ANOMALOUS IONIZATION IN THE UMBRAE OF SUNSPOTS

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SUMMARY

New observations are presented of sunspot spectra in regions containing lines of ionized elements, obtained with the rapid scanning spectrometer at the Oxford-Gornergrat Observatory. The umbral spectra are corrected for scattered light from penumbra and photosphere by making use of scans of the solar limb and sky background. The corrected spectra show anomalously strong lines of Fe II and Cr II. The existence of the anomaly for Fe II depends critically on the accuracy of the scattered light measurement. A numerical experiment shows that the measured value of 26 per cent for the relevant spot is unlikely to be greatly in error. These anomalies cannot be explained even in terms of a non-homogeneous model of an umbra in which there is a state of L.T.E. in each component, and it seems probable that the lines arise from a non-equilibrium mechanism. The possible presence of a similar anomaly in the spectra of magnetic stars is briefly discussed.

1. INTRODUCTION

Observed spectra of sunspot umbrae often show lines of ionized atoms, particularly Fe II and Cr II, that are unexpectedly strong for the temperatures that are commonly assumed to exist in these regions. Zwaan (1965) has suggested that these lines are not present in the true umbral spectrum, but are due to the intrusion of scattered light from the penumbra and photosphere. This attitude is also taken by Kneer (1973), who uses observations of 6149 Fe II to deduce the amount of scattered light in his image. On the other hand, Fricke & Elsässer (1965) and Hénoux (1969), among other authors, suggest that the lines are indeed present in the true umbral spectrum. In a recent paper Mallia & Petford (1972) describe their own observations made at the Gornergrat Observatory of the University of Oxford, as a result of which they also suggest that the lines are formed in the umbra. The purpose of the present paper is to consider again the problem of the reality of these lines in the umbral spectrum using new observations made at the Gornergrat Observatory (Blackwell, Mallia & Petford 1969). These observations were obtained using umbrae of larger diameters than those observed by Mallia & Petford, and are of considerably better quality.

2. OBSERVATIONAL DATA

Observational details are given in Table I. All of the spectra were obtained using a diaphragm of diameter 4" and at a resolving power of about 200 000. The noise level in the umbral spectra was close to 1 per cent. To obtain this noise level, integration was continued for about 25 min during which time some 7000 scans were integrated in the spectrometer. The ratios of the intensities of umbral,
Table I

Sunspot data

<table>
<thead>
<tr>
<th>Designation</th>
<th>Date of observation</th>
<th>Rome number</th>
<th>Apparent umbral area</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1971 September 30</td>
<td>6224</td>
<td>191 complex</td>
</tr>
<tr>
<td>B</td>
<td>1969 October 27</td>
<td>5583</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>1971 April 18</td>
<td>6095</td>
<td>127 (on 1971 April 19)</td>
</tr>
</tbody>
</table>

(Taken from *Monthly Bulletin of Solar Phenomena*, Osservatorio Astronomico di Roma.) Unit of area: \(10^{-6} \times\) solar hemisphere.

Penumbral and photospheric continua were obtained from the final integrations made by the computer.

3. SCATTERED LIGHT CORRECTION

Particular attention has been paid to the problem of scattered light because the prime aim of the investigation was to decide whether the anomalous ionized lines could be attributed to this source. We have determined the scattering function in the usual way from profiles of the solar limb, obtained at wavelengths close to those of the spectral scans and using the same size of diaphragm. As an example, original data for two opposite limbs obtained on 1971 September 30 are plotted in Fig. 1. An average scan for the immediate neighbourhood of the solar limb is shown in Fig. 2, whilst Fig. 3 shows the averaged sky brightness at greater distances from the limb. These diagrams illustrate the quality of the sky obtainable at the Gornergrat, the brightness at a distance of 1' from the limb being only 0.15 per cent of the brightness of the centre of the solar disk. At this distance from the limb the sky brightness is usually recorded with an intensity some ten times greater than

![Fig. 1. Observed sky brightness in the region of two opposite solar limbs, represented by filled and open circles, obtained 1971 September 30.](image-url)
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Fig. 2. Averaged observed sky brightness in the immediate neighbourhood of two opposite solar limbs, compared with sky brightness calculated using adopted scattering function.

Fig. 3. Observed sky brightness at greater distances from the solar limb, compared with brightness calculated using adopted scattering function.

Table II

Composition of observed umbral light at 5400 Å (Spot B)

<table>
<thead>
<tr>
<th>Source of Light</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>True umbral light</td>
<td>74</td>
</tr>
<tr>
<td>Light scattered from penumbra</td>
<td>15</td>
</tr>
<tr>
<td>Light scattered from photosphere</td>
<td>11</td>
</tr>
</tbody>
</table>

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this (Zwaan 1965) although David & Elste (1962), Fay, Wyller & Yun (1972),
and Stellmacher & Wiehr (1970) have also recorded very low brightness values.

In interpreting these and other limb curves we follow the method of Minnaert
et al. (1949) and Wanders (1934), using a combination of two Gaussian functions
to represent the short-range portion of the scattering curve, particularly for the
region in the neighbourhood of 10" from the theoretical limb, and a function of
the form \( C + D/(E + R^2) \) to represent the long range scattering. This need for
two Gaussian functions has been noted by David & Elste (1962) and by Kneer
& Mattig (1968), whilst Staveland (1970) has used three Gaussian functions. The
success of our representation of the scattering function is shown by the comparison
between the observations and the calculated brightness curves given in Figs 2 and 3.
However, we emphasize that the accuracy of the correction for scattered light is
still subject to the limitations mentioned by Mallia and Petford. An example of
the results of an analysis of light in the image of an umbra is given in Table II.

4. EXAMINATION OF IONIZED LINES IN THE CORRECTED SPECTRA

We now consider the individual spectra, corrected for the presence of scattered
light, and the evidence they show for the existence of enhanced ionized lines.

4.1. Lines of Cr II in the region \( \lambda \)5305–5314

In Fig. 4 we show a composite of the photospheric and penumbral spectra in
this region together with the observed umbral spectrum, and the umbral spectrum
after correction for light scattered from photosphere and penumbra. This diagram
also shows the positions of some molecular lines taken from the work of Sotirovski
(1972), together with some equivalent widths measured from our traces. All of
these spectra were obtained from spot A.

Although the region is complex, there are two lines of Cr II at 5305.866 and
5313.585 which appear reasonably unblended. Table III gives the observed equiva-
lent widths of these lines in the photospheric, penumbral and umbral spectra,
and calculated values for their equivalent widths in the penumbral and umbral
spectra. For these calculations we used the Harvard-Smithsonian model atmo-
sphere for the photosphere, that of Moe & Maltby (1969) for the penumbra, and
the atmosphere of Stellmacher & Wiehr (1970) for the umbra. The product \( gF\lambda \)
for each line, needed for the penumbral and umbral calculations, was obtained
from the photospheric equivalent widths. All calculations assumed a state of L.T.E.
and ignored the effect of any penumbral and umbral magnetic fields. The table
shows a large discrepancy between the observed and calculated equivalent widths
of the Cr II lines in the umbral spectra, the ratio of the observed to calculated values
being 22 for the 5305.866 Å line and 39 for the 5313.585 Å line. However, there is
no corresponding anomaly for the penumbral spectrum.

The prominence of these two lines of Cr II, and more particularly that of the
5313.585 Å line, make it unlikely that the umbral anomaly can be wholly accounted
for by hidden blending. There remains the possibility that it results from a faulty
correction for light scattering from the penumbra, this being more important as a
source of false light than the photosphere. As we have noted, the correction appro-
priate to the time of observation cannot be very reliably determined, but a com-
parison of the profiles of the 5305.866 Å line in the observed penumbra and
umbra strongly suggest that the line in the corrected spectrum is chiefly of umbral
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Fig. 4. Composite of photospheric, penumbral and observed umbra spectrum for spot A. Together with umbra spectrum corrected for scattered light, showing Cr II lines in the region of 5310 Å.
Table III

<table>
<thead>
<tr>
<th>Line transition</th>
<th>Excitation potential</th>
<th>W(photosphere)</th>
<th>W(penumbra)</th>
<th>W(umbra)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{5}P_{5/2} - ^{5}D_{7/2})</td>
<td>3.83 eV</td>
<td>25 mA</td>
<td>23 mA</td>
<td>20 mA</td>
</tr>
<tr>
<td>(^{5}P_{5/2} - ^{5}D_{7/2})</td>
<td>4.07</td>
<td>34</td>
<td>28</td>
<td>27</td>
</tr>
</tbody>
</table>

Origin. This comparison shows that whereas in the penumbral spectrum the line is merely broadened by the Zeeman effect due to the magnetic field there, in the umbral spectrum the line is clearly split into two components, symmetrical about the position of the photospheric line, with an observed separation of 79 mÅ. Supposing that the umbral splitting of this 5305-866 Å line of Cr II is magnetic, use of a Landé splitting factor, \(g = 1.63\), for the principal line in the Zeeman pattern gives a corresponding magnetic field of 1800 Gauss. An independent value for the magnetic field is given by the Cr I line 5312-863 Å, which is on the same scan and which shows a splitting of 102 mÅ. Using an effective value of \(g\) equal to 1.84 for this line, we obtain a magnetic field of 2100 Gauss. This line is only broadened, not split, in the penumbral spectrum. Also, the field given by the Ti I line at 5313-244, which is predominantly of umbral origin, is very close to 2100 Gauss. The close agreement between the umbral field values for 5312-865 Cr I and 5305-866 Cr II and the Ti I line, and the close coincidence between the mean wavelength of the doublet shown by the Cr II line in the umbral spectrum and the wavelength in the photospheric spectrum, shows that the observed splitting of 5305-866 Cr II is probably due to the Zeeman effect. A possible argument that might be advanced against this interpretation is that the two Zeeman components in the corrected umbral spectrum are of unequal depth (the fact that they are of equal depth in the uncorrected spectrum arises by chance and is not of especial significance). However, this asymmetry could be attributed to instrumental polarization effects, due principally to reflections at the coelostat and other mirrors in the optical train. There is some support for this from the similar asymmetry shown by the 5313-585 Cr II and the 5312-863 Cr I lines, although the fact that the 5312-244 Ti I line is asymmetric in the opposite sense shows that an apparent Zeeman splitting may be affected by or even be due to blending by an unknown line, and it should be noted in this case that the \(P_{3}(93)\) line of the (o, o) band of TiO falls at 5305-87 Å. However, judging by the equivalent widths of the neighbouring lines in this band, this line may be expected to have an equivalent width of only about 10 mÅ, which is too small to be responsible for the observed splitting. Certainly the observed profile cannot be attributed to scattering from the penumbral regions because these have insufficient field strengths. We deduce that the observed 5305-866 Å line in the umbral spectrum does indeed originate in the umbra.

The other Cr II line at 5313-585 Å is only slightly broadened in the penumbral and umbral spectra, but this behaviour is completely understandable because this line is less sensitive to a magnetic field, having an effective \(g\)-value of only 1.03. The fact that it is broader in the observed umbral spectrum than in the penumbral spectrum shows that it is certainly of part umbral origin at least. The line is blended with the \(R_{2}(116)\) line of the (o, o) band of TiO at 5313-58 Å (Sotirovski 1972),
but the blending line is weak and can account for only a small proportion of the observed equivalent width. We do not consider the other two lines of Cr II in this region, at 5308-329 and 5310-697, because these are in heavily blended regions. There is no evidence that they are absent from the umbral spectrum.

4.2. Lines of Fe II in the region \( \lambda \lambda 5425-5436 \)

This spectral region contains two ionized lines of interest, 5425-259 Fe II and 5427-803 Fe II; of these, only the former line is classified by Moore, Minnaert & Houtgast (1966). We discuss here scans of this spectral region obtained from the two spots A and B. Fig. 5 shows a composite of photospheric and corrected umbral scans of this whole region obtained from these two spots.

At first sight the line 5425-259 Fe II appears to be strong in the observed umbral spectrum, with a splitting in the spectrum of spot B, for example, corresponding to the not unreasonable magnetic field of 2700 Gauss, although it is high in comparison with other measurements on this spot, but a closer examination shows a less clear situation. In Figs 6 and 7 we plot the profile of this line on an expanded scale in the photospheric spectrum, and in the penumbral and umbral spectra of spots A and B. Fig. 7 shows that in the spectrum of spot A the centre of gravity of the observed umbral line is at a longer wavelength with respect to the corresponding photospheric and penumbral lines. This shift suggests that the observed umbral line has a longer wavelength blend which, in combination with an Fe II line originating either in the true umbral spectrum or in scattering from the penumbra and photosphere simulates a magnetic doublet of reasonable separation. In this example of spot A, it is of interest that the true umbral spectrum, corrected for scattered light, shows almost no trace of the Fe II line and there remains after this correction only the supposed unidentified blending line, which is displaced 82 mA towards longer wavelengths from the photospheric and penumbral lines of Fe II. Further evidence that the doublet nature of this line in the umbral spectrum of spot B should not be interpreted as a true magnetic splitting is provided by the fact that other lines in this region on the same scan are only broadened and none shows an actual splitting, even though many have a larger Landé splitting factor than the Fe II line.

Although the 5425-259 Fe II line is almost absent from the spectrum of spot A, Fig. 6 shows it to be quite strongly present in the spectrum of spot B, where it has an equivalent width of 19 mA. The equivalent width in the photospheric spectrum is 45 mA. If this apparent difference between the spectra of the two umbras is really genuine, it should be accompanied by differences in other quantities such as continuum intensity and the equivalent widths of sensitive lines. We now enquire whether such differences also exist.

The continuum intensity corresponding to the part of the umbra being examined may be obtained from the computer output. Table IV lists the observed values of the continuum intensity obtained in this way for spots A and B, after correction for the presence of scattered light from photosphere and penumbra. Values for the umbral intensity obtained by some observers are listed in Table V for the sake of comparison. The continuum intensity of spot A is in reasonable agreement with these values, and it is also comparable with the lowest of the measures of Makita & Morimoto (1960) which refer to the darkest portion of the umbra. Clearly, the observed region of spot B, is unusually bright, indicating that it has a higher temperature than the region observed in spot A. On this basis it is satisfying
Fig. 6. Line profiles in the region of 5425.259 Å Fe II (a) photospheric spectrum, (b) observed umbral spectrum of spot B, (c) umbral spectrum of spot B corrected for scattered light.

Table IV

Continuum intensity in the region of 5400 Å obtained from the spectra of Figs 4 and 5, and corrected for scattered light.

<table>
<thead>
<tr>
<th>Spot</th>
<th>I(umbra)/I(photosphere)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.051</td>
</tr>
<tr>
<td>B</td>
<td>0.16</td>
</tr>
</tbody>
</table>

Table V

Measured intensity of umbral continuum at 5310 Å (interpolated values quoted where necessary)

<table>
<thead>
<tr>
<th>Reference</th>
<th>I(umbra)/I(photosphere)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mattig (1971)</td>
<td>0.059</td>
</tr>
<tr>
<td>Maltby (1970)</td>
<td>0.072</td>
</tr>
<tr>
<td>Fay et al. (1972)</td>
<td>0.084</td>
</tr>
<tr>
<td>Wohl et al. (1970)</td>
<td>0.11</td>
</tr>
<tr>
<td>Wittman &amp; Schroter (1969)</td>
<td>0.086</td>
</tr>
<tr>
<td>Hénoux (1969)</td>
<td>0.11</td>
</tr>
</tbody>
</table>
Fig. 7. Line profiles in the region of 5425.259 Fe II for spot A (a) penumbral spectrum, (b) observed umbral spectrum, (c) corrected umbral spectrum.

Table VI

<table>
<thead>
<tr>
<th>Model</th>
<th>Continuum intensity (I_{umbra}/I_{photosphere})</th>
<th>W(5425.259 Fe II)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Umbra $\theta = 0.30^{(1)}$</td>
<td>0.204</td>
<td>8.2 mA</td>
</tr>
<tr>
<td>$\theta = 0.35^{(2)}$</td>
<td>0.189</td>
<td>6.0</td>
</tr>
<tr>
<td>$\theta = 0.45^{(3)}$</td>
<td>0.094</td>
<td>1.5</td>
</tr>
</tbody>
</table>


Table VII

<table>
<thead>
<tr>
<th>Line</th>
<th>Excitation potential</th>
<th>Measured equivalent widths (mÅ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5432.548 Mn I</td>
<td>0.00 eV</td>
<td>Spot A: 380, Spot B: 216</td>
</tr>
<tr>
<td>5426.258 Ti I</td>
<td>0.02</td>
<td>Spot A: 223, Spot B: 119</td>
</tr>
</tbody>
</table>
that spot B shows the $5425\pm259$ Fe II line more strongly than spot A. Results of calculations of continuum intensities and equivalent widths of $5425\pm259$ Fe II for a range of model atmospheres of differing values of $\Delta \theta = \theta(\text{umbra}) - \theta(\text{photosphere})$ are given in Table VI; these calculations show that the observed continuum intensities are compatible with existing umbral models, and that the equivalent width of the $5425\pm259$ Fe II line rises steeply with the continuum intensity.

That spot B is hotter than spot A is also shown by measured equivalent widths of low excitation lines of neutral atoms. Such measures are shown in Table VII for $5432\pm548$ Mn I and $5426\pm258$ Ti I from which it will be seen that these two lines are weaker in spot B than in spot A, confirming the above conclusions.

Having established from considerations of continuum intensity and the equivalent widths of atomic lines that the spot B (which shows the $5425\pm259$ Fe II line) is hotter than Spot A (which does not), we now enquire whether the equivalent width of the line in spot B is anomalous. Using the results of Table VI we find that the calculated equivalent width appropriate to the observed continuum intensity of $0.16 \times \text{photospheric intensity}$ is $3.9 \text{mA}$. The observed equivalent width, equal to $19 \text{mA}$, is a factor 4.9 greater than expected, showing that the anomaly exists for this line also. It is not possible to ascertain whether an anomaly is present for the same line in spot A because the expected equivalent width corresponding to its continuum intensity is only $0.6 \text{mA}$ and the presence of the blend discussed above makes the detection of a weak line difficult.

The $5427\pm803$ Fe II line is well delineated in both photospheric and penumbral spectra, but it is not easily detected in the umbral spectrum because of the complexity of this region. We have not detected it with certainty in the spectra of spots A and B, but show a sequence of plots in Fig. 8 which show its existence in the spectrum of spot C. This spectrum has a lower noise level than the others, and it is significant that it also shows $5425\pm259$ Fe II quite strongly. No calculation of expected intensity is possible because the line is unclassified.

5. THE EFFECT OF AN ERROR IN THE MEASUREMENT OF THE SCATTERED LIGHT

The deduction that the equivalent width of the $5425\pm259$ Fe II line is anomalous depends on an accurate correction for the amount of scattered light present in the spectra of spot B. The proportion of scattered light was deduced to be 26 per cent from limb scans, and we have no reason to doubt its accuracy. However, should this value be in error in the sense that the true amount of scattered light is greater, a different conclusion might be reached. We now study this possibility.

A maximum limit to the proportion of scattered light may be found by putting the residual intensity of the $5426\pm258$ Ti I line in the corrected spectrum equal to zero, for any greater proportion will give a negative residual intensity. Application of this method gives the maximum as 55 per cent. We now repeat the reduction of the original umbral spectrum of spot B to a new true spectrum using this maximum proportion of scattered light. In this new reduced spectrum, the Fe II line at $5425\pm259$ Å is quite obliterated. The calculated equivalent width corresponding to the new reduced continuum intensity of $0.097 \times \text{photospheric intensity}$ is only $1.7 \text{mA}$.

In order to investigate the possibility that the proportion of scattered light is actually much greater than the measured value of 26 per cent, we compare with observation the calculated values of the equivalent widths of atomic lines using the
maximum possible value of 55 per cent. The results of this comparison are shown in Table VIII; this table also shows the calculated values of the continuum intensity for the umbral methods of Stellmacher & Wiehr ($\Delta \theta = 0.45$) and Branch ($\Delta \theta = 0.35$). Study of this table shows that the reduced equivalent widths in spot B corresponding to the assumed 55 per cent scattered light are closely similar to those of spot A, although the reduced continuum intensity of spot B ($0.097$) is almost double that of spot A ($0.051$). However, the reduced equivalent widths for spot B obtained using the measured value for the scattered light show a much better...
Table VIII

Calculated and observed equivalent widths of lines of neutral atoms in umbral spectra

<table>
<thead>
<tr>
<th>Line</th>
<th>Calculated</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\theta = 0.45$</td>
<td>$\theta = 0.35$</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>$\Delta = \text{mA}$</td>
<td>Spot A (true scattered light) = 26%</td>
</tr>
<tr>
<td>$5312*863$ Cr I</td>
<td>54</td>
<td>—</td>
</tr>
<tr>
<td>$5426*258$ Ti I</td>
<td>97</td>
<td>95</td>
</tr>
<tr>
<td>$5432*955$ Mn I</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>$5435*666$ Ni I</td>
<td>54</td>
<td>78</td>
</tr>
<tr>
<td>$5436*302$ Fe I</td>
<td>65</td>
<td>78</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>39</td>
</tr>
</tbody>
</table>

Continuum intensities

<table>
<thead>
<tr>
<th>Column 1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.094</td>
<td>0.189</td>
<td>0.051</td>
<td>0.160</td>
<td>0.097</td>
</tr>
</tbody>
</table>

agreement with the calculated values than do those obtained using the maximum 55 per cent scattered light. In each case comparison is with the model giving the appropriate continuum intensity, i.e. column 5 is in better agreement with column 3, than column 6 is with column 2. Even so, the agreement between calculated and observed equivalent widths is not particularly good, but the calculations have been made with the simplifications of a one-stream model, a state of L.T.E. and with neglect of Zeeman splitting. Introduction of the latter above would improve the agreement between columns 5 and 6.

We deduce from this numerical experiment that the measured value of 26 per cent scattered light gives a spectrum in much better agreement with calculation than the maximum of 55 per cent, and therefore have confidence in our conclusion about $5425*259$ Fe II based on the measured value for the scattered light. Of course, this comparison assumes there are no anomalies among the neutral lines, but we have made the comparison only to justify the measured amount of scattered light.

We conclude from the above analysis that the few lines of Cr II and Fe II that we have been able to examine are anomalously strong in the umbral spectrum, finding enhancement factors of between 5 and 40, based on the Stellmacher and Wiehr umbral model. This enhancement is not apparently shared by lines of neutral atoms. We now consider possible explanations for these anomalies.

6. INTERPRETATION USING ONE AND TWO STREAM EQUILIBRIUM MODELS

We begin by supposing that a sunspot umbra possesses a fine structure of hot and cold regions, each being in a state of L.T.E. Such a separation has been observed directly, and the brighter regions named by Danielson (1964) as ‘umbral dots’. The properties of these umbral dots have been discussed by, for example, Beckers & Schroter (1968a, b).

As a single column atmosphere cannot account for both the neutral and ionized lines together with the continuum intensity, we now enquire whether the observations can be explained in terms of a two-component atmosphere. We suppose,
arbitrarily, that the hotter component produces a 5305·866 Cr II line of equivalent width 25·4 mÅ (i.e. the photospheric equivalent width), whilst the cooler component produces a Cr II line of equivalent width 1·0 mÅ, corresponding to the calculated value for a one-component model. The observed equivalent width for spot A is 21·8 mÅ. If the relative area of the cooler component is $A_c$, then the value of $A_c$ is calculated from the relation,

$$1·0 \times A_c + 25·4 (1 - A_c) = 21·8$$

giving,

$$A_c = 0·15.$$ We now proceed to calculate the continuum intensity from this mixture of hot and cool components. Assuming the model of Stellmacher & Wiehr (Table VI), the calculated continuum intensity of the cool component, $I_c$, is given by

$$I_c = 0·094 \times I_h$$

where the hot (h) component is identified with the photosphere. The average continuum intensity that would be measured by the spectrometer, $I_{av}$, would then be,

$$I_{av} = (0·15 \times 0·0940 + 0·85 \times 1·0) \times I_{photosphere}$$

$$= 0·86 \times I_{photosphere}.$$ In fact, the observed intensity is only $0·081 \times I_{photosphere}$. This simple calculation makes it clear that the observed Cr II enhancement is incompatible with the observed continuum intensity, even for a multi-component model, assuming the existence of L.T.E. and the naive supposition that the hot component can be identified with the photosphere.

Consideration of the behaviour of lines of neutral atoms leads to a similar result. We take as an example of this the line 5426·258 Ti I. Supposing that this line has an equivalent width in the hot column of 6 mÅ (corresponding to the photospheric equivalent width), and of 97 mÅ in the cold column (using a Stellmacher and Wiehr model atmosphere for computation), then the above results for $A_c$ and $A_h$ derived from the behaviour of the 5305·866 Cr II line leads to a calculated equivalent width in the umbral spectrum of $0·85 \times 6 + 0·15 \times 97 = 20$ mÅ. In contrast with this, the observed equivalent width is 223 mÅ for spot A. Again, it is clear that a two-component model, and indeed a multicomponent model is unable to account for the observed enhancement.

6. SUMMARY OF CONCLUSIONS

6.1. Observations

Our principal purpose in making these observations has been to decide whether the lines of ionized elements that are often observed in umbral spectra are a real feature of the spectrum or whether they are a spurious intrusion due to scattered light from penumbra and photosphere. Measurement of the amount of scattered light is not easy. However, our technique should result in the reduction of the amount of scattered light, and it is well suited to the problem of its measurement. Its particular advantages are, (1) rapid scanning photoelectric recording, (2) use of photo-electric guiding on the observed umbra, (3) use of automatic discrimination against the intrusion of penumbral light, (4) use of limb scans to determine the
scattered light correction, and (5) photoelectric measurement of continuum intensity made simultaneously with the spectral measurements. In addition, the observations that we describe here were made under good conditions, and the long range scattering especially, measured by the sky brightness, was unusually small.

Our most reliable evidence comes from observations of the Cr II lines in the region of 5310 Å. In this case, not only is it difficult to believe that these strong lines result from the intrusion of penumbral light, or are contributed to significantly by unknown and undetected blends, but such sources seem to be eliminated by the observed magnetic fields.

The interpretation of the 5425.259 Fe II line is less straightforward because of the presence of a long wavelength blend. Nevertheless, its appearance in spot B, but not in spot A, is in accordance with independent knowledge of the temperatures of these spots, and the line seems to be of anomalous intensity in spot B.

6.2. Origin of the phenomenon

An explanation of these anomalous intensities is not easily found. The observed spectrum cannot simply be considered as a mixture of high and low temperature spectra because the observed continuum intensity is too low for such a mixture which does not in any case reproduce the observed equivalent widths of low excitation lines of neutral atoms. A further difficulty in any interpretation is that the neutral lines are apparently normal in their behaviour. It would therefore be physically impossible for all ionized lines to be enhanced because this would imply an increase in element abundance; consequently, the enhancement must be dependent on the line being examined, and a non-L.T.E. situation surely exists in the context of a multicomponent atmosphere. Any suggestion about the reasons for a state of non-L.T.E. must be speculative, but it is possible that it could arise from the passage of proton streams through the upper layers of the umbral atmosphere, or to the influx of radiation from surrounding photospheric layers which are at a higher temperature.

7. RELATION TO SPECTRA OF MAGNETIC STARS

In these circumstances, it is of interest to enquire whether analogous effects are present in the spectra of magnetic stars, the magnetic fields of which are comparable with umbral fields. Basically, such an investigation involves using a model atmosphere technique to obtain the abundances of elements corresponding to the various lines of at least two ionized species; the model atmosphere is determined by other independent considerations, such as the distribution of energy in the continuum. Among the few published investigations of spectra that are suitable for such an enquiry is that of Mihalas & Henshaw (1966) which is based on the observational material of Sargent & Searle (1962) and Searle & Sargent (1964). This work is relevant in that it shows that the Si II 4200 line is often anomalous compared with other Si II lines in the same spectrum, sometimes appearing a factor ten times stronger than expected. Mihalas and Henshaw offer an explanation for this, but it is possible that the anomaly is of the kind described here for umbral spectra. Aller (1967) remarks that the star HR 6870 (HD 168733) shows iron lines from three stages of ionization, Fe I, Fe II and Fe III, indicating anomalous ionization. Faraggiana & Hack (1962) note that in 73 Draconis the ionization temperature derived from the equilibrium Fe II/Fe I is too low for the colour of the star, although
the validity of this particular example is uncertain through lack of precise knowledge of oscillator strengths of lines from the two states of ionization. These examples could be multiplied indefinitely, and all may be criticized on various counts, but we content ourselves by concluding that the possibility of anomalous ionization in magnetic stars exists. If it does, it may profoundly affect abundance determinations and may even be partly responsible for apparently anomalous abundances.

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