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Letter to the Editor

The O V 1213.9 Å forbidden line in the quiet Sun

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Abstract. We present the first unambiguous detection of the O V 1213.9 Å ($2s^2\ ^1S_0 \rightarrow 2s2p\ ^3P_2$) forbidden line in the solar spectrum, using observations obtained with the SUMER instrument on board SOHO. The wavelength separation of the forbidden to the ($2s^2\ ^1S_0 \rightarrow 2s2p\ ^3P_1$) intercombination line at 1218.35 Å is 4.5±0.1 Å in excellent agreement with theoretical predictions. The observed line ratio, combined with the latest calculations, allows us to derive an electron density of $\log N_\mathrm{e}/\mathrm{cm}^{-3} = 8.5 \pm 0.15$ for the quiet Sun. However, the O V 1213.9 Å line was not detected in the *HST* spectra of Procyon and we can only place a lower limit of $\log N_\mathrm{e}/\mathrm{cm}^{-3} \geq 7.8$ to the electron density in this object.

Key words: atomic data – line identification – Sun: chromosphere – Sun: corona – stars: individual: procyon

1. Introduction

It is now well established that emission line ratios can be used as powerful electron temperature and density diagnostics for many astrophysical plasmas; the Solar transition region/corona (Dere, 1978); early and late type stars (Jordan, 1988 and Shore & Sanduleak 1984); planetary nebulae (Keyes, Aller & Feibelman 1990); H II regions (Fich & Silkey 1991); Symbiotic stars (Schmid & Schild, 1990). See Keenan (1996) for a recent review. The large dynamic range (0.1–0.00003) of the Be-like O V (1213.90 Å/1218.34 Å) ($2s^2\ ^1S_0 \rightarrow 2s2p\ ^3P_2$ / $2s^2\ ^1S_0 \rightarrow 2s2p\ ^3P_1$) line ratio and the fact that it is temperature insensitive makes it potentially a very useful density diagnostic over the $7 < \log N_\mathrm{e}/\mathrm{cm}^{-3} < 11$ density range (see for example Keenan et al. 1995).

The emission lines of O V have been observed in a variety of astronomical objects including the Sun and late-type stars (Doschek 1996; Maran et al. 1994), supernova remnants (Cornet et al. 1995) and from hot gas around an eclipsing neutron star (Anderson, Wachter & Margon, 1994). The O V (1218.35 Å) intercombination line has been observed in various solar features by *Skylab* (Doschek 1996) and the *High Resolution Telescope and Spectrograph* (Brekke 1993), as well as in gaseous nebulae (Doschek & Feibelman 1993). Both forbidden and intercombination lines are located in the wings of the strong Lyman-α feature, but the forbidden line is far more difficult to detect, due to it's faintness. Sandlin, Brueckner & Tousey (1977) tentatively identify the line in some solar limb spectra from *Skylab*, and more recently McKenna et al. (1997) have detected the line in a high resolution *HST* spectrum of RR Tel, with a wavelength separation from the intercombination line of 4.62 ± 0.12 Å.

In this paper, we present high spectral resolution, high signal-to-noise spectra of the quiet Sun in the wavelength region of the O V intercombination and forbidden lines. The observations were obtained with the Solar Ultraviolet Measurements of Emitted Radiation instrument (SUMER) on-board the Solar and Heliospheric Observatory (SOHO). We use recent level population calculations to derive the forbidden to intercombination line ratio and estimate the electron density for the emitting region. The potential usefulness of these lines for calculating electron densities in the the Sun, as well as other astronomical objects, is demonstrated.

2. Observational data and reduction

SUMER is designed to study the solar chromosphere, transition region and corona, and has a resolving power of $\lambda/\Delta\lambda =$ 17700–38300 (first order) at 800–1610 Å, and an angular resolution of 1 arcsecond (see Wilhelm *et al.* 1995). This is an ideal instrument for measuring detailed spectroscopic diagnostic line ratios in various solar features. The spectral regions selected for our observations were from 1213 to 1215 Å, and from 1217.5 to 1219.5 Å, for the forbidden and intercombination lines respectively. These regions lie on the wings of the Lyman-α feature (1215.6 Å), and the Lyman-α feature was placed on one of SUMER's two 1:10 attenuators, located near the detector edge.

The observations were carried out on September 2nd 1996 on a quiet region. The 1×300 arcsecond slit (orientated North–South), was centred 318 arcseconds east of Sun centre, 154 arcseconds north of Sun centre. A raster of 45×300 arcseconds was performed, comprising sixty separate 30 second exposures with a raster increment of 0.753 arcseconds east, in each spectral

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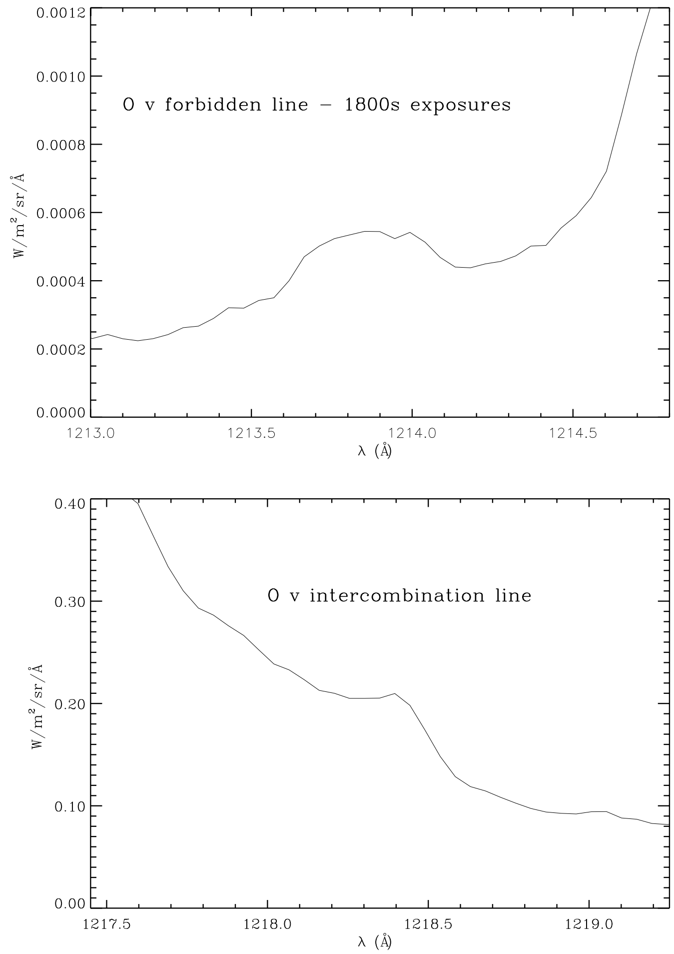

Fig. 1. The temporally averaged spectra of the forbidden and intercombination line regions, totalling 1800 seconds each. The lines are centred in the middle of each plot, and the instrumental count rates have been radiometrically calibrated. No separation of O V lines and the Lyman-α wings has been performed.

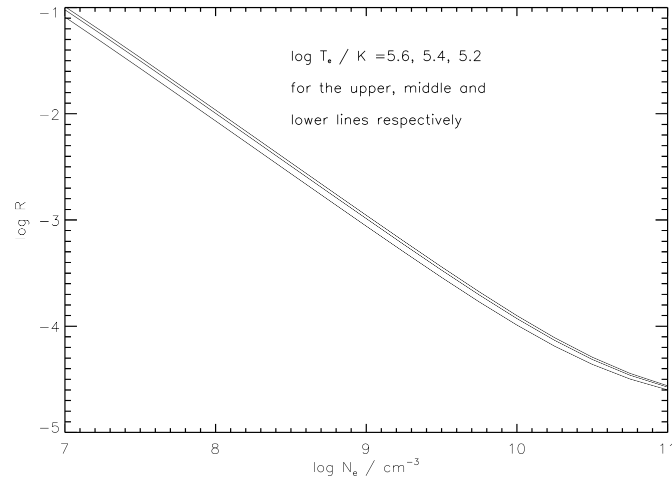

Fig. 2. The theoretical O V line ratio $\log R$, where R = I(1213.9 Å)/I(1218.35 Å), plotted against $\log N_{\rm e}/{\rm cm}^{-3}$ for three values of $\log T_{\rm e}/{\rm K}$; 5.2, 5.4 and 5.6.

region. The O V forbidden line can be seen in each of the 60 spectra at the expected wavelength.

The nonuniform detector sensitivity creates a pattern of hexagon shapes and small circular bumps in the data, which were removed by flat-fielding. The data were also radiometrically calibrated, and destretched (a process that corrects for both wavelength and spatial distortions on the detector), using standard SUMER software. A temporal average of all 60 spectra in each wavelength region is shown in Fig. 1.

3. Theoretical line ratios

The O V model ion used in this work consists of the twelve energetically lowest LS terms, making a total of 20 fine-structure levels, and was first presented in Ryans et al. (1998). Relative level populations, line intensities and resulting line ratios were calculated for electron temperatures and densities in the range of $7 < \log N_{\rm e}/{\rm cm}^{-3} < 11$ and $5.2 < \log T_{\rm e}/{\rm K} < 5.6$, appropriate for the solar transition region and corona. We used the energies from Moore (1980), electron impact excitation rates of Kato, Lang & Berrington (1990), Einstein A-coefficients from Hibbert (1980), as well as the proton excitation rates given in Ryans et al. (1998), and the equilibrium code of Dufton (1977).

In Fig. 2 we plot the log of the theoretical O V forbidden to intercombination line ratio $\log R$, as a function of electron density for three electron temperatures; $\log T_{\rm e}/{\rm K}$ = 5.2, 5.4 and 5.6. It can be seen from the figure that R is very sensitive to $N_{\rm e}$. As the radiative decay rate of the 2s2p ^{3}P$_1$, ^{3}P$_2$ levels (or upper levels of the forbidden and intercombination lines) are very small, collisional de-excitation becomes an important depopulation mechanism over an appropriate $N_{\rm e}$ range ($A_{{\rm m}\rightarrow 1} \simeq N_{\rm e} C_{{\rm m}\rightarrow 1}$, where A is the spontaneous radiative de-excitation rate, C is the electron collisional rate per unit $N_{\rm e}$ and m represents the metastable state). We can also see that R is temperature insensitive. This is because the upper energy levels of the lines are very close together, and R essentially becomes a function of the effective collision strengths of the levels, which are related to the collisional excitation rate coefficients, and are only slowly varying functions of $T_{\rm e}$ (see Keenan 1992; Mason 1997; for a detailed discussion).

4. Results and discussion

We found the wavelengths of the two lines by best-fit Gaussians to the data of Fig. 1. These were found to be 1218.35 Å for the forbidden line, and 1213.95 Å for the intercombination line, in good agreement with 1218.35 Å and 1213.90 Å from Sandlin, Brueckner & Tousey (1977). Our line separation of 4.5$\pm$0.1 Å is in excellent agreement with the theoretical prediction of 4.54$\pm$0.01 Å from Edlén (1983), and the observed value of 4.62 $\pm$ 0.12 Å from McKenna *et al.* (1997). The full-width-at-half-maxima were found to be 0.29$\pm$0.03 Å and 0.25$\pm$0.03 Å respectively, which are the same to with the errors, as one would expect for two lines from the same ion. A linear sloping continuum was subtracted off the spectra to calculate line fluxes, and the resulting line ratio $\log R = -2.50 \pm 0.15$, corresponding to an electron density $\log N_{\rm e}/{\rm cm}^{-3} = 8.50 \pm 0.15$.

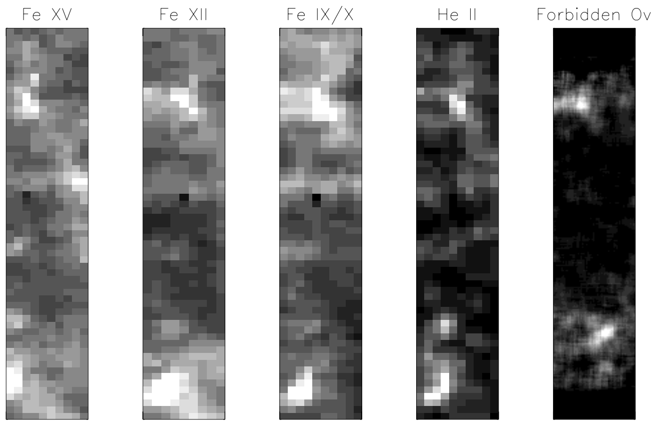

Fig. 3. Four EIT images of the observed region, as well as the forbidden O V image. The bottom left-hand corner of each image is at the point 318 arcseconds east of sun centre, 154 arcseconds north of sun centre, and each image is 45 by 300 arcseconds in extent.

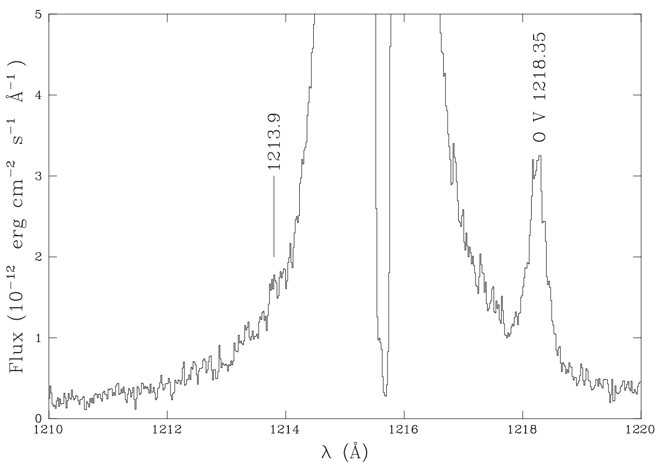

Fig. 4. The HST spectrum of Procyon in the O V wavelength region.

By summing over the forbidden O V line, and subtracting off the Lyman-α wing, an image of the Solar surface in forbidden O V was produced. Fig. 3 shows a smoothed version of this image plotted along side images of the same region taken by the Extreme Ultraviolet Imaging telescope (EIT) on SOHO, at approximately the same time. The images are in order of decreasing formation temperature, and the main features of the EIT images are present in the forbidden O V image. The O V bright points are about 20 arcseconds across. It can also be seen that the contrast between the intensity of the network (the bright points) and the intensity of the cell (in between the bright points) is high, similar to the He II image (which is a chromospheric line), but markedly different from the other images which include higher temperature coronal lines. Both these features are consistent with emission from the chromosphere/transition region, and the bright point dimension agrees well with that observed by Gallagher et al. (1998), who presented intensity cuts across Coronal Diagnostic Spectrograph O V line features.

The detection of these O V lines in the quiet Sun has prompted us to search for the line in the *HST* spectra of stellar sources. As the intensity of the line increases significantly at low densities, a low activity star like Procyon is a good candidate for this study. In Fig. 4 we present the *HST* spectrum of Procyon in the Lyman α wavelength region. The intercombination line is evident whereas the forbidden line is not detected. The upper limit to the line flux would imply a $\log R \leq -1.7$ and hence $\log N_{\rm e}/{\rm cm}^{-3} \geq 7.8$. This value is consistent with the chromospheric and coronal models of Procyon constructed by Brown & Jordan (1981), which imply $\log N_{\rm e}/{\rm cm}^{-3} = 8.7$ at a temperature of 2×10^5 K.

In summary, the high spectral and spatial resolution provided by SUMER has allowed us to unambiguously detect for the first time the O V 1213.9 Å forbidden line for the quiet Sun. The ratio of this line to the O V 1218.35 Å intercombination line gives an electron density of about $3\times10^8{\rm cm}^{-3}$.

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