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MODERN VIEWS OF THE SUN

(RETIRING PRESIDENT'S ADDRESS, ANNUAL MEETING, JANUARY 25, 1916)

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A YEAR AGO I had the honor of giving you as my Presidential Address a résumé of the recent advances in our knowledge of the constitution of the sidereal universe. This year I have thought it desirable to consider one member only of the innumerable millions in that universe, and a comparatively insignificant member when compared in relative size and brightness with other stars; and yet a member which is to us all important, without whose presence and beneficent radiation all life on our globe would cease.

This, to us all important star, the sun, has in all times and all ages excited the keenest interest and wonder in mankind. It was in several races invoked as one of the deities who rule over mankind, and indeed, though perhaps not realized to the full by its followers, sun worship had a better basis for its existence, so far as man's material welfare is concerned, than any of the pagan religions.

In modern times we are only at the beginning in obtaining some idea of the real nature, constitution and influence of the sun. Indeed, we need go no farther back than to the first Herschel to find that the sun was then considered a solid body essentially like the earth, surrounded by luminous, light-giving clouds, and that the sun-spots were mountains on this huge globe sticking up their heads through the clouds. It was probably not until the discovery of spectrum analysis, little more than half a century ago, that the true nature of the sun began to be dimly realized. Just as in the study of the stars, the last decade or so has seen more real advances in the study of the constitution, structure and motions of the sidereal universe than all preceding time, so the last twenty years of solar research have been more fruitful in teaching us the nature of this dominant orb of our system than all the labors and speculations of earlier periods.

And yet, just as in sidereal astronomy the advances of the present would have been impossible without the patient and painstaking observations of past generations, so in solar research we owe more than is generally realised to those who have carefully observed and faithfully recorded the visible phenomena of the sun, who have attempted to correlate them with terrestrial phenomena and who have advanced hypotheses, no matter if mistaken, to account for the observed facts.

The importance of the problem of the constitution of the sun is being more and more realized not only by astronomers and scientists, but by representative governing bodies and the intelligent public as well. This is indicated by the formation, within the last ten years or so, of the International Union for Co-operation in Solar Research, an association of the prominent astronomers, physicists and other scientific men of the world, interested in solar research, with the purpose of intelligently co-ordinating and combining the energies of all institutions into the most profitable channels of attack, and of preventing useless duplication of work. This organization has already been of immense advantage in standardizing and systematizing the methods of research and arranging for co-operative work in the various problems. It forms an authoritative international body whose decisions on systems of units, nomenclature, etc., shall be final. The adoption of standard methods in the determination of wave lengths and of a number of standards of wave length for universal use, correct probably within one-thousandth of an Angström unit, or one part in five million, is one example of a decision which more than justifies its formation; and a second is the adoption of the Harvard system of classification of stellar spectra for universal use.

The other instance of the dawning realization of the importance of the study of the sun has been the organization, under the auspices of the Carnegie Institution, of the Mt. Wilson Solar Observatory, also established just over ten years ago. This is probably the best equipped observatory in existence, with nearly every appliance that man can devise to assist in its special work on the sun, with the allied physical and astronomical problems. Under the able direction of Mr. Geo. E. Hale, our knowledge of the structure and movements of the sun's upper atmosphere has already been wonderfully extended and I shall have occasions frequently to refer to the discoveries made there.

In view of the limited time at my disposal it has seemed best to give you a brief account of present day views of the nature of the sun without attempting other than incidental reference to the historical development of the subject. To make the subject as comprehensible as possible to the layman, let us open it, even at the risk of some lack of sequence later, at the very beginning. If we look at the sun through smoked glass we see an intensely bright disc with a sharp circular boundary which is called the limb, and, sometimes, with dark spots on its surface. If we use a telescope of higher and higher power, of course with the intensity suitably diminished by shade glasses or other means, we find that the outer boundary still appears perfectly sharp and circular, that we see many more spots, that the surface of the sun, generally called the photosphere, is not uniformly bright but is mottled in a way that has led to its being called the rice grain structure, and that some parts near the limb and also often near spots are much brighter than the general surface, such parts being called faculæ. If these observations are continued we would find, as was discovered about eighty years ago, that the numbers and sizes of the spots and faculæ varied, that they passed through a complete cycle of change, through maximum and minimum spottedness, in a little over eleven years. Another evident, and even obtrusive, fact of observation is that in addition to sending us a great deal of light we also receive a considerable amount of heat.

In addition to these observational facts let us recount a few well known dimensions. The sun, whose diameter is 865,000 miles, is situated nearly 93,000,000 miles from us. Its volume will evidently be $(865/8)^3$ or 1,306,000 times that of the earth. A simple dynamical calculation, based on the known times of revolution of the moon around the earth and of the earth-moon system around the sun, shows that the sun has 332,800 times the mass of the earth. The density of the earth which has been very accurately determined by the physicists is 5·52 times that of water and hence the sun is 1·41 times as heavy as an equal valume of water. If expressed in pounds the mass of the earth is 1317 followed by 22 ciphers and of the sun 438 followed by 28 ciphers. It readily follows that the attraction of the sun at its surface is 27·6 times that of the earth at its surface, and a man weighing 150 pounds would weigh over two tons on the sun and would be crushed to death under his own weight if he had not been already turned into vapor long before he reached the surface.

The sun being 93,000,000 miles from the earth, it is evident, even to the least observing and thoughtful, that it must be exceedingly bright and hot to give such striking evidence of these effects at that enormous distance. No doubt most of us have been present at a fire and have noticed how rapidly the heat diminished as we moved away, that, even if unpleasantly hot at a hundred yards, it was quite comfortable at two hundred. It seems quite reasonable to say that, if the sun radiates so much heat at 93,000,000 miles, it must be hotter than any temperature attainable on the earth.

It is evident that no direct method of determining the temperature of the sun can be used, but there are several indirect methods, fortunately, by which we can obtain the temperture of the visible radiating surface, the photosphere. These are mostly too technical for a lecture of this kind, but one of them, perhaps, may be made to come within its range. Theory and experiment have shown that the radiation, the emission of heat and other energy, from a perfect radiator, (the sun is probably not quite a perfect radiator), varies as the fourth power of the temperature. This is known as Stefan's law and it is evident that if we can find the radiation sent out by the sun we can determine its temperature by extracting the fourth root of the radiation. The radiation or amount of energy emitted by the sun at the distance of the earth has been very carefully and accurately determined, (of this I shall have something to say later on), and has been found to amount to 1·95 calories per square centimetre per minute. This is the value outside our own atmosphere, but owing to the absorption of the latter less than two-thirds of this reaches the earth's surface. 1·95 calories means in plain language that if you have a little cube of water each side being a centimeter, two-fifths of an inch long, (less than a thimble full of water altogether) and if the sun is allowed to shine directly on one of these sides for one minute, and no heat is lost by reflection or otherwise, the temperature of the water would be raised 1°·95 C. or 3°·5 F. Put in another way the amonnt of heat reaching us from the sun is sufficient to raise the temperature of a layer of water two-fifths of an inch thick 3°·5 F in one minute. Knowing the amount per square centimenter 93,000,000 miles from the sun we get the total emission by multiplying 1·95 by the superficial area in square centimetres of a sphere 186,000,000 miles in diameter. Dividing this enormous amount by the superficial area of the sun we get the amount radiated per unit area, and applying the proper constants and extracting the fourth root we obtain the temperature of 5860° C. absolute. As the sun is probably not a perfect radiator its temperature would be higher than this figure and the other methods indicate a temperature not less than 6200° C., probably approaching 7000°. On the ordinary Fahrenheit scale these are 10700 and 12100 degrees. Ordinary cast iron melts at 2000 and platinum at 3200 degrees, soyou willrealize that the photosphere must be composed of gases and vapors only.

Our ordinary methods of observation and analysis have shown us that the visible surface of the sun has a mottled appearance, is cyclically invaded by sun-spots and faculæ and is at such an excessively high temperature—nearly 12,000° F.—that it is unlikely to be composed of anything but gases and vapors.

To learn more of the structure of the photosphere and the upper solar atmosphere other methods of attack are necessary and let us now see what we can learn from the spectrograph and spectroheliograph and various auxiliary attachments of them.

Everyone, surely, in these days knows what a marvellous increase in our knowledge of the constitution and physical condition of the heavenly bodies has come to us by means of the spectroscope or spectrgraph, the latter being the modern form designed to photograph the spectrum. We all know, for example, that by comparing the positions of lines crossing the spectrum of any body with the positions of the lines in the spectra of the various elements, we can surely identify the elements present in the body. And, further, we know that if the lines crossing the spectrum are separate bright lines the body is composed of incandescent gases and vapors. If the lines are dark, then between the spectrograph and the bright body there is a layer of cooler gases, not necessarily cold, but only at a lower temperature than the bright body. If the spectrum is one continuous band of color without lines the body is an incandescent, solid or liquid, or possibly a gas under great pressure. Furthermore, any shift from the normal positions of any of these lines shows that the gas or vapor producing these lines is in motion towards or from us or is under pressure, motion and pressure shifts of lines being usually easily differentiated. The accuracy of modern spectrographs is so great that we can easily determine, on the sun at any rate, where there is plenty of light, a motion of the gases equal to the speed of a man running.

A little reflection will show how much these unique properties and possibilities of the spectrograph enable us to determine of the constitution, physical condition and motions in the photosphere and upper atmosphere of the sun usually called the chromosphere. The solar spectrum is apparently a continuous spectrum crossed by thousands of dark lines. The continuous part shows that the light-emitting part, the photosphere, is either incandescent, solid or liquid matter or else gaseous material under great pressure. The dark lines show that above the photosphere is a layer of gases and vapors at a lower temperature, sometimes called the reversing layer. A comparison of the positions of these lines with those of the terrestrial elements testifies absolutely to the presence of the vapors of some forty elements in this reversing layer, and possibly to a dozen more. Nevertheless, every scientific man believes that all the terrestrial elements are present in the sun and the lines of some of them do not show in the spectrum only because they give relatively weak spectra which are overpowered by the stronger spectra of those whose lines are visible.

When the exceedingly bright photosphere of the sun is covered by the moon at total solar eclipses, the spectrograph shows that the cooler gases in the reversing layer are really incandescent and at a high temperature. At the instant the photosphere is obscured the spectrum changes or flashes from a dark-line to a bright-line spectrum, every dark line practically being replaced in the same position, though not always of the same intensity, by a bright line. This, of course, is indubitable proof of the presence of thisl ayer of incandescent gases, while the length of the curved lines for the different elements enables a close estimate of the heights to which the vapors of these elements extend above the photosphere. The depth of this reversing layer or chromosphere is not uniform and the height to which the various gases ascend is different, depending in general upon the density, the heavier gases remaining at the lower levels and not often exceeding a height of 700 kms., about 450 miles. Hydrogen, calcium, helium, sodium and a few others rise to much greater heights up to 10,000 or 15,000 kms., 6,000 to 9,000 miles. Rising higher still above the photosphere are the prominences which are apparently eruptions or outbursts of luminous gas which the spectrograph has shown are generally hydrogen and calcium. These were first seen at eclipses but can now be observed and photographed at any time. The prominences pass through a similar cycle to the spots and are apparently related in some way, although even when there are no spots the sun is never free from prominences. These prominences sometimes shoot up to the enormous height of two or three hundred thousand miles, occasionally reaching a velocity of two hundred miles a second. They are, to my mind, striking confirmation of the disturbed condition of the interior of the sun.

But, besides these tremendous eruptions, the spectroscope shows that the chromosphere, and probably also the photosphere, is rarely quiescent. Over and near sun-spots, for instance, the work of Evershed first showed by the displacement of the spectral lines that the vapors were in motion and this work has been further extended and rendered beautifully complete by the work of Hale and St. John, at Mt. Wilson. Before treating more particularly of the motions and structure of sun-spots, I wish to speak of an instrument by which the chromosphere can be photographed at different levels and in the light of different gases.

The principle of this instrument was independently brought out by Hale and Deslandres, about 1890, but the first spectroheliograph, as it is called, was constructed and used by Hale in 1891. This instrument, by which the distribution of the various gases and vapors at various levels in the sun's atmosphere can be photographed, is an ingenious application of the principle of the spectroscope, Many of the elements, especially calcium and hydrogen, give very strong and broad absorption lines in the sun's, spectrum. It occurred to Hale that by isolating the light from one of these lines in a spectrograph it might be possible that by suitably moving the sun and spectrograph relatively, to obtain a photograph of the sun in the light of this gas. Various forms of spectroheliographs for accomplishing this aim have been devised but I need only describe the simplest.

If we have a large spectrograph with a slit as long as the diameter of the solar image, this will form a spectrum as wide as the sun crossed by lines as long as the solar diameter. If in the place of the photographic plate we place a metal plate with a slit in it, adjustable to any position, it will be possible for us to place this slit on any desired line in the solar spectrum. Evidently, under such circumstances, only the light from the gas or vapor producing this line can get through the second slit. A plate placed immediately behind this second slit will record the distribution of this particular luminous vapor over the particular narrow segment of the sun which is on the first slit. If then the plate and image of the sun are kept stationary and the spectrograph as a whole moved transversely across them, we will record successively on the plate successive segments of the solar disc in the light of the particular vapor whose line is on the second slit, or in other words we will obtain a photograph of the sun in the light of this particular vapor. This photograph will evidently record the distribution of this vapor, and this vapor only, over the sun's disc.

The spectroheliograph has been used almost continuously since its invention to obtain photographs of the sun in the light of calcium vapor, and the records of calcium flocculi, as the cloud-like formations covering the sun's surface are called, has been a valuable supplement to the direct photographs in ordinary light and clearly show the turbulent and ever changing state of the chromosphere. At Mt. Wilson the sun's surface has also frequently been photographed in the green, blue and violet lines of hydrogen and occasionally in iron lines. These photographs show an entirely different characteristic appearance and structure from each other and from the calcium spectroheliograms.

But probably the most striking spectroheliograms are these made in the light of the red line of hydrogen, $H\alpha$ as it is called. These have only been obtained at Mt. Wilson comparatively recently, after the introduction of specially stained plates highly rise to much greater heights up to 10,000 or 15,000 kms., 6,000 to 9,000 miles. Rising higher still above the photosphere are the prominences which are apparently eruptions or outbursts of luminous gas which the spectrograph has shown are generally hydrogen and calcium. These were first seen at eclipses but can now be observed and photographed at any time. The prominences pass through a similar cycle to the spots and are apparently related in some way, although even when there are no spots the sun is never free from prominences. These prominences sometimes shoot up to the enormous height of two or three hundred thousand miles, occasionally reaching a velocity of two hundred miles a second. They are, to my mind, striking confirmation of the disturbed condition of the interior of the sun.

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But probably the most striking spectroheliograms are these made in the light of the red line of hydrogen, *Ha* as it is called. These have only been obtained at Mt. Wilson comparatively recently, after the introduction of specially stained plates highly sensitive to red light. It is the red light of hydrogen which ascends to the highest levels in the chromosphere and which is the most prominent in eruptions and prominences. The spectroheliograms in this light have a characteristic appearance entirely different from those made in the blue or violet lines of hydrogen or in any other vapors. The most striking features about them are the curious whirls or twisted appearance of the gaseous matter around sun-spots, and the strong resemblance of these whirls to the lines of force around magnets led Hale to suspect that there might be a magnetic field around sun-spots.

This supposition was very natural as the relation between the spottedness of the sun and the activity of the earth's magnetism had long been recognized, the curves of sun-spot numbers and those representing the daily range in the declination and horizontal force corresponding in the most remarkable manner. Further it has been noticed that terrestrial magnetic storms are often nearly coincident with the central passage of a large sun-spot over the sun's disc.

To suspect that whirls in the *Hα* spectroheliograms were indications of magnetic fields and to prove it were two entirely different matters. Even if such a field were possible of detection by magnetic methods on the earth, it would be impossible to definitely correlate such magnetic effects with any sun-spot showing whirls.

But here again the wonder-working powers of the spectroscope were brought into requisition by Hale in a most ingenious manner. About 1896, Zeeman discovered that most lines of the spectrum are separated into two components when the incandescent vapor producing these lines is in a strong magnetic field, and is observed by the spectroscope along the lines of force. With less powerful fields the lines are only widened. In addition to this doubling or widening the light is changed in character, it has become polarized, a curious one-sided form of light, and this polarization can be detected by suitable optical apparatus, such as a Nicol prism. When such a test was applied by Hale to some of the lines in the spectrum of a sun-spot it was found that they behaved in exactly the same way under the analysis of the Nicol prism, as their terrestrial counterparts did when the vapor producing them was in a magnetic field.

Here then was incontestable proof that the curious whirls around sun-spots in the *Ha* spectroheliograms were of a magnetic character and that there was a magnetic field around sun-spots. By comparing the widening and the behavior of the sun-spot lines with their terrestrial counterparts under fields of varying strength, it was found at Mt. Wilson that the fields around sun-spots varied up to a maximum of 4500 gausses, which is about 7000 or 8000 times the strength of the earth's field but not as strong as the average electro-magnet. The polarity of the spots was found to vary in a somewhat irregular manner, large spots in northern and southern hemispheres being usually of opposite polarity and the same thing being true of the two main members of a spot group.

The strength of these fields is not sufficiently great to account for the magnetic storms on the earth which occasionally derange magnetic and telegraphic apparatus and which must be due to some more powerful and as yet unknown influence. But it seems evident that the striking similarity between the curves of spot numbers and the daily range of the terrestrial magnetic elemenls can be simply explained by the influence of the magnetic fields around sun-spots.

More recently Hale has shown, in a somewhat similar way, that, in addition to the fields surrounding spots, the sun has a general magnetic field similar to the earth, only about 80 times as strong. The magnetic poles of the sun coincide approximately with its axis of revolution, the north magnetic pole being towards the north as in the earth. The Zeeman displacements by so weak a field as this are exceedingly minute and require the greatest care and precision in measuring. These discoveries and measurements of the magnetic fields in the sun are striking examples of the wonderful experimental work carried on at Mt. Wilson and are of the utmost importance.

But they have been supplemented by much additional evidence as to the physical conditions in and around spots. Considerably earlier than the discovery of the magnetic effects it was shown that the spot vapors were at considerably lower temperatures than those over the surrounding photosphere. This was done by a mass of cumulative evidence gathered by means of the spectrograph. It has long been known that the spot spectrum is different from the ordinary solar spectrum. Some of the lines are widened and strengthened, some are weakened, some are doubled as noted above, and many fine lines not present in the photospheric spectrum are present in spots. In the case of the widened and weakened lines it was found that these lines behaved in general in a similiar way in terrestrial spectra as in sun-spots when the temperature of the vapors producing them was reduced, thus showing that the spot vapors are at a lower temperature. It was further found that the numerous fine lines in the spot spectra were due to the formation of such compounds as magnesium and calcium hydride and titanium oxide, which can only exist at considerably lower temperatures than the photosphere. These facts formed convincing evidence that the vapors over sun-spots were at lower temperatures than over the surrounding photosphere.

As stated earlier, the radial motions of the vapors over sun-spots were first observed by Evershed, but his work has quite recently been much extended by St. John, at Mt. Wilson. These motions have, of course, been measured by the spectrograph from the displacements of the lines from their normal positions, and they vary for different elements and for different levels in the chromosphere. The hydrogen and calcium at the upper levels move inward at about two kilometres a second, this velocity diminishing as we go down and come to the heavier elements, finally turning into an outward motion, of the order of one-half a kilometre per second, for many of the lines of iron and other metals which lie at low levels. There seems to be a circulation of the vapors from above in and downward, and from below up and outward.

Based on these results, on the lower temperatures in the spot-vapors and on the whirling motion and magnetic field around sun-spots, Hale has advanced a working hypothesis on sun-spots which includes all the data so far obtained and offers a reasonable explanation of the observed facts. According to this hypothesis a sun-spot is the result of an eruption or some other deep-seated cause, of which nothing is definitely known, which tends to produce rapid local upward movement of a column of gas from within the sun towards the surface of the photosphere. This column is given a whirling motion by differences in velocities or irregularities of some kind, producing a vortical motion much like a tornado or waterspout, the circulation in the spot being vertically upward and then outward along the photophere. Expansion produces cooling at the centre of the whirl or vortex and a comparatively dark cloud, the umbra of the sun-spot results. A rapid flow of negative ions sets in toward the cooler gases at the centre and these ions whirled in the vortex produce a magnetic field. Higher up in the solar atmosphere the descending gases, hydrogen and calcium, are drawn in toward the centre producing the whirls shown on the *Hα* spectroheliograms and giving the spectroscopic evidence of inward motion previously adduced.

From the researches I have been discussing, it is evident that we have a clear conception, probably not far from the truth, of conditions in the sun's atmosphere or chromosphere, of the distribution in height of the various elements, of their circulation in prominences, and especially in sun-spots, and we find that, perhaps except over sun-spots, they appear to be entirely gaseous and are in general at a high temperature, though, of course, (and this is evident from the dark line spectrum produced) in the outer layers considerably lower than the photosphere.

But hitherto, except for ascertaing that the temperature of the photosphere is not less than 6200° C. and possibly near 7000° C., 12000° F., we have not hazarded any hypothesis as to its constitution and physical condition, still less, as to the conditions below the photosphere in the interior of the sun which appear to be hopelessly beyond direct investigation. The comparatively low density of the sun, 1·4 times water, taken in conjunction with its enormous gravitational force, seems to point to a gaseous constitution of the interior. This view is strengthened by the enormous temperatures that must prevail in the inside of a globe whose outer visible surface is at a temperature of nearly 12000° F., which must increase with the depth. Any of these temperatures are probably above the critical temperature at which liquefaction can take place; and though it is possible that the enormous pressures and temperatures in the interior of the sun may in some way modify ordinary gaseous properties, it seems very unlikely that it can be either solid or liquid.

If the sun is wholly gaseous we have to answer the question: What causes the bright photosphere and what produces the apparently sharply-defined boundary between it and the upper atmosphere or chromosphere? The view probably held, until very recently at any rate, by most astronomers was, perhaps, most clearly expressed by Young, in his book on "The Sun," who says: "It seems almost impossible to doubt that the photoshere is a shell of clouds. As to the precise constitution of this shell, however, the form and magnitude of the component cloudlets, the chemical elements involved, and the temperature and pressure, there is room for a great deal of uncertainty and difference of opinion. The more common view apparently . . . . . . is that the clouds are formed mainly by the condensation of the substances which are most conspicuous in the solar spectrum, such as iron and the other metals. As to the form of the clouds also, it has usually been assumed that, as a consequence of the ascending currents by which they are formed, they are columnar, their heights being much greater than their other dimensions." It is evident that the rice grain structure is readily explainable by this hypothesis, and the spots, faculæ, prominences and chromosphere do not offer any graver difficulties than would be met with in other hypothesis.

The question of temperature, however, is a serious objection as it is now practically certain that the radiating surface, the photosphere, the "shell of clouds" according to Young, is at a greater temperature than 6000° C. Moissan placed the temperature of his electric furnace at 3500° C. and stated that all known elements were vaporized at that temperature. Under these conditions it does not seem possible to have a photosphere of condensed droplets of metals and other explanations of its nature have been advanced.

The theory of Schmidt explains the sharp boundary of the photosphere by assuming that it is wholly gaseous. Owing to the curvature of the rays of light by refraction through the solar atmosphere, whose density must rapidly increase with the depth, the refraction would become so great at a certain diameter of the sun that the line of sight from the earth would be curved sufficiently to pass around and around the sun. At a greater diameter the line of sight would pass through the outer layers of gas and emerge on the other side. The sharply-defined limb would evidently be the limiting diameter where the refraction would be such as to cause the line of sight to follow around the circumference. Although this optical hypothesis gives a reasonable explanation of the photosphere, matters are considerably complicated when we attempt to explain sun spots, and it has not received much acceptance from observers of solar phenomena.

Julius has also advanced an interesting theory which explains solar phenomena by the effects of anomalous dispersion, and though astronomers are willing to admit that anomalous dispersion may have some place in modifying the observed effects, Julius's views have received even less acceptance than Schmidt's.

Abbot in his recent book, 1911, on "The Sun" has elaborated a theory, first generally stated by Secchi and contributed to by Schuster and Schwarzschild, which seems to explain in a satisfactory manner most solar phenomena. In this theory it is assumed that the sun, except perhaps in sun-spots, is wholly gaseous and vaporous, the photosphere being too hot to contain solids or liquids. Further, the density of the gases rapidly diminishes and their temperature rapidly falls from within outwards across the apparent boundary of the sun. Abbot explains the sharp boundary of the photosphere by the molecular scattering of the light in passing through the layers of gases and vapors surrounding the sun, and computes, based on the work of Rayleigh and Schuster, that this gaseous scattering would prevent us seeing further than 5000 miles into the interior when looking at the centre of the sun, and to less than 500 miles when looking at the limb. This latter amount is sufficiently small, about one second of arc, to make the limb appear sharply defined.

He answers the objections of the advocates of a cloudy photosphere that the enormous radiation into space must so cool the outer layers as to condense vapors, by stating that the visible photosphere, the "cloudy" layer, is certainly above 6000° C., at which temperature no vapors can condense, and that the conveyance of heat from the interior is so rapid as to maintain the temperature at this high level.

Another argument against the cloud theory that has occurred to me may be interpolated here. If the temperature of the cloudy layer is low enough to condense some of the vapors, why are not these same vapors in the reversing layer, which produce the dark lines in the solar spectrum and are admittedly at a lower temperature and higher level, also condensed. Furthermore, the lighter non-condensible elements, such as hydrogen and helium, which are admittedly incandescent to the height of about 10,000 miles, may serve as a sort of intermediary between the high temperature of the photosphere and the low temperature of space, and maintain the temperatures of the lower level metallic vapors above the condensing point.

The rice grain structure of the photosphere is easily explained on this hypothesis by differences of temperature caused by irregularities of convection and radiation, while the fundamentally continuous character of the spectrum of the photosphere can be produced by gases in thick layers under high pressures. The darkening towards the limb follows naturally as we see further into the interior at the centre of the sun and hence to layers of higher tempesature and brighter, than at the limb.

The phenomena of the absorption lines in the solar spectrum, of the reversing layer, upper chromosphere and prominences, as well as of the corona, of which time permits only the mention, are at least as readily explainable on this hypothesis as any other, and the same is true of sun-spots of which a working hypothesis was given above.

What we have hitherto said gives us a clear idea of the mechanism of the sun's outer atmosphere, of its distribution, currents and motions, but tells us nothing as to the fundamental cause of the eruptions which produce spots and prominences, nor as to the reason for the cyclical changes which they go through. Further, the change in the speed of rotation for different latitudes, and, still more remarkable, the variation of this speed, which now seems to be well established, remains a mystery. Various theories by Secchi, Faye, Oppolzer, Halm, Emden and others have been advanced to account for these phenomena, but in view of our absolute lack of direct knowledge of what goes on below the photosphere, it is evident that, even if time permitted, little of definite value could be said of the nature and cause of these deep-seated phenomena.

We have hitherto spoken only incidentally of what is to us certainly the most important function of the sun, its radiating power, by which all life on our globe is sustained. The determination of the quantity of heat reaching the earth from the sun has long interested physicists and astronomers, but it is only within comparatively recent years that accurate measurements of this quantity have been made. It is chiefly to the labors of Langley and his successor in this work, Abbot, that we now know that the average radiation reaching the earth's atmosphere is nearly two calories per square centimetre per minute. Somewhat more than one-third of this quantity is absorbed by the earth's atmosphere and the other two-thirds reaches the surface. More recently Abbot has shown, by the most careful and accurate work, that the mean yearly values of this radiation vary over a range of perhaps five per cent., being greater at sun-spot maximum than at minimum. In addition to this long-period the sharp boundary of the photosphere by the molecular scattering of the light in passing through the layers of gases and vapors surrounding the sun, and computes, based on the work of Rayleigh and Schuster, that this gaseous scattering would prevent us seeing further than 5000 miles into the interior when looking at the centre of the sun, and to less than 500 miles when looking at the limb. This latter amount is sufficiently small, about one second of arc, to make the limb appear sharply defined.

He answers the objections of the advocates of a cloudy photosphere that the enormous radiation into space must so cool the outer layers as to condense vapors, by stating that the visible photosphere, the "cloudy" layer, is certainly above 6000° C., at which temperature no vapors can condense, and that the conveyance of heat from the interior is so rapid as to maintain the temperature at this high level.

Another argument against the cloud theory that has occurred to me may be interpolated here. If the temperature of the cloudy layer is low enough to condense some of the vapors, why are not these same vapors in the reversing layer, which produce the dark lines in the solar spectrum and are admittedly at a lower temperature and higher level, also condensed. Furthermore, the lighter non-condensible elements, such as hydrogen and helium, which are admittedly incandescent to the height of about 10,000 miles, may serve as a sort of intermediary between the high temperature of the photosphere and the low temperature of space, and maintain the temperatures of the lower level metallic vapors above the condensing point.

The rice grain structure of the photosphere is easily explained on this hypothesis by differences of temperature caused by irregularities of convection and radiation, while the fundamentally continuous character of the spectrum of the photosphere can be produced by gases in thick layers under high pressures. The darkening towards the limb follows naturally as we see further into the interior at the centre of the sun and hence to layers of higher tempesature and brighter, than at the limb.

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If the sun is emitting energy at the rate of 2 calories per square centimetre per minute at the distance of the earth, it is evident that its total emission will be twice the area in square centimetres of the surface of a sphere 186,000,000 miles in diameter or that the sun radiates 525 followed by 25 ciphers calories per minute.

If the sun were a body cooling without any means of replenishing its stores of heat, this radiation would cause it to fall in temperature about 1°·4 C. per year, which would be about 3000° C. within historic times. As the radiation varies with the fourth power of the temperature, the earth 2000 years ago would have been receiving five times as much heat as at present, which is manifestly not the case.

What then maintains the energy of the sun at a constant or nearly constant rate of emission? Some idea of the enormous quantity of heat given out will be evident when it is stated that it would require the burning over the whole solar surface of a layer of anthracite coal 23 feet thick every hour. At this rate, if the sun were made entirely of carbon, it would not have lasted five thousand years.

A theory brought forward by Mayer, about the middle of the last century, assumed that the solar energy was maintained by the falling of meteorites into the sun. Such bodies would reach the sun with a velocity of about 400 miles per second and would generate on impact more than 6000 times the heat of an equal weight of coal. To maintain the sun's heat there should fall on every square yard of the sun's surface about 2 pounds every hour. This would increase the solar diameter about one second of arc in 5000 years, a quantity impossible to detect probably in less than 2000 or 3000 years. But the increase in mass of the sun would affect the length of the year, shortening it by about one-eighth of its value in 2000 years. Furthermore, sufficient meteoric matter in the solar system to maintain the sun's heat would cause the earth to receive ten million times as much as at present and either one of these deductions is sufficient to cause the rejection of the theory.

The theory now generally accepted as being the principal cause in the maintenance of the sun's heat — its shrinkage under its own gravitational force and the transformation of the work done by this shrinkage into heat — was first proposed by Helmholtz, about 1853. It has been computed by various writers that a shrinkage of about 250 feet per year in the diameter is now sufficient to make up for the loss by radiation. Newcomb calculated that it will require to shrink to about one-half its present size to maintain the present rate of radiation for 7,000,000 years. Further, if the original nebula, which on condensing, formed the sun originally filled a sphere whose diameter was that of Neptune's orbit, it would have furnished about 25,000,000 times as much energy as the sun now loses in a year.

If the rate of giving out energy had been constant this would make a period of 25,000,000 years during which the earth had been receiving heat as at present. In various ways geologists have estimated the age of the earth as somewhere between 50,000,000 and more than 100,000,000 years, with most of them inclining to the longer period, and the difficulty arises of explaining the discrepancy between the 25,000,000 years and the much longer time required for geological processes on the earth.

It was thought when radio-activity was discovered that this hitherto unknown source of energy might serve to bridge over the gap between the astronomical and geological epoch. But it seems doubtful at present and is not yet definitely settled whether radio-active processes are or have been, considerable sources of solar energy.

It seems to me quite probable that in the earlier stages of the sun's and earth's history the greater internal heat of the latter and possibly different atmospheric conditions may have markedly accelerated the geological processes, while at the same time the sun may not have been radiating at so rapid a rate. Its greater diameter in early ages would also, probably, affect matters favorably so far as reconciling the two views are concerned. It is possible that by such means the life of the sun could perhaps be extended to fit the geological estimates or the latter may by later researches be diminished. However this may be, the contraction theory seems the only one in sight for accounting for the maintenance of the solar radiation.

I have by no means been able, in this paper, to cover even a small fraction of the ground required to adequately treat this subject, but I hope sufficient has been said to give you some idea of the most recent views on the constitution of our luminary and to show you that we are, probably, only on the threshold of what we may hope to learn by improved methods about this, to us, most important star of the universe.