THE MINUTE STRUCTURE OF THE SOLAR ATMOSPHERE

By George E. Hale and Ferdinand Ellerman

MOUNT WILSON SOLAR OBSERVATORY, CARNEGIE INSTITUTION OF WASHINGTON

Received by the Academy, January 10, 1916

During a total eclipse of the sun, when the light of the disk is completely cut off by the moon, the solar atmosphere is momentarily revealed. The exceedingly faint corona, extending millions of miles into space, can be seen only at such times. But the more brilliant chromosphere, the comparatively shallow atmosphere of luminous gases which completely encircles the sun, and the prominences which rise out of it, can be observed on any clear day with the aid of a spectroscope. First applied to this purpose in 1868, the spectroscope has yielded a large store of information regarding the number, distribution, and nature of the prominences and the structure of the upper chromosphere, as seen in elevation at the sun's limb. It has also permitted the observation of certain phenomena of the solar atmosphere in projection against the disk, but on account of the brilliant background, only their general outlines can be thus detected. In order to study their details we must have recourse to the spectroheliograph.

FIG. 1. DIRECT PHOTOGRAPH OF SUN-SPOT GROUP, 1915, AUG. 7, SCALE: SUN'S DIAMETER =24 CM. (Negative reproduction

With this instrument, first applied to the investigation of the solar atmosphere in 1892, a large number of new phenomena have been brought to light. The spectroheliograph may be briefly described as a moving spectroscope, driven at a uniform rate across the solar disk, and admitting to the photographic plate through a narrow slit the light of a single spectral line. Thus monochromatic images of the solar atmosphere, showing the otherwise invisible clouds of hydrogen or of calcium, iron, or other vapor (the flocculi) are recorded permanently for study. In a region on the solar image, for example, where direct observation shows nothing, or perhaps a group of sun-spots, the spectroheliograph may disclose extensive phenomena of great interest in the solar atmosphere (compare fig. 1, a direct photograph of a group of sun-spots, with fig. 5, Plate I, showing two spectroheliograms of the hydrogen flocculi above and surrounding the group). The purpose of this paper is to compare the structure thus revealed at various levels in the solar atmosphere with that of the lower-lying photosphere and sun-spots.

Langley's well-known paper[1] 'On the Minute Structure of the Solar Photosphere,' illustrated with his unrivalled drawings, is still our best source of information regarding the structural details of the photosphere and sun-spots.[2] After referring to the spots and faculae, Langley goes on to say:

> On attentive examination it is further seen that the surface of the sun everywhere . . . . is not absolutely uniform, but is made up of fleecy clouds, whose outlines are all but indistinguishable. . . . . Under high powers used in favorable moments, the surface of any one of the fleecy patches is resolved into a congeries of small, intensely bright bodies, irregularly distributed, which seem to be suspended in a comparatively dark medium. . . . .

These bright bodies, called 'rice-grains' by Stone, were found by Langley to average from 1″.4 to 2″.6 between centers, the distance decreasing with increase of telescopic power.

"In moments of rarest definition I have resolved these 'rice-grains' into minuter components, sensibly round, which are seen singly as points of light, and whose aggregation produces the 'rice-grain' structure. These minutest bodies, which I will call 'granules,' it will appear subsequently can hardly equal 0″.3 in diameter, and are probably less." In the two squares near the lower right-hand corner of the drawing (fig. 2, Plate I), the granules are the minute bodies forming the not very definite clusters or 'rice-grains.' The squares are 11″.6, corresponding nearly to 5000 miles, on a side. From a careful estimate of the size and number of the granules and 'rice-grains,' Langley concludes that "the properly luminous area is less than one-fifth of the solar surface."[3]

The sun-spots shown in the same figure combine details from several different spots, but accurately indicate the general character of the structure, which is described by Langley as follows:

"The penumbra is all but wholly made up, as it appears on a first examination, of cloud-forms whose structure makes them seem like fagots or sheaves of some elongated objects." Under the highest powers "the penumbra is resolved into 'filaments' of extreme tenuity, which by their aggregation make the 'thatch' (a term used by Dawes), just as the minute granules of the photosphere compose the 'rice-grains'." . . . . "It seems to me that there is no room for doubt, that 'filaments' and 'granules' are names for different aspects of the same thing, that filaments in reality are floating vertically all over the sun, their upper extremities appearing at the surface as granules; and that in the spots we only see the general structure of the photosphere, as if in section, owing to the filaments being here inclined."

Referring later to the extremely fine filaments, estimated at not over 0″.03 in diameter, which are sometimes seen on the umbra, Langley remarks on their resemblance to the filamentous structure depicted in spectroscopic drawings of the chromosphere. To this resemblance, which is shown by recent observations to extend to many additional phenomena, we may now direct our attention.

It has long been known that the surface of the chromosphere, as seen at the sun's limb with a spectroscope, commonly appears as a series of slender filaments like blades of grass, supposed by Secchi to correspond with the grains of the photosphere. To study the structure of these filaments in projection against the disk we may utilize the spectroheliograph, which permits their cross-sections to be photographed at several different levels. Thus, by setting the camera slit on the H_1 or K_1 line, which represents the low-lying calcium vapor, we can determine the size and form of the cross-section at a level below that seen visually in the chromosphere at the limb. The calcium lines H_2 and K_2 represent a somewhat higher level, illustrated in figure 3, Plate I. At this elevation the minute structure is similar to that of the photosphere, but the average size of the small bright flocculi is greater, if we may judge from a comparison with the grains in Langley's drawing, reproduced in figure 2 on the same scale. The smallest calcium flocculi photographed, however, are less than 1″ in diameter, and thus do not differ greatly in size from the average photospheric grains.[4]

Spectroheliograms made with light from the center of the $H\alpha$ line of hydrogen depict a still higher level, shown on the same scale in figure 4, Plate I, and on a smaller scale in the stereoscopic picture (fig. 5, Plate I). Figure 4 is enlarged to a scale of nearly a meter to the sun's diameter from an excellent photograph made under almost perfect seeing with the new 13-foot spectroheliograph, recently built in our instrument shop for the 60-foot tower telescope on Mount Wilson. The spectrum is that of the first order of a grating by Anderson, used with a plane mirror at such an angle as to give a dispersion of 3.6 mm. to the angstrom at $H\alpha$. As the camera slit transmits only the central part (about half the width) of the $H\alpha$ line, a high level in the chromosphere is represented. The diameter of the solar image at the focal plane of the 60-foot tower telescope is 17 cm., so that the scale of figure 4 corresponds to an enlargement of $5\frac{1}{2}$ diameters.

For some physiological cause it is difficult or impossible to convey a correct impression of the hydrogen flocculi from positive reproductions of spectroheliograms. For this reason the stereoscopic picture is reproduced as a negative, and in this the bright structure gives a fairly good idea of the appearance of the absorbing hydrogen (corresponding in reality to *dark* flocculi) on the original negative. Figure 4, in order to be directly comparable with figure 2 and figure 3, is reproduced as a positive, and the flocculi shown by it are therefore the dark regions, which occupy a somewhat smaller total area than the brighter spaces between them. Langley estimated that the bright 'rice-grains' cover less than one-fifth of the total area of the photosphere. The corresponding ratios for the calcium (H_2) flocculi range from 10%, when only the smallest and brightest flocculi are included, to 30% and more when the fainter flocculi are also measured. In the case of hydrogen ($H\alpha$) the ratios vary from 40 to 60%, depending upon the limit of darkness adopted for the faintest objects included. These results are derived, moreover, from only a small number of measures of minute flocculi in thinly occupied areas, and are subject to much uncertainty because of the very wide range of intensity of the flocculi, which renders it difficult to distinguish the less conspicuous ones from the background. The ratios may therefore be considerably modified as the result of a special study of this question, which is now in progress.[5]

The smallest of the dark hydrogen flocculi shown in figure 4 are about 2″ in diameter, or approximately twice the diameter of the smallest calcium flocculi shown in figure 3 at the H_2 level.

The foregoing results, in harmony with those of Langley, Secchi, and Evershed, support the view that the photosphere and the gaseous atmosphere above it are formed of columns of hot gases, rising by convection from the interior of the sun. At the photospheric level precipitation may occur of any materials refractory enough to withstand the high temperature, or if these substances do not exist, the conditions may be such as to cause the gases to emit a continuous spectrum. Higher up, where calcium and hydrogen persist, the radiation of the H and K lines in the gaseous columns still exceeds that of the intervening regions, and bright calcium flocculi are consequently recorded. At the still higher level represented by the $H\alpha$ line, the reduced temperature causes the hydrogen to show its presence mainly by absorption, so that the hydrogen flocculi are darker than the background of generally diffused gases.[6] The stereoscopic picture (fig. 5) permits this hypothesis to be further tested.

Helmholtz estimated the minimum angle between two objects just separated by the unaided eyes to be one minute of arc, but Pulfrich has shown that stereoscopic vision can be obtained when this angle is considerably smaller. Enlargement of the image by a telescope, and the effect of increased inter-ocular distance realized by combining two photographs of a rotating object like the sun, permit the angle to be reduced to surprisingly small values. Thus even on Helmholtz's basis, two photographs of hydrogen flocculi on the central meridian of the sun, taken only five minutes apart at the focus of the 60-foot tower telescope, can be combined to give stereoscopic relief. At a distance of 45° from the central meridian this interval must be increased to nearly 7 minutes, but further magnification of the image can be utilized to reduce the minimum time for this region to five minutes or even less. A short time interval serves very well near the limb, in spite of the smaller displacement, because of the enhanced effect of relief due to the curvature of the sun.

The accompanying stereoscopic picture represents the hydrogen flocculi above and surrounding a southern group of sun-spots about 45° west of the central meridian on August 7, 1915. The two exposures were made at 6h. 19m. and 6h. 26m. a.m., respectively, and were thus separated by a time interval of 7 minutes. The enlargement from the original negative is 1.4 diameters, corresponding to a solar image about 24 cm. in diameter. The conditions necessary to secure stereoscopic vision are thus fully realized. It should be noted, however, that while the appearance of relief is probably genuine, so far as the chief elements of structure are concerned, certain false effects are present due to slight distortion of the images. These have the appearance of a horizontal depression running centrally across the picture, between two rounded ridges, on which lie the fringes of distended flocculi above and below the axis of the spot-group. Other false effects may arise in the case of individual details which change materially in form between the exposures. These are few in number, however, and may be readily detected.

In examining the photograph, one is struck by the general resemblance to Langley's drawings of sun-spots and the photosphere (fig. 2). While the difference in scale between the minute phenomena depicted by Langley and the coarser details of the higher atmosphere must be borne in mind, the resemblance can hardly be devoid of significance. As we have already seen, the minute hydrogen flocculi, in undisturbed regions away from spots, are granular in appearance, though larger than the minute grains of the photosphere. At some distance from the spot group (near the margin of the picture) they give place to slender filaments, extending toward the axis of the group as the much finer penum-

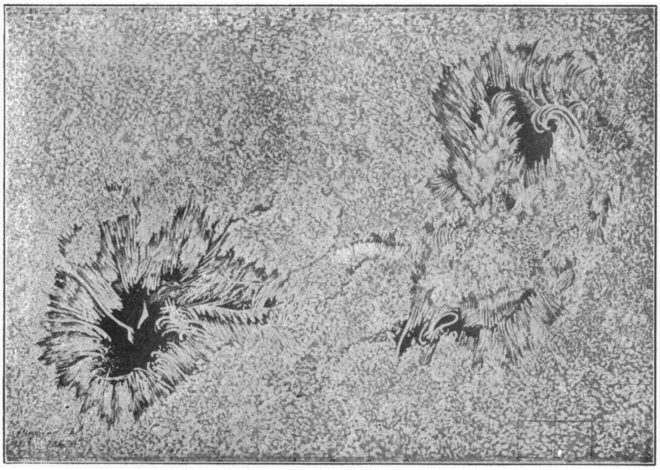

FIG. 2. MINUTE STRUCTURE OF PHOTOSPHERE AND SUN-SPOTS (LANGLEY) SCALE: SUN'S DIAMETER=94 CM. (*Amer. J. Sci.*, 1874)

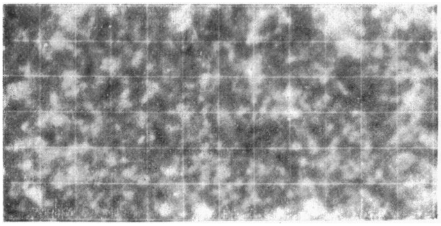

FIG. 3. MINUTE STRUCTURE OF CALCIUM (H_2) FLOCCULI. SCALE: SUN'S DIAMETER=94 CM. (From the Chicago University Press)

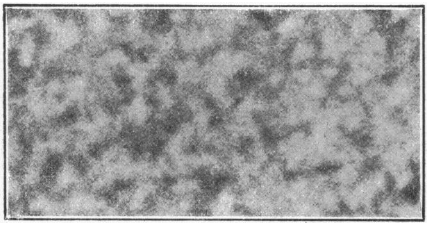

FIG. 4. MINUTE STRUCTURE OF HYDROGEN ($H\alpha$) FLOCCULI. SCALE: SUN'S DIAMETER =94 CM.

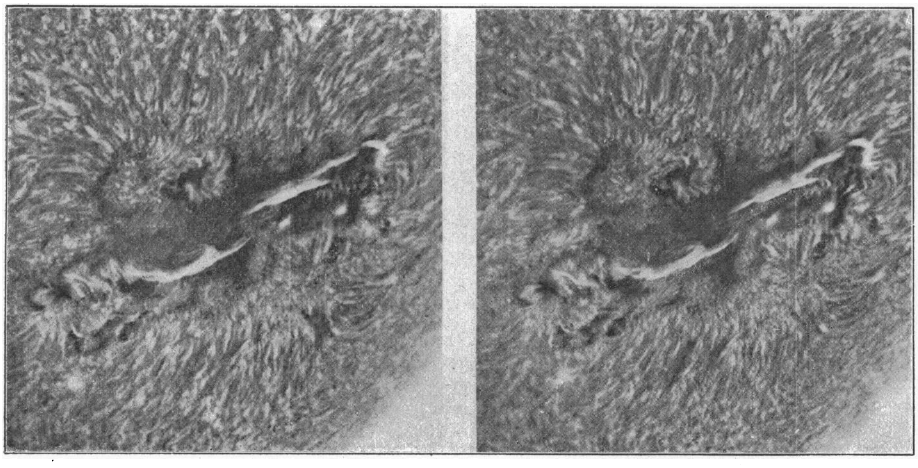

FIG. 5. STEREOSCOPIC PHOTOGRAPH OF HYDROGEN ($H\alpha$) FLOCCULI, 1915, AUG. 7, 6^h 26^m AND 6^h 19^m A.M., P.S.T. SCALE: SUN'S DIAMETER=24 CM. (Fig. 5 is a negative reproduction)

bral filaments extend toward the umbra of a sun-spot in Langley's drawing. On either side of this axis, as defined by the long dark flocculus (here bright) which appeared later as a prominence at the sun's limb, they stop abruptly at the edge of a region of honeycomb structure, out of which the long prominence rises like a high ridge. This prominence is shown by the original negatives to be composed of slender filaments, in some parts parallel for long distances, in others apparently intertwined. At its western (right-hand) extremity the prominence curves sharply in a clockwise direction toward the upper spot near the western end of the group (fig. 1), indicated at this level only by a minute white dot, much smaller than the direct image. The extreme western spot, though perhaps the largest in the group, is partially obscured in figure 5, though the hydrogen flocculi may be seen curving toward it. The neighboring spot to the east, however, is plainly visible, and its effect upon the long ridge-like prominence is shown by a second clockwise twist.

The next large spot in the group is clearly seen in the stereoscope, but its smaller companions to the east are obscured by the extensive bright hydrogen flocculi which cover much of the central part of the image, producing the apparently dark background near the middle of the negative print. It should be added that the three large spots just mentioned were shown by spectroscopic observations to be of the same magnetic polarity, indicating that their vortices were rotating in the same direction. This is in harmony with the clockwise curvature of the hydrogen flocculi shown by the stereoscope to be flowing toward each of the spots.[7]

Further to the west (above the center of fig. 1), is a bipolar spot-group, over which the hydrogen vortex is beautifully shown in figure 5 for the western (clockwise) member of the group, though the vortex above the eastern spot is less obvious. The crater-like depression at the center of the western vortex is plainly visible in the stereoscope, which also brings out the bright (dark in fig. 5) star-like boundary surrounding this member of the pair. The magnetic polarity of this spot was the same as that of the three already mentioned.

The two eastern spots near the lower left corner of figure 1 form another bipolar group, but both are partially or wholly obscured in figure 5, and the vortex structure about them is not well defined. At this end of the long ridge-like prominence some divergent filaments rise to a considerable height. These present a remarkable wave-like form in spectroheliograms taken on August 9. It is interesting to note that the highest parts of the prominence and all of the other high level phenomena are dark (bright in fig. 5), as would be expected on the hypothesis that they result from the absorptive effect of the cooler hydrogen.

It may be added that many spectroheliograms previously and subsequently obtained, especially when this region was carried to the west limb by the sun's rotation, fully bear out the above interpretation of the stereoscopic effect, which is in harmony with the conclusions already stated. Thus they confirm the usefulness of the stereoscopic method, and further substantiate the view as to the nature of these long dark flocculi (called 'filaments' by Deslandres) which we expressed when we first detected them with the $H\beta$ line at the Yerkes Observatory in 1903[8] and again when we photographed them with $H\alpha$ on Mount Wilson in 1908.[9]

We have shown in this paper that the minute structure of the quiescent solar atmosphere resembles that of the photosphere. In disturbed regions, the small granular elements (minute flocculi) are replaced by numerous slender filaments, lying side by side, and recalling the structure of the penumbra in sun-spots. While these results appear to support the hypothesis that the solar atmosphere consists of parallel columns of ascending and expanding gases, which are drawn out horizontally in spot penumbrae and in disturbed regions of the chromosphere, such questions as the dimensions of the columns and the direction of motion and velocity of the vapor in sun-spots and in the atmosphere about them are reserved for subsequent discussion.

A full account of this work, with additional observations and photographs, will be published in the *Astrophysical Journal.*

[1] *Amer. J. Sci.*, Ser. 3, **7**, 87 (1874). Figure 2, Plate I, is taken from this article.

[2] This remark applies to visual observations. The valuable photographic results of Janssen, Hansky, Chevalier and others will be discussed in another paper.

[3] Chevalier, from a series of measures of the bright grains on his excellent photographs of the photosphere, concludes that they cover approximately one-third of the solar surface; *Ann. Obs. Zô-Sè*, **8**, C 20 (1912).

[4] We have shown in a previous paper (*Pub. Yerkes Obs.*, **3**, Part I, p. 14) that the average cross-section of the calcium flocculi at the lower (H_1) level is apparently smaller than at the H_2 level. Thus the calcium vapor probably expands as it rises.

[5] Figure 3, which is taken from our paper cited above, does not give a correct impression of the area occupied by the minute calcium flocculi, as several larger aggregations are present. In determining the size of the minute flocculi, the instrumental conditions, as well as the seeing, must also be taken into account.

[6] The bright eruptive flocculi of hydrogen are not in question here.

[7] The direction of rotation of sun-spot vortices will be discussed in another paper.

[8] *Pub. Yerkes Obs.*, **3**, part I, p. 21.

[9] Solar Vortices. *Contrib. Mt. Wilson Solar Obs.*, No. 26, *Astrophys. J.*, **28**, 100 (1908).