Observations of the O I λ 7773 triplet in intermediate-type supergiants using a linear photodiode array

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Summary. Partially resolved spectra of the infrared oxygen triplet in A–G supergiants have been obtained with a new self-scanned photodiode array system. Curve of growth analyses indicate that the lines are formed in non-LTE. A line is identified at λ 7777.9 which is strong in A supergiants and which will complicate the analysis of low resolution spectra. At a resolution of 0.45 Å/diode the CN lines which appear in G8 and later stars are blended with the O I triplet rendering its equivalent width unreliable as a luminosity indicator.

1 Introduction

The study of the neutral oxygen λ 7773 triplet is interesting for several reasons. The combined strength of the lines at λλ 7771.94, 7774.17 and 7775.39 has been established as a measure of stellar luminosity. The relationship was first noted by Keenan & Hynek (1950) for B5–G2 stars and has since been confirmed by several authors. The coverage of spectral types has recently been extended to B1 by Thomas, Morton & Murdin (1979). A knowledge of luminosity class or absolute magnitude of course allows stars to be used as distance indicators.

The strength of the λ 7773 feature is very temperature sensitive due to the high excitation potential (9.15 eV) of the metastable 3s5S lower level. The lines are particularly strong in supergiants where the extended atmospheres allow low collisional de-excitation rates. In this situation, however, the lines are likely to be formed in conditions of non-LTE (Johnson, Milkey & Ramsey 1974; Eriksson & Toft 1979). In fact Baschek, Scholz & Sedlmayr (1977) have suggested that the lines are formed in non-LTE even in main-sequence models; the effect being always to increase the equivalent widths compared with the LTE case. Note that for cool supergiants the lines can be enhanced, also in LTE models, because the continuous opacity (due to H−) is lowered.

The O I triplet may also be useful for the determination of oxygen abundance if the non-LTE effects can be reliably estimated. In the later spectral types the [O I] magnetic dipole

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transitions at \( \lambda 6300 \) and 6363 can be used (e.g. Lambert & Ries 1977); the only other alternatives are [O i] \( \lambda 5577 \) and the \( \lambda 8446 \) triplet, both of which are seriously blended (with C\(_2\) lines in the first case and Fe i lines in the latter).

Until recently the lack of suitable detectors has tended to restrict observations to the measurement of equivalent widths. The recent availability of solid state arrays means that the feature can be examined in more detail. With this in mind, a study of several intermediate-type supergiants was made during the first observing runs with a silicon photodiode array system built at Durham University.

2 The observations

The observing system was based on a prototype self-scanned photodiode array chip manufactured by the Plessey Co. Ltd in conjunction with the Royal Greenwich Observatory. Each chip contains four linear arrays of 256 diodes which are paired to form two parallel lines of 512 elements. The pixel size is 200 \( \times \) 40 \( \mu \)m with a centre-to-centre spacing of 50 \( \mu \)m. A voltage sampling readout method was used followed by digitization to 12 bits. The device has a non-destructive readout capability which allowed an exposure to be monitored. The devices are not available commercially but, at present, a batch of 22 are on loan to the group (four of which have all 1024 elements operational). Data acquisition was controlled via CAMAC by a PDP 11/03 microcomputer and data stored on paper tape under the control of a CATY 2 program. The system has since been upgraded to include a DEC RX02 floppy disc unit. Further details of device and system characteristics have been given elsewhere (Campbell et al. 1979; Hedge et al. 1978).

The observations were carried out during 1978 August and 1980 January using the coude spectrograph of the 30-inch telescope at the Royal Greenwich Observatory. Spectra were taken with a single line of 256 diodes at a reciprocal dispersion of 0.45 \( \AA / \)diode (\( \approx 10 \) \( \AA \) \( \text{mm}^{-1} \)) to give a spectral range of 115 \( \AA \). The detector was cooled to \( \approx -110^\circ \)C using a cold finger dipped into liquid nitrogen. Micrometer adjustments provided horizontal, vertical and rotational alignment of the cryostat and tungsten and neon lamps were used for flat field and calibration. The projected slit width was 37 \( \mu \)m at the detector (1 arcsec on the sky) and to achieve sampling at the Nyquist rate or higher, two or more spectra were taken at slightly differing grating angles.

With a 12-bit ADC the noise was, at that time, digitization limited. Recent laboratory calibrations indicate that the step size was \( \approx 130 \) detected photons with a rather low quantum efficiency of \( \approx 20 \) per cent (at 8000 \( \AA \)) and that the readout noise (with correlated double sampling) can be as low as 40 electrons. It is likely that variations in the fixed pattern noise (caused, for example, by drifts in the chip temperature) also produced some contribution to the noise. As an example of the overall performance, a spectrum of an \( m_v = 2.3 \) star could be obtained with a SNR of \( \approx 100 \) in 15 min. Note that poor weather and seeing conditions limited the observations to stars brighter than \( m_v = 5 \).

3 Data analysis

Several stages of data manipulation were necessary after the spectra had been extracted from the raw video levels. In some of the earlier runs misalignments resulted in a fall-off in signal to one end of the array which was not removable on division by a flat field spectrum. This was corrected by fitting clear regions of the continuum to a fifth-order polynomial.

Some problems were encountered in aligning the array. Odd—even effects were often produced since the switching transistors are sensitive to light and those associated with odd and
Observations of the O I λ 7773 triplet

Figure 1. A comparison of equivalent widths.

even diodes are situated on either side of a row. Fortunately, these extra signals were removed satisfactorily in the data analysis. The magnitude of the correction was assumed to be proportional to the true signal and, to a first approximation, the effect of a slight misalignment was to produce a linear variation in the effect along the array.

Finally, when summing spectra taken at slightly different grating angles the data were first interpolated to 2048 points by adding zeros to the Fourier transform. The grating shifts could then be determined to 1/8 of a diode. The method of interleaved sampling is discussed by Bracewell (1965) and, before adding, the spectra should be convolved with window functions. In practice this was found to be unnecessary and a simple addition was performed. Care was taken however to minimize Gibbs-effect errors using the techniques described in Keating (1978) and Lanczos (1964).

To establish that the observing system could provide reliable equivalent widths, spectra of e Peg around Hα were compared with the results of Harmer, Lawson & Stickland (1978) and a spectrum of α Boo around λ 5400 with the Arcturus atlas (Griffin 1968). The results are shown in Fig. 1. For α Boo our results are on average 5 per cent too large and for e Peg 5 per cent too small, although this is not a true comparative test because of the differences in resolution and spectrograph characteristics. An upper limit of 5 per cent was placed on the combined contributions to the continuum of scattered light and drift in the acquisition electronics from observations of the residual signal in saturated lines of the atmospheric A band. This is an upper bound since the lines were not fully resolved.

4 Results

The spectra of the programme stars are shown in Fig. 2. The baselines and estimate of the continuum positions are also marked. An underexposed spectrum of α Lep is also included. The oxygen triplet can be seen partially resolved in all except the late-type stars. In α Cyg and η Leo there is a strong component to the blend at λ 7777.9; this is present to a lesser extent in the other supergiants and is tentatively assigned to a predicted line of Si I (as discussed later). Gaussian fits were made to this, the oxygen triplet and the nearby Fe I line at λ 7780.56 using a least squares technique. The equivalent widths of these and the Fe I/Ni I λ 7748 blend are given in Table 1. The errors are estimated to be ~ 10 per cent and are mainly due to random errors in the data and to inaccuracies in the placement of the
continuum level. $W(O\,i)$ indicates the total equivalent width of the triplet and this is compared with previous studies in Table 2. According to Sorvari (1974) his results are not reliable for $W > 1.2$ and these are not included; nor are Parsons' (1964) since these only give a central depth. Other measurements of the triplet have been made by Sargent & Searle (1962) and Slettebak (1951) on Ap stars and Albers (1969) on southern Milky Way stars.
Table 1. Equivalent widths (in Å).

<table>
<thead>
<tr>
<th>Star</th>
<th>Type</th>
<th>Number of Observations</th>
<th>W(OI)</th>
<th>OI W(7772)</th>
<th>OI W(7774)</th>
<th>OI W(7775)</th>
<th>OI W(7777.9)</th>
<th>OI W(7748)</th>
<th>OI W(7780.6)</th>
</tr>
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<tbody>
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<td>αCyg</td>
<td>A2 Ia</td>
<td>3</td>
<td>1.9</td>
<td>0.75</td>
<td>0.59</td>
<td>0.57</td>
<td>0.74</td>
<td>~0</td>
<td>0.31</td>
</tr>
<tr>
<td>εAur</td>
<td>B8 Ia</td>
<td>4</td>
<td>2.4</td>
<td>0.98</td>
<td>0.84</td>
<td>0.58</td>
<td>0.19</td>
<td>~0</td>
<td>0.07</td>
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<tr>
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<td>A0 II</td>
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<td>2.0</td>
<td>0.76</td>
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<td>0.82</td>
<td>~0</td>
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<td>F0 Ib</td>
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<td>1.2</td>
<td>0.40</td>
<td>0.39</td>
<td>0.39</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>αPer</td>
<td>F5 Ib</td>
<td>3</td>
<td>1.56</td>
<td>0.54</td>
<td>0.49</td>
<td>0.54</td>
<td>0.19</td>
<td>0.18</td>
<td>0.32</td>
</tr>
<tr>
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<td>F8 Ib</td>
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<td>0.66</td>
<td>0.48</td>
<td>0.44</td>
<td>0.22</td>
<td>0.24</td>
<td>0.30</td>
</tr>
<tr>
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<td>G0 Ib</td>
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<td>0.64</td>
<td>0.31</td>
<td>0.22</td>
<td>0.11</td>
<td>0.09</td>
<td>0.32</td>
<td>0.19</td>
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<tr>
<td>µPer</td>
<td>G0 Ib</td>
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<td>0.66</td>
<td>0.32</td>
<td>0.22</td>
<td>0.11</td>
<td>0.12</td>
<td>0.44</td>
<td>0.34</td>
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<tr>
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<td>G2 Ib</td>
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<td>0.41</td>
<td>0.17</td>
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<td>0.13</td>
<td>0.03</td>
<td>0.27</td>
<td>0.28</td>
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<tr>
<td>εGem</td>
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<td>~0</td>
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<td></td>
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<td>0.27</td>
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<td>~0</td>
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<td></td>
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<tr>
<td>γAnd</td>
<td>K3 II</td>
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<td>~0</td>
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<td></td>
<td>0.58</td>
<td>0.21</td>
</tr>
<tr>
<td>γUMa</td>
<td>K3 IIII</td>
<td>2</td>
<td>~0</td>
<td></td>
<td>~0</td>
<td></td>
<td></td>
<td>0.33</td>
<td>0.22</td>
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Table 2. A comparison with other measurements of W(OI).

<table>
<thead>
<tr>
<th>Star</th>
<th>Present work</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>d</th>
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<tr>
<td></td>
<td>(±10%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>αCyg</td>
<td>1.9</td>
<td>2.19</td>
<td>~0</td>
<td>~0</td>
<td>~0</td>
</tr>
<tr>
<td>εAur</td>
<td>2.4</td>
<td>2.34</td>
<td>2.51±0.05</td>
<td>~0</td>
<td>~0</td>
</tr>
<tr>
<td>nLeo</td>
<td>2.0</td>
<td>1.84</td>
<td>~0</td>
<td>~0</td>
<td>~0</td>
</tr>
<tr>
<td>αLep</td>
<td>1.2</td>
<td>0.96</td>
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<td>1.17±0.06</td>
<td>~0</td>
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<td>αPer</td>
<td>1.56</td>
<td>1.15</td>
<td>0.95±0.04</td>
<td>1.05±0.03</td>
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</tr>
<tr>
<td>γCyg</td>
<td>1.57</td>
<td>1.16</td>
<td>1.18±0.03</td>
<td>1.15±0.04</td>
<td>~0</td>
</tr>
<tr>
<td>δAqr</td>
<td>0.64</td>
<td>0.54</td>
<td>~0</td>
<td>~0</td>
<td>~0</td>
</tr>
<tr>
<td>αAqr</td>
<td>0.41</td>
<td>0.6</td>
<td>~0</td>
<td>~0</td>
<td>~0</td>
</tr>
</tbody>
</table>

a: Keenan & Hynek (1950)  
 b: Osmer (1972a)  
 c: Baker (1974)  
 d: Rao & Mallik (1978)

The spectra of α Per and γ Cyg (Fig. 2) are cases where a large number of nearby blended lines make the local continuum rather hard to define; this may explain the discrepancies between our values of W(OI) and previous results.

5 Discussion

5.1 The Behaviour of the Oxygen Triplet

A correct interpretation of the oxygen triplet in giants and supergiants demands an understanding of non-LTE effects (Eriksson & Toft 1979). In non-LTE the depth of a line is increased substantially because the lack of collisions in the low density atmospheres allows the lower level to become overpopulated. According to Baschek et al. (1977) the departure

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coefficients are increased by a factor of 4–10. The effects may extend even to main-sequence stars but Sneden, Lambert & Whitaker (1979) have found none in dwarfs.

In layers close to the surface the source function will be less than the Planck function and the cores of lines formed in this region will be deeper. There will also be curve of growth effects as strong lines (for instance those in A and F supergiants) will be either on the square root or flat parts of the curve of growth and for these the enhancement in equivalent width will be less. The usual microturbulence effect will result in a raised flat part of the curve of growth (and hence the equivalent widths will increase). Baschek et al. (1977) point out that the detailed effect of non-LTE is difficult to assess since a large microturbulence results in the cores being formed in deeper layers where thermalization by collisions is more important; on the other hand, the reduced core depth produces a mean radiation field which is more non-locally determined. The radiative transition rates are also changed. There is some indication from the data that the ratio of $W(7772)$ to $W(\text{O I})$ increases with spectral type, as would be expected on moving from the flat to the linear region of the curve of growth.

If the equivalent widths of the oxygen triplet are entered (as ordinates) on to the correct curve of growth for a star (i.e. one which takes into account non-LTE, microturbulence and other effects) then the mantissas should give the ratio of the $f$ values, i.e. 0.431:0.301:0.184 (from Wiese, Smith & Glennon 1966). However, if the curve of growth has been estimated from measurements of lines formed in LTE, then the derived $f$ values will be wrong. For the stars in this study the triplet equivalent widths lie on the linear or flat parts of the curve of growth; these regions are raised and steepened in non-LTE since lines can grow deeper before saturation occurs. This results in a larger spread of the equivalent widths.

One simple, though approximate, method of obtaining the LTE curve of growth is to plot experimental widths against empirical strengths, $\log X$, i.e. to perform a differential analysis. This was done for the stars $\epsilon$ Aur, $\alpha$ Per, $\gamma$ Cyg, $\alpha$ Aqr and $\beta$ Aqr, using equivalent width data from D. J. Stickland (private communication) for $\epsilon$ Aur and $\alpha$ Per, Greenstein (1948) for $\alpha$ Per and Osmer (1972b) for $\alpha$ Per, $\gamma$ Cyg, $\alpha$ Aqr and $\beta$ Aqr. Empirical strengths were taken from Catchpole, Pagel & Powell (1971). It is admitted that there are several sources of error in this kind of analysis — both in the data and due to the presence of such effects as stratification of the stellar atmosphere. However, the present results indicate that non-LTE effects are important in that the equivalent width ratios are less like 1:1:1 than would otherwise be expected.

5.2 THE BEHAVIOUR OF NEARBY LINES

The use of broadband photometry for measurement of the equivalent width of the O \textsc{I} triplet relies on the absence of strong nearby lines. We see from Fig. 2 that, in fact there is a strong feature in the A and F supergiants to the red of the triplet (at $\lambda 7777.9$). This is likely to be the Si \textsc{i} $4p^3P^o-7s^3P^o$ transition which is listed as a predicted line in Moore, Minnaert & Houtgast (1966), Moore (1967) and Swensson et al. (1970). The line seems to be misplaced at $\lambda 7797.56$ in Lambert & Warner (1968). The equivalent width of the feature decreases sharply with temperature until the line disappears at G8 — this is consistent with the high excitation (6.08 eV) of the Si \textsc{i} transition. CN lines are strong in the spectra of the cooler stars. In $\epsilon$ Gem the blend of (6–3)$Q_2$ (48) and (7–4)$R_1$ (37) at $\lambda 7772.9$ is seen between the first two components of the oxygen triplet and pronounced CN lines (together with TiO) appear in $\alpha$ Ori (M2Iab). However, the absence of these and other CN lines in the hotter stars indicates that the likelihood is small of the feature being due, for instance, to the $\lambda 7777.52$ (7–4)$Q_4$ (30) CN transition. There is also a suggestion that the Cr \textsc{i} $\lambda 7771.74$ line appears in the blue wing of the $\lambda 7772$ \textsc{O I} component in $\epsilon$ Cyg, $\epsilon$ Aur and $\eta$ Leo.
Finally, we discuss the behaviour of some of the nearby metal lines which can be seen clearly in the diode array spectra. Rao & Mallik (1978) measured the equivalent width of the $\lambda$ 7748 $\text{Fe} \, i$ line and used the product of $W(\text{O} \, i)$ and $W(7748)$ as a new luminosity indicator, the intention being to eliminate temperature effects as $W(\text{O} \, i)$ should decrease with decreasing temperature whilst $W(7748)$ increases. In our spectra the $\text{Fe} \, i$ line is unresolvably blended with $\text{Ni} \, i$ RMT 156 but the equivalent width of the blend shows the same correlation with temperature. The $\lambda$ 7780.6 $\text{Fe} \, i$ line has a higher excitation potential (4.45 compared to 2.94 eV) and is not temperature sensitive.

6 Conclusions

It is seen that with a photodiode array good quality spectra can be obtained with a small telescope and poor seeing conditions. The sensitivity in the near infrared enables spectral features to be examined in detail where previously only broadband photometry has been possible. For the $\text{O} \, i$ triplet the existence of nearby lines, both in the intermediate and late type stars, means that these photometric results must be interpreted with care.

It is possible (Athay & Skumanich 1968) that many near infrared lines are formed in conditions of non-LTE and it would seem that, with their high quantum efficiency, solid state detector arrays are eminently suitable for their study.

We note that, although the Plessey arrays are prototype devices and the number of pixels is rather small (512), the good noise performance makes them competitive with other solid state detectors. So far, the array most used for spectroscopy in the near infrared has been the Reticon; this has a higher readout noise (~ 800 electrons) and cannot be read out non-destructively (Vogt, Tull & Kelton 1978).

Acknowledgments

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References