ART. XLIX.—*The Ultra-Violet Spectrum of the Solar Prominences;* by GEORGE E. HALE.*

IN various papers published during the past year, I have called attention to some of the advances in our knowledge of the Solar Prominences which might be expected to follow the application of photographic methods to a study of their forms and spectra. A recent number of this Journal, August, 1891, p. 160, contains reproductions of some photographs obtained in the course of my investigations on this subject at the Kenwood Physical Observatory. I am indebted to Professor Lockyer for the use of a measuring machine during a recent visit to London, and I am now able to give my determinations of wave-length for the new prominence lines, and some conclusions to be drawn from them. But perhaps it will first be well to consider for a moment the apparatus and methods at present employed in the work.

To the eye end of the 12·2 inch equatorial refractor of the Kenwood Observatory a large solar spectroscope is rigidly attached by three steel tubes, and as the spectroscope extends about five feet beyond the focus of the telescope, the declination axis is placed at the center of the combined lengths of the two instruments, in order to reduce the amount of counterbalance required at the object-glass end. The result is very satisfactory, and there can certainly be little fear of flexure in the combination. The whole spectroscope may be rotated by a rack and pinion, so as to make the slit tangential or radial at any point on the sun's limb. The object-glasses of the collimator and observing telescope have $3\frac{1}{4}$ inches clear aperture, and $42\frac{1}{2}$ inches focal length. The 4-inch Rowland grating is ruled with 14,438 lines to the inch, and as the telescopes make with each other a constant angle of 25°, different orders of

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spectra are brought into the field of view by rotating the grating. A diagonal eye-piece at the end of the observing telescope allows the spectrum to be observed after the photographic plate is in position.

In photographing the spectrum of a prominence the following is the ordinary process. Let us suppose that it is desired to use a radial slit, in the H and K region of the spectrum. The C line in the second order is brought into the field, and while observing this line the spectroscope is rotated until the slit is radial at some point on the limb where a prominence is seen. The driving-clock is then started, and the telescope clamped, so that the sun's image is kept as nearly as possible stationary on the slit plate. A small strip of metal, pushed in just behind the slit, excludes the direct solar light, except from a small region near the limb. The whole collimator is next moved by a screw until the slit is brought to the proper focus of the equatorial for K, and the collimator and observing telescope are set at the focus for the same line, the positions being taken from a table of foci, determined by experiment, for the principal lines in the spectrum. After placing the sensitive plate in position, the grating is rotated until the K line in the fourth order is in the middle of the field, the slit is covered, the slide drawn, and the proper exposure given. The exposure of course depends upon the aperture and focal length of the equatorial, the width of the slit, the brilliancy of the grating, the sensitiveness of the plate, etc., but with the ordinary dry plate of sensitometer No. 23 furnished by the Seed Company, and a slit about 0·001 inches wide, I usually find that an exposure of from 20 to 30 seconds gives the best result.

For the first time without an eclipse the prominence spectrum was thus photographed early in April of the present year. The only bright lines then obtained were found to fall nearly at the centers of the dark bands H and K of the solar spectrum, but these were remarkably strong, seeming to fully equal C in intensity, and were present in every prominence photographed. Work was continued on the violet and ultra-violet for some weeks, but, with the exception of some lines which had all the appearance of ghosts of the brilliant H and K reversals, no new lines were discovered until June 23, when an exceptionally bright prominence was found. This gave four lines in the ultra-violet, and the least refrangible of these was found to be double. A line slightly less refrangible than H, nearly but not quite at the position where the first ghost would be expected to fall, was much stronger than any of the other ghosts, and it seemed very possible that it was an independent line. This prominence remained visible for several days, and

a number of photographs of its spectrum were made with both radial and tangential slit.

In reducing the wave-lengths of these lines it might be considered easy to obtain values for a given line agreeing closely in the hundredths place of tenth-meters, but two causes have combined to lessen the accuracy of determinations. The H and K reversals almost invariably show some indications of motion of the prominences in the line of sight, and the consequent distortion renders somewhat difficult the proper setting of the spider line of the measuring machine. Again the plate-holder used was made for another purpose, which required that the plane of the plate should be at right angles to the axis of the observing telescope. As the object-glass of the telescope is corrected for the visual region, it is evident that near K there must be a slight change in focus from one side of the plate to the other, and a small error is thus introduced. It will be seen, however, that the measures are sufficiently accurate to allow very little doubt as to the identity of most of the lines. The fact that the solar spectrum, due to the diffuse light of the atmosphere, is photographed simultaneously with the prominence spectrum, is of great advantage in determining the position of the prominence lines, though it has a corresponding disadvantage in concealing very faint lines, which would otherwise be brought out. The wave-lengths of certain standard lines in the solar spectrum have been taken from the list published by Professor Rowland,* and it has thus been easy to find the wave-lengths of the prominence lines by simple interpolation. The value of the micrometer screw has been determined for several regions on every plate by measuring the positions of properly distributed standard lines, the number of separate settings of the spider line in each case ranging from five to fifteen, depending upon the character of the line measured. In the following table the first column contains the wave-lengths of the ultra-violet prominence lines; the second the positions assigned by Ames to the lines in the hydrogen stellar series; and the third, the wave-lengths of the calcium lines at H and K, which Professor Rowland has been kind enough to furnish in advance of publication. I am informed that they are provisional only, but may be relied on to within 1 or 2 in the last place of decimals. In the case of hydrogen, Ames considers that the error in any wave-length cannot amount to more than 0·05 of a unit,† and my own values for the prominence lines must possess at least an equal degree of accuracy, though I am inclined to believe some of them even more reliable. In the fourth and fifth columns I

* This Journal, p. 182, 1887.

† Phil. Mag., July, 1890, p. 49.

have added Cornu's measures of the hydrogen lines,* and Dr. Huggins' wave-lengths of lines in the hydrogen stellar series,† both reduced to the scale of Rowland's map.

Prominences.	Hydrogen.	Calcium.	Hydrogen.	First Type Stars.
Hale.	Ames.	Rowland.	Cornu.	Huggins.
3968·56	----	3968·61 (H)	----	----
3933·86	----	3933·80 (K)	----	----
3888.73	----	----	----	----
3970·11(?)	3970·25	----	3969·6	3969·6
3889·14	3889·15	----	3888·5	3888·2
3835·54	3835·6	----	3835·1	3834·6
3798·1	3798·0	----	3797·5	3795·6
3770·8	3770·7	----	3770·0	3768·1
----	3750·15	----	3749·9	3746·1
----	3734·15	----	3734·2	3730·6
----	3721·8	----	3721·1	3717·9
----	3711·9	----	3711·1	3707·9
----	----	----	----	3699·4

Let us first consider the prominence lines which lie near the centers of the broad dark shades at H and K. In his observations of the chromosphere and prominence spectrum at Mount Sherman, in 1872, Professor Young succeeded in seeing these reversals in a number of cases, but the character of the bright lines could not be made out, and it was considered probable that the broad dark bands were included in the reversal, only the brighter central portions, however, being strong enough to affect the eye. We now find, on the contrary, that the substance producing the bright prominence lines may possibly be entirely distinct from that causing the broad bands in the solar spectrum, for though the lines certainly do lie near the centers of the bands, they are narrow and sharp, and it is easily conceivable that their position may be simply the result of chance, though perhaps probability would point the other way. We are hardly in a position to discuss the cause of the unique appearance of the dark H and K bands, but it may be that we may learn something in this connection from Dr. Huggins' important investigations of stellar spectra. It will be remembered by everyone that in his memoir "On the Photographic Spectra of Stars" communicated to the Royal Society in 1880, Dr. Huggins arranged the stars observed in a series, in which the principal criterion of position was the character of the K line. In Arcturus, for instance, this line is broader and more diffuse than in the sun itself, while in Sirius it has narrowed down to

* Journal de Physique, 1886. † Phil. Trans., Part II, 1880, p. 669.

a fine, sharp line. Other stars give intermediate breadths, and in some instances it has entirely disappeared. In the case of H the question is complicated by the fact that hydrogen and calcium possess lines which form a close double at this point, so it is best to consider only K. From the variations of this line it will be seen, apart from the interesting subject of stellar evolution so evidently suggested, that the narrow dark line at the center is very possibly produced by the same substance which, vibrating under different conditions, causes by its absorption the broad dark band.

As the central dark line is known with a high degree of certainty to be due to calcium, it becomes likely that the band is due to the same substance, and as the central dark line of H is also a calcium line, it might perhaps be safe to attribute the H band to the same metal, though in neither case is it well to be too positive in the assertion, for it is somewhat peculiar that the bands and lines appear together in the solar spectrum. If the same substance produces both, and each requires different conditions, possibly of temperature or pressure, for its production, these conditions must presumably exist at different elevations above the photosphere.

The question now arises whether the bright lines in the prominence spectrum agree in position with the dark lines at the center of the H and K bands. Only one or two of my prominence spectra happened to be given the proper exposure to bring out both the bright and dark lines, but in these the coincidence is fairly satisfactory. I have not as yet, however, been able to obtain the wave-lengths of the dark lines in hundredths of a tenth-meter, but Professor Rowland's determinations of wave-lengths for the corresponding calcium lines will answer nearly as well. These have been given in the third column of the table of wave-lengths. It will be seen that in the case of H the prominence line is 0·05 tenth-meters more refrangible, while at K the prominence line is 0·06 tenth-meters less refrangible. Professor Rowland considers his values correct within 1 or 2 hundredths tenth-meters, while the probable errors in the position of the prominence lines, deduced on the assumption of equal weights for the wave-lengths given by each of six plates, are 0·021 and 0·036 tenth-meters for H and K respectively. On the whole, then, there can be little doubt that these prominence lines are due to calcium, and are therefore probably true reversals of the central dark lines of the H and K bands.

It will be of interest next to consider briefly the character of these two prominence lines. In all cases they are quite narrow and sharp, except when motion in the line of sight has produced broadening or distortion. In seven photographs made

with a radial slit both lines gradually become narrower as the distance from the limb increases, and have a pointed appearance. This might be due to an actual decrease in the width of the lines, but, as there is usually a certain increase of intensity toward the limb, the effect may be purely photographic. In several plates, however, there is so little change of intensity that the widening can hardly be due to this cause. The arrow-head appearance so frequently seen with the C and F lines, is often shown when the slit is radial. A rather curious appearance has been found on three plates made with radial slit, and in the two which best show the effect there is a very sudden decrease of intensity in the upper part of the lines. Instead of becoming narrower toward the top, the lines seem to expand symmetrically on either side, and the edges become hazy and indistinct. As in the case of the pointed lines, there is also an expansion toward the limb, but here the edges are clearly defined. The arrow-head appearance is shown in two of these plates. With a tangential slit two plates show the lines expanded at the ends, and in one plate they are pointed. Though in most cases the forms of H and K are very similar, there is a single instance where K is shown sharply double in the fainter portions at each end of the line, and at one end the components seem to diverge slightly. That this is not the result of poor focusing is attested by the sharpness of the lines in the background of solar spectrum; at the same time the appearance is hardly that of an ordinary reversal. One further peculiarity will show that it is safest, for the present at least, not to draw any conclusions from such appearances as have been noted. In a certain position of the mirror of the measuring machine the illumination was such that the edges of the radial black lines appeared bright, while the Fraunhofer lines of the solar spectrum were also bright, as with ordinary illumination. One of the negatives, in which H and K were broader and fainter at the top, brought out the effect particularly well. The central dark line extended two-thirds of the distance to the top of the prominence, and in the upper part it was excessively narrow and delicate. Lower down it gradually widened, until at a point very near the limb the widening became much more rapid, and at the limb itself the line was nearly as wide as when seen under ordinary conditions.

A paragraph from Dr. Schuster's report on the results obtained with the spectroscopic cameras at the total eclipse of August 29, 1886, seems to refer to a somewhat similar appearance. Speaking of the photographs of the coronal spectrum, Dr. Schuster remarks:* "A bright line shows black on the negative, and is bounded on both sides by an apparently lighter

* Phil. Trans., vol. clxxx, (1889), (A.), p. 328.

background. This is a well-known contrast effect. The H and K lines, for instance, seem to be surrounded by a lighter band, which follows the contour not only of the lines, but also of the wing by the side of the prominence. If, now, a Fraunhofer line happens to be by the side of a bright line, the contrast is strengthened, and both the bright and the dark lines appear more distinctly than they otherwise would. This is the only simple way in which I can explain some of the appearances of the photographs." The first part of the quotation is all that concerns us at present, for in the negative which I have mentioned as showing this peculiarity particularly well, the Fraunhofer lines are hardly visible above the limb, and none appear within the dark bands at H and K. As Dr. Schuster does not speak of the illumination, I assume that the appearance was generally seen, and this constitutes another point of difference. A penumbra formed by light reflected from the back of the plate would probably extend but little higher than the central line, but in the future plates backed with a dyed collodion film will be employed to obviate any effects of this kind. No entirely satisfactory explanation of the peculiar appearance of these lines has as yet suggested itself.

But on another point there is little room for doubt. The bright H and K lines certainly extend to a very considerable elevation above the sun's limb, and it is extremely probable that calcium is carried to the very top of the highest prominences. With the improved apparatus to be used in a continuation of this research, I hope to be able to ascertain the relative heights of various lines in the prominence spectrum. For instance, while a photograph is being made of H and K, the height of C in the same prominence can be measured with a micrometer. The comparative observations and photographs made up to the present time suggest the belief that calcium attains the highest elevations reached by hydrogen, and the remarkable brilliancy of H and K at the eclipse of 1882 attest the importance of calcium in the prominences. Dr. Schuster is of the opinion that the coronal spectrum contains calcium injected by the prominences, and this may only very gradually descend again to the level of the photosphere.* This supposition seems a very plausible one, and if it be at the same time considered probable that the H and K bands and their central lines are produced by the same substance, the possibility is suggested that the broad dark shades may be caused by the absorption of the cooler vapor at a considerable elevation, while the absorption near the photosphere gives rise to the narrow central lines. This view need not necessarily conflict

* Phil. Trans. vol. clxxx, 1889, (A.), p. 328.

with a belief in a shallow reversing layer, where absorption ordinarily takes place, for the H and K bands are unique in the solar spectrum. It rests, however, on somewhat insecure foundations, and cannot be credited with much weight.

On account of the dark shades at H and K it has proved quite easy to photograph prominence forms with an open slit. With other prominence lines the brilliancy of the background is much increased when the slit is opened, but this is not the case with H and K, and it is often possible to use a slit nearly a quarter of an inch wide. The fourth order spectrum has been employed for this work, and the best results are obtained with an exposure of about one second. It is considered that great advantage will result from a material reduction of this exposure, as the disturbances in our atmosphere have as yet made it impossible to secure the finest details of structure.

It is of interest to note, however, that the first photograph ever taken of the rapid development of a prominence was made in this way by my assistants on July 8, 1891, at 23h. 45m., Chicago M. T. As at first observed through C, the prominence was low, but very bright, and changing rapidly. A great tongue moved rapidly out to an elevation of about 80,000 miles, and at this time the extension was photographed through H and K. In fifteen minutes the prominence had returned to its original form. A reproduction of the photograph is given in the August number of this Journal, and though much has been lost in the printing process, some idea of the actual appearance of the prominence may be gained. A new apparatus for photographing the prominences is now being constructed as the outcome of my investigations on this subject, and this is expected to do away with many of the difficulties previously encountered. It will consist of two curved slits, moved in opposite directions across the ends of the stationary collimator and observing telescope by means of a peculiar form of clepsydra. The sun's image and photographic plate will be stationary, and the apparatus is thus to be constructed on the principle of the second method devised by myself in 1889, but so altered as to avoid the defects of the original scheme.*

Decision must be reserved for the present as to the line at λ 3970·11. The wave-length has been determined from four plates, and its probable error is 0·030, but as the line is not far from where a ghost of H should fall, I cannot be certain that it belongs to the prominence spectrum. At the same time it is

* For previous papers on prominence photography see—Technology Quarterly, vol. iii., No. 4, 1890; Astronomische Nachrichten, Nos. 3006, 3037 and 3053; Sidereal Messenger, June, 1891; This Journal, August. 1891.

very much brighter than any other of the seven ghosts of H and K, and its position with respect to H is not symmetrical with that of the first ghost on the opposite side of this line, while in the case of K the ghosts are very regularly spaced. My assistants report that they were able to *see* H very plainly double in a brilliant metallic prominence observed July 27, and on one or two occasions Professor Young has made out the same thing. The agreement in wave-length with Ames's hydrogen line at 3970·25 is by no means satisfactory, and more observations and measures are required before a conclusion can be reached.

No one can doubt that the next four prominence lines are members of the well-known hydrogen series, for their agreement in wave-length with the values given by Ames is certainly very striking. Cornu's measures show considerable differences, as do also those of Dr. Huggins, but the small dispersion employed by the latter in this investigation must be borne in mind. There can be little question that Ames' wave-lengths are very near the truth, for they almost exactly correspond with those calculated by Balmer's formula. The measures of the prominence lines also serve to confirm them.

The remaining prominence line at λ 3888·73 has not been accounted for. It forms a close double with the hydrogen line at λ 3889·14, and with it attains as great elevations above the limb as those reached by H and K. The character of the lines, however, is quite different, for while the hydrogen line is wider, and slightly diffuse, the line at λ 3888·73 is very narrow and sharp. I have seen no statement that the hydrogen line has shown any signs of duplicity, and, as Mrs. Huggins has had the kindness to examine the corresponding line in some very sharp photographs of steller spectra with the same result, we have reason to consider an independent origin probable.

The results so far obtained can only be regarded as preliminary, for with the improvements now being carried out in the telescope and spectroscope, and the much greater frequency of metallic eruptions as the maximum sun-spot period is approached, it is certainly to be hoped that many more lines will be photographed. The ultra-violet spectra of sun-spots have also been worked upon with some indications of success, and there will evidently be no lack of opportunity in the new and interesting fields thus opened to investigation.

London, August 13, 1891.