Modern Views of the Sun—I*

An Important Star Whose Real Nature Is Only Beginning to Be Understood

By J. S. Plaskett

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 realized 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. George E. Hale, our knowledge of the structure and movements of the sun's upper atmosphere has already been wonderfully extended and I shall have occasion 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 disk 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 faculae. If these observations are continued we would find, as was discovered about eighty years ago, that the numbers and sizes of the spots and faculae 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 volume of water. If expressed in pounds the mass of the earth is 1,317 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 temperature 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 centimeter 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 thimbleful 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 deg. C., or 3.5 deg. F. Put in another way, the amount 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 deg. F. in one minute. Knowing the amount per square centimeter, 93,000,000 miles from the sun, we get the total emission by multiplying 1.95 by the superficial area in square centimeters 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 tempera-

ture of 5,860 deg. 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 6,200 deg. C., probably approaching 7,000 degrees. On the ordinary Fahrenheit scale these are 10,700 and 12,100 degrees. Ordinary cast iron melts at 2,000 and platinum at 3,200 degrees, so you will realize 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 faculae and is at such an excessively high temperature—nearly 12,000 deg. 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.

Every one, surely, in these days knows what a marvelous increase in our knowledge of the constitution and physical condition of the heavenly bodies has come to us by means of the spectroscope or spectrograph, 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 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 toward 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 this layer 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 kilometers, about 450 miles. Hydrogen, calcium, helium, sodium and a few

*Address of the retiring president of the Royal Astronomical Society of Canada at its annual meeting, 1916. Republished from the *Journal* of the Society.

others rise to much greater heights up to 10,000 or 15,000 kilometers—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 Mount 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 disk 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 disk.

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 Mount 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 those made in the light of the red line of hydrogen, *H α* , as it is called. These have been obtained at Mount 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 disk.

To suspect that whirls in the *H α* 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 *H α* 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 Mount Wilson that the fields around sun-spots varied up to a maximum of 4,500 gauss, which is about 7,000 or 8,000 times the strength of the earth's field, but not as strong as the average electromagnet. 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 elements 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 toward 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 Mount 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 similar 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 radical 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 Mount 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 kilometers 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 kilometer 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 toward the surface of the photosphere. This column is given a whirling motion by differences in velocities or irregularities of some kind, producing a vertical motion much like a tornado or waterspout, the circulation in the spot being vertically upward and then outward along the photosphere. Expansion produces cooling at the center 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 center and these ions whirled in vortex produce a magnetic field. Higher up in the solar atmosphere the descending gases, hydrogen and calcium, are drawn in toward the center, producing the whirls shown on the *H α* spectroheliograms and giving the spectroscopic evidence of inward motion previously adduced.

(To be continued.)

Nitrogen: Its Virtues and Its Vices

PERSONS who talk of the importance of chemistry in this war are usually talking of one thing only though they may not know it—and that thing is nitrogen. The chief chemistry of the war is practically centered on nitrogen. Recognizing this fact, it is strange to think that we live by breathing an atmosphere containing 80 per cent of this element which in certain combinations is dealing out death on an appalling scale in all the fields of action. There are practically no useful explosives employed in which the action of nitrogen is not concerned. Without its aid the great ships at sea could not be sunk, or innocent victims on land killed, or property destroyed by the aeroplane and dirigible; while it serves to mow down whole columns of men in the field, for rifles, howitzers, machine-guns, and grenades are all dependent upon, and made terribly deadly by, the offices of nitrogen. We every day pass on to our lungs something like 450 gallons of nitrogen per 24 hours, which would be enough to make 30 pounds of tri-nitro-toluol, or 40 pounds of gun-cotton. In our early training in the elements of chemistry we were wont to regard nitrogen as a singularly uninteresting gas on account of its negative behavior. It did not burn like hydrogen, it did not support combustion like oxygen, and, in short, its presence was generally assumed because of its inactivity and because it did not directly respond to any test. And yet this element is the greatest of all as a munition power; it is hardly an exaggeration to say that applied nitrogen is going to be a factor in deciding the issue of the war. It is remarkable, also, that this element forms the central figure in the protein group or tissue-repairing material of our foods. To say that without protein we die, practically means that without nitrogen we die. The gas without positive tests is as necessary in one form for our support as in other forms it is ready to destroy us. Nitrogen's power depends in the first place on the fact that it carries in oxygen to compounds which are thus rendered explosive, turning all the elements into a huge volume of gas, itself being set free. The very inertness of nitrogen, or its objection to affinity, means that on the least provocation it will easily release its partner oxygen, handing this over to the combustion of other elements present, with the formation of volumes of gases, the nitrogen returning to what is apparently its congenial condition, the free state. As a fertilizer in the soil nitrogen acts as a stimulant and supplies the necessary nitrogen to the plant. In other words, it is a plant food. Thus the remarkable thing about nitrogen above all other elements is its power to destroy life or to sustain it according to the associates with which it is in company. With certain accomplices it forms death-dealing explosives, with others it becomes a nutritive material. It is the essentially romantic element, devil or god, according to its associations.—*The Lancet*.