per second. Such a piece of matter would tend to carry with it the very tenuous gases which are floating above the solar surface, and may well impart to them a velocity ranging from 100 to 200 miles. If actually falling into the Sun, the conversion of their motion into heat, or the kinetic energy supplied by the splash, would be sufficient to account for the observed velocities.[1]

The explanation of the violent disturbances which are observed to take place on the solar surface does not come within the range of my main subject, but it was necessary to point out

[1] (Note added February 1903.) Matter falling into the Sun and producing what has been called a "splash" could account for velocities very much larger than that of the velocity of sound; in fact, there is no limit to the velocity that could be generated in this fashion, as the energy of impact is, at the first instant, concentrated into a very small amount of matter. If the splash takes place near the Sun's limb, but on the visible portion, great receding tangential velocities may be observed. If the splash takes place behind the Sun's limb, the tangential velocities would be approaching the Earth.

that the convection currents, which are necessary to the temperature distribution which is now generally admitted by astronomers, are actually observed to take place on the surface of the Sun with greater violence than we might *a priori* have expected. A detailed study of solar phenomena is in my opinion the only sure guide in our investigations on stellar constitution, and it is probable that many of the unsolved problems, which still meet us in the interpretation of stellar spectra, will be cleared up in the solar and terrestrial laboratories rather than by mere statistical comparisons and classifications. There are, in fact, many similarities between solar and stellar phenomena. One of the most curious facts revealed by the photographs of star spectra is, as has already been pointed out, the peculiar behavior of calcium, which forms the main connecting link between hydrogen and metallic stars; and this behavior of calcium shows itself with equal persistency in the spectra of solar prominences, which, as regards the hydrogen lines, do not present a spectrum far different from that of *a Aquilæ* or *Procyon;* while the similarity between the spectrum of the chromosphere and that of some of the stars has been pointed out by Sir Norman Lockyer.

Before leaving the subject of the Sun, I may refer briefly to an argument which seems to me to be fatal to any theory which involves the decomposition of the elements right through its mass. We may say with certainty that no amount of pressure can increase the density of any substance much beyond what it is in its liquid state. Liquid hydrogen has a density of about 0.09, or less than the fifteenth part of the average density of the Sun. I conclude that the interior of the Sun cannot be made up of hydrogen or of any substance which might be formed by the breaking up of hydrogen, for such decompositions are, as far as we can judge, never accompanied by an increase of density. On the other hand, the mean density of the Sun is quite consistent with the supposition that its interior is mainly composed of the same substances as are known to us on the Earth.

We may now return to the main subject of our inquiry, which is the critical discussion of the arguments that have convinced the great majority of astronomers of a process of evolution which in the course of time makes each star pass successively through a number of stages, in which the spectrum changes from that of the helium stars to that of the hydrogen stars, and hence to that of stars with prominent calcium lines and of the solar stars.

The first fact which requires explanation is the one which is generally, though not universally admitted, that the temperature of the photosphere of the stars diminishes in the order in which they have just been named. If the hydrogen star is always hotter than the solar star, this would suggest that the chemical composition stands in some direct causal relationship to the temperature, but it is open to discussion which is the cause and which the effect. Is the photosphere of *a Leonis* hotter because it is surrounded by an atmosphere chiefly containing hydrogen, or does *a Leonis* only show us the hydrogen spectrum because its atmosphere is too hot to show anything else? The discussion of this point is altogether independent of our ideas regarding evolution. Even if we do not wish to enter at all into the previous history of a star or its future development, we are bound to search for an explanation of the constitution of the present universe, which shows us hydrogen stars and solar stars, the former being apparently hotter than the latter.

But if we take the theory of evolution into account, we have further to explain the fact that, if the above be true, a star cools as it grows older, while the theory of Homer Lane, of which an outline has been given, states that the star should get hotter. The apparent disagreement between theory and observation has been a stumbling-block to astronomers, but it is due in great measure to the want of definiteness in our meaning, when we speak of the "temperature" of a star. We do not observe the temperature of the center, or the temperature of the gaseous mass below the photosphere, and it is with this temperature that the theoretical analysis deals. What we can observe is the photosphere and the absorbing layer above it, and the temperature of these portions of the Sun are not touched by Lane's theory. If our ideas of the photosphere are correct, and it consists of condensed clouds of metallic or carbon vapor, the temperature of these clouds will be quite independent of the temperature inside the star; and, for all we know, might under certain circumstances remain the same for a long period of a star's life, during which time the star may condense to a fraction of its original volume, and its interior become hotter and hotter, until the condensation has reached the point at which the laws of gaseous compression no longer hold. The surface of a star is pouring out energy in the form of radiation, and the temperature of the surface will depend on the balance of a number of delicately poised conditions. Equilibrium is reached when the loss of heat by radiation is balanced by an equal gain of the heat from the inside or from the outside. The gain in the case of our Sun is in great part due to the convection currents from beneath, which keep the photosphere at the temperature at which, under the existing pressure, the metallic vapors condense. So far we should expect the photosphere to become more luminous as the star contracts, because the greater the intensity of gravitational attraction, the more active the convection currents may be expected to be. But two factors may operate in the opposite direction. In the first place, we must not assume that the inflow of outside meteoric matter, which not so long ago was considered to be the chief cause of the maintenance of solar heat, is altogether inactive. Even in the case of the Sun, it has already been pointed out that several phenomena point directly to the generation of heat at the surface of the Sun by the impact of falling masses. What in the Sun is a subordinate cause may in some of the stars become predominant, and the photosphere may recuperate itself for the loss of energy which it radiates into space, not only from the inside, but also from the outside. If this is the case, we need not be surprised that the temperature of the photosphere is apparently higher in the younger stars, or that the spectrum of these younger stars resembles that of the solar prominences.

But even without having recourse to outside influence, it is possible to account for the higher temperature of the hydrogen stars in a more direct way, by making the hydrogen atmosphere itself responsible for it. The temperature of the photosphere must be largely affected by the absorbing properties of the gases surrounding it. If, for instance, these gases were largely to absorb the infra-red radiation, the effect of such absorption would be observed in a rise of temperature. We need only point, in illustration of this, to the way in which the glass roof and sides of a hothouse protect the plants inside against loss of heat by radiation into space. If it were possible to imagine hydrogen to absorb infra-red rays, this gas would, by stopping the loss of these rays, increase the visible, and especially the blue and violet, radiations, and the fact that the metallic lines shown by hydrogen stars are principally the high temperature lines would thus be accounted for. Such an explanation will only remain a mere surmise, unless it is confirmed by independent evidence, but perhaps the phenomena accompanying the formation of faculæ on the Sun may be found to furnish such evidence, although only of an indirect character. The faculæ are bright streaks on the solar surface specially seen in the neighborhood of spots, and, according to recent observations, they are closely connected with the prominences which seem chiefly to lie above them. If the suggested explanation for the high temperature of hydrogen stars be correct, the same explanation would apply to any portion of the solar surface which has masses of hydrogen hanging over it, and the increased luminosity of those portions of the Sun which lie underneath the prominences, would be a necessary consequence. To prevent misunderstanding, it is well to point out that the infra-red absorption need not be due to the same molecules of hydrogen which give the well-known hydrogen spectrum, and which are almost certainly not identical with the diatomic hydrogen molecule which we prepare in the laboratory. The luminous hydrogen in the stars must be surrounded by cooler hydrogen, and the space surrounding the prominences will similarly contain masses of cool hydrogen, having radiating and absorbing properties differing from those of the luminous substance. If I have dwelt on an explanation which at present is little more than a guess, it is only to emphasize that we need not hesitate on theoretical grounds to accept the evidence of observation, that the photosphere of the hydrogen stars is hotter than the photosphere of a star giving a solar spectrum. The suggestions I have put forward are sufficient to show that the temperature of the photosphere is regulated by considerations which lie altogether outside the calculations of Lane.

We are now prepared to admit that the hydrogen star is hotter than the solar star, and that, if there has been a process of evolution, this hydrogen period of a star is earlier than the solar period. The reason for this second statement will appear more clearly farther on. This brings us to the next stage of our problem. Why does the hydrogen disappear in the process of cooling, and why is its spectrum replaced by that of the metallic vapors? The simplest explanation—simple because it cuts the Gordian knot—is that offered by Sir Norman Lockyer. If the hottest star shows no metallic lines, it is because the temperature is too high for the existence of the molecule which alone can emit the radiation corresponding to these lines. The atoms are decomposed or dissociated, or whatever name we may attach to what must practically be a splitting of what is generally considered an "atom," or, in other words, unsplitable by chemical agencies. When a star cools, and its photosphere has reached the temperature at which the more complex molecule can exist, the corpuscles, according to Lockyer's theory, will recombine and ultimately form metallic vapors such as we know on the Earth. This explanation involves a hypothesis that is possible and consistent, but which, before it can be generally accepted, must either be shown to be the only hypothesis consistent with the facts, or to be supported by strong outside evidence. A great difficulty of the dissociation hypothesis lies in the fact that, as in the case of the Sun, so also in the case of the *Algol* variables, of which the density is approximately known, that density is greater than the density of solid hydrogen, although these stars have spectra which are generally of the hydrogen or calcium type. In order to maintain the theory, it would be necessary to imagine that dissociation only takes place on the surface of the star, and that the pressure inside is sufficient to produce recombination, in spite of the higher temperature which reigns there.

What are the alternative suggestions which have been made? Sir William Huggins, who touched on this in his presidential address delivered to the British Association at Cardiff, draws attention to the effect of convection currents in mixing up different layers of the gaseous matter forming the star. If convection currents could be completely stopped, the heavier gases would sink to lower levels, and the outer layer of a star would be made up of hydrogen and the lighter metallic vapors. It is owing to convection that a mixing takes place, and the stronger the convection the more complete is this mixing. The following quotation will show the position Sir William Huggins takes up in this matter:

Now, the conditions of the radiating photosphere and those of the gases above it, on which the character of the spectrum of a star depends, will be determined, not alone by temperature, but also by the force of gravity in these regions; this force will be fixed by the star's mass and its stage of condensation, and will become greater as the star continues to condense.

In the case of the Sun the force of gravity has already become so great at the surface that the decrease of the density of the gases must be extremely rapid, passing in the space of a few miles from the atmospheric pressure to a density infinitesimally small; consequently the temperature-gradient at the surface, if determined solely by expansion, must be extremely rapid. The gases here, however, are exposed to the fierce radiation of the Sun, and, unless wholly transparent, would take up heat, especially if any solid or liquid particles were present from condensation or convection currents.

From these causes, within a very small extent of space at the surface of the Sun, all bodies with which we are acquainted should fall to a condition in which the extremely tenuous gas could no longer give a visible spectrum.

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Passing backward in the star's life, we should find a gradual weakening of gravity at the surface, a reduction of the temperature-gradient as far as it was determined by expansion, and convection currents of less violence producing less interference with the proportional quantities of gases due to their vapor densities, while the effects of eruptions would be more extensive.

At last we might come to a state of things in which, if the star were hot enough, only hydrogen might be sufficiently cool relatively to the radiation behind to produce a strong absorption. The lower vapors would be protected, and might continue to be relatively too hot for their lines to appear very dark upon the continuous spectrum; besides, their lines might be possibly to some extent effaced by the coming in under such conditions in the vapors themselves of a continuous spectrum.

In such a star the light radiated toward the upper part of the atmosphere may have come from portions lower down of the atmosphere itself, or at least from parts not greatly hotter. There may be no such great difference of temperature of the low and less low portions of the star's atmosphere as to make the darkening effect of absorption of the protected metallic vapors to prevail over the illuminating effect of their emission.

In a discussion before the Royal Society in 1897 I took up an essentially similar position.[1] "The chief difference (I then wrote) between a hydrogen and a solar star lies in the more or less effectual mixing up of the constituents. If we could introduce a stirrer into *α Lyræ* there can be no doubt whatever that the low-temperature lines of iron would make their appearance, while, on the other hand, if we could stop all convection currents on the surface of the Sun, the hydrogen which now lies under the photosphere would gradually diffuse out and give greater prominence to its characteristic absorption."

I still believe this statement to be true, but I have modified my opinion in so far as I do not now believe the difference in the condition of the surface of stars like *Sirius* or our Sun to be sufficient to eliminate convection almost entirely in one case and make it the predominant factor in the other. The mean density of *Sirius* is probably not greater than that which our Sun had when its diameter was about five times as great as it is now. But even then, with a gravitational force still greater than that on the surface of the Earth, convection currents must have been active in stirring up and mixing the strata down to a considerable depth below the surface. The conditions which I imagined, in 1897, to hold in the hydrogen stars are not, according to my present opinion, consistent with the formation of a photosphere, which, I now believe, necessarily involves effective convection currents. Hence, there must be some other cause for the elimination of hydrogen out of the atmosphere of stars, when they have reached the solar stage. We are reasoning, of course, on the supposition that the difference in the type of spectra is not due to any inherent chemical difference in the composition of the stars. The evidence for this assumption will have to be further examined, especially in view of the fact that, if my suggestion

[1] *Proc. R. S.*, **61**, 209.

should prove to have a solid foundation, and if the presence of masses of hydrogen is the cause and not the result of the higher temperature of the photosphere, the difficulty we are now trying to overcome disappears. Here, as in the previous discussion, it is not so much my intention to argue in favor of one hypothesis or another, but rather to show the different possibilities which may, in a natural way, account for much that is obscure at present.

If we had only to account for those stars which chiefly show hydrogen and calcium, we might attribute their spectra to the action, in an exaggerated form, of the same cause which produces the prominence spectrum of our Sun. And if we believe that the influx of meteoric matter is directly or indirectly responsible for the prominences, we should be led to suppose that the stars of the *Procyon* type are bodies in which the aggregation of meteoric masses from outside still plays an important part in regulating the temperature and spectrum of the superficial layers. This, though in many ways a satisfactory explanation, does not account for the spectra in which hydrogen is seen without the calcium, nor for other types of spectra which are generally considered to precede the *Procyon* type.

But the disappearance of hydrogen as the star condenses is not perhaps a phenomenon which should surprise us so much. Hydrogen is readily absorbed by many metals, even at a high temperature, and it is highly probable that gases show phenomena of molecular absorption like solids or liquids, when they are subjected to a pressure so high that their density approaches the density of the liquid state. I can see nothing improbable in the supposition that when a star condenses, and its pressure reaches a high value in the interior, it should begin to absorb hydrogen, helium, and possibly oxygen, nitrogen, and the other constituents which have either not been observed in the Sun, or only give faint evidence of their presence. If this opinion is correct, a quantity of matter, suddenly transported from the interior of the Sun to the outside, would violently give up the hydrogen which it was able to contain under its original pressure. The phenomena observed on the surface of the Sun would seem to lend countenance to such a view; at any rate they do not contradict it. Another and perhaps simpler explanation is suggested by considering the process of the formation of a star from its first beginnings. Its consideration may therefore be deferred until we are prepared to look at the question of evolution as a whole. I repeat that it is only my intention to put forward suggestions, which may be found to have some truth in them, and which should, therefore, be taken into consideration.

But from such speculative inquiries we may once more turn to the more solid search for further facts. Results which have an important bearing on our subject have been obtained from the observation of double stars, for they allow us to obtain a value for the state of condensation of the matter composing some of these stars. Professor E. C. Pickering and, later, Mr. Monck have deduced a remarkable equation, which connects together the intrinsic brightness of a star's surface, its mean density, and other quantities which may be obtained by observation. We may thus calculate the density on the supposition that all stars emit an equal amount of light per unit surface. As regards stars showing a similar type of spectrum, this supposition is probably nearly correct, but the results have to be used with caution when comparing a hydrogen and a solar star, for the mere fact that the spectrum of the latter is filled with absorption lines would induce us to believe—quite apart from any question as to the temperature of the surface—that the amount of light leaving the star is less per unit surface for stars giving a solar spectrum, than for stars which only show hydrogen lines. The result of calculation showed that on the average the density of the solar stars was fifteen times greater than the density of the hydrogen stars;[1] but this number was founded on information which, as regards the nature of the spectrum emitted, was, in many cases, deficient. Pending a renewed inquiry into this important subject, I am struck by the slight systematic difference shown between the stars of different spectroscopic types. A density fifteen times as great means, for the same mass, a diameter reduced in the value of 2½ to 1, and even this difference would

[1] PROCTOR-RANYARD, *Old and New Astronomy.*

disappear if the hydrogen stars had an emissive power six times as great as that of the Sun.

The differences of density shown by individual stars of the same spectral type are considerably greater. Thus γ *Leonis* gives a spectrum almost identical with that of *Arcturus*, which is generally considered to belong to a later period than the solar stage; its density on the assumption of equal emissive powers is 0.0002 as compared with that of the Sun. It is not possible to admit an emissive power 300 times as great as that of the Sun, and hence the density of γ *Leonis* must be very considerably less than that of the Sun. As far as the observations go, the stars which are purely hydrogen stars show smaller variations in density than the solar stars, and have a density which is unmistakably smaller, but great variations are found in the intermediate stages in which the calcium lines are prominent. η *Cassiopeiae*, for instance, has a density almost equal to that of the Sun, being the third in order of density of all known stars, while γ *Virginis*, giving a similar spectrum, has a density sixty times smaller. The difficulty which, in the case of the binaries we have just discussed, arises from our ignorance of the intrinsic brightness of their surface, is overcome in the case of another set of close double stars, the so-called *Algol* variables. These binaries are characterized by the fact that they consist of two stars of unequal brightness, one of which passes periodically in front of the other so as to produce a variation in the combined brightness of the stars. But I must resist the temptation of entering into a detailed description of the peculiarities of these interesting stars, and content myself by referring to the conclusions of A. W. Roberts and H. N. Russell, which have given an average density considerably less than that of the Sun. Thus Roberts finds for the mean of four of these variables 0.18 for the greatest density consistent with the observations, while the corresponding density found by Russell for the average of seventeen variables is 0.20, closely agreeing with the former result. This means a density equal to about one-eighth of the solar density. For the fainter component of *S Velorum*, the greatest possible density is only 0.03 as compared with the Sun. The spectra of these stars all seem to belong to the pre-solar type, and their low density therefore confirms the results arrived at from the consideration of other binaries, though we should not lose sight of the fact that the average density of the stars of the solar type seems to be considerably less than that of the Sun itself, so that the average density of the *Algol* variables is not much less than half the average density of the solar stars.

Interesting facts are brought to light when we investigate the distribution of types of spectra in different parts of the heavens. Such investigations are subject to the dangers accompanying all statistical inquiries, especially when the discussion must, to a great extent, turn on the differentiation between accidental and systematic deviations from the average. We owe a spectroscopic survey of the sky to Professor E. C. Pickering, who, with instruments belonging to the Henry Draper Memorial equipment, classified the spectra of 10,345 stars north of 25° of southern declination, and has since completed the investigation for stars which lie farther south. He has very fully discussed the results of the first of these surveys. Almost exactly half belong to the hydrogen type, 10 per cent. to the intermediate or calcium type, 12 per cent. to the solar type, and 25 per cent. to the *Arcturus* type. If we only take the stars which are brighter than magnitude 6.25, the hydrogen type includes relatively more, viz., 61 per cent., while only 5 per cent. belong to the solar type. The percentage of the Arcturian type is reduced to 18. If the region considered is divided into two equal portions, one lying as much as possible along the Milky Way, and the other away from it, it is found that, of all the stars considered, the Milky Way shows a preference for the stars of the hydrogen type, 3,560 of these stars being mapped in the region of the Milky Way, and 1,658 away from it; the corresponding numbers for the calcium type are 650 and 430. Neither the solar stars nor those having a spectrum similar to that of *Arcturus* show, when their total number is considered, a preference for any particular part of the sky. Out of the total number of stars, 6,252 belonged to the portion of the sky which included, and 4,095 to that portion which did not include, the Milky Way.

When we consider the distribution of stars of different magnitudes, we find that the hydrogen stars, which are of the fourth magnitude and brighter, seem to be distributed pretty evenly all over the heavens, and that it is only the weaker stars which show this effect of clustering in the regions of the Milky Way. The brighter solar stars, on the other hand, seem to be relatively more frequent in the Milky Way than away from it, and the more even distribution shown by the solar and Arcturian stars seems rather due to the fact that the stars of smaller magnitudes belonging to these types are chiefly found in the regions which lie away from the Milky Way. Thus, taking the stars down to the sixth magnitude, we find the numbers in the district of the Milky Way, and away from it, for the hydrogen stars to be 152 and 84, while for the Arcturian stars it is 453 and 341, in both cases an increased number in the Milky Way.

The results obtained by Dr. Frank McClean, who confined himself to stars above the 3.5 magnitude in both hemispheres, are not altogether in accordance with the above. Out of a total number of 276 stars, 30 per cent. only were found to belong to the hydrogen type, 17 per cent. to the *Procyon* or calcium type, while 31 per cent. were Arcturian or solar. An unusually large number, viz., 32 per cent., were classed as helium stars, and this leads to the supposition that a number of stars which figure in Pickering's list as hydrogen stars belong really to the helium subdivision. These helium stars show a very decided tendency to cluster in the Milky Way, but the distribution of the other types is, according to McClean, remarkably uniform. Thus, dividing the sky into two equal portions, the first of which includes the Milky Way, the numbers for the hydrogen type are 20 and 16, a very slight excess in favor of the Milky Way. For the calcium type the numbers are 21 and 27, and for the solar and Arcturian types combined, 45 and 40. The total number of stars of the hydrogen and calcium types is thus remarkably nearly equal to that of the solar and Arcturian types.

A promising line of inquiry has been entered upon by Mr. W. H. S. Monck, who finds that the apparent proper motion of solar and Arcturian stars is considerably greater than that of the Sirian stars. Out of over 5,000 of the latter stars found in the *Draper Catalogue*, 225 are known to have a proper motion of not less than one tenth of a second per annum in one or other of the elements; this gives a percentage of less than 4.5. On the other hand, the percentage of solar and Arcturian stars having the same proper motion is 20 and 15 respectively. This points to the fact that the hydrogen stars are farther away than the solar and Arcturian stars of equal magnitude; or that, on the supposition of an equal distribution in space, and equal average real motion, the hydrogen stars are more luminous, a fact which is quite in agreement with our previous conclusions.

But a novel and unexpected result is the position of the Capellan or solar stars as being the nearest to us, while the Arcturian stars are intermediate between them and the hydrogen stars. Mr. Monck concludes that the Arcturian stars are not cooled-down Capellans, but we shall find that if the explanation I have suggested as to the higher temperature and greater luminosity of the hydrogen stars is correct, the apparently anomalous position of the Arcturian stars is readily explained.

I have intentionally confined myself to a detailed discussion of only two of Secchi's types of stars, but must now briefly refer to other celestial bodies, so that we may be able to obtain a general view of the evidence on which the theory of stellar evolution rests.

There are two kinds of nebulous bodies which may be distinguished by their spectra. One of them, of which the nebula in *Orion* may be taken as a specimen, shows us bright lines of hydrogen, of helium, and of some unknown substance. The second kind, of which the nebula in *Andromeda* is a conspicuous example, apparently give a continuous spectrum, which is weakened so much by spectroscopic dispersion that it is extremely difficult to form a definite judgment as to the nature of the light emitted. While Professor Scheiner believes that he has obtained by photography the absorption lines corresponding to the darkest groups of solar lines, the observations of Sir William and Lady Huggins seem to give very strong evidence of the presence of bright lines in the spectra of these bodies. It is to be hoped that the matter may soon be cleared up, as these nebulæ include all those of spiral form, in which local condensations occur, suggesting a similarity to what we may suppose to be the origin of the formation of more compact celestial bodies. The gaseous nebulæ of the *Orion* kind are nearly all situated close to the Milky Way, while the nebulæ having the *Andromeda* character show the opposite behavior, and obviously avoid the plane of the Galaxy. Passing on to bodies which appear to be intermediate in character between stars and nebulæ, we also find them confined to the Milky Way. These bodies, as seen through a telescope, appear to be stars, but their light, when resolved by the spectroscope, shows bright lines, either alone or in conjunction with dark lines. Their distribution along the Milky Way is irregular, and they tend to cluster together in certain parts of it. These bright line stars vary to some extent in composition; they show as a rule the lines of hydrogen and some unknown lines. Helium appears in some, but not in all of them. There appears to be a gradual transition from these bright line stars to the helium stars, which also are chiefly found in the neighborhood of the Milky Way, and many of which are grouped together; thus all the bright stars of *Orion*, except *Betelgeuze*, and most of the weaker stars are helium stars. The high temperature of these helium stars is testified by the presence of oxygen lines, first identified by Dr. F. McClean, the particular spectrum of oxygen which appears in them being only obtainable in terrestrial oxygen by very intense sparks. The oxygen lines which, for instance, are found in the solar spectrum undoubtedly belong to a more complex molecule, and a lower temperature. There is again, apparently, a continuous transition from the helium stars to the hydrogen, calcium, solar, and Arcturian stars which I have described. The remaining types of spectra belong to lower temperatures still, as in place of the metallic lines, or in addition to them, certain bands appear, which experiments show us invariably belong to lower temperatures than the lines of the same element. Secchi's Type III possesses bands, as to the identity of which there is no consensus of opinion. These stars also cluster in the Milky Way, and a majority of them have the peculiarity of being variable in intensity. The variations are of longer period than that of the *Algol* variables, and at the maximum the bright lines of hydrogen are seen in many cases. Lockyer holds that the carbon bands appear as bright lines, and this view, as far as I am able to judge of the evidence, is probably correct.

Nothing is known as to the reason of the light-variation, but among the causes which can produce the same effect at regularly recurring intervals there is only one which we can at present apply to celestial bodies with any show of reason, and that is the orbital revolution of the bodies around each other; but this question lies beyond the range of our present discussion.

The bands shown by Secchi's fourth type of spectra have been identified, and belong to carbon. The stars showing these spectra are all weak, but over 200 are known. Dunér, to whom we owe the first systematic investigation of these stars, has shown that they also congregate in the Milky Way, not only absolutely, but also relatively to the other stars. Mr. T. E. Espin has further investigated and confirmed this point. Out of a total of 224, the region within ten degrees of the Milky Way includes 123, or more than half, while 74 per cent. lie within twenty degrees of it.

We can only form vague guesses as to the manner in which matter was originally spread through space and has gradually condensed, probably, though not necessarily, through an intermediate nebular stage into the numerous luminous spherical bodies which we observe at night. If an evolutionary process has been going on, which is similar for all stars, there is little doubt that from the bright line stars down to the solar stars, the order has been: (1) helium or *Orion* stars, (2) hydrogen or Sirian stars, (3) calcium or *Procyon* stars, (4) solar or Capellan stars. The Arcturian stars are placed by most observers after the solar stars, but as mentioned above, the researches of Monck seem to bring them to an earlier stage of evolution. Opinions are divided as to the proper place to assign to the stars of the third type. There is, on the one hand, no definite boundary line between them and the Arcturian stars, the transition being gradual; the evidence of an evolution from the second or solar to the third type is as strong as that which is generally recognized to indicate an evolutionary process from the Sirian to the solar type. On the other hand, the facts that these stars are nearly all variable, that they probably contain bright lines, and that they aggregate in the Milky Way, lend force to Lockyer's contention that the stars are in an early state of formation, and that the low temperature of their absorbing layer indicates that it is still rising in temperature. The carbon stars of the fourth type have been uniformly placed at the end of the succession of spectroscopic changes, though, according to many astronomers, this last stage does not succeed the third type stage, but follows the solar stage. These authorities would either, like Lockyer, remove the third type into the early features of a star's history, or derive it independently from the solar stage. According to this latter view, stars having reached the solar stage would bifurcate, and, according to their chemical composition, develop either the spectrum of the third or that of the fourth type.

The views I have expressed, and suggestions I have made in the previous pages, have led me to the following succession of events, as being in harmony with observed facts.

We may start from matter distributed with approximate uniformity through space, and leave out of account the question whether that original matter was in the form of our present elements, or in some primordial state, out of which our elements have been formed. If the latter case, the conditions must have been such that in different portions of space this primordial matter would condense into our elements, nearly, though probably not absolutely, in the same relative quantities. The formation of the elements I assume to take place simultaneously with the condensation into larger conglomerations.

The first point I want to draw attention to is that the effect of the first condensation must have been accompanied by a rejection of helium, hydrogen, and other light gases, because the development of heat which accompanies the early agglomeration, and raises the temperature of the gaseous bodies, must through the known laws of expansion increase their volume. The gravitation toward the condensed portions of matter not being sufficient to retain the hydrogen, it will diffuse and tend to spread through the adjoining portions of space. In regions where there is no violent motion, it appears to me that matter will tend to concentrate itself around certain nuclei, which will begin to attract each other and clash together. A number of stars will then form, and these stars will at first not contain hydrogen or helium in appreciable quantities. These lighter gases will be left behind as nebulous masses, because it has been shown that unless the gravitation toward the center of a celestial body exceeds a certain value, light gases cannot form a permanent constituent of the atmosphere. This seems to be a not unlikely explanation of the gaseous nebulæ. These bodies are by observation found to be connected with stellar clusters, as has been shown by the remarkable photographs of the nebulous regions surrounding the *Pleiades*, and the spectroscopic investigation of the great nebula of *Orion*.

As soon as a star has grown sufficiently to be capable of retaining the hydrogen and helium, atmospheres of these gases will form around the stars, and the temperature of the photosphere will rise to its maximum. A process of diffusion of hydrogen and helium into the star will at once begin, and may be helped by the process of absorption which has already been alluded to. The helium will be retained first, as it is denser than hydrogen, and we may therefore expect to find helium stars showing the hydrogen lines either weakly or not at all. As a star grows in size the hydrogen will be more and more condensed on its surface from the outside, and we may get a considerable atmosphere of that gas forming around the star. The helium which has first condensed will also first diffuse toward the inside, and we then get the typical hydrogen star. The process of diffusion of the hydrogen, helped quite probably by an absorption due to molecular action, will continue to go on until a stage of equilibrium is reached, in which there is some, but possibly very little, hydrogen near the surface of the star.

It may be objected that the above explanation leaves out of account the peculiar behavior of calcium in the intermediate stage between the hydrogen and solar star. My answer is that the same objection applies to all other explanations. We must at present accept it as a fact that there is a peculiar connection between some of the lines of calcium and the hydrogen line. This is shown by the phenomena which take place on the Sun, as strongly as by those which take place in the stars. The connection may be a chemical one, or may have a hitherto unsuspected origin. I have spoken of these lines which Fraunhofer designated by H and K as "calcium" lines, as so far we have only been able to obtain these lines when there was ground for the supposition that calcium was present. At the same time I do not think many spectroscopists would be surprised if it were found that these lines did not belong to the metal calcium at all. That was the opinion arrived at by Stas for reasons which to my mind are insufficient, but the opinion may ultimately turn out to be correct, even though for the moment experiment does not lend much countenance to it.[1] At present, therefore, we must content ourselves with accepting the peculiar behavior of these lines and their connection with hydrogen as an observed fact, but the acknowledged want of a sufficient explanation of the fact cannot be quoted as an objection to any particular view on the connection between different types of spectra.

A word may also be said as to the peculiarity of helium, which does not show its presence among the Fraunhofer lines, although it is known to be present in the Sun, because its lines appear bright in the chromosphere. There are two causes which may prevent a line from being visible as an absorption line: the vibration which gives rise to the line may be too nearly homogeneous, or it may be too intense.

It has never to my knowledge been pointed out, though it is obviously true, that an absolutely homogeneous vibration can never give rise to an absorption line in instruments of finite resolving powers. That is a possible, though perhaps not a very probable, explanation of our failure to detect helium among the

[1] (Note added February 1903.) The fact that the difference in the wave-numbers of H and K is nearly double that between the first and second line of the characteristic calcium triplets weighs strongly in favor of the lines being due to calcium. While writing the above I had for the moment forgotten this argument.

absorption lines. The second explanation is contrary to what is generally accepted as true, but only because writers are accustomed to consider the radiation from the solar photosphere to be the radiation of a perfectly black body. If the drops or liquid masses which form the photosphere have any power to reflect or scatter light, such as for instance we know rain drops to possess, the solar radiation need not, as regards intensity, exceed, say, half that due to a black body of the same temperature. It would then become quite possible for a *cooler* body in front either not to show any absorption lines, or even to show them as *bright* lines.[1] The absence among the Fraunhofer lines of the high temperature radiations observed in the chromosphere is probably due to this cause.

Returning now to the secular changes in the stars, I may point out the distinctive features of the views which I have suggested. These views, in the first instance, open out the possibility of much greater variations in their life-history than has generally been admitted. The amount of hydrogen, according to my present view, which a star is able to condense depends on its mass, and on the amount of hydrogen which happens to be present in the neighborhood. Whatever there was originally may already have been drawn toward a previously formed and bigger star. Hence the possibility that a star may form and never pass through the hydrogen stage. Even when the star has as small a density as γ *Leonis* probably has, it may give the spectrum of a solar star, simply from the want of a hydrogen atmosphere. On the other hand, there may be stars which, having attracted a large quantity of hydrogen, but being of comparatively small total mass and small size, are not able to absorb the gas completely, and may remain hydrogen stars without passing through the solar stage at all. Finally, the difference between the Arcturian and solar star may not be one of age at all, but of mass. If the Arcturian star is one which is bigger, it will be able to absorb the hydrogen more completely, and the final

[1] (Note added February 1903.) I have obtained interesting results by a mathematical discussion of the phenomena of radiation through a foggy atmosphere. These I hope soon to be able to publish in this JOURNAL.

state of equilibrium will be such that the hydrogen lines will be thinner than in the Capellan or solar star.

This seems a plausible explanation of the results of Mr. Monck, who finds the Arcturian star to have a smaller proper motion than the solar stars. They are, if my views are true, brighter though cooler, because their surface is larger, and hence, on the average, they are farther away. The theory, if I may call it so, also gives an explanation of a very curious fact, which I venture to think has not so far been satisfactorily accounted for. In the case of double stars, it is often found that the brighter one is yellow and gives a solar spectrum, while the smaller one is blue and gives a hydrogen spectrum. The larger one, though it may originally have attracted more hydrogen to itself, will be able to absorb it more rapidly, and thus pass through the stages of spectroscopic evolution more quickly.

There is a marked difference between this explanation and that advocated by Sir William Huggins, according to whom a star of small mass would run rapidly through the various stages of evolution. We both agree, of course, in the main fact, that a small mass would lose heat more rapidly, but, according to the views here put forward, there is a counterbalancing tendency in the fact that a large mass would absorb the hydrogen more quickly, and therefore show a more rapid tendency to pass from the state in which it gives a hydrogen spectrum to the state in which the metallic lines become prominent.

I will not discuss the question of the spectra of the third and fourth types, for the reason that we have not sufficient data to form any decided opinion about them. As regards the spectra of the third type, it has already been mentioned that opinions differ as to whether their position is anterior to the hydrogen or posterior to the solar star, and there are valid arguments on both sides. The carbon stars are really disconnected from the others, and though they may ultimately be found to have a place in a general system of classification, there is at present nothing to show that they are not *sui generis* and the result of condensation in a space where carbonaceous matter happened to be abundant. It has already been mentioned that they seem to show bright lines, and therefore probably belong to an early, rather than a late, stage of condensation. I know that the great principle of uniformity will be quoted against any supposition that a particular class of stars is essentially different in its composition from others, but I believe, on the other hand, that the skies bear ample evidence of real differences in composition. There is only need to mention, for instance, the dark bodies which by their passage in front of companion stars, produce the variation of light of the *Algol* variables. The obscuring stars have a density considerably less than that of water, and, as their temperature is low, they must be composed of elements differing widely from those which make up the Earth or the Sun. I cannot therefore admit the validity of an argument based on the so-called law of uniformity, which has always proved a fallacious guide.

Examples are plentiful in the history of science where the law of uniformity might have been quoted, and has been quoted, in support of obsolete moribund theories. Thus the savage, knowing that fire can be made by intelligent hands, unconsciously applied the law of uniformity to conclude that the lightning which set fire to the forests was caused by intelligent beings, surpassing him in grandeur as much as a lightning flash surpassed the feeble fire he could strike himself. When he saw the Sun apparently moving in his orbit, he was compelled by the law of uniformity to conclude that an intelligent being must carry that body in a chariot. When the mediæval magician felt that everything in this world seemed created and centered around man; when, moreover, he saw the Moon obviously describe an orbit around the Earth, he could quote the law of uniformity against the Copernican doctrine, which needlessly removed the center of the universe from what to him seemed its evident position. Even in more recent times false analogies, and conscious or unconscious appeals to the law of uniformity, have been constant sources of deception.

We are led by pure reasoning, and without any consideration of imaginary laws, to consider the universe to be in the state of a clockwork which is running down. We can form some idea guided by our experience and observation, how a star may have formed and may pass through its various stages to extinction; but to say that all stars must necessarily pass through the same stages, to conclude that *Sirius* will ever look like *Arcturus*, is to put ourselves in the position of one, who having discovered that there is a certain law which apparently connects the ages of children with their height, calls the law of uniformity to witness that a man who is five feet high is necessarily younger than one who measures six. If the law of uniformity had reigned at creation, there could have been no life, for there can only be uniformity in death; but if there were sufficient diversity of position, of mixture, and of composition, to allow of aggregations of matter culminating in the formation of worlds, we may be sure that we shall be able to trace that diversity in the present composition of the stellar system. The universe shows law, order, and regularity, but it refuses to be forced from birth to death through a single channel. There is uniformity no doubt, but it is a uniformity which at all times, and in all places, is relieved by endless variety.