THE WORK OF THE RUMFORD SPECTROHELIOGRAPH

BY GEORGE E. HALE

A paper on the Rumford spectroheliograph, published by Mr. Ellerman and myself as Part I, Vol. III, of the "Publications of the Yerkes Observatory," has been reviewed by several writers, to whom we are indebted for the careful discussion they have given to the work of the instrument. In the course of these reviews certain questions have been raised regarding our interpretation of phenomena shown in the photographs. It is my object in the present paper to reply to these questions, in order that the true purpose and function of the spectroheliograph may be made as clear as possible.

Taking the reviews in order of publication, we come first to the interesting and valuable article by Mr. Evershed in the April 1904 number of The Observatory. Since Mr. Evershed's own work with the spectroheliograph dates back to 1892, it is obvious that his criticisms deserve most careful consideration. In one particular Mr. Evershed's interpretation of the spectroheliograph results differ from the one which we have employed as a working hypothesis. He is inclined to adopt the view that photographs taken with the second slit set on H or K represent the true faculae, rather than the low-lying, dense vapor of calcium. His remarks on this subject are as follows:

In discussing the results obtained in this way, Professor Hale adopts this view as a "working hypothesis," namely, that the calcium flocculi are depicted sectionally in at least three different levels above the photosphere, and the evidence afforded by these photographs certainly seems to bear out this idea. A serious objection, however, would seem to follow from the fact that in the photographs


261
of the spectrum itself the true reversals of H and K seem to be entirely confined to the central H and K region of the lines. Only in the rare cases of violent eruptions are there ever any signs of lateral spreading of the bright lines; and the shading on each side appears almost always to be uniformly dark, except only where it is crossed by the faintly bright continuous bands of the true faculae. These bands, however, sometimes give a deceptive appearance of true reversal of the shading, as is well seen in Plate II, Fig. 2.

An alternative hypothesis would be that the K images really represent the true faculae, and are photographed by the continuous spectrum superposed upon the K band. On this view they cannot be regarded as low-level calcium vapor. It is possible, however, that the true calcium emission may become evident where shown up upon the dark background of a spot. The interesting comparisons given on Plates V and VI would have been more instructive on this point had the region photographed been situated near to the limb, where the faculae proper would have shown up in much greater contrast.

The increase in brightness of the flocculi with the slit set nearer the center of the band, but still outside K, might be explained as an effect of contrast only. It is to be borne in mind, however, that in this position, so near to K, there is the possibility of partial reflection of the bright K from one of the (highly polished) jaws of the slit itself.

In favor of Mr. Evershed's view, we have the following arguments:

1. If, as Mr. Evershed believes, the dense calcium vapor which gives rise to the H and K bands lies "appreciably below and between the highest summits of the faculae," we would naturally expect the spectroheliograph to show the true faculae when the second slit is set on these bands; for the increased absorption due to the bands would cut down the brightness of the background, and leave the faculae, assumed to be unaffected by this absorption, standing out in strong contrast. Moreover, on this assumption the contrast should increase as the second slit is moved nearer to the center of the bands, since the corresponding increase in the intensity of the dark bands would tend to reduce the brightness of the background upon which the faculae appear in the photographs.

2. Mr. Evershed argues that if the H and K photographs really represent the low-lying calcium vapor, these dark bands in the solar spectrum should give indications of reversal where they cross the flocculi. As a matter of fact, such reversals do not seem to be present, at least in a great majority of cases.

Without regarding it as free from objection, I am still inclined to retain the working hypothesis employed in our former paper. The following considerations have led to this conclusion:
1. If Mr. Evershed is right in his view that the faculæ overlie the dense calcium vapor represented by H$_{\alpha}$ and K$_{\alpha}$, the continuous spectrum of the faculæ should cross these dark bands with no diminution of brightness. A clear understanding of the spectrum in this region can be obtained only from a study of photographs taken with very high dispersion. Plate XIV is a reproduction of such a photograph recently secured on Mount Wilson with a Littrow spectrograph of 18 feet focal length. The 4-inch plane grating, having 14,438 lines to the inch, which was formerly used with the Kenwood spectroheliograph, was employed in the present instance with an objective of 4 inches aperture and 18 feet focal length, serving for both collimator and camera. An image of the Sun was formed on the slit of the spectroscope by an objective of 6 inches aperture and 61$\frac{1}{2}$ ft. (18.74 m) focal length, supplied with light by a 15-inch cœlostat. The photograph reproduced in Plate XIV was taken in the third-order spectrum. The scale is sufficient to show that the continuous spectrum of the faculæ rapidly decreases in intensity as it approaches the center of H$_{\alpha}$ and K$_{\alpha}$, where it almost entirely disappears. All of the photographs I have examined show this effect with greater or less clearness.

It seems to me that under these circumstances we should hardly expect the photographs to show the faculæ with increasing contrast, as the slit is moved from the edge toward the center of H$_{\alpha}$ or K$_{\alpha}$. On the contrary, we should expect the contrast of the faculæ to decrease rapidly, whereas the phenomena we have attributed to low-level calcium vapor steadily increase in contrast, though their absolute intensity diminishes.

In the light of existing evidence, I regard the photosphere as composed of innumerable clouds of condensed vapor, forming the summits of columns extending radially outward from the Sun's interior. The distance from the Sun's center at which condensation occurs depends upon the temperature gradient and upon the nature of the vapors which compose the columns. Probably only a few easily condensable substances are represented in the photospheric clouds. At any rate, hydrogen, helium, and calcium rise above the point of condensation, and continue upward into the chromosphere and

---

*The entire apparatus was extemporized for use pending the erection of the Snow telescope on Mount Wilson.*
prominences. Magnesium, sodium, iron, and other substances
represented in the flash spectrum also rise above the photospheric
level.

At certain parts of the disk, where the convection currents rising
from the Sun's interior are especially strong, the level of condensation
is carried farther from the center because of the higher temperature.
These regions are the faculae, which therefore resemble the other
parts of the photosphere in structure, though the photospheric clouds
which compose them attain higher elevations.

The height at which condensation occurs in the faculae is ordinarily
below the level attained by calcium vapor of such density as to pro-
duce bands of fully one-half the width of H, and K, in the solar
spectrum. This is indicated by the fact that the continuous spectrum
of the faculae is usually weakened by absorption over more than half
the width of these bands (Plate XIV). In general, the denser calcium
vapor probably rises from the interior in the same columns with the
vapors which condense to form the faculae, though this does not always
appear to be true. Hence, photographs of the faculae, taken directly,
or with a spectroheliograph having its second slit set on the con-
tinuous spectrum, will usually give forms resembling those obtained
when the second slit is set near the edge of H, or K,. The calcium
vapor expands as it rises, and consequently the forms of sections of
the flocculi, corresponding to higher levels, defined by the position
of the second slit as it is set nearer the center of the band, will continue
to show wider divergencies from the forms of the faculae.

I believe that the evidence afforded by the flash spectrum as to
the elevation attained by the denser calcium vapor will not be found
to conflict with these views.

2. I frankly admit that I can offer no satisfactory reply to Mr.
Evershed's second objection. It certainly seems that H, and K, should show evidences of reversal over the flocculi, if they represent
the calcium vapor in them. But one fact must not be overlooked:
since calcium vapor undeniably extends deep into and below the
photosphere, and since it has been shown to be so conspicuous in
the H, and K, flocculi, it must play a very important part and

\footnote{This is clearly shown on the untouched photograph from which Plate XIV is
made, though it may not come out well in the reproduction.}
exhibit a wide range of density in the intermediate region. Hence, we should expect photographs taken with the second slit set on H, or K, close beside H, or K, to show bright areas intermediate in form between the faculæ and the H, or K, flocculi. This is precisely what we do get. These bright regions are greater in area than the faculæ, though they are inferior in this respect to the H, or K, flocculi. The area, as well as the contrast, of the flocculi increases as the second slit is moved toward the center of the band. Careful tests have been made to determine whether this increase in area (which is accompanied by changes in form) is to be attributed to an actual increase in the area of the flocculi. The results show, in my opinion, that the difference cannot be attributed to any effect resulting from increase of contrast arising from change of exposure time, or to other similar causes. Nor do I think the changes in form can be accounted for wholly by the effect of calcium vapor over the dark regions of sun-spots, where Mr. Evershed considers it might make its appearance felt. Reflection from the slit jaws, in such a way as to produce the phenomena observed, seems to me entirely out of the question.

If the objects photographed with H, or K, light were the faculæ, their forms should remain the same, whether the second slit be set on the continuous spectrum or at any point on the H, or K, bands (excepting, of course, at the center of the bands, where H, or K, light would enter). As we have already seen, however, neither the forms nor the areas remain constant.

Professor Schuster's very important paper on "Radiation through a Foggy Atmosphere" has removed the difficulty of accounting for the bright H, and K, lines on the dark bands H, and K,. In fact the bright reversals are precisely what we might expect, in view of the exceptional emissive power of these lines, and the great height to which calcium rises above the photosphere.

Dr. W. J. S. Lockyer, who reviews our paper in Nature, takes no exception to our working hypothesis on the photography of sections of flocculi corresponding to different levels. On the contrary, he gives a very lucid account of the method, illustrated by a diagram which brings out the principle involved in a very satisfactory manner.

Professor Hasselberg's address and Mr. Maunder's recent article in Knowledge also give a clear account of photography at different levels; but as they contain no criticism of our results, these papers require no reply.

Dr. Lockyer's difficulty relates to the question of bright and dark flocculi, especially with reference to the distribution of hydrogen and calcium vapor in the solar atmosphere. After referring to hydrogen and calcium in the flocculi, Dr. Lockyer remarks: "Since the existence of each of these substances on the Sun's disk is indicated by bright markings, it is not quite clear why Professor Hale calls the dark patches dark calcium or dark hydrogen, as in these parts calcium and hydrogen respectively are, according to the very principle of the spectroheliograph, shown to be absent."

In my understanding of the principle of the spectroheliograph, the instrument is quite as capable of recording defect of radiation as excess of radiation, i.e., absorption phenomena are not less within its province than radiation phenomena. The spectroheliograph, according to this view, does not show that calcium or hydrogen are necessarily absent from any part of the solar disk. It simply indicates the existence of brighter or darker masses of these gases in certain regions. Thus, the dark flocculi shown on the disk, when the hydrogen line is employed, probably represent the higher and cooler masses of hydrogen gas seen in projection against the hotter and more uniformly diffused hydrogen in the lower chromosphere. Calcium vapor may also rise to a considerable height and cool to a temperature below that of the calcium vapor diffused throughout the lower chromosphere. Such a mass of vapor, if registered with a spectroheliograph of sufficient dispersion to permit photographs to be taken with the H$\alpha$ or K$\alpha$ line, would doubtless appear as a dark calcium flocculus. At present such objects are somewhat rare, since H$\alpha$ and K$\alpha$ are usually very narrow lines. Nevertheless, an illustration of a dark calcium flocculus, photographed with the spectroheliograph, is given in our paper.

I am therefore unable to agree with Dr. Lockyer's view, "that the regions where calcium exists correspond to those regions where hydrogen is absent." The known association of calcium and hydrogen in the chromosphere and prominences would seem to me to render such a
view very improbable, even if there were no other reasons against it. Bright hydrogen flocculi, in most cases easily distinguishable as such on the original negatives (but much less satisfactorily in the reproductions), are frequently found in disturbed regions, usually in the vicinity of sun-spots. Dark hydrogen flocculi, representing the absorption of comparatively cool hydrogen (probably, in most cases, at considerable altitudes) usually resemble, in general outline, the bright calcium flocculi in the same regions of the solar disk. As soon as it becomes possible to photograph with the H$_3$ or K$_3$ line, I think it probable that dark calcium flocculi, corresponding to the higher levels, will be frequently found in association with dark hydrogen flocculi. It will, of course, be understood that the term "flocculus," since it is used only to designate objects photographed in projection, does not, in itself, make any attempt to distinguish low-lying vapors from those immediately above them.

I am indebted to Dr. Lockyer for his article, and regret that I failed to make my meaning clear.

I wish I could conscientiously accept the compliment paid me by M. Deslandres, in ascribing to himself and to me the discovery of the flocculi in 1892. It is a well-known fact, however, that Professor Young, many years before, observed visually reversals of the H and K lines in the vicinity of sun-spots, and that Rowland and Jewell photographed these reversals before such investigations were undertaken by M. Deslandres and myself. I am sure that M. Deslandres will agree with me that the further records of this early work should also be accurately preserved, and that the photography of the flocculi should not be confused with the photography of their forms with the spectroheliograph. Since M. Deslandres has referred again to the history of the spectroheliograph, I may perhaps be pardoned for giving an outline of the facts. The spectroheliograph was first successfully employed in photographing the forms of flocculi at the Kenwood Observatory in the beginning of 1892, and Mr. Evershed constructed and used a spectroheliograph not many months later. In 1893 M. Deslandres obtained his first results with a spectroheliograph. In 1894, with a spectroheliograph having only a single prism, M. Deslandres made photographs of the solar disk with the second slit set on some of the dark lines. The images obtained in this way
are considered by M. Deslandres to represent the vapors in the reversing layer which correspond to the dark lines employed. He thus clearly recognized the principle which we have used in our more recent work; but his opinion as to the dispersion necessary in such work differs very widely from my own. Feeling certain that photographs obtained in this way, with an instrument of low dispersion, could not be depended upon to show anything more than the faculæ themselves (which can also be photographed by setting the second slit on the continuous spectrum), I did not think it worth while to make experiments in this direction until a suitable instrument should become available. The discovery of the dark hydrogen flocculi, and the results we have obtained with various lines of iron and other substances, are the natural consequence of employing dispersion sufficient to cause the dark line to cover completely the second slit. As I have always lacked confidence in experiments of my own with low dispersion, I have naturally felt that M. Deslandres stood equally in need of more powerful apparatus.

The paper of Professor Julius raises some questions of great interest, which I am not yet prepared to discuss in detail. While I think it possible that anomalous dispersion may ultimately prove to have a bearing on certain classes of solar phenomena, I have a strong belief in the objective existence of the photosphere, faculæ, spots, chromosphere, flocculi, prominences, and corona. On some other occasion I hope to have an opportunity to discuss the more general questions in the theory of Professor Julius. At present I confine myself to brief remarks on certain points raised in his discussion of the results obtained with the spectroheliograph.

The H₂ and K₂ lines are ascribed by Professor Julius, not to strongly radiating calcium vapor, but to light of nearly the same wave-length which has undergone anomalous dispersion in passing through a “tubular structure” containing calcium vapor. This explanation requires “that the brightness of the calcium flocculi must, as a rule, increase as the monochromatic light in which the Sun is photographed approaches the true absorption line.” As a matter of fact, the relative brightness (contrast) of the flocculi increases as the slit is moved nearer H₂ or K₂, but their absolute brightness diminishes, so that longer exposures become necessary in successive
settings of the slit. In order that the contrast may increase, it is therefore necessary to suppose that the background decreases in brightness more rapidly than the flocculi.

The theory of anomalous dispersion requires, according to Professor Julius, "the bright and dark structure generally to appear coarser and more woolly as the spectroheliograph is adjusted for kinds of rays that are more liable to anomalous dispersion"—i.e., as the second slit is moved toward the center of H₂ or K₁. As a matter of fact, however, it is mainly the larger flocculi that show such an effect, which we have attributed to expansion at higher altitudes. The finest and sharpest details ever recorded on our photographs were obtained with the H₂ line.

According to the theory of anomalous dispersion, the appearance of dark flocculi "is a direct consequence of the fact, that the particular distribution of the light in the solar image is not produced by local absorption and emission, but by irregular ray-curving. The rays are only caused to change their places; so an excess of light in the bright flocculi must necessarily be counterbalanced by a deficit in the surroundings." I do not think that a careful study of our original negatives would bear out this view, especially in the case of H₁ and K₁ photographs.

In my opinion, as already stated, the dark hydrogen flocculi are due to the absorption of comparatively cool hydrogen gas in the upper chromosphere and prominences. Professor Julius accounts for their darkness on the ground that "the ray-curving in the solar gases must generally be less with waves belonging to those narrower dispersion bands than with waves lying near the centers of the broad H and K bands." If "ray-curving" is a factor, and if the reasoning here is consistent with that in the first part of Professor Julius' paper, there remains the difficulty that the still narrower lines of iron and other substances give bright instead of dark structures.

Without further discussion, for the present, of Professor Julius' interesting paper, I can only say that our working hypothesis, though admittedly weak in some particulars, appears to me decidedly preferable to an explanation based wholly on the idea of anomalous dispersion. However, the possibility that anomalous dispersion may
in some degree affect results obtained with the spectroheliograph must not be overlooked in future work with this instrument.

While retaining our working hypothesis, I do so with full consciousness of its defects, and with a strong desire to remedy them, either by completing the present explanation, or by substituting a better general view, if such can be found.

Mount Wilson,
February 1905.