The electron pressure in the outer atmosphere of $\epsilon$ Eri (K2 V)

C. Jordan,1* S. A. Sim,1 A. D. McMurry2 and M. Aruvel3

1Department of Physics (Theoretical Physics), University of Oxford, 1 Keble Road, Oxford, OX1 3NP
2Institute of Theoretical Astrophysics, University of Oslo, PO Box 1029, Blindern, N-0315 Oslo, Norway
3St. Catherine’s College, Oxford, OX1 3UJ

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ABSTRACT
Observations of $\epsilon$ Eri (K2 V) have been made with the Space Telescope Imaging Spectrograph on the Hubble Space Telescope. The spectra obtained show a number of emission lines which can be used to determine, or place limits on, the electron density and pressure. Values of the electron pressure are required in order to make quantitative models of the transition region and inner corona from absolute line fluxes, and to constrain semi-empirical models of the chromosphere. Using line flux ratios in Si iii and O iv a mean electron pressure of $P_e = N_eT_e = 4.8 \times 10^{15} \text{ cm}^{-3} \text{ K}$ is derived. This value is compatible with the lower and upper limits to $P_e$ found from flux ratios in C iii, O v and Fe xii. Some inconsistencies which may be because of small uncertainties in the atomic data used are discussed.

Key words: atomic data – stars: atmospheres – stars: individual: $\epsilon$ Eri – stars: late-type – ultraviolet: stars.

1 INTRODUCTION
Ultraviolet (UV) spectra of the cool dwarf $\epsilon$ Eri (HD 22049, K2 V) have been obtained with the Space Telescope Imaging Spectrograph (STIS) on the Hubble Space Telescope (HST). The STIS instrument (Kimble et al. 1998; Woodgate et al. 1998) combines coverage of a wide spectral range in one exposure with high spectral resolution and sensitivity. These properties make STIS ideal for measuring electron densities ($N_e$) from emission line flux ratios. The wavelength region observed includes the range 1170–2365 Å, which contains many such density sensitive lines. In some cases, the observed flux ratios provide the best test to date of the atomic data currently available.

For lines formed at electron temperatures $T_e \geq 2 \times 10^4 \text{ K}$, the fluxes in optically thin permitted transitions can be used to find the emission measures ($\int \Delta N\Delta t$ where $N_H$ is the hydrogen number density and $\Delta t$ is the region over which the line is formed), and the mean emission measure distribution (EMD) (see e.g. Griffiths & Jordan 1998). To make a model of the atmosphere, at least one value of $N_e$ must be determined at a known value of $T_e$. The electron pressure, defined here as $P_e = N_eT_e$, throughout the transition region can then be found by assuming that the atmosphere is in hydrostatic equilibrium (see Jordan & Brown 1981). In dwarf stars where the surface gravity is relatively large, $P_e$ varies only slowly with $T_e$, and is the most suitable parameter to determine. Spectra obtained with the International Ultraviolet Explorer (IUE) were used to model the transition region of $\epsilon$ Eri (Jordan et al. 1987; Philippides 1996). The only way of estimating $P_e$ was to compare the density dependent emission measures derived from the flux in the Si iii intersystem line at 1892.0 Å, with the mean EMD found from density independent line fluxes. This led to $5 \times 10^{15} \leq P_e \leq 1.5 \times 10^{16} \text{ cm}^{-3} \text{ K}$, around an order of magnitude larger than in the quiet solar transition region. The chromospheric model by Thatchter, Robinson & Rees (1991) was also based to some extent on the results obtained from IUE.

In interpreting stellar spectra, one can only derive a mean value of $P_e$ at a given $T_e$. This will clearly be an approximation if contributions from both quiet and active regions are present. Since the pressures at which the various line ratios have their optimum sensitivity to $P_e$ are not the same, it is important to measure $P_e$ from as many line ratios as possible. [See also the discussion of the weighting of density measurements by Judge, Hubeny & Brown (1997) and McIntosh, Brown & Judge (1998).]

The observations and data reduction are described in Section 2. The values of $P_e$ that result from the observed flux ratios and available atomic data are given in Section 3. Our conclusions regarding the optimum value of $P_e$ in $\epsilon$ Eri and which atomic data would bear further examination are given in Section 4.

2 OBSERVATIONS AND DATA REDUCTION
The observations of $\epsilon$ Eri were carried out on 2000 March 17,18. The data set identifications, wavelength ranges covered, exposure times, gratings and detectors used are given in Table 1. The detectors used in STIS are Multi-Anode Microchannel Arrays (MAMAs), with either CsTe or CsI coatings.
The spectra were calibrated using the ON-THE-FLY CALIBRATION (OTFC) software provided by the HST archive and were corrected for scattered light between different spectral orders using the IRAF two-dimensional scattered light algorithm (sc2d). In the wavelength range from 1140 to 1735 Å, the two exposures obtained were summed to produce a combined spectrum. The spectra are given. The observed wavelengths of the lines of interest here are listed in Table 2, together with the reference wavelengths which are taken from Kurucz & Bell (1995), except for the lines of Si IV. For these lines we use values from Kaufman & Martin (1993), for reasons discussed by Harper et al. (1999). The transitions involved are also given. The lines observed have all been previously identified in solar or stellar spectra. For lines above 2000 Å, wavelengths in air (λair) are given in Tables 2 and 3 and in the text of the paper. Other lines of moderate strength present in Figs 1 and 3–6 have also been previously observed and identified, and are marked only by symbols to indicate the atom or ion. Fig. 2 shows lines of Ni II (see Section 3.1); other lines present in Fig. 2 will require a study of a wider wavelength range to establish secure identifications.

For each line a suitable background level was chosen and in the majority of cases the flux was measured by two methods; Gaussian fits to the line profiles were made and the total flux was also measured by integrating between the points where the line merged with the local continuum. The measurement uncertainties in the fluxes of the stronger lines are only a few per cent, but can exceed 10 per cent for the weakest lines. The calibrations of the absolute fluxes of the stronger lines are only a few per cent, but can exceed 10 per cent for the weakest lines. The calibrations of the absolute fluxes are estimated to have accuracies of 8 and 5 per cent, respectively.\(^1\) The fluxes measured and their estimated errors are given in Table 2.

Some regions and lines present particular difficulties. In Fig. 1 the lines of Si II are in regions where the background contains broad photospheric absorption lines of Fe II and a mixture of narrow weak emission and absorption lines. The quoted uncertainties include the effects of varying the background adopted. Similar difficulties arise in measuring the fluxes of the Fe XII lines.

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**Table 1. STIS observations of e Eri.**

<table>
<thead>
<tr>
<th>Data set</th>
<th>Wavelength range (Å)</th>
<th>Exposure time (s)</th>
<th>Grating</th>
<th>Detector</th>
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<tr>
<td>O55P01010</td>
<td>2574–2846</td>
<td>180</td>
<td>E230H</td>
<td>CsTe MAMA</td>
</tr>
<tr>
<td>O55P01020</td>
<td>1574–2382</td>
<td>1800</td>
<td>E230M</td>
<td>CsTe MAMA</td>
</tr>
<tr>
<td>O55P01030</td>
<td>1140–1735</td>
<td>2899</td>
<td>E140M</td>
<td>Cs MAMA</td>
</tr>
<tr>
<td>O55P01040</td>
<td>1140–1735</td>
<td>2899</td>
<td>E140M</td>
<td>Cs MAMA</td>
</tr>
</tbody>
</table>

**Table 2. Emission lines used in determining electron pressures.**

<table>
<thead>
<tr>
<th>Ion</th>
<th>Wavelength(^a) (Å)</th>
<th>Wavelength(^b) (Å)</th>
<th>Transition</th>
<th>Flux at Earth ((10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si II</td>
<td>2334.39</td>
<td>2334.41</td>
<td>3s^3p^2 P^0_1/2–3s^3p^2 P^0_1/2</td>
<td>3.31 ± 0.07</td>
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<tr>
<td></td>
<td>2334.60 bl.</td>
<td>2334.61</td>
<td>P^0_1/2–P^0_3/2</td>
<td>2.32 ± 0.07</td>
</tr>
<tr>
<td></td>
<td>2350.18</td>
<td>2350.17</td>
<td>P^0_1/2–P^0_3/2</td>
<td>3.04 ± 0.07</td>
</tr>
<tr>
<td>Ni II</td>
<td>2125.15</td>
<td>2125.12</td>
<td>(^1)P^4_4s P^2_2–(^3)G^4_2</td>
<td>⩾ 0.27 ± 0.03</td>
</tr>
<tr>
<td></td>
<td>2161.22</td>
<td>2161.22</td>
<td>P^2_2–G^2_2</td>
<td>⩾ 0.95 ± 0.06</td>
</tr>
<tr>
<td>Si III</td>
<td>1206.53</td>
<td>1206.50</td>
<td>3s^2 1S^0–3s^3p^2 P^0_1/2</td>
<td>3.60 ± 0.10</td>
</tr>
<tr>
<td></td>
<td>1294.58</td>
<td>1294.55</td>
<td>3s^3p^2 P^1–3p^2 P^2</td>
<td>0.05 ± 0.005</td>
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<tr>
<td></td>
<td>1296.77</td>
<td>1296.73</td>
<td>P^0–P^1</td>
<td>0.041 ± 0.005</td>
</tr>
<tr>
<td></td>
<td>1299.09 bl.</td>
<td>1298.93 bl.</td>
<td>P^2_1–P^2_2</td>
<td>0.167 ± 0.005</td>
</tr>
<tr>
<td></td>
<td>1301.17</td>
<td>1301.15</td>
<td>P^1–P^0</td>
<td>0.028 ± 0.005</td>
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<tr>
<td></td>
<td>1303.35</td>
<td>1303.32</td>
<td>P^3–P^1</td>
<td>0.062 ± 0.005</td>
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<tr>
<td></td>
<td>1892.09</td>
<td>1892.03</td>
<td>3s^2 1S^0–3s^3p^2 P^1</td>
<td>1.26 ± 0.02</td>
</tr>
<tr>
<td>C IV</td>
<td>1175 bl.</td>
<td>1175 bl.</td>
<td>2s^2 1P^0–2p^2 P^0</td>
<td>3.26 ± 0.10</td>
</tr>
<tr>
<td></td>
<td>1908.73</td>
<td>1908.73</td>
<td>2s^2 1S^0–2s^2 P^1</td>
<td>&lt; 0.13</td>
</tr>
<tr>
<td>Si IV</td>
<td>1404.82 bl.</td>
<td>1404.81</td>
<td>3s^3p^2 P^2_1–3s^3p^2 P^2_1/2</td>
<td>0.069 ± 0.005</td>
</tr>
<tr>
<td></td>
<td>1406.06</td>
<td>1406.02</td>
<td>P^2_1/2–P^0_1/2</td>
<td>0.032 ± 0.007</td>
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<tr>
<td></td>
<td>1416.95</td>
<td>1416.89</td>
<td>P^2_1/2–P^0_1/2</td>
<td>0.042 ± 0.007</td>
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<tr>
<td></td>
<td>1423.84</td>
<td>&lt; 0.010</td>
<td></td>
<td></td>
</tr>
<tr>
<td>O IV</td>
<td>1399.79</td>
<td>1399.78</td>
<td>2s^2 1P^0–2s^2 P^1</td>
<td>0.054 ± 0.005</td>
</tr>
<tr>
<td></td>
<td>1401.19</td>
<td>1401.16</td>
<td>P^0–P^0</td>
<td>0.181 ± 0.005</td>
</tr>
<tr>
<td></td>
<td>1404.82 bl.</td>
<td>1404.81</td>
<td>P^0–P^0</td>
<td>0.069 ± 0.005</td>
</tr>
<tr>
<td></td>
<td>1407.43</td>
<td>1407.38</td>
<td>P^0–P^0</td>
<td>0.052 ± 0.005</td>
</tr>
<tr>
<td>O V</td>
<td>1218.36</td>
<td>1218.34</td>
<td>2s^2 1S^0–2s^2 P^1</td>
<td>0.68 ± 0.04</td>
</tr>
<tr>
<td></td>
<td>1371.33</td>
<td>1371.30</td>
<td>2s^2 P^1–1D^2</td>
<td>0.105 ± 0.005</td>
</tr>
<tr>
<td>Fe XII</td>
<td>1241.99</td>
<td>1242.00</td>
<td>3s^2 1P^0–3p^2 P^0</td>
<td>0.098 ± 0.007</td>
</tr>
<tr>
<td></td>
<td>1349.40</td>
<td>1349.38</td>
<td>3s^2 1P^0–P^0</td>
<td>0.052 ± 0.015</td>
</tr>
</tbody>
</table>

\(^a\)Observed wavelength, corrected for the stellar radial velocity of 15.5 km s\(^{-1}\).

\(^b\)Wavelengths from Kurucz & Bell (1995), except for Si IV (see text).

\(^c\)Wavelengths in air for λ > 2000 Å.
Ni II lines shown in Fig. 2. For the lines of C III around 1176 Å, shown in Fig. 4, individual Gaussian fits were made and the total flux in the multiplet was also measured. The region where the C III 1908.7 Å line is expected is also shown; the upper limit to the flux was found by assuming that the line is just present at the level of the noise and the linewidth was assumed to be the same as that of the Si III line at 1892.0 Å. The region to the blue side of the Si III 1206.5 Å line, shown in Fig. 3, is affected by problems that remain in the correction for scattering between different spectral orders. Lines of O IV and S IV are shown in Fig. 5. Only the O IV line at 1401.2 Å is strong enough to determine the linewidth by fitting a Gaussian profile. The linewidth was then fixed at this value when making Gaussian fits to the weaker lines. The upper limit to the S IV line at 1423.8 Å was derived from the average noise level and the same width as above. The line of O V at 1218.3 Å lies in the wing of the H Lyman α line. This background was interpolated through the base of the line before measuring the line flux.

3 ELECTRON PRESSURES

For each ion studied, the emission line flux ratios have been calculated as a function of $P_e$ for a few values of $T_e$ around the optimum temperature for the line formation. These temperatures are based on the ionization equilibrium number densities of Arnaud & Rothenflug (1985) and also take into account the variation of the mean EMD with $T_e$, found from optically thin lines whose emission measure loci do not depend on $N_e$. The full EMD will be given in a forthcoming paper, but is similar to that derived for ε Eri from earlier observations with the IUE by Jordan et al. (1987) and Philippides (1996). Arnaud & Rothenflug (1985) do not take account of the reduction in the dielectronic recombination rate which occurs at high densities. Thus the optimum temperatures of line formation adopted may be a little too high. In general, we have used the CHIANTI (v3.01) data base (Dere et al. 1997; Landi et al. 1999) to calculate the line ratios. In some cases we have explored the effects of using alternative transition probabilities, as discussed below. CHIANTI does not currently include ion–proton collision rates. We have added these for O IV and mention their possible effects in other ions.

3.1 Lines of Si II

In addition to several permitted multiplets, including the resonance lines around 1810 Å, we observe three lines in the 3s23p 2P – 3s3p 2P multiplet, at 2334.4, 2334.6 and 2350.2 Å. These are shown in Fig. 1. The line at 2328.5 Å is too weak to detect and that at 2344.2 Å is blended with lines of Fe II. With the higher resolution of STIS, the fluxes in the lines at 2334.4 and 2334.6 Å can be determined more accurately than from the previous stellar spectra. The fluxes in the two lines have been found individually by fitting the two lines simultaneously with Gaussian profiles, using linewidths equal to that observed for the line at 2350.2 Å. This allows the best test to date of the relative transition probabilities ($A$-values) for the 2334.4- and 2350.2-Å lines. The mean ratio derived is $A(2P_{1/2} - 2P_{3/2})/A(2P_{1/2} - 2P_{1/2}) = 1.08 ± 0.06$. This is significantly smaller than the value of 1.52 calculated by Nussbaumer (1977), whose $A$-values are currently adopted in CHIANTI, and which were also used by Judge, Carpenter & Harper (1991). It is slightly smaller than the more recent value of 1.29 calculated by Dufton et al. (1991).

As suggested by Carpenter et al. (1988) the line at 2334.6 Å is blended with a transition in Ni II. Si II photons can be absorbed leading to fluorescent emission in other lines of Ni II which share the common upper level, 3d6(5D)4p 5G1/2. Judge et al. (1991) and Dufton et al. (1991) examined the ratio $F(2334.4 + 2334.6 Å)/F(2350.2 Å)$ in several late-type stars and found that it was smaller than expected at the relevant densities. Judge et al. (1991) concluded that this discrepancy could be reduced but not...
entirely eliminated by adding in all the photons that escape in the Ni II lines. Dufton et al. (1991) suggested that the discrepancy might be caused by an unidentified blend in the 2350.2 Å line. However, in e Eri the 2350.2 Å line is clean and narrow and shows no evidence of being part of a blend.

Our measurement of the ratio $F(2334.4\,\text{Å})/F(23346\,\text{Å})$, which has a value of $1.48 \pm 0.03$, should be the most reliable to date. This observed value is clearly larger than the maximum value of 0.67 predicted at high pressures using the atomic data in CHIANTI and $T_e = 6300$ K. The limiting value varies little with $T_e$. (We corrected a typographical error in the $A$-value given in CHIANTI for the 2334.4 Å line, which should read $4.55 \times 10^3\,\text{s}^{-1}$.) In view of this disagreement between the observed and calculated ratios, we changed the $A$-values in our CHIANTI files to those given by Dufton et al. (1991). With these $A$-values, the maximum value of the flux ratio becomes 0.80, which is larger, but still lower than that predicted at high pressures using the atomic data in CHIANTI and $T_e = 6300$ K.

Figure 2. The spectral ranges 2121–2129 and 2157–2165 Å, containing lines of Ni II (indicated by ▼) at $\lambda_{\text{vac}}$ 2125.79 and 2161.89 Å.

Figure 3. The spectral ranges 1204–1208, 1294–1304 and 1890–1894 Å, showing, respectively, the resonance line of Si III at 1206.50 Å, lines in the 3s3p $^3P$–$^3P$ multiplet, indicated by *, and the intersystem line at 1892.03 Å. Others lines in the middle segment are because of O I (‡), Si I (×) and Fe II (†).
observed. We have not considered changes in the ion–electron collision rates, which in CHIANTI are from Dufton & Kingston (1991). Dufton & Kingston (1994) suggest that at the above temperature, the rates involved here should be accurate to within a few per cent. These collisional rates were used by Dufton et al. (1991) and by Judge et al. (1991). We do observe the decays in the Ni II lines at 2161.2 and 2125.1 Å, which are shown in Fig. 2, but the strongest line at 2416.1 Å, which has been observed in a variety of giants (see Judge et al. 1991) is outside the range of our observations. The weakest line at 2083.7 Å is not detected.

Figure 4. The spectral ranges 1174–1177 Å, containing the C III multiplet 2s2p 3P–2p2 3P, and 1907–1910 Å, showing a possibly marginal detection of the C III intersystem line at 1908.73 Å.

Figure 5. The spectral ranges 1398–1402, 1404–1408, 1416–1418 and 1423–1425 Å. These show the intersystem lines of O IV (†) and S IV (×). The S IV line at 1423.79 Å is not detected.
Fluorescence is clearly occurring since decays from the \( ^2G_{9/2} \) level are not detected. Thus we conclude that some photons have been lost from the line at 2334.6 Å.

The flux ratio of the two Ni II lines observed does not agree with the optically thin value, adopting \( A \)-values derived from the oscillator strengths given by Kurucz & Bell (1995), but the observed ratio can be used to find the relative escape probabilities, using the method of Jordan (1967). The relative optical depths in the nickel lines have been found by assuming that the lower levels have Boltzmann populations at around 8000 K. By assuming that the line at 2125.1 Å is optically thin (since the line at 2083.7 Å is not observed) the fluxes in the other decays can be predicted. (See Judge et al. 1991, for more detailed considerations in the context of the giant star \( \alpha \) Tau.) It is estimated that a flux of \( 1 \times 10^{13} \) erg cm\(^{-2}\) s\(^{-1}\) has been lost from the SiII 2334.6-Å line. With this added to the observed flux, the new value of the ratio \( F(2334.4 \text{ Å})/F(2334.6 \text{ Å}) \) is 0.95, which is still larger than the upper limit of 0.67 at high pressures. It is difficult to put an error bar on the estimate of the Ni II line flux, but with lower opacities the total flux lost could be larger. A better treatment of the radiative transfer will be attempted when a new model of the chromosphere has been completed.

The ratio \( F(2334.6 \text{ Å})/F(2350.2 \text{ Å}) \) can also be compared with the values calculated using CHIANTI. Without the addition of the photons lost to the lines of Ni II, the observed ratio of 0.73 ± 0.03 is below the lower limit of 2.3 at high pressures, using the \( A \)-values of Nussbaumer (1977), or 1.6, adopting the \( A \)-values of Dufton et al. (1991). Including the loss to the nickel lines, the ‘observed’ ratio becomes 1.2, which is still too small. The above limiting ratios in the high-density limit depend on the adopted branching ratio for decays from the \( ^4P_{1/2} \) level. We have found (see above) that this does not agree with the observations. A change in the theoretical ratio in the direction indicated by the observations could act to bring both the density sensitive flux ratios into the density sensitive regimes. It would therefore be worthwhile to try to improve the theoretical \( A \)-values.

As noted by Judge et al. (1991), at the chromospheric temperatures where these Si II lines are formed, the proton to electron density ratio is relatively small and ion–proton excitation is not expected to be important.

The ratio of the fluxes observed in the permitted lines at 1816.9 and 1808.0 Å shows that these lines are optically thick. Radiative transfer calculations are required to make use of this and other flux ratios involving the permitted and inter-system lines (see Judge et al. 1991).

### 3.2 Lines of Si III

The resonance line at 1206.5 Å, the inter-system line at 1892.0 Å and lines in the \( ^3P^-^3P^o \) multiplet around 1299 Å are all observed, as shown in Fig. 3. Apart from the lines at 1298.9 Å, the other members of the \( ^3P^-^3P^o \) multiplet are weak and with the range of possible errors in their fluxes given in Table 2, their ratios simply limit the range of \( P_e \) to \( 10^{15} - 10^{16} \) cm\(^{-3}\) K. Although the lines have a maximum emissivity at around \( 5 \times 10^4 \) K, the form of the mean EMD reduces this to around \( 3 \times 10^4 \) K. If \( T_e \) were much larger than \( 3 \times 10^4 \) K, the pressures derived would be below the lower limit found from the C III lines (see Section 3.3). The collisional rates in CHIANTI are from Dufton & Kingston (1989), which were used earlier by Dufton et al. (1983). The \( A \)-values used in CHIANTI for the transitions discussed here are from Dufton et al. (1983), apart from that for the inter-system transition, which is about 6 per cent larger in CHIANTI. We have made calculations using both these \( A \)-values and also using the experimental value measured by Kwong et al. (1983), which is slightly larger than that in CHIANTI. We find that the difference between the largest and smallest \( A \)-values produces an uncertainty in the pressure of \( \Delta \log P_e \approx 0.06 \), which is similar to that produced by the possible errors in the fluxes. We therefore give the results using CHIANTI. Proton rates have not been included in the calculations, as justified by Dufton et al. (1983).
Table 3. Summary of electron pressures (log $P_e$) derived, at given values of log $T_e$, where $P_e$ is in cm$^{-3}$ K and $T_e$ is in K.

<table>
<thead>
<tr>
<th>Ion</th>
<th>Line ratio</th>
<th>log $T_e$</th>
<th>log $P_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si III</td>
<td>1298.9 Å/1892.0 Å</td>
<td>4.5</td>
<td>15.72 ± 0.04</td>
</tr>
<tr>
<td></td>
<td>1206.5/1892.0 Å</td>
<td>15.78 ± 0.05</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1206.5 Å/1298.9 Å</td>
<td>15.58 ± 0.10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>mean:</td>
<td>15.60 ± 0.10</td>
<td></td>
</tr>
<tr>
<td>C III</td>
<td>1175 Å/1908.7 Å</td>
<td>4.7</td>
<td>15.53 ± 0.03</td>
</tr>
<tr>
<td>O IV</td>
<td>1399.8 Å/1410.2 Å</td>
<td>5.15</td>
<td>16.16 ± 0.17</td>
</tr>
<tr>
<td></td>
<td>1407.4 Å/1410.2 Å</td>
<td>16.14 ± 0.20</td>
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</tr>
<tr>
<td></td>
<td>(1399.8+1407.4 Å)/1410.2 Å</td>
<td>16.15 ± 0.18</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1410.2 Å/1404.8 Å</td>
<td>15.28 ± 0.08</td>
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</tr>
<tr>
<td></td>
<td>(1399.8+1407.4 Å)/1404.8 Å</td>
<td>15.62 ± 0.02</td>
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</tr>
<tr>
<td></td>
<td>overall mean:</td>
<td>15.67</td>
<td></td>
</tr>
<tr>
<td>O V</td>
<td>1218.3 Å/1371.3 Å</td>
<td>5.36</td>
<td>≤15.41+0.55</td>
</tr>
<tr>
<td></td>
<td>1206.5 Å/1892.0 Å</td>
<td>15.78 ± 0.04</td>
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</tbody>
</table>

*Ion–electron rates from CHIANTI, proton rates from Foster et al. (1997), $A$-values from Brage et al. (1996).

The ratio $F(1298.9 \, \text{Å})/F(1892.0 \, \text{Å})$ gives $P_e = 5.2 \times 10^{15}$ cm$^{-3}$ K; the ratio $F(1206.5 \, \text{Å})/F(1892.0 \, \text{Å})$ gives $P_e = 6.0 \times 10^{15}$ cm$^{-3}$ K, and the ratio $F(1206.5 \, \text{Å})/F(1298.9 \, \text{Å})$ gives $P_e = 3.8 \times 10^{15}$ cm$^{-3}$ K. From the ranges of $P_e$ given in Table 3, derived from the quoted errors in the observed ratios, it can be seen that the three pressures almost overlap in range. The mean pressure derived is $4.9 \times 10^{15}$ cm$^{-3}$ K. The pressures derived from the different $A$-values agree with each other to within 15 per cent.

The small differences between the values of $P_e$ derived from the three observed line ratios could in principal be caused by a high opacity in the 1205.6 Å line. Depending on the geometry, more or fewer photons could eventually escape in the outward direction than the fraction of one half expected for an optically thin line in a plane–parallel layer. However, only a small increase in the estimated errors in the fluxes, or small errors in the atomic data would be required to give the same pressure from all three ratios. The only evidence that the 1205.6-Å line might be slightly optically thick is that it has a larger linewidth (in velocity units) than the line at 1892.0 Å. Although the 3s3p $^3P-3p^2 \, ^1D$ transition lies at 1206.5 Å, this line is predicted to have a flux which is a factor of 23 smaller than that of the 1206.5-Å line and is unlikely to cause the additional broadening. Reducing the observed 1206.5-Å line flux would result in a lower pressure from $R_2$ and a higher pressure from $R_3$, thus decreasing the discrepancy between the two results, and vice-versa.

### 3.3 Lines of C III

The ratios of the fluxes of lines within the 1175-Å multiplet are sensitive to $N_e$ for $P_e \sim 3 \times 10^{15}$ cm$^{-3}$ K, and also to high line opacities. Using atomic data from CHIANTI, the observed line ratios are close to the values expected in the high-density limit for a temperature of line formation around $5 \times 10^4$ K. Some ratios are slightly below the minimum value predicted, but there is no systematic behaviour that suggests significant line opacities. Owing to the relatively high noise levels (see Fig. 4), we can conclude only that $P_e \geq 3 \times 10^{15}$ cm$^{-3}$ K.

The sum of the flux in the 1175-Å multiplet is easier to measure. The ratio of this flux to that in the intersystem line at 1908.7 Å is sensitive to $N_e$. If present, the line at 1908.7 Å is at the level of the noise (see Fig. 4). Keenan & Warren (1993) have calculated the ratio $F(1175 \, \text{Å})/F(1908.7 \, \text{Å})$ using ion–electron collision rates which, for the transitions of interest here, are the same as those in CHIANTI. They include ion–proton rates from Doyle (1987). Work by Ryan et al. (1998) has shown that these rates are too large. Since we have only an upper limit to the 1908.7-Å line flux, we have not included proton excitation. Keenan & Warren (1993) adopt $A$-values from Allard et al. (1990), which are very similar to those in CHIANTI. Both sets of calculations indicate that at $T_e = 5 \times 10^4$ K, $P_e \geq 3.4 \times 10^{15}$ cm$^{-3}$ K.

### 3.4 Lines of S IV

The lines of S IV at 1406.0 and 1416.9 Å are observed, as shown in Fig. 5. These form part of the 3s3p $^3P-3p^2 \, ^2P$ multiplet. The line at 1423.8 Å is not detected above the level of the noise. The ratio $F(1416.9 \, \text{Å})/F(1406.0 \, \text{Å})$ is sensitive to $P_e$, but the observed ratio of 0.76 ± 0.08 exceeds the theoretical limit of 0.65 at low pressures ($P_e = 10^{14}$ cm$^{-3}$ K at $T_e = 1.1 \times 10^5$ K), using CHIANTI. The error estimate for the ratio was found by varying the underlying background level and widths of both the lines, rather than from the possible error in an individual line flux. For pressures in the range of $5 \times 10^{14}$ cm$^{-3}$ K, the observed ratio is larger than the theoretical values by factors of between 1.4 and 1.7. Thus there does appear to be a real discrepancy between the observed and theoretical ratios. The atomic data in CHIANTI are from Tayal (1999, 2000), but do not include proton excitation rates. Using atomic data from Dufour et al. (1982) (which give similar results to those from CHIANTI), Harper et al. (1999) found a discrepancy in the same sense when making comparisons with ratios observed in the slow nova RR Tel, where the lines are strong. There are no obvious potential blends with the line at 1416.9 Å.

The non-detection of the line at 1423.8 Å gives $F(1423.8 \, \text{Å})/F(1416.9 \, \text{Å}) \leq 0.31$ (with a possible range from 0.26 to 0.40). At $T_e = 1.1 \times 10^5$ K, and $15.7 < \log P_e < 16.1$, this is compatible with the theoretical ratios of 0.31–0.41.

Although the flux in the S IV 1404.8-Å line can be estimated from the theoretical ratios $F(1406.0 \, \text{Å})/F(1404.8 \, \text{Å})$ and $F(1416.9 \, \text{Å})/F(1404.8 \, \text{Å})$, given the above problem with the $F(1416.9 \, \text{Å})/F(1406.0 \, \text{Å})$ ratio, it is simplest to use the relative $A$-values for the 1404.8- and 1423.8-Å lines. Adopting the $A$-values CHIANTI (from Tayal 1999), the upper limit to the flux in the 1423.8-Å line predicts $F(1404.8 \, \text{Å}) \leq 1.3 \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$. This is consistent with the theoretical ratio $F(1406.0 \, \text{Å})/F(1404.8 \, \text{Å})$ over the pressure range above, but not with the $F(1416.9 \, \text{Å})/F(1404.8 \, \text{Å})$ ratio.

### 3.5 Lines of O IV

Four of the five lines of the $2s^22p \, ^3P-2s2p^2 \, ^2P$ multiplet are observed, as shown in Fig. 5, although the line at 1404.8 Å is blended with the S IV discussed in the previous section. Apart from the line at 1401.2 Å the lines are weak.

The ratio of the fluxes in the lines at 1407.4 and 1399.8 Å depends only on the relative transition probabilities from the common upper level ($^3P_{1/2}$). The observed ratio is 0.96 ± 0.20, which agrees (to within the uncertainties) with the values of 0.97 ± 0.14 and 1.01 calculated by Brage, Judge & Brekke (1996) and Nussbaumer & Storey (1982), respectively, and the value of 0.99 ± 0.02 deduced from high quality spectra of the slow nova RR Tel by Harper et al. (1999). However, all these ratios are slightly larger than the value of 0.925 derived using the $A$-values in CHIANTI, which are from Dankworth & Treffitz (1978). The total $A$-values for
decays from the $^3P_{1/2}$ level calculated by Brage et al. (1996) and Dankwort & Trefftz (1978) have a difference of about 14 per cent. There are only small differences in the branching ratio to the 1404.8-Å line, from the $^3P_{3/2}$ level (they range from 0.85 to 0.90).

The ion–electron collision rates in CHIANTI for the transitions which are most important here are from Zhang, Graziani & Pradhan (1994). These are also used in the calculations by Brage et al. (1996) and Harper et al. (1999). Using the atomic data in CHIANTI, the observed values of the ratios $F(1399.8 \, \text{Å})/F(1401.2 \, \text{Å})$ and $F(1407.4 \, \text{Å})/F(1401.2 \, \text{Å})$ lead to pressures of $1.3 \times 10^{16}$ and $1.7 \times 10^{16} \text{cm}^{-3} \, \text{K}$, at an optimum temperature of line formation of $1.5 \times 10^4 \, \text{K}$. Since the 1399.8- and 1407.4-Å lines are weak we have also used the ratio $F(1399.8 + 1407.4 \, \text{Å})/F(1401.2 \, \text{Å})$ to find the mean pressure, which is $1.5 \times 10^{16} \text{cm}^{-3}$. These pressures are larger than those found from the Si III lines, even when the likely errors in both sets of results are taken into account.

CHIANTI does not include ion–proton excitation rates, although these were included by Brage et al. (1996) and Harper et al. (1999). Values are available from the work of Foster, Reid & Keenan (1997) and we have included these by multiplying the ion–electron rates in CHIANTI by the appropriate factors. We have also used the A-values of Brage et al. (1996) instead of those by Dankwort & Trefftz (1978). The pressures derived and the errors arising from the possible range of observed flux ratios are given in Table 3. They are in fact similar to those found using the original CHIANTI files and give a mean pressure of $1.4 \times 10^{16} \text{cm}^{-3} \, \text{K}$.

Without correcting for the blend with the $\text{Si IV}$ line, the ratios that involve the line at 1404.8 Å give only lower limits to the electron pressure. Using the revisions to the CHIANTI files as described above, the ratio $F(1401.2 \, \text{Å})/F(1404.8 \, \text{Å})$ gives $P_e \simeq 9.8 \times 10^{14} \text{cm}^{-3} \, \text{K}$, and the ratio $F(1399.8 + 1407.4 \, \text{Å})/F(1404.8 \, \text{Å})$ gives $P_e \simeq 2.6 \times 10^{15} \text{cm}^{-3} \, \text{K}$. Since these pressures are below the lower limit found from the C III lines, it is clear that the contribution from $\text{Si IV}$ must be taken into account when using the 1404.8-Å line. In the previous section we found an upper limit to the flux in the $\text{Si IV}$ line ($1.3 \times 10^{-15} \text{erg cm}^{-2} \, \text{s}^{-1}$). This has been subtracted from the total flux observed in the 1404.8-Å line.

The above two ratios now give larger pressures (see Table 3), but the values derived do not agree with each other. From Table 3 it can be seen that the ratios involving the 1401.2-Å line give pressures that are either significantly larger or smaller than that derived from the ratio $F(1399.8 + 1407.4 \, \text{Å})/F(1404.8 \, \text{Å})$. The difference between the ratios could in principle be decreased by increasing the contribution from the $\text{Si IV}$ line. However, this then disagrees with the $\text{Si IV}$ ratio $F(1404.8 \, \text{Å})/F(1423.8 \, \text{Å})$. Harper et al. (1999) suggested that there could be a problem with the atomic data for the 1401.2-Å line, from their study of the $\text{O IV}$ lines in RR Tel, where the lines have a high signal-to-noise ratio. The mean pressure from the ratios involving the 1401.2-Å line does agree with that found from the ratios not involving this line. The overall mean pressure from the $\text{O IV}$ lines is $4.7 \times 10^{15} \text{cm}^{-3} \, \text{K}$, which is close to the mean determined from the Si III lines. Since the differences between individual pressures are because of the uncertainties in the atomic data rather than in the flux measurements, it is not possible to put a formal uncertainty on this mean pressure.

### 3.6 Lines of O V

We observe the $2s^2 \, ^1S_0 - 2s2p \, ^3P_1$ line at 1218.3 Å and the $2s2p \, ^1P - 2p^2 \, ^3D$ line at 1371.3 Å, as shown in Fig. 6. At a temperature of line formation around $2.5 \times 10^4 \, \text{K}$, the ratio of these line fluxes becomes sensitive to the pressure for $P_e \geq 10^{15} \text{cm}^{-3} \, \text{K}$. However, the value of the ratio in the low-density limit is very sensitive to $T_e$. The observed ratio combined with the ratios calculated from CHIANTI leads to very high pressures of around $8 \times 10^{15} \text{cm}^{-3} \, \text{K}$. Applied to ratios observed in the quiet Sun (see Keenan et al. 1995), these calculations also lead to densities which are much larger than those found from density sensitive flux ratios in C III (see Macpherson & Jordan 1999). We have also examined the results of using the calculations by Keenan et al. (1995), who use unpublished ion–electron collision rates of Berrington & Kingston and ion–proton collisional rates from Doyle (1987). The proton rates calculated by Ryans et al. (1998) at $T_e = 2.5 \times 10^7 \, \text{K}$ are up to 40 per cent smaller, which will tend to reduce the theoretical ratio found by Keenan et al. (1995) at low pressure. There is very little difference between the $A$-values used in CHIANTI and those used by Keenan et al. (1995). The ratio observed in ε Eri is $6.48 \pm 0.70$. This agrees with the maximum value of $6.4$, corresponding to the low-density limit, in the calculations by Keenan et al. (1995) at $T_e = 2.5 \times 10^7 \, \text{K}$ and gives an upper limit of $4.3 \times 10^{15} \text{cm}^{-3} \, \text{K}$ to $P_e$. The optimum temperature for the line formation is slightly smaller ($2.3 \times 10^7 \, \text{K}$), and with this temperature, the observed flux ratio gives $P_e \simeq 2.6 \times 10^{15} \text{cm}^{-3} \, \text{K}$, and an upper limit of $9 \times 10^{15} \text{cm}^{-3} \, \text{K}$, showing how sensitive the derived pressure is to $T_e$.

Earlier calculations by Dufton et al. (1978) showed that the ratio in the low-density limit is also sensitive to the amount of proton excitation included between the $^3P$ and $^3P^0$ levels. A difference in the ratio of only 10 per cent can cause substantial differences in the value of $P_e$ derived in the regime where the ratios begin to decrease below the low-density limit.

Because of the problem apparent in using the ratios from CHIANTI, Landi (private communication) has provided us with new files which include updated electron collisional excitation data. The calculated ratios (which do not include proton excitation) are more similar to those published by Dufton et al. (1978) (including proton excitation) than those of Keenan et al. (1995). The observed ratio still leads to very high pressures when applied to the quiet Sun, and to $P_e \simeq 1.4 \times 10^{16} \text{cm}^{-3} \, \text{K}$ for ε Eri, a lower limit since including proton excitation tends to increase the pressure derived.

At present the use of this ratio is limited by its sensitivity near the low-density limit to the temperature of line formation and to even small uncertainties in the atomic data. It is important to improve the theoretical ratios since an apparently high pressure could in principle be caused by the presence of non-thermal electrons enhancing the 1371.3-Å line. Meanwhile, we give in Table 3 the value of $P_e$, and its upper limit, derived from the calculations by Keenan et al. (1995).

### 3.7 Lines of Fe XII

We have identified the magnetic dipole lines at 1242.0 and 1349.4 Å in our STIS spectra of ε Eri (see fig. 1 in Jordan et al. 2001). Using the atomic data in CHIANTI, the ratio $F(1242.0 \, \text{Å})/F(1349.38 \, \text{Å})$ becomes sensitive to $P_e$ when $P_e \simeq 6 \times 10^{15} \text{cm}^{-3} \, \text{K}$, or when $P_e \simeq 10^{13} \text{cm}^{-3} \, \text{K}$. In between these pressures the value of the ratio is approximately constant at a value of 1.88, for $T_e = 1.4 \times 10^8 \, \text{K}$. The observed ratio is $1.9 \pm 0.2$ (the ratio is more accurate than the absolute fluxes, because of the way in which we varied the background). This gives $P_e \simeq 6 \times 10^{15} \text{cm}^{-3} \, \text{K}$, but the uncertainty of ±10 per cent in the ratio allows pressures of up to $1.5 \times 10^{16} \text{cm}^{-3} \, \text{K}$.

Binello et al. (2001) have carried out new calculations of the
Fe XII level populations at $N_e = 10^8$ and $10^{12}$ cm$^{-3}$ and we have compared the ratios they predict with those from CHIANTI. At $10^9$ cm$^{-3}$, Binello et al. (2001) predict a ratio of 2.7, compared to 1.8 from CHIANTI. At $10^{12}$ cm$^{-3}$ the ratio is 4.0, compared to 3.7 from CHIANTI. The smaller difference at high densities is consistent with the similarity of the $A$-values in the two sets of calculations. However, it is clear that at intermediate densities the results from Binello et al. (2001) predict a ratio which is larger than that observed. Since the ratios observed in two other active dwarf stars (70 Oph A and κ Cet) are approximately 2.2 and 2.0, respectively, both smaller than the effective minimum of 2.7 from Binello et al. (2001), the observed ratios agree better with the older calculations in CHIANTI. Binello et al. (2001) find that their new calculations give an improved consistency for densities derived from the extreme ultraviolet (EUV) lines of Fe XII in the solar spectrum, so the problem may be restricted to the relative populations of the $2^2P_{3/2,1/2}$ levels. Including the ion–proton collisions would act to bring these populations closer together, which would help to reduce the discrepancy between the observed and calculated ratios, so the present agreement with the results in CHIANTI may be fortuitous.

The population of the $3s^23p^3 \ 2^2P_{1/2}$ level derived from CHIANTI can also be compared with the values predicted by Gabriel & Jordan (1975), who used observations of the quiet solar corona to normalize their early calculations. At $T_e = 1.7 \times 10^6$ K and $N_e = 3 \times 10^8$ cm$^{-3}$, the two different methods used by Gabriel & Jordan (1975) predict fractional populations $[N(2^2P_{1/2})/N_{ion}]$ of $1.7 \times 10^{-12}$ and $1.0 \times 10^{-12}$, compared to the value of $1.6 \times 10^{-12}$ from CHIANTI. The former value, from the preferred method, agrees well with the current values in CHIANTI.

The ratios of the fluxes in the UV forbidden lines to those in the permitted lines observed with the Extreme Ultraviolet Explorer (Laming, Drake & Widing 1996) are also sensitive to $N_e$. However, as discussed by Jordan et al. (2001), the observed flux ratios differ from those predicted using the CHIANTI data base by about a factor of 3. This difference is not removed by adopting the new calculations by Binello et al. (2001) and is most likely because of the fact that the UV and EUV lines were not observed simultaneously.

4 SUMMARY AND CONCLUSIONS

The pressures found are summarized in Table 3, together with the uncertainties arising from the flux measurements.

The ratios observed in Si III give the most self-consistent set of pressures. The degree of self-consistency does not depend on which $A$-value is adopted for the inter system line. Using the $A$-values of Duf ton et al. (1983) and Kwong et al. (1983) leads to mean pressures which differ by only $-0.2$ and $+0.4$, respectively, from the value of $log P_e = 15.69$ given in Table 3. The lines used may be formed at slightly different temperatures. This will be investigated once the atmospheric model is completed. If $T_e$ were lower, all three ratios would give higher pressures, and vice-versa. Duf ton & Kingston (1989) do not give a formal accuracy for the collision rates. Thus the accuracy of the pressures measured from these line ratios is limited by the accuracy of the flux ratios and perhaps by the ion–electron collisional rates.

The situation for O IV is less satisfactory. As discussed in Section 3.5, ratios involving the strongest line at 1401.2 Å give significantly different pressures. The relative pressures derived hardly depend on the value of $T_e$ adopted. The absolute values of $P_e$ would be smaller if a lower $T_e$ were used. The ratio $F(1399.8 + 1407.4 Å)/F(1401.2 Å)$ has the least sensitivity to $P_e$. Zhang et al. (1994) give a possible error of 20 per cent in the collision rates, which is larger than those in the flux ratios and there is independent evidence of a problem with the 1401.2-Å line (Harper et al. 1999). However, combined errors of more than 20 per cent would be needed to bring the values of $P_e$ derived from the two ratios involving the 1401.2-Å line into an overlapping range of possible values. Given the accuracy of the line flux ratios, further work on the collision rates would be worthwhile.

The ratio $F(1399.8 + 1407.4 Å)/F(1404.8 Å)$ is the most sensitive to $P_e$, but the value of $P_e$ derived from this ratio depends on the estimate of the contribution to the line at 1404.8 Å from the Si IV blend. As stressed in Section 3.5, it is not possible to reduce the contribution from the O IV line without impairing errors in the data for Si IV. Since the observed ratio $F(1416.9 Å)/F(1406.0 Å)$ in Si IV is inconsistent with the theoretical ratios at all $P_e$, the atomic data for Si IV also merit further attention. Meanwhile we average the pressures found ($log P_e = 16.15, 15.28$ and 15.62; see Table 3) to obtain a mean value of $log P_e = 15.67$, which agrees with that found from the Si III lines.

The main difficulty with the O V ratio is that it is close to the maximum value at low pressures at the estimated temperature of line formation. To use this ratio the atomic data need to be accurate to better than 10 per cent, which may not be possible. However, the resulting pressure is also very sensitive to the temperature of line formation. We can only conclude that the range of possible values given in Table 3 is consistent with the values found from the other ions. If $T_e$ were lowered below that adopted, the pressure implied would rapidly become higher than that found from other ions.

The flux ratio observed for the 1242.0- and 1349.4-Å lines of Fe XII gives only an upper limit to $P_e$ using the data in CHIANTI, and cannot be accounted for by the more recent calculations of Binello et al. (2001), which give more consistent densities from solar EUV lines. It would be worthwhile to investigate the effects of proton collisions between the upper levels of the UV lines.

The new observed flux ratios for the Si II lines at 2334.4 and 2350.2 Å show that the present theoretical A-values require small corrections. These would go some way in reconciling the theoretical pressure sensitive ratios with the observations. The observed ratios involving the line at 2334.61 Å do not agree with the theoretical values. Fluorescent decays in Ni II are observed, confirming earlier suggestions that absorption by the Ni II line at 2334.59 Å is removing photons from the Si II line at 2334.61 Å. Chromospheric modelling is required to determine whether or not allowing for the photons lost to the Ni II lines will remove all the apparent discrepancies between the observed and theoretical ratios.

For many of the lines of interest the accuracy of the relative fluxes measured from the ε Eri spectra is higher than that claimed for atomic data used in the calculated line ratios. In the long term we hope that the new results will stimulate further work on the atomic data, where improvements are feasible. However, the interpretation of the stellar line ratios will always be limited by the spatial averaging involved. Modelling from the absolute line fluxes is in progress and will be used to establish a new mean EMD and hence improve the temperatures of line formation adopted here. Meanwhile we conclude that the best pressure to adopt in the modelling process is $P_e = 4.8 \times 10^{13}$ cm$^{-3}$ K. Based on the possible errors in the measured Si III ratios, the minimum uncertainty in this pressure is ±13 per cent.
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