THE INSTRUMENTAL PROFILE OF A DAO 1.22m TELESCOPE COUDE SPECTROGRAPH IN FIRST AND SECOND ORDERS, WITH RETICON DETECTOR.

by

A.J. BOOTH*, D.E. BLACKWELL* AND J.M. FLETCHER

ABSTRACT

The instrumental profile of the 96-inch camera of the coudé spectrograph of the 1.22-m telescope at the Dominion Astrophysical Observatory has been determined, for the first and second orders of the mosaic grating, by means of a He-Ne laser and a Reticon detector. Although the first-order profile appears to be somewhat degraded, compared with an earlier photographic determination, the profiles determined here still compare well with those found for other coudé spectrographs, whether photographically or with a Reticon. The effects of the instrumental profiles on equivalent-width measurements are considered.

RESUME

Le profil instrumental de la chambre photographique de 96 po du spectrographe de coudé du télescope de 1,22 m de l’Observatoire fédéral d’astrophysique a été déterminé, pour les premier et deuxième ordres de la mosaique de diffusion, au moyen d’un laser He-Ne et d’un détecteur Reticon. Bien que le profil de premier ordre semble un peu dégradé, comparativement à une détermination photographique antérieure, les profils déterminés se comparent encore bien à ceux obtenus d’autres spectrographes de coudé par procédé photographique ou au moyen d’un Reticon. Les effets des profils déterminés sur les mesures à largeur équivalente sont présentés.

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I. INTRODUCTION

It has long been appreciated (Griffin 1969) that the far wings of spectrograph instrumental profiles can contribute substantially to the filling-in of absorption lines by what is generally termed "scattered light". During the course of other work on the coudé spectrograph of the 1.22-m telescope we have determined the instrumental profile of the first and second orders of the mosaic grating with the long camera and the 1872 usable-element Reticon detector, using a He-Ne laser. A previous measurement has been made of the instrumental profile for this mosaic-grating system in the first order (Fletcher et al. 1980, hereafter FHH), but it was based on photographic detection and there are significant differences between our profile and the earlier one. These will be discussed more fully below.

II. EXPERIMENTAL PROCEDURE

A full description of the spectrograph has been published by Richardson et al. (1968, 1971). In our experimental set-up, a He-Ne laser was used to produce essentially monochromatic light of wavelength 632.8164nm. The laser output was fed directly into the red image-slicer (IS32R) through a diffuser made from several sheets of white paper, which were vibrated rapidly in order to remove collimation and coherence in the beam. In this way, we ensured that the spectrograph optics were filled, as from a stellar source. The diffuser also provided a controllable amount of attenuation of the source intensity.

About 20 exposures were made in each order with differing exposure times and attenuation. This was necessary in order to have unsaturated spectra of the line peak as well as spectra of the far wings with a high signal-to-noise ratio, and to be able to link these two. Exposures were made with a shutter timed by a stop watch, rather than by reliance on the time between read-outs of the Reticon. In this way we ensured that, between exposures, no light fell on the Reticon, which has a short-term "memory" for bright illumination. Reticon output from the A/D converter was recorded on magnetic tape and reduced in the usual way to produce spectra on a linear intensity scale of 0 to 10,000.

III. DATA ANALYSIS

(a) Wavelength Calibration

The wavelength scale for the spectra was fixed by reference to solar spectra obtained with the same grating positions by admitting light from the daytime sky. Lines were identified from the spectra of Delbouille et al. (1973) and wavelengths were taken from Moore et al. (1966). Line positions were found to the nearest 0.1 pixel by fitting a quadratic expression to the 5 pixels at the line centre. A linear and a quadratic least-squares fit to the wavelength/pixel data were made. The difference made to the calibrated wavelengths by the inclusion of the quadratic term was only 0.7 percent at maximum, so a linear fit was considered sufficient. The absolute scale was fixed by finding the peak of the laser line, again by fitting a quadratic, and setting this to 632.816nm. The results of the wavelength calibration are given in Table 1 along with the uncertainties. All spectra were calibrated from the given values.
Table 1. Wavelength Calibration Data

<table>
<thead>
<tr>
<th></th>
<th>1st order</th>
<th>2nd order</th>
</tr>
</thead>
<tbody>
<tr>
<td>dispersion (pm/pixel)</td>
<td>7.298</td>
<td>3.321</td>
</tr>
<tr>
<td>uncertainty (pm/pixel) (%)</td>
<td>0.007</td>
<td>0.010</td>
</tr>
<tr>
<td></td>
<td>0.1</td>
<td>0.3</td>
</tr>
</tbody>
</table>

(b) Intensity Calibration

Firstly, as is usual, we corrected the Reticon data for the relative gains of the four amplifier channels. Next the true zero of the intensity level was set. It was found that there was a zero offset in the Reticon data of about -3 (compared with a maximum intensity readout of about 10,000) with the actual offset dependent on time since the last Reticon read-out. We measured this offset by repeated readings from the Reticon after no light had been allowed to fall on it for various integration times. For up to about 400s integration time the mean offset of all Reticon elements was found to be quite accurately represented by a linear fit to an offset/log(time) relation. We found the equation,

\[ \text{Offset} = -0.533 - 1.399 \log_{10} (\text{time}) \]

from a least-squares fit, with time in seconds. The rms deviation of the fit was 0.35. For integration times longer than 400s, the scatter of the measured offset greatly increased, but there was some indication that it tended towards zero. All spectra were therefore set on a true zero scale by adding a constant offset dependent on Reticon integration time given by the above formula, all our spectra having integration times <400s.

Next, the spectra were flat-fielded by division by summed spectra of a white-light source (a tungsten-filament lamp). This should remove any pixel-to-pixel variations in the Reticon. However, as the source did not have a truly flat spectrum an apparent gradation in sensitivity may be introduced across the Reticon. The slope of this gradation is, however, no more than about 10 percent, and this has a negligible effect on the size of the profile wings in relation to the line peak.

All the spectra for each grating order had then to be set on a common intensity scale by allowing for exposure time and attenuation of the laser beam. For those spectra with the same amount of attenuation, the intensity scale was simply divided by the exposure time in seconds. With a few exceptions this gave good agreement between spectra, with standard deviations of 5.6 percent and 4.3 percent in intensity in the first and second orders, respectively, in regions of good signal-to-noise ratio and no saturation. In the exceptional cases, there were differences of about a factor two, and these were rejected. In order to place sets of exposures made with different attenuations onto the same scale, spectra were chosen from each set, in which the first grating ghost had been recorded with a good signal-to-noise ratio and was not saturated. The mean intensities derived for each spectrum from the three pixels at the peak of the ghost were made to agree. The resulting agreement between sets was as good as the agreement within a set.

All the first-order and all the second-order spectra were than averaged to obtain mean profiles for both orders. Saturated pixels were rejected, as were the four nearest neighbours to a saturated pixel. A saturated pixel was defined as one having an intensity level of more than 9,000. The linearity of the Reticon was tested and found to be good to intensity levels of more than 11,000.
Low-signal pixels were also excluded from the averages (signals of less than 100 and 66 in the first and second orders respectively) in order not to introduce unnecessarily noisy data.

Finally, the mean profiles were scaled to have a peak intensity of unity at line centre. The scale factor was obtained by a least-squares fit of a Voigt function to the line centre (10 centre pixels), the Voigt function being found to give a much more satisfactory fit than a quadratic or Gaussian. The scale factor was found to be insensitive to the exact number of data points used in the fit.

IV. DISCUSSION

The mean profiles for both grating orders are given in Figures 1a and 1b on a log-intensity scale against wavelength. The tabulated values are also available in machine-readable form.

Figures 2a and 2b show the central regions of the line on an expanded scale. From the Voigt-profile fits to the line peaks we have obtained half-maximum widths of the profiles in wavelength units and these are given in Table 2. The corresponding linear sizes were calculated with an assumed pixel size of 15μm, as given by the Reticon manufacturer, and the measured dispersions of Table 1. For comparison, the projected slit-width is about 18μm, and the diffraction width for the gratings is <10μm. The remaining excess width is considered to be caused by high-order spherical-aberration and zonal errors on the collimator. The first-order FWHM is in reasonable agreement with that of 31μm measured photographically by FHH. The wavelength width in the second order can be compared to those found for the Mount Wilson (4.0pm, Griffin, 1968) and ESO (approximately 5pm, Enard, 1981) coudé spectrographs.

<table>
<thead>
<tr>
<th>Table 2. Full Widths at Half Maximum of Instrumental Profiles</th>
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<tr>
<td></td>
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<tr>
<td>------------------</td>
</tr>
<tr>
<td>wavelength fwhm (pm)</td>
</tr>
<tr>
<td>linear fwhm (μm)</td>
</tr>
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</table>

Figures 1 and 2 demonstrate the general shape and properties of the profiles. The large number of ghosts is evident, especially in the second order. This is as expected for a ruled replica grating. The ghost positions can be seen to agree very well in the first order between our profile and that of FHH which is superimposed on Figure 1a. The mean relative intensities in the observed ghosts compared to the main profiles are 0.19 per cent and 0.71 per cent for the first and second orders respectively. Further, the mean relative intensities of the first ghosts are 0.14 per cent and 0.55 per cent respectively for first and second orders, so these dominate. The ghost intensities fall off rapidly in the far wings so further ghosts should have a negligible effect. This can be compared to 0.5 per cent for the second order in the Mount Wilson coudé spectrograph (Griffin, 1968). The small amplitude structure in both profiles is not due to noise, being typically 3-4 pixels wide, and reproducing precisely from spectrum to spectrum. It should be noted that the photographic spectrum of FHH is heavily smoothed. This type of structure is also seen in the Mount Wilson profile. The structure is also very similar in the first and second orders, as can be seen in Figure 3 where the two
Figure 1a. Instrumental profile of first grating order at 632nm (solid line). The photographic profile obtained by Fletcher et al. (1980) is shown FHH.
Figure 1b. Instrumental profile of second grating order at 632nm.
Figure 2a. Instrumental profile of first grating order at 622 nm, central region.
Figure 2b. Instrumental profile of second grating order at 632nm, central region.
Figure 3. Instrumental profile of the first and second orders, pixel number from line centre as ordinate. The second is displaced downwards by an offset of 0.5 to avoid confusion.
profiles are superimposed. In this figure pixel numbers are plotted as abscissae, showing the close similarity of the profiles in linear (or equivalently angular) dimensions. This is to be expected if the profile is largely produced by scattering by the grating or at the Reticon (see below).

The wings of the measured profiles can be divided into four general sections. From about ±25 to ±90 pixels from line centre, the profiles fall off as pixel$^{-2}$ (or equivalently $\lambda^{-2}$). Beyond this, the fall-off is less rapid, the exponent being of the order of -1.6. This is illustrated in Figures 4a and 4b, which give the profiles in a log-log plot. The actual profiles are raised above the general fall-off by two broad humps centered at about ±170 and ±500 pixels, the former being much the more prominent. The inverse square fall-off is to be expected for light scattering from random surface irregularities. This, and the slower fall-off at larger distances from the line centre have been observed by FHH and by Dravins (1978) for the ESO coudé spectrograph. Dravins has shown that the general slow fall-off in the wings is a consequence of scattering by the grating for ruled (as opposed to holographic) gratings, and our profiles are very similar in both shape and intensity level to both his and the Mount Wilson profile (Griffin, 1968). The FHH photographic profile shows distinctly weaker wings than ours which we tentatively attribute to the use of the Reticon (giving scattering at its window) and an increased level of degradation of the surfaces of the optical elements since that profile was obtained.

The broad humps (plus some of the general background) are almost certainly caused by scattering at the Reticon. Evidence for this is given in Figure 5 where the red wing of the second-order mean profile is plotted together with a spectrum deliberately recorded so that its peak did not fall on the Reticon. This second spectrum was put on the same intensity scale as the mean profile by matching the intensity of the four rightmost visible ghosts. The spectrum is rather noisier than the mean profile, but note that the humps no longer appear when the peak of the line does not fall on the Reticon. It is also noteworthy that by 2.5nm from the line centre, the contribution from scattering in the Reticon is negligible. This does, however, demonstrate, that for the best accuracy in assessing the effects of the instrumental profile, it is necessary to have a different profile for the parts of the spectrum that fall off the Reticon and this will affect the spectrum actually recorded on the Reticon, especially those pixels near the ends.

V. WAVELENGTH VARIATION OF THE INSTRUMENTAL PROFILE

The variation of the FWHM of the instrumental profile with wavelength was investigated by recording spectra of an iron/argon hollow-cathode lamp at a variety of wavelengths in the first and second orders. The prominent arc lines were then fitted with a Gaussian profile, by a least-squares technique, and their wavelengths and FWHM values recorded. In Figure 6 we plot the FWHM against $\lambda/N$ ($N =$ order) of these lines, corrected for the projected slit width at the appropriate wavelength. This correction was crudely made by subtracting the slit width in quadrature. This should provide a reasonable approximation to the truth, however. Also plotted is a least-squares straight-line fit to these data. As can be seen, this is a reasonable fit to the data, given the errors in the FWHM values, which are about 10 percent. The standard deviation of the fit, at -0.001pm, is the same order of magnitude. This is in qualitative agreement with what would be expected if the wavelength dependence was governed by the well-known grating formula:

$$\lambda/\delta\lambda = nN,$$

where $n$ is the total number of rulings. Unfortunately, the slope obtained from the fit, $2.66 \times 10^5$, is about a factor of 3 too large to be accounted for by the number of grating rulings. Hence, either the arc lines must be further widened in a wavelength-dependent way, or the instrumental width of the
Figure 4b.

Instrumental profile of second order on log-log scale (base 10). Lines of slope 0.16 per pixel² also shown.
Figure 5.
Red wing of second order profile (A) with spectrum taken with peak of line moved off end of the Reticon (B).

\[ \text{Red wing of second order profile (A) with spectrum taken with peak of line moved off end of the Reticon (B).} \]
profile must be angle-dependent. The fitted intercept (at -0.00091nm) is, however, satisfyingly close to zero.

In addition to the FWHM of the instrumental profile, we are also concerned with the wavelength dependence of the far line-wings. In order to investigate this, several long exposures of the Fe/Ar arc were made in the region of a few strong arc lines. Figure 7 compares the profiles for the lines 561.563nm, 623.071nm, and 675.285nm for the second order, and 714.702nm and 866.793nm for the first order. Of these five lines the first two are Fe I, the other three are Ar I. In the figure, the central intensities of the lines (found from shorter exposures where the lines are not saturated) have been set to unity, and the plot is log_{10}(intensity) against pixel number of the 500 pixels nearest the line centres. As can be seen, there is a very good match in the shapes of the line wings, when allowance is made for the presence of weak arc lines and the levelling out of the line at the lowest intensities. This latter effect is caused by the finite dynamic range of the Reticon which fixes the minimum value the lowest intensity points can have relative to the highest points with a ratio of about 10^4. Since the range of grating angles covered by these lines is small (only 16°), pixel number corresponds approximately to angle. This again demonstrates that the line wings have constant angular size as was claimed in Section IV above because of the similarity of the first- and second-order laser line wings.

In summary, then, the instrumental profile FWHM has the expected \( \lambda/N \) dependence for a grating, and the wings have a constant angular size, which is probably determined by scattering effects in the grating and Reticon window.
Figure 7. Log(intensity) against pixel number of five Fe/Ar lines: 561.563nm, 623.071nm, 675.283nm, 714.702nm, and 866.793mm. Line centres are saturated, so are not shown. Dotted profile: first order laser profile on same scale.
VI. EFFECT ON EQUIVALENT-WIDTH MEASUREMENTS

Following Griffin (1969), we have attempted to determine the effect of the instrumental profile, in particular the far wings, on the measurement of equivalent widths from stellar spectra. As Griffin pointed out, an equivalent width measured over a restricted range (say 0.1 nm), may be as much as 10 per cent less than the true equivalent width when the instrumental profile has extensive wings. This is because light from the continuum is scattered into the line by these wings; the effect is large because the wings, although weak, are virtually infinite in extent. In his paper Griffin suggests that there is no way of overcoming this problem short of using double-pass spectrographs (or other types where the instrumental wings are very weak). We suggest, however, that provided an accurate measurement of the instrumental profile is available, the error can be assessed, and approximately accounted for, reducing it to perhaps 2 per cent or 3 per cent, and making it random instead of systematic.

In order to test whether or not the observed spectrum is degraded only by the measured instrumental profile, we first investigated the spectrum of the solar flux with the spectrograph. The primary mirror of the telescope was covered with crumpled aluminium foil before it was pointed at the sun, so that we could obtain solar spectra with reasonable integration times (3s-10s) and without any danger of overheating the equipment. Further, the foil scatters light from the whole solar disk, to give an integrated disk spectrum. This procedure was considered preferable to using light reflected from the dome, or sky light, as these can contain a fluorescent component. Figure 8 shows a short section of

Figure 8. Solar integrated disk spectrum from Kurucz et al. (1984), solid line; our spectrum, dotted line; and Kurucz et al. spectrum convolved with our instrumental profile, dashed line.
the solar spectrum obtained in this way near 635.5nm in the second order (dotted line). This section was chosen to be near the laser wavelength of the measured instrumental profile. The figure also shows a plot of the same wavelength region from the Fourier-Transform-Spectrometer (FTS) spectrum of integrated sunlight obtained by Kurucz et al. (1984) (solid line). Because the FTS is expected to have negligibly small instrumental wings, this should be the true solar spectrum. The dashed line in the figure gives the result of numerically convolving the second-order instrumental profile into the FTS spectrum. As can be seen, this process results in a spectrum which reproduces our measured spectrum very well, the central intensity of the Fe I line being given to ±1 per cent. The disagreement in the red wing of the line is almost certainly due to greater absorption in a telluric water-vapour line in our spectrum. We are thus reasonably confident that a convolution of our measured instrumental profile into the true spectrum gives our measured spectrum with little additional degradation.

Next, assuming LTE, we calculated theoretical solar-line profiles (for the integrated disk) at a wavelength of 632nm, corresponding to the laser wavelength, from the model atmosphere computed by Holweger and Muller (1974). The true equivalent widths and central depths of these lines are given in Table 3, and the profile of one is presented in Figure 9 (solid line). These computed profiles were then convolved with the instrumental profiles for the first and second orders, and the equivalent widths of the resulting lines were measured by integrating the profile numerically over various wavelength ranges. The equivalent widths of the original lines are exactly calculable because their functional form is known. The widths of the convolved lines are, of course, always less than these as some absorption is lost in the wings outside the integration range. The differences between the true equivalent widths and the measured values from the convolved lines are also given in Table 3. The profiles of the convolved lines for one of the theoretical lines are also shown in Figure 9 for the first- and second-order instrumental profiles.

### Table 3. Results From Theoretically Calculated Line Profiles

<table>
<thead>
<tr>
<th>true equivalent width (pm)</th>
<th>true depth %</th>
<th>Percentage equivalent-width difference due to convolution with instrumental profile</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>first order range (pm):</td>
</tr>
<tr>
<td></td>
<td></td>
<td>760</td>
</tr>
<tr>
<td>0.3216</td>
<td>5.5</td>
<td>1.0</td>
</tr>
<tr>
<td>0.9304</td>
<td>15.4</td>
<td>1.0</td>
</tr>
<tr>
<td>2.3116</td>
<td>34.6</td>
<td>1.0</td>
</tr>
</tbody>
</table>

N.B. 1pm = 10mA

Several points can be noted from these results. Firstly, for weak lines, such as those studied here, the relative changes in equivalent width are virtually independent of line strength; hence the ratios of equivalent widths are unaffected. This is to be expected, provided that the equivalent width is measured over a wavelength range that would have included the whole of the original line profile (in this case about ±9pm). The nature of the effect in this case is the removal of a fixed portion of the core of the line absorption into the wings of the instrumental profile. Second, to obtain a result accurate to 1 per cent, it is necessary to integrate over a range of nearly 0.8nm (8Å) which is completely unrealistic in real solar-type spectra. Thirdly, the line profile might be judged to have
Figure 9. Calculated solar line profile, solid line; and same profile convolved with first-order instrumental profile, dotted line; and second-order instrumental profile, dashed line.

returned to the continuum when it is less than 1 per cent of the line depth from the continuum level. This occurs at about 20 pm from the line centre for the second-order convolved profile, which is an entirely more reasonable range over which to integrate a real spectral line, but even here the difference between observed and theoretical profiles is over 7 per cent.

It should be noted that the above results take into account only the effect of the loss of absorption into the far wings. In addition to this, as Griffin points out, there will be a tendency to place the continuum too low in measurements of the spectrum, because the line profile never reaches the true continuum level. The magnitude of this effect was assessed by measuring the equivalent width with the continuum placed at the level of the line profile where integration began. For the line of ~15 per cent original depth this increased the difference between observed and theoretical profiles at ±20 pm from 7.6 per cent to 12.8 per cent and at ±30 pm from 6.1 per cent to 9.8 per cent in the second order. It is to be expected that the effect will be the same for the other lines.

The fact that these equivalent-width changes were largely independent of the line strength suggested that it might be possible to assess the magnitude of the error in a real measurement from these results and hence correct for it. In order to test this, equivalent widths were measured from our second-order spectra and from the FTS spectra for the same lines. The lines were chosen to be free from blends and of moderate strength. Table 4 gives the results of these measurements. We measured the equivalent widths over a range of about ±30 pm in both spectra by placing the continuum between the highest points to each side of the line within ~50 pm and integrating between these points. As can be seen, the results suggest that the differences all lie in the range of ~6 per cent to ±11 per cent calculated above for the differences with and without the continuum effect over integration ranges
All equivalent widths measured over a range of ~30 pm.

>25 pm, in the second order. We ascribe the small value of the difference for 633.082 nm to the presence of numerous very weak lines in the spectrum which mask the continuum position irrespective of the presence of extended line wings. This is illustrated in Figure 10 where the same section of spectrum as in Figure 9 is plotted for the FTS at normal and 10 times magnification. On the magnified spectrum it can be seen that there is scarcely any measured point which is not influenced by the presence of a line, even for parts that appear flat on the full scale spectrum. We suspect that this effect dominates over the influence of the instrumental wings and is obviously the same for both our spectrum and the FTS spectrum. For the other two lines the continuum is much less influenced by the presence of very weak lines so we see the full effect of lowering of the continuum by the extended instrumental wings.

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>FTS spectra equivalent width (pm)</th>
<th>Our spectra equivalent width (pm)</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>633.082</td>
<td>27.5</td>
<td>3.492</td>
<td>3.289</td>
</tr>
<tr>
<td>615.162</td>
<td>9.8</td>
<td>5.079</td>
<td>4.579</td>
</tr>
<tr>
<td>612.621</td>
<td>10.6</td>
<td>2.337</td>
<td>2.088</td>
</tr>
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</table>

Figure 10. The same section of solar spectrum obtained by Kurucz et al. in Figure 7, on normal and ten-times magnification scale.
This good agreement between our calculations and measurements suggests that applying a correction of between 6 per cent and 11 per cent to measured equivalent widths will give the true value with an accuracy of about ±2 per cent. Further, if some estimate can be made of the condition of the nearby continuum in terms of weak lines, the estimate can be refined by choosing between the lower or higher of these values. We also believe that this work is of more general value to those who wish to measure accurate equivalent widths because it suggests a method whereby the spectrum of a standard source (i.e. the integrated disk of the Sun) can be obtained to be compared with its true spectrum which has already been determined. The Sun is a very useful standard source, in that it is bright (thus giving high signal-to-noise ratio in short time), is nearly always observable, and does not necessitate night-time observations (so does not take up stellar observing time).

VII. CONCLUSION

We have determined the instrumental profile of the 1.2m telescope coudé spectrograph with the Reticon detector, with good signal-to-noise ratio over the whole Reticon length. This profile is significantly worse with regard to the intensity of the far wings compared to a previous determination with photographic detection, but is closely comparable to the profiles of other coudé spectrographs. This profile should be of those wishing to determine "scattered light", equivalent widths and stellar line profiles from spectra obtained with this instrument.

The profile is presented in detail for the wavelength of the He-Ne laser line (632.816nm) only, but the wavelength dependence has been investigated and the given profile can hence be scaled for any other wavelength.

We have investigated the effects of this profile on equivalent-width determinations and have shown that it leads to an underestimate of ~10 per cent. A method of obtaining an estimate of the correction factor needed to turn measured equivalent widths into true ones is suggested.

REFERENCES


Dominion Astrophysical Observatory,
Victoria, B.C.,
October, 1989.