Determining Energy Balance in the Flaring Chromosphere from Oxygen V Line Ratios

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ABSTRACT

Context. The impulsive phase of solar flares is a time of rapid energy deposition and heating in the lower solar atmosphere, leading to changes in the temperature and density structure of the region.

Aims. We use an O v density diagnostic formed of the λ1392/λ248 line ratio, provided by the Hinode/EIS instrument, to determine the density of flare footpoint plasma, at O v formation temperatures of \( \sim 2.5 \times 10^5 \) K, giving a constraint on the properties of the heated transition region.

Methods. Hinode/EIS rasters from 2 small flare events in December 2007 were used. Raster images were carefully co-aligned to identify and establish the footpoint pixels, multiple-component Gaussian line fitting of the spectra was carried out to isolate the density diagnostic pair, and the density was calculated for several footpoint areas. The assumptions of equilibrium ionization and optically thin radiation for the O v lines used were assessed and found to be acceptable. Properties of the electron distribution, for one of the events, were deduced from earlier RHESSI hard X-ray observations and used to calculate the plasma heating rate, delivered by an electron beam adopting collisional thick-target assumptions, within 2 semi-empirical atmospheres. The radiative loss rate for this plasma was also calculated, for comparison with possible energy input mechanisms.

Results. Electron number densities of at least \( 2 \times 10^{12} \) cm\(^{-3} \) were measured during the flare impulsive phase using the O v \( \lambda 1392/\lambda 248 \) diagnostic ratio. For one footpoint, the radiative loss rate for this plasma was found to exceed that which can be delivered by an electron beam, of the properties implied by the RHESSI data. However, when assuming a completely ionised target atmosphere the heating rate exceeded the losses. A chromospheric thickness of 70-700 km was found to be required to balance a conductive input to the O v-emitting region with radiative losses.

Conclusions. Electron densities have been observed in footpoint sources, at transition region temperatures, far higher than previously expected. The following analysis shows that for heating by collisional electrons, it is difficult, or impossible to raise the temperature of the chromosphere to explain the observed densities without assuming a completely ionised atmospheric density structure.

Key words. Sun – atmosphere, chromosphere, transition region, flares, UV radiation, X-rays

1. Introduction

Solar flares are the result of a sudden reconfiguration of the active region magnetic field, releasing on the order of \( 10^{31} \) ergs of energy (for a medium-sized event) in a matter of minutes. They are visible across the electromagnetic spectrum, but particularly in the dramatic appearance of high temperature extreme ultraviolet (EUV) and soft X-ray emissions. The maximum intensity from the EUV and SXR plasmas occur roughly coincident with, or slightly lagging, an abrupt hard X-ray (HXR) burst emitted by electrons that have been accelerated to non-thermal energies and lose energy via bremsstrahlung radiation in a dense, collisional plasma. HXR imaging spectroscopy by the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) (Lin et al. 2002) has successfully shown that this emission is mainly confined to compact footpoint regions in the lower solar atmosphere — chromosphere to low-corona — and in some cases dense loop sources. The energy collisionally deposited in the chromosphere by electron-electron and electron-ion collisions is capable of explaining rapid heating of footpoint plasma, to millions of kelvin. Theoretical models of collisional energy deposition and the response of the atmosphere have a long heritage and are now very detailed in terms of their treatment of dynamics and radiation transfer (e.g. Nagai & Emslie 1984; Allred et al. 2005; Liu et al. 2009); observational constraints are of course needed to test whether the models are adequate.

How these electrons are accelerated out of an initially (almost) thermal distribution remains a mystery, and decades of effort have focused on using observational signatures to try and understand this. This is not straightforward: observational signatures, other than those directly produced by the accelerated electrons themselves (i.e. HXR and gyrosynchrotron radiation) tend to say more about the heated medium than about the energetic particles that heat it, though direct collisional effects from non-thermal particles may be detectable from detailed examination of spectral features (e.g. Kulínová et al. 2011). However, the distribution of density and temperature in the flare-heated atmosphere, as a function of time, bears some relation to the distribution in space and time of the heating, and thus to the distribution of non-thermal particles which are thought responsible for the collisional heating. The standard ‘collisional thick target’ model for the heating of the flare atmosphere invokes collisional loss by non-thermal electrons (remote from their acceleration location)
and efforts to model the flare atmospheric response have tended to focus on this.

Theoretical problems with this model, primarily the large beam number density required by observations and the associated difficulties with the beam propagating stably, have led to alternatives being proposed to the collisional thick target model, such as local acceleration or re-acceleration of electrons in the chromosphere (Fletcher & Hudson 2008; Brown et al. 2009), while flare heating of the chromosphere by wave dissipation (Russell & Fletcher 2013) or by thermal conduction (Graham et al. 2013) have also been suggested. None of these proposed mechanisms have been implemented into atmospheric modeling so far, or their radiation signatures evaluated.

Flare energy deposition leads to rapid heating and ionisation of compact regions of the lower solar atmosphere to nearly 10 MK (e.g. Mrozek & Tomczak 2004; Fletcher et al. 2013; Graham et al. 2013) and expansion of the local plasma, known as chromospheric evaporation, observed spectroscopically in the EUV and SXR (e.g. Antonucci & Dennis 1983; Czaykowska et al. 1999; Milligan & Dennis 2009). The resulting flaring solar atmosphere is strongly stratified in density and temperature, and we need observations to completely specify its properties over a broad range of temperatures. Interpreting the atmospheric structure from optically thin observations of footpoint radiation is extremely challenging as height information cannot be directly extracted. We can however measure the density at specific temperatures and compare these to the structure of a modelled pre-flare or flaring atmospheres. In this paper we focus on the properties of plasma at a temperature of 2.5 x 10^5 K (log T = 5.4) using a sensitive O iv ratio J192.1248.

Previous work with Hinode/EIS has identified flare footpoint densities of a few times 10^{10} to 10^{11} cm^{-3} (Watanabe et al. 2010; Del Zanna et al. 2011; Graham et al. 2011) at temperatures of 1-2 MK, but higher densities were documented in the late 70’s and early 80’s using the Skylab NRL normal incidence slit spectrograph S082B (Barto et al. 1977) and the Ultraviolet Spectrometer and Polarimeter (UVSP) instrument on board the Solar Maximum Mission (SMM) (Woodgate et al. 1980; Doschek et al. 1977) and Feldman et al. (1977) derived flare densities from O iv ratios at 10^5 K from Skylab slit data. The spectral profiles had distinct velocity-shifted components with densities of 10^{11} and 10^{10} cm^{-3} in the stationary, and at least 10^{13} cm^{-3} in the downward moving component. At similar line formation temperatures Cheng et al. (1982) used the O iv 1401Å to Si iv 1402.7Å ratio and found that a pre-flare density of 2.5 x 10^11 cm^{-3} rose to 3x10^{12} cm^{-3} during the flare impulsive phase. This enhancement was also located within a footpoint kernel and coincided temporally with a HXR burst. The limited spatial resolution in these instruments did however make the distinction between loop and footpoint sources difficult.

In this paper we make new measurements of flare footpoint densities at transition region temperatures, finding equal, and further enhanced densities, while addressing the earlier ambiguity in identifying the emitting region by employing the spectral capabilities offered by Hinode/EIS. Section 2 introduces the data and spectral fitting of the diagnostic lines, Section 3 reveals the measured footpoint densities, Section 4 considers the validity of the assumption of optically thin plasma in ionisation equilibrium, and finally Sections 5 & 6 interpret the results within the framework of an atmosphere heated collisionally by electrons, and one heated solely by a conductive flux.

![Fig. 1: Diagnostic ratio for O iv 192.904Å / 248.460Å](image)

2. Hinode/EIS Data

Good diagnostics of density below log T = 6.0 are uncommon in the EIS spectral range and, as far as we are aware, have not been used in the study of flare footpoint plasmas. Transition region lines during the flare impulsive phase are observed to rise almost simultaneously with the HXR response (Poland et al. 1984; Mariska & Poland 1985) and density measurements of the emitting plasma at these temperatures are therefore extremely useful to help locate the heated plasma within the atmosphere in relation to the HXR emission. The O iv n = 3 transitions at 192.904Å and 248.460Å are observed by Hinode/EIS and their ratio forms a diagnostic pair sensitive to densities above 10^{12} cm^{-3} (Widing et al. 1982). A formation temperature at equilibrium of 250,000 K places their maximum emission within the transition region in the quiet-sun (Vernazza et al. 1981) and the diagnostic curve is shown in Figure 1.

In this article we analyse data from these lines during the impulsive phases of two C-class flares; SOL2007-12-14T01:39 (Flare 1) and SOL2007-12-14T14:16 (Flare 2). The flares have been the subject of previous papers; in an emission measure analysis (Graham et al. 2013), and evaporation and non-thermal broadening study (Milligan & Dennis 2009; Milligan 2011) respectively.

The impulsive phase in each flare was mostly captured in one raster scan by EIS and the raster closest to the GOES SXR derivative peak was chosen to best represent the time of maximum energy deposition (see Graham et al. 2013). RHESSI coverage was not available for Flare 1, but the presence of non-thermal RHESSI HXR footprints was confirmed for Flare 2 (Milligan & Dennis 2009). Footpoints were identified in both flares by the sudden appearance of compact enhancements in the cooler EIS lines, e.g He ii and Fe viii at log T = 4.5 - 5.7, explained by a rise in the chromospheric temperature, and enhanced electron densities in the Fe xiii - xiv diagnostics at temperatures between log T = 6.1 - 6.3 (Milligan 2011), again a sign that the dense lower atmosphere is being heated (Graham et al. 2011). Again we refer the reader to the previous work in Graham et al. (2013) for more details on the raster selection and footpoint identification.

Both flares used the same CAM_ARTB_RHESSI_b_2 study having an exposure time of 10 sec using the 2′′ slit covering a 40″ × 144″ area. No slit stepping was used and so the raster is continuous in the x direction and crosses the footpoints during the impulsive phase, advantageous in these smaller events. The
rasters were prepared with the standard SolarSoft EIS_prep routine.

2.1. EIS Wavelength Correlation

The diagnostic lines in question occur on the two different CCDs of the EIS spectrograph, which are not identically aligned with respect to the grating. This introduces a spatial offset in the slit direction (y-axis) between features observed on each CCD. In addition, the short wavelength CCD is tilted slightly relative to the grating, creating a further wavelength-dependent offset (longer wavelengths appearing lower on the CCD). In the case of a diagnostic ratio it is extremely important to remove these effects to ensure that we observe the same feature in both wavelengths. The tilt was characterised by Young et al. (2009) and a correction included in the eis_ccd_offset.pro routine. We use the same routine to find the y-offset required to correct for both the grating tilt and spatial offset.

We also performed our own cross-correlation using the Fe xii 202Å and Fe xiv 274Å profiles for a range of binary threshold olds. We found an average shift of 16.7′′ in the y-axis (slit axis) but also a shift of 1.0′′ in the x-axis. Our y-offset is comparable with the 17.06′′ shift given by the eis_ccd_offset routine, affirming the Young et al. (2009) prediction. However, the x-shift is not well documented but is perhaps due to an optics focusing issue (noted by Warren et al. (2008)) and does not appear to be dependent on wavelength.

In Figure 2 we show example fitted intensity images in several emission lines from the Flare 1 raster after correlation. Here we use our measured x-shift while using the wavelength dependent y-offset calculated by the EIS routine. The white dotted lines cross the same (x, y) location in each image, centred on the footpoints in O v 192Å, and intersect the corresponding bright emission in all lines for the northern footpoint. The southern footpoint has an anomalous shift of around 1′′ in x when observed at some wavelengths, which is curious as the shift is not apparent in its northern companion, ruling out a problem with the grating tilt. It is also not temperature sensitive, as both Fe xxiii and O v are equally offset while the He ii 256Å image shows no change. The offset is puzzling as an instrumental effect would be expected to alter the other footpoint’s position, yet there is no obvious relation to the line temperature or wavelength. We can not discount the effects of optical depth here, as the active region lies at 450″ on the solar disc with a 29 degree projection to Earth. A small filament seen in TRACE images (not shown here) lies just to the north of the footprint, perhaps absorbing some emission from lines with a higher opacity. We discuss the opacity in Section 4.

2.2. Line Fitting Technique

Multiple component Gaussian fits with several constraints are required to extract the diagnostic line intensities. The oxygen 248Å line is relatively unblended but the density-sensitive 192Å transition lies in a challenging part of the EIS spectral range. Several oxygen and iron lines formed at different temperatures lie in close proximity and interpreting their individual intensities is difficult, or sometimes impossible without constraints from other lines in the raster. Significant contributions, as predicted by the CHIANTI v7.1.3 atomic database (Dere et al. 1997, Landi et al. 2013), are listed in Table 1.

Table 1: Emission lines within the 192Å and 248Å profiles. The O v 192Å intensities relative to the 192.904Å line are taken from CHIANTI v7.1.3, for a density of $n_e = 10^{12}$ cm$^{-3}$.

| Ion   | Wavelength (Å) | log T$_{max}$ (K) | Relative Intensity |
|-------|----------------|-------------------|--------------------|
| O v   | 192.751        | 5.4               | 0.22               |
| O v   | 192.797        | 5.4               | 0.51               |
| O v   | 192.801        | 5.4               | 0.17               |
| O v   | 192.904        | 5.4               | 1.0                |
| O v   | 192.911        | 5.4               | 0.17               |
| O v   | 192.915        | 5.4               | 0.011              |
| Fe xi | 192.627        | 6.2               | -                  |
| Ca xvii | 192.858     | 6.8               | -                  |
| O v   | 248.461        | 5.8               | -                  |
| Al vii| 248.459        | 5.8               | -                  |
| Ar xii| 248.697        | 5.8               | -                  |

Fig. 3: Density sensitivity of the blended O v lines with respect to the 192.904Å transition.

192Å - The target 192.904Å line lies in a complex profile of six O v lines, two coronal Fe xi lines, and a hot Ca xvii line; including a linear background makes a total of 29 free parameters. In order to reduce the required number of free parameters we use a fitting routine based on the technique described in Ko et al. (2009). The neighbouring five O v lines are first constrained by fixing their intensities, centroids, and line widths relative to the target 192.904Å fit. The intensity ratios are estimated from CHIANTI for an electron density of $10^{12}$ cm$^{-3}$ and are shown in Table 1.

There is some density sensitivity among the other oxygen lines relative to 192.904Å, plotted in Figure 3 however only the 192.797Å line has any significant density sensitivity, and only up to $10^{12}$ cm$^{-3}$. As we do not know the density before fitting we have tested that the choice of density will have a minimal effect. Changing the density from $10^{12}$ to $10^{10}$ cm$^{-3}$ raises the fitted 192.904Å intensity by < 10%. By using the higher density of $10^{12}$ cm$^{-3}$ it serves to reduce the diagnostic ratio, erring on the side of a lower density estimate.

Fe xi 192.627Å is distinct from the overall profile and can be fitted with little constraint, only requiring that the width be ±40% of the well-observed Fe xi 188.230Å line. Fe xi 192.814Å is tied to the Fe xi 188.230Å line by a constant intensity ratio of 0.2, which is insensitive to density. The centroid shift of both

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iron lines within the profile were also tied to the 188Å line. Finally, the parameters of the last remaining Ca xvi line are left mostly unconstrained, with the only limit imposed being that the centroid position should not be red-shifted.

248Å - The 248Å O v line is more straightforward to fit as the Ar xiii contribution is in most cases resolvable. Al viii however, lies near the O v line centroid and some extra constraint is needed. From CHIANTI, using the DEM derived in Graham et al. (2013), the Al viii contribution is 10% of the O v intensity for photospheric abundances.

2.3. Footpoint Pixel Selection

In Figures 3 (a) and (b) we show the intensity maps in the 192.904Å and 248.460Å lines (left and right columns) for each flare (Figures (a) and (b)). The compact footpoints are clearly identified against the background active region emission. In each flare two footpoint regions are defined by 6′′ x 7′′ white boxes; including all of the pixels within and under the white lines. The brightest 192Å pixel in each footpoint region is marked by a black cross on both wavelengths. We noted that the brightest emission in both 192Å and 248Å lines did not always coincide. This is particularly clear in Flare 1 (Figure 3(a)), where for Footpoint 1 the strongest emission in 248Å is found one pixel (2′′) to the right of 192Å (discussed in the previous section).

To acknowledge these small position uncertainties the intensity ratio is calculated using two methods. In the first method, spectra for each footpoint are averaged over the region within the white box, which is the same for both lines, before fitting and finding the ratio. The second method takes the ratio from the pixel brightest in 192Å within the footpoint regions and makes the ratio with same pixel in 248Å; plus a binning by ±1 pixels in the y-direction (a 2′′ x 3′′ region) to account for any correlation uncertainty. Densities from the box method are likely to return a lower limit on the density as it includes pixels from outside of the footpoint regions. The latter ‘pixel’ method assumes that the brightest emission originates from the same source in both lines but has enough spread to account for uncertainties in the correlation. Of course if the source size is smaller than the instrumental point spread function (3′′-4′′ in EIS) then the density in unresolved structures may yet be higher.

3. Results

3.1. Fitted Spectra

The fitted spectra for the bright pixels in Figure 5 (Flare 1) show a clear enhancement of the O v 192Å line (red line, right hand profiles) compared to the pre-flare (Figure 7) with the line being distinct from the rest of the profile. This 192.904Å transition is excited from a metastable level and is expected to be brighten quickly as the dense emitting plasma is heated; similar line profiles in transition region brightenings were also found by Young et al. (2007). The unconstrained Ca xvi emission (blue line) in these footpoints makes a small contribution among the other predicted Fe xi and O v intensities (green dashed and black dotted lines respectively). In Figure 5 the Ca xvi (blue line) emission is more significant, possibly due to more hot loop material being present along the line of sight.

We have highlighted the spectra partly to demonstrate the robustness of the fitting method. Between the constrained intensities of the Fe xi and O v lines there is a small range of parameter space that the free O v 192.904 and Ca xvii 182.853 lines can occupy. The spectra here demonstrate that large changes in the intensity ratio between the calcium and oxygen lines are handled well among the various constraints, for example, nowhere do we see predicted line intensities for Fe xi 188.213 or the five constrained O v lines exceeding the profile boundary. Assum-
ing that the atomic physics used to predict the constraints is to be trusted, these two free lines can be extracted from the blend reliably.

The O\textsuperscript{v} 248Å fits (left hand plot on Figures 5 and 6) are more straightforward, however, the EIS effective area is lower here and the data uncertainties are larger. The Al\textsc{iii} contribution (blue line) in the red-wing can be fitted with minimal constraint. The background level is noisy but the line here is distinct enough to be removed from the O\textsuperscript{v} 248Å line. Al\textsc{iii} (green dashed line) lies within the O\textsuperscript{v} profile and was fitted with a fixed 10% contribution of the O\textsuperscript{v} line. Accounting for these blends will reduce the 248Å line intensity; as the line is the denominator, therefore overestimating the blends will increase the density estimate.

3.2. Densities

The footpoint densities were found by comparing the measured ratio to the diagnostic curve in Figure 1 and our results are given in Table 2. Taking the absolute error from the fit parameters for width and peak intensity, the error in total intensity of the 192Å and 248Å lines can be calculated, and thus on the ratio. An estimate of the density error is made by taking these limits on the ratio and finding an upper and lower limit to the density on the diagnostic curve.

In all of the footpoints we find that the ‘pixel’ derived density is at least \( \log n_e = 11.4 \), in line with the measurements from Skylab and UVSP where the density varied between \( \log n_e = 11.5 \) – 12.5 (Cheng et al. 1982; Keenan et al. 1991), though our results exhibit some extreme variation beyond this value. For example, the line ratio we find at Flare 2 FP1 is beyond the limits of the diagnostic sensitivity, implying that the density lies above \( \log n_e = 14.0 \) (see the diagnostic curve in Figure 1). As an upper limit to the density cannot be found here we can only sensibly estimate a lower limit to the density. The lower limit of the ratio measurement gives us a value of \( \log n_e > 11.97 \) (these ‘saturated’ densities are marked by an asterisk in Table 2).

A simple explanation of the larger variation in the new results could be through the improved spatial resolution of EIS. In Cheng et al. (1982) the UVSP spectrometer used a 4′′x 4′′ slit mode, much larger than our pixel sources, while in Feldman et al. (1977) the Skylab spectrograph had limited resolution along the slit, making footprint identification difficult. Even though our pixel method uses a 2′′x 3′′ y-axis binning to account for correlation error, the EIS point spread function size is approximately the same, and less than the slit size used for UVSP. It is entirely possible that we are now observing much smaller sources, and seeing high densities in places that were previously unresolved.

Checking the results for the box-averaged method reveals similar values of density with a tendency to reduce the density in Flare 1 FP1 and Flare 2 FP2. In Section 2.1 we noted that Flare 1 FP1 has an unexplained shift in the position of the footpoint in 248Å relative to 192Å so we omit it from the pixel-method results. Using the box method it shows a density approaching \( \log n_e = 12 \). On the contrary Flare 2 FP2 displays a higher density when gathering from a larger area. The high density source may in fact be much larger here as numerous other pixels in the region have saturated densities with ratios between 3 and 4.5.

To summarise, three of the footpoints show densities ranging between \( \log n_e = 11.50 \) – 12.50 while in one case the density is
Fig. 5: Fitted spectra for Flare 1 using the brightest pixels for Footpoints 1 and 2 - plots (a) and (b) respectively. For both spectral profiles the total fit and data is shown in black solid and dashed lines respectively. The calibrated 1-σ errors on each data point is also plotted. The oxygen lines forming the diagnostic ratio are plotted in red in both columns, with the various blends described by the legend.

Fig. 6: As for Figure 5 but showing spectra from Flare 2, Footpoints 1 and 2 - plots (a) and (b) respectively.
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Fig. 7: As described in Figure 5 but with a sample spectra taken from a non-flaring region 55” to the north of the Flare 1 footpoints - note the dominant iron Fe x1 contribution in the green dashed line.

Table 2: O V footpoint densities derived from the $I_{192}/I_{248}$ ratio. Density estimates denoted by an asterisk have an upper limit beyond the maximum of the diagnostic curve; the density therefore either represents a lower limit or has no estimated upper limit. The pixel values use a source of 2” x 3” and the box is taken from a 6” x 7” region.

| Footpoint       | $I_{192}/I_{248}$ (pixel) | $\log n_e$ (cm$^{-3}$) | $I_{192}/I_{248}$ (box) | $\log n_e$ (cm$^{-3}$) |
|-----------------|---------------------------|-------------------------|-------------------------|-------------------------|
| Flare 1 FP1     | -                         | 2.30 ± 0.12             | 11.85 ± 0.31            |
| Flare 1 FP2     | 1.89 ± 0.09               | 11.45 ± 0.16            | 1.52 ± 0.04             | 11.11 ± 0.08            |
| Flare 2 FP1     | 2.57 ± 0.22               | 12.30 ± 1.45 - 11.92    | 2.83 ± 0.05             | > 14.27*                |
| Flare 2 FP2     | 2.56 ± 0.05               | 12.27 ± 0.21            | 1.87 ± 0.26             | 11.43 ± 0.04            |

conservatively at least $\log n_e = 11.92$, and possibly greater than $\log n_e = 13$.

4. Understanding the Assumptions

The high densities in Flare 2 should be examined carefully considering the effect of relaxing the assumptions of optically thin plasma in ionisation equilibrium, under which the CHIANTI diagnostic curves are calculated. In this section we calculate the optical depth for both diagnostic lines in two semi-empirical atmospheric models: the VAL-E bright network model (Vernazza et al. 1981), representing the case that the atmosphere is heated without having time to respond hydrodynamically, and the F1 model (Machado et al. 1980) representing the structure of an atmosphere that has already adapted to flare energy input. Additionally, we investigate the diagnostic curves for non-equilibrium line formation temperatures.

4.1. Optical Depth

The optical depth at line centre for both O V lines is calculated using the expression in Mihalas (1978) (used to the same effect in Dzifčáková & Kulinová (2011) for Si ii transitions). Assuming a thermal Gaussian absorption profile, where $\Delta \nu_D = (\nu_0/c)(2kT/M)^{1/2}$, the optical depth at line centre is given by

$$\tau_{\nu_0\nu_i} = \frac{B_{ij}}{4\pi^{3/2}} \frac{\nu}{\Delta \nu_D} \int \left( \frac{g_j}{g_i} \right) \frac{n_i}{n_j} \frac{n_{\text{ion}}}{n_{\text{el}}} \frac{n_H}{n_e} \frac{n_{\text{al}}}{} n_{\text{al}} dS,$$  

where $B_{ij}$ is the Einstein absorption coefficient from the lower level $i$ to upper level $j$. $B_{ij}$ can be expressed in terms of the radiative decay coefficient,

$$B_{ij} = A_{ji} \left( \frac{g_j}{g_i} \right) \left( \frac{1}{2\hbar^2} \right),$$

where $g_i$ and $g_j$ are the statistical weights for levels $i$ and $j$ and $A_{ji}$ is the Einstein coefficient for spontaneous de-excitation. Crucially, the terms inside the integral depend on position in the atmosphere; the relative population of level $i$, $n_i/n_{\text{al}}$, is sensitive to density, the ion abundance $n_{\text{ion}}/n_{\text{al}}$ is strongly dependent on temperature, and $n_H/n_e$ varies with depth. These parameters are taken from the CHIANTI database and we assume constant photospheric abundances, $n_{\text{al}}/n_H$, given by Grevesse & Sauval (1998).

The optical depth at line centre is found for both lines by integrating from a chosen depth through the atmosphere above it, and in Figures 8 (a) and (b) we show how it varies with temperature for both the VAL-E and the F1 atmospheres. The optical depth quickly plateaus where the ion abundance peaks, as the absorbing ion is not yet formed at lower temperatures. The 192Å line always remains below $\tau = 1$ whereas 248Å remains completely optically thin with $\tau < 10^{-8}$. The large difference in optical depths between the lines is mostly due to the difference in population of their lower levels. The optically thin assumption in this case is valid for both lines, and the diagnostic ratio should not be altered.

We should however note that Equation 1 considers only the balance between the absorption of photons and spontaneous and stimulated emission, where the absorption profile is equal to the emission profile. A more complete description would include the...
After detailed analysis of high resolution *Hinode*/EIS spectra we can confirm the presence of footpoint densities above $\log n_e = 12$ at a temperature of $2.5 \times 10^5$ K. One footpoint clearly reaches the limits of the diagnostic, therefore our results are also the first to suggest that densities at transition region temperatures may be found above $\log n_e = 13$.

Here we will investigate the energy input required to produce the observed temperature and density in the same two semi-empirical atmospheric models as Section 4 the VAL-E bright network model and the F1 flare model. Heating of the O v emitting region by both accelerated particles, and thermal conduction will be considered in turn. The heating rates by accelerated particles are also calculated for each model using a modified, completely ionised density structure, a reasonable assumption as the appearance of highly ionised states of oxygen, iron, and calcium is clear evidence that the emitting region is ionised by rapid heating and collisions (Allred et al. 2005).

The two model atmospheres are plotted in Figures 10 (a) and (b). In the VAL-E model, the electron density only reaches $\log n_e = 12$ below 500 km, well into the temperature minimum region. The structure of the F1 model is similar to VAL-E, except that the transition region has been ‘pushed’ down to around 1400 km (note the different x-axis scales) and the density enhanced up to $\log n_e = 12$ at higher altitudes. The completely static model may be a strong assumption however, as pressure-driven density enhancements may occur during rapid heating. In future we plan to extend this work to include atmospheric structures calculated from radiative hydrodynamic codes, e.g Fisher et al. (1985) and Allred et al. (2005).

5. Flare Heating of Dense Plasma

After detailed analysis of high resolution *Hinode*/EIS spectra we can confirm the presence of footpoint densities above $\log n_e = 12$ at a temperature of $2.5 \times 10^5$ K. One footpoint clearly reaches the
have been obtained in other medium sized events (Graham et al. 2011). We therefore expect this to be fairly typical among other events.

We calculate the heating rate per hydrogen nucleus as a function of density within the respective model atmosphere. The heating rate, $Q$, is then easily evaluated at each height. To aid the interpretation of the diagnostic results, $Q$ is plotted in Figures 10 (c) and (d) against the model electron density, for both model derived and fully ionised density structures (diamonds and crosses respectively). As $Q$ is not expressed as a function of electron density, only of column depth, the reader should be aware that the heating rate can have two values at a single density. The model heights at some intermediate points are plotted for clarity.

The column depth, $N$, represents the quantity of material traversed by the electron beam. From the atmospheric profiles in Figures 10 (a) & (b) we obtain the column depth as a function of height by integrating $\int_{\infty}^{\infty} n_H(S) dS$ at each position in the atmosphere, where $n_H$ is the hydrogen density and $S$ is the height in the model atmosphere. The heating rate, $Q$, is then easily evaluated at each height. To aid the interpretation of the diagnostic results, $Q$ is plotted in Figures 10 (c) and (d) against the model electron density, for both model derived and fully ionised density structures (diamonds and crosses respectively). As $Q$ is not expressed as a function of electron density, only of column depth, the reader should be aware that the heating rate can have two values at a single density. The model heights at some intermediate points are plotted for clarity.

Predictably, we find that the heating rate falls off rapidly with increasing density, especially in the final few 100 km towards the photosphere. The optically thin radiative loss rate per particle, $n_e \Lambda(T)$, was taken from CHIANTI for the O V formation temperature.

The rate is expressed as

$$Q(N) = \frac{1}{2} \frac{K \gamma (\delta - 2)}{\mu_e} \beta \left( \frac{\delta - 2}{2 + \beta} \right) F_P \left( \frac{N}{N_c} \right)^{\beta - 2} \text{ ergs s}^{-1},$$

where $K = 2 \pi e^4$,

$$\beta = 2x \Lambda + (1 - x) \Lambda'' / \Lambda' + x(\Lambda - \Lambda'),$$

and the Coulomb logarithm for an ionized target, $\Lambda$, and effective Coulomb logarithms for neutral targets, $\Lambda'$ and $\Lambda''$, are given in Hawley & Fisher (1994). The ionisation fraction, $x$, can be either assumed to be constant or estimated from the ratio of model electron density to hydrogen density.
perature above. The point where this line intersects the heating rate indicates where the atmosphere, if heated to O v temperatures, will radiate energy away as quickly as it is deposited, by optically-thin radiative losses. In deeper layers the energy deposition does not deliver enough energy to raise the ambient temperature.

For the model ionisation structure, given by \( n_e / n_H \), the critical density for zero net heating in the VAL-E model is approximately \( \log n_e = 12.2 \), and in the F1 atmosphere \( \log n_e = 12.4 \). The measurements for Flare 1 are comfortably below these values, yet Flare 2 displays footpoint densities of at least \( \log n_e = 12.3 \) and possibly over \( \log n_e = 13.0 \), placing them close to, or below the depth that can be heated to \( 2.5 \times 10^5 \) K by the fast electrons (between 100-300 km). Difficulty in depositing enough energy at these depths is not entirely surprising, as driving heating into the temperature minimum region has always been a challenge to explain white light sources. What is a curiosity, especially given the conservative nature of our diagnostic method, is the observation of extremely dense footpoint plasma at transition region temperatures which could not have been directly heated by an electron beam in situ.

If we assume that both atmospheres are completely ionised, i.e \( n_e = n_H \), then the heating rate intersects the radiative loss rate at a density 3 orders of magnitude higher. The O v emitting region therefore occurs much higher, at approximately 1200 km where the heating rate far exceeds the radiative losses. This position is still deeper than where the fully ionised region ends in the F1 atmosphere, \( \sim 1400 \) km, and without a further diagnostic to directly probe the ionisation state throughout the atmosphere we can only deduce that the location of heating lies somewhere between 200-1200 km.

5.2. Conductive heating of the O v emitting region

In addition to any source of direct heating there may be a significant or dominant conductive energy transport into the deeper layers of the atmosphere. The emission measure distributions obtained in Graham et al. (2013) were consistent with a flaring chromosphere that was in conductive and radiative balance, where a directly heated layer at 10 MK supplied a conductive flux to the chromosphere below, balanced by radiative losses.

In a steady-state atmosphere with no dynamic flows the energy balance equation is,

\[
\begin{align*}
\nabla \cdot F_c - E_R + E_H &= 0 \\
\text{(6)}
\end{align*}
\]

where \( F_c \) is the conductive flux, \( E_R \) is the radiative loss rate, and \( E_H \) the heating rate from additional sources. If we assume that no direct heating reaches the region where conductive energy input is balanced by radiative losses, then

\[
\nabla \cdot F_c - n_e^2 \Lambda(T) = 0 \\
\text{(7)}
\]

for a radiative loss rate \( \Lambda(T) \) at the temperature of O v formation (\( \log T = 5.4 \)). The conductive flux in 1-D is expressed as

\[
F_c = k_\sigma T^{5/2} \frac{dT}{dS} \\
\text{(8)}
\]

where \( k_\sigma = 9.2 \times 10^{-7} \) for classical Spitzer conductivity. The temperature gradient or length scales are not known in the chromosphere, and the conductive flux can only be estimated. However, by making some simple assumptions we can estimate the scale of the emitting region required to balance a purely conductive heating term. In 1-D the conductive term in Equation (7) then becomes

\[
dF_c / dS = k_\sigma \left( \frac{5}{2} T^{3/2} \frac{dT}{dS} + T^{5/2} \frac{dT}{dS^2} \right) \\
\text{(9)}
\]

If the top of the chromosphere is impulsively heated to \( T_{\text{max}} = 10 \) MK then we can replace \( dT / dS \) with \( (T_{\text{max}} - T) / L \), where \( T \) is the temperature of the plasma that is emitting oxygen lines, and \( L \) is the chromospheric scale length required to balance conductive energy inputs with radiative losses. By assuming a uniform temperature gradient, i.e \( dT / dS^2 = 0 \), the conductive flux for a scale length in units of km becomes

\[
dF_c / dS \sim \frac{2.75 \times 10^6}{L^2}. \\
\text{(10)}
\]

By rearranging Equation (7), and inserting the result above, the chromospheric length scale \( L \) is

\[
L = \left( \frac{2.75 \times 10^6}{n_e^2 \Lambda(T)} \right)^{1/2}. \\
\text{(11)}
\]

Our requirement is to supply enough conductive flux to the chromosphere below a 10 MK layer to allow plasma at \( T = 10^{5.5} \) K to radiate. The density of the chromosphere will vary with depth, but if we assume that the average density of the whole region is between \( 10^{10} - 10^{12} \) cm\(^{-3} \) then the conductive input will be balanced by the radiative losses for a chromosphere of thickness 70-700 km. Inspecting the atmospheres in Figures 10 (a) and (b) shows that these thickness are reasonable within the picture of a compressed, lower altitude transition region. However, the semi-empirical models shown do not include a sufficiently high temperature component at \( \sim 10 \) MK, as found by several more recent studies (Mrozek & Tomczyk 2012; Graham et al. 2013; Fletcher et al. 2013).

6. Conclusions

The location, or depth in a 1-D interpretation, of energy deposition within the flaring chromosphere remains an important constraint on the global plasma behaviour of the flaring chromosphere. We have presented in this paper new confirmation of 250,000 K footpoint plasma with electron densities of \( \log n_e (\text{cm}^{-3}) = 11.4 - 12.3 \) in two flares, with one footpoint yielding a saturated diagnostic implying that the density may be above \( \log n_e = 13 \). The assumptions of optically thin plasma in ionisation equilibrium were found to be acceptable and the diagnostics were deemed to be reliable at these temperatures.

With our measurement of the electron density (and knowledge of the temperature) of the region emitting the O v emission we have been able to estimate its properties under different assumptions about the energy input. If we assume an atmosphere structured according to VAL-E or F1 then beam collisional heating would balance radiative losses at a temperature corresponding to the O v formation temperature at a location at or below 300 km above the photosphere. If the calculation is repeated for the VAL-E and F1 mass density structure but assuming complete ionisation then the O v emitting region is found 1200 km above the photosphere. Energy transport from a directly heated slab via a conduction flux was also considered and can provide
the necessary O v emission given a chromosphere of thickness 70–700 km, depending on the model density, which is consistent with the emission depths that we have estimated. A combination of both transport methods will be considered in future.

The surprising result is that for the VAL-E and F1 ionisation structure, at the implied height of the O v emission, the radiative loss rate is equal to the energy input rate, i.e. it will be insufficient to raise the ambient plasma temperature to explain the O v emission. However, under the assumption of a completely ionised atmosphere we find that the heating rate is sufficient to explain the O v emission. The ionisation state of the flaring chromosphere clearly plays an important role in determining the energy balance in flare footpoints and on diagnostics of this kind. By coupling further temperature and density diagnostics with radiative-hydrodynamic models, and including new observations of ionisation/recombination signatures ([Heinzel & Klein 2013]), then the location of the emitting region may be better constrained.

In closing we bring to attention the spectra obtained by the Skylab and UVSP spectrographs, as few studies of this kind have been made in recent years yet they are of great diagnostic value. Whilst it is possible with EIS to make this particular diagnostic, the long wavelength detector is degrading (Del Zanna 2013) and the 248Å line is becoming difficult to observe without a specifically targeted EIS study (longer exposures may be necessary which are not best suited to flare observations). The Extreme-Ultraviolet Variability Experiment (Woods et al. 2012) measures the strong O v 629.73Å to 760.30Å ratio among others, but footpoint identification is difficult with new spatial resolution. Data from the Interface Region Imaging Spectrometer (IRIS) (De Pontieu et al. 2014) is extremely promising though, as the O iv 1404.78Å to 1399.77Å ratio (Dudík et al. 2014) should provide a useful diagnostic at transition region temperatures and with improved spatial and temporal resolution.

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