SUNSPOT PROMINENCES AND THE YELLOW CORONAL LINE

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Received January 28, 1952

ABSTRACT

A study of twenty-five cases of bright emission of the yellow coronal line $\lambda$ 5694, from 1946 through 1951 revealed close association between this emission and fast-moving prominences of the "sunspot" type. It also showed that unusually sharp discontinuities and intensifications of the red coronal line $\lambda$ 6374 occurred at the regions where the yellow coronal line was seen. In a few cases small Doppler effects in $\lambda$ 6374 also appeared at the solar-limb position of the $\lambda$ 5694 emission. The observations lead to the preliminary speculation that the source of the emission corona lies in a few, relatively small, active regions scattered over the solar disk.

INTRODUCTION

For many years astronomers have been aware of the nearly complete independence of the solar corona and the prominences seen at the limb of the sun. This independence was one of the surprising facts discovered from day-to-day observations of the corona made possible in 1930 by Lyot's new coronagraphic techniques. Lyot's earliest birefringent-filter photographs of the corona, taken over a decade ago in the monochromatic light of the emission lines $\lambda$ 5303 and $\lambda$ 6374, revealed further how completely different were the changes and motions of coronal gases from those of prominences.

In 1937, at about the time he started his work of photographing the corona in monochromatic light, Lyot discovered a new line of the coronal-emission spectrum at 5694 Å. This yellow coronal line, recent studies have shown, displays a striking association with certain types of prominences and with active solar regions. The results have been described by Waldmeier, who made extensive observations of $\lambda$ 5694 at Arosa, Switzerland, and by Roberts. The yellow coronal line is generally visible only over regions of marked solar activity as evidenced by sunspots and by the small, sharply curved, and highly changeable "sunspot" prominences of the types classified as IIIa, IIIb, and IIIc by Pettit. The yellow-coronal-line emission probably arises from Ca xv, the atom of highest ionization potential in the corona, and its association with them suggests that prominences of this "sunspot" type differ markedly in their physical conditions from the other forms of prominences that are often more brilliant, more massive, and more spectacular in evolution.

RESULTS

The yellow coronal line $\lambda$ 5694 can be detected only relatively infrequently with the coronagraphs at Climax and at Sacramento Peak. Thus the occasions when it appears are unusual ones. For the line to show on the coronal spectra, which are taken daily (or more often) when weather permits, two conditions must be fulfilled: (1) a region of unusually intense emission of $\lambda$ 5694 must be present near the solar limb, and (2) the air

1 M.N., 99, 580, 1939.
above the coronagraph must be very free from dust or other contaminants—more so than is necessary for observation of other coronal lines.

To date I have isolated and examined twenty-five different occurrences of the yellow coronal line when the line was bright enough on coronograph spectra to be clearly perceived against the background of scattered light from the photosphere of the sun. There are additional instances to be studied later. In several of the cases there were ten or fifteen separate spectra available for examination and, in addition, numbers of photographs of the prominences in Ha at the same location taken within a short time of the spectra.

Table 1 lists the twenty-five cases and gives the dates of the observations of the yellow-

### Table 1

**Regions of Emission of the Yellow Coronal Line**

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Date</th>
<th>Position Angle (Heliographic)</th>
<th>Case No.</th>
<th>Date</th>
<th>Position Angle (Heliographic)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Feb. 27, 1946</td>
<td>60°-65°</td>
<td>13</td>
<td>July 24, 1949</td>
<td>110°-115°</td>
</tr>
<tr>
<td>2</td>
<td>July 27, 1946</td>
<td>60°</td>
<td>14</td>
<td>Aug. 7, 1949</td>
<td>253°</td>
</tr>
<tr>
<td>3</td>
<td>Nov. 27, 1946</td>
<td>250°-255°</td>
<td>15</td>
<td>Sept. 16, 1949</td>
<td>260°</td>
</tr>
<tr>
<td>4</td>
<td>Nov. 30, 1946</td>
<td>250°</td>
<td>16</td>
<td>Nov. 7, 1949</td>
<td>293°</td>
</tr>
<tr>
<td>5</td>
<td>Feb. 12, 1947</td>
<td>255°-260°</td>
<td>17</td>
<td>Nov. 19, 1949</td>
<td>271°</td>
</tr>
<tr>
<td>6</td>
<td>Mar. 19, 1947</td>
<td>75°</td>
<td>18</td>
<td>Nov. 21, 1949</td>
<td>80°</td>
</tr>
<tr>
<td>8</td>
<td>June 14, 1947</td>
<td>90°-95°</td>
<td>20</td>
<td>Feb. 13, 1950</td>
<td>80°-95°</td>
</tr>
<tr>
<td>9</td>
<td>July 24-26, 1947</td>
<td>280°-290°</td>
<td>21</td>
<td>May 6, 1950</td>
<td>85°-90°</td>
</tr>
<tr>
<td>11</td>
<td>Aug. 20, 1947</td>
<td>70°-75°</td>
<td>23</td>
<td>Feb. 4, 1951</td>
<td>283°</td>
</tr>
<tr>
<td>12</td>
<td>Aug. 24, 1947</td>
<td>70°-75°</td>
<td>24</td>
<td>Apr. 10, 1951</td>
<td>80°</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>25</td>
<td>Apr. 25, 1951</td>
<td>285°</td>
</tr>
</tbody>
</table>

coronal-line emission at the solar limb and the position angles at which the emission occurred, measured from the north of solar rotation, with angles increasing to the east.

In twenty-three of the twenty-five cases there is strong evidence that centers of great activity of sunspot-type prominences were present within a few degrees of the positions of the maxima of the yellow-line emission, and the other two cases are not certainly negative. In twenty-two out of the twenty-five cases the line-of-sight velocities in the sunspot-type prominences were significantly greater than the usual velocities for prominences in general.

For example, on February 3, 1950, at 290° (case 19 in Table 1) small features of the associated active-region prominences showed a range of line-of-sight velocities up to 100 km/sec, typical of such active-region prominences, whereas prominences in general do not usually show velocities in the line of sight exceeding 40 km/sec. Sunspot prominences of this type, on the other hand, generally show velocities like this even when the yellow coronal line is absent. This absence can be attributed to the difficulty of observing the yellow line, and it is probable that in most instances better observations would reveal the line. For this reason, spectra with a higher-resolution coronograph, allowing observations closer to the solar limb, are important. The prominence velocities were judged qualitatively from the Doppler displacements visible in the emission spectra of Ha and of D3 of helium on the spectrograms containing the yellow-line emission.

The results reveal the clear relationship between the yellow coronal line and the appearance of these sunspot-type prominences with their high-velocity surges, down-flowing arches, and loops; prominences of the sunspot type are not sufficiently common to show any similar association with regions chosen at random on the solar surface, even within the sunspot latitude belt alone.

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At the points where the yellow-line emission shows, it also appears that unusually sharp discontinuities in and intensifications of the intensity of the red coronal line \( \lambda 6374 \) are likely. In twenty-three out of the twenty-five cases listed in Table 1, the red coronal line exhibited maxima that appeared to be unusually sharp for the red line, as compared with its appearance over most solar regions. In many of these cases the red-line emission rose from a minimum to a maximum in less than 5°. This behavior is typical only in active regions that include sunspot-type prominences.

In at least three cases a phenomenon far more rare than the occurrence of yellow-line emission was evident: a definite broadening or asymmetry in the red coronal line, which it seems reasonable to attribute to Doppler displacement from large-scale motions, showed just at the position of the yellow-line emission. Probably less than a dozen cases of any discernible Doppler effects in coronal lines appear in the entire decade of coronal observations from Climax.

For most of the cases the green coronal line \( \lambda 5303 \) (Fe xiv) was relatively bright at the point of emission of the yellow line, but the green line showed neither sharp discontinuities nor any association that would have been viewed as particularly significant in the absence of the other phenomena.

Figure 1 (top) contains examples of the phenomena under investigation and corresponds to cases 1 and 17 in Table 1. At the top, in this figure, are shown prominence photographs in Ha, surmounting polar diagrams giving the intensity distributions (on independent, arbitrary scales) for the three coronal lines. The slit of the spectrograph in each case was placed directly on the region shown in the photograph, and the spectra were obtained for positions corresponding to the photographs, at a single height close to the solar limb.

Figure 1, a, shows a typical case of the phenomena associated with yellow-coronal-line emission. In this case, the center of activity toward which the small high-velocity sunspot streamers converged was at about 63°. At the time of this photograph the converging sunspot prominences were not particularly evident, but examination of other parts of the film records showed them to be present and constantly changing in typical fashion. The large, relatively stable prominence from 70° to 85° continued to shoot streamers toward the point of convergence.

In many cases the point of maximum yellow-line emission is not at the location of the brightest parts of the associated prominences but rather at the center of symmetry or convergent point for continuing spurts of high-velocity prominence streams. In many cases intense flarelike prominences frequently formed at or very near the center of activity, and in some cases the emission spectra of these exhibited large line broadening so characteristic of solar flares on the disk, though it is possible that none of the cases yet examined shows a limb feature of sufficient brightness to be called a typical flare. It may also be that the spectrograph slit was placed too high above the limb, in these cases, to record flares if they were present, or it may be that the spectra were never taken at precisely the time and place where a full-fledged flare occurred at the limb.

Several of the cases given in this list have been associated with outstanding regions of solar activity. One case, that of June 14, 1947, was the subject of an earlier paper. Most notable, perhaps, was the case of November 19, 1949. On this date an outstanding outburst of activity took place on the sun. This event, by a fortunate series of circumstances, has been very extensively observed with many types of recording devices. The solar activity was unambiguously associated with the largest changes of cosmic-ray and neutron \(^9\) counts yet recorded and with other terrestrial disturbances.

Figure 1 (bottom) shows the yellow-line and related observations of November 19, 1949.

\(^7\) M. A. Ellison, Pub. R. Obs. Edinburgh, 1, No. 4, 53, 1950 (see also p. 64); M.N., 109, 37, 1949.


Fig. 1.—Association between sunspot-type prominences and coronal-emission lines. Hα prominences shown at the top, with the yellow, red, and green coronal lines plotted below on independent arbitrary line-intensity scales. Positions shown are heliographic position angles. The maxima of the yellow line coincide with centers of sunspot-type prominence activity.
At about 270°, where the yellow line peaked at 16:34 U.T., there was a decided center of prominence activity. Loops and knots from the prominence shown at the right, from 270° to 280°, continued to "rain" down toward the center located at about 268°. The large, relatively quiescent prominence shown at the left, which extended to about 265°, showed little activity, except that at its right extremity it also "rained" prominence material toward the center.

Independent evidence shows that the outstanding solar phenomenon recorded on this date was a chromospheric flare that occurred a short distance inside the disk, below the center of activity visible at the limb. The flare was recorded at Wendelstein Observatory in Bavaria and at the Royal Observatory in Edinburgh before sunrise in Colorado, and thus several hours before our observations at Climax. It appeared at approximately 10:30 U.T. very near the solar equator and well toward the west limb of the sun (268° heliographic latitude and 70° west from the central meridian) at the center of activity shown in Figure 1 (bottom). The flare increased rapidly in intensity, peaking at about 10:32 U.T., at which time the Hα line reached the greatest line width yet recorded at the Royal Observatory. By 10:36 U.T. the peak had passed, showing that the flare was a very rapid one both in rise and in fall. By 12:09 U.T. no appreciable Hα emission remained to be seen. All these phenomena took place before 16:34 U.T., the time of the first spectrogram at Climax, on which the graphical material of Figure 1 (bottom) is based.

Ellison and Conway also report that prominence material was ejected across the limb with the extremely high line-of-sight velocity of 550 km/sec and an average velocity in the plane perpendicular to the line of sight of about 300 km/sec. The prominence, too, was invisible after about 11:00 U.T. Associated with the flare, Ellison and Conway reported bright helium λ 6678 emission and a short-lived outbreak of continuous emission from the flare.

A complete ionospheric fade-out occurred at 10:29 from about 5 Mc/sec to about 20 Mc/sec, and atmospheric noise at 22 kc/sec was suddenly enhanced at the same moment as the flare, both phenomena testifying to the enormous and sudden increase in the D-region ionization at the instant of the flare. The fade-out lasted about 5 hours. At the same time, sudden breaks (crochets) in the geomagnetic intensity took place.

Mr. Fleming, the observer at Climax, who first noted the unusual activity of this solar region, initiated a program of special spectra and photographs of the region, co-ordinated by radio with similar photographs taken at the Sacramento Peak Station of Harvard College Observatory in New Mexico. We can assume that, had the phenomena of the disk been located somewhat closer to the limb on this date, we would have observed the yellow line as being more brilliant. But in this case the disk phenomena probably would not have been observed, and one does not know whether the terrestrial phenomena would have been detected with such magnitude. It may also be that the yellow-line intensity had already declined from an earlier peak by the time of our first Climax observation.

The behavior of the regions of yellow-line emission is under continuing scrutiny; I hope to be able to study the rate of decline of line intensity following outbursts for the yellow and red coronal lines from new observations taken at closer intervals and to make more detailed studies of associated solar activity for dates surrounding those of yellow-line occurrence, using existing observational materials. The present work, however, leads to some speculative conclusions and ideas that rest on admittedly shaky observational ground but that perhaps merit tentative mention now and further observational test as soon as possible.

CONCLUSIONS AND SPECULATIONS

Waldmeier has already suggested that the yellow coronal line is intensified over solar flares. The present work seems entirely consistent with this observation, though I have

not, in most cases, specifically studied in this paper the effect of individual flares on the yellow-line emission. Most of the active regions identified here with the yellow-line emission were, however, highly productive of flares.

It seems probable that prominence activity can be divided sharply into two types, depending on whether or not the prominences are identified with centers of great activity near the solar surface. Furthermore, it seems likely that active-region prominences are clearly associated with emission of the yellow coronal line and the related phenomena here described. The largest and brightest prominences, on the other hand, are frequently quiet-region prominences, totally unrelated to coronal maxima. Thus the inclusion of all prominences in studies of corona-prominence correlations failed to reveal significant positive association to Lyot and other earlier workers. For the same reason, efforts to correlate observed prominence areas with terrestrial magnetic and radio disturbances have been relatively unproductive. The correlation between the typical active-region prominences associated with yellow-coronal-line emission should reveal a very different result.

The association of the active-region prominences with emission of $\lambda$ 5694 radiation probably originating in $Ca\ xv$ suggests that prominences of the two types are sharply differentiated in physical conditions such as temperatures, pressures, strength of associated magnetic fields, etc. Waldmeier's recent findings confirm this supposition.

The behavior of $\lambda\lambda$ 5303, 6374, and 5694 suggests that the emission corona may find its source in relatively few active centers of the sun that are usually the seat of well-defined sunspots, bright plages, sunspot-type prominences, etc. The gases that radiate the emission lines of the corona, according to this speculation, emanate from these sources and spread gradually over the surface of the sun, moving perhaps 200,000 km in a time of the order of a week, and decline in brightness of emission the farther they move away from the point of origin.

Obvious difficulties stand in the way of this idea and suggest that it must be viewed with caution. If the process by which the coronal gases move from the localized sources is one of atomic diffusion, even granting nonisotropic, diffusion controlled, perhaps, by magnetic conditions of the solar atmosphere near the active regions, it is troublesome to think of recombination times for the emitting ions of the order of weeks.

Other obstacles arise from the fact that the lines $\lambda\lambda$ 5303, 6374, and 5694 exhibit systematic differences in behavior as they move, according to this concept, from their localized sources. The brightness of $\lambda$ 5694 declines sharply with distance from the source, $\lambda$ 6374 declines at an intermediate rate, and $\lambda$ 5303 declines slowly with distance.

Yet the shape and location of the emission regions of the different coronal lines suggest the concept, as does the character of the day-to-day changes of coronal intensities at the solar limb. And the excellent motion pictures of Lyot, taken in the light of emission lines of the corona, agree with the assignment of extremely low velocities of motion to clouds of emitting coronal ions. Figure 2 shows a typical example of the isophotal contours for $\lambda$ 5303, corresponding to cases 24 and 25 in Table 1.

Further study of these active solar regions is most important. It seems likely to me that they bear close relationship not only to some of the better-known geophysical effects of solar activity but also to the production of solar radio noise and to changes in cosmic-ray intensities. Piddington and Minnett, for example, have discussed hypothetical "hot" regions of the sun's atmosphere, which they hold responsible for the slowly varying component of the sun's radio spectrum (in the range 600 mc/sec and above). There seems a fair chance that their "hot" regions are the same active centers discussed in this paper by Menzel, Roberts, and Evans.

13 Ibid., 28, 208, 1951.
ISOPHOTES OF SOLAR CORONA ON 18 APRIL 1951
STATION: SACRAMENTO PEAK    LINE: 5303 A

Fig. 2.—Isophotal contours of the green coronal-emission line for April 18, 1951, based on east- and west-limb observations for a 2-week period centered on April 18, 1951. Bright emission of the yellow coronal line occurred during the east- and west-limb passages of the principal center of activity shown in the Northern Hemisphere.
paper. Furthermore, Simpson\textsuperscript{15} has found day-to-day changes of cosmic-ray intensities that seem to be correlated with the solar location of active centers like these. We hope, therefore, to be able soon to undertake work of a more quantitative sort on these solar regions.

My thanks are due to the many observers at Climax and at Sacramento Peak for their part in the observations reported here and to Mrs. Kathryn Virnelson, who assisted in the reduction work reported. Also I wish to express my gratitude to my associate, John W. Evans, as well as to Richard N. Thomas and Donald H. Menzel, for their help and criticism during this work. From Alan H. Shapley and Roger Moore, of the National Bureau of Standards, I have had helpful comments and discussions which I gratefully acknowledge. To Harvard College Observatory I express appreciation for the opportunity to examine spectra and to use data obtained from its solar station at Sacramento Peak, operated under Contract W19-122ac-17 with the Geophysical Research Division of the Air Force Cambridge Research Center. I wish, finally, to acknowledge support of certain phases of this work by the Research Corporation, the Office of Naval Research, and the National Bureau of Standards.