SPATIALLY-RESOLVED DIAGNOSTICS OF CORONAL HEATING IN SOLAR ACTIVE REGIONS

A. Fludra¹ and J. Ireland²

¹CCLRC Rutherford Appleton Laboratory, Didcot, OX11 0QX, UK
²L3com. Analytics Corp., NASA GSFC, Greenbelt, MD 20771, USA

ABSTRACT

We study the relationship between EUV spectral line intensities and the photospheric magnetic field in solar active regions, using magnetograms from SOHO-MDI and EUV spectra of the Fe XVI 360.8 Å line (2 × 10⁶ K) and the O V 629.7 Å line (220,000 K) from the Coronal Diagnostic Spectrometer on SOHO, recorded for several active regions. Two complementary analysis methods are compared - a global analysis applied to the coronal line emission (Fe XVI), and a spatially-resolved analysis of the transition region emission (O V). We overlay and compare spatial patterns of the O V emission and the magnetic flux concentrations, with a 4" × 4" spatial resolution, and search for a relationship between the local O V line intensity and the photospheric magnetic flux density in each active region. While this dependence exhibits a certain amount of scatter, it can be represented by a power law fit. The average power index from all regions is 0.7 ± 0.2. Applying static loop models, we derive the dependence of the volumetric heating rate on the magnetic flux density, \( E_\phi \propto B_\phi^{0.8} \), and compare it to the dependence predicted by the coronal heating models.

Key words: EUV emission; active regions; magnetic field; coronal heating.

1. INTRODUCTION

One of the fundamental questions in solar physics is identifying the mechanism that heats the solar corona. While a large theoretical effort has resulted in many models, it is not known yet which of those processes operates on the sun. Observational constraints on the coronal heating models can be obtained from relationships between the photospheric magnetic flux and intensities of EUV spectral lines and X-rays emitted from the solar atmosphere. Active regions provide the best data to study this topic, due to strong concentrations of magnetic field, a large range of magnetic flux density, and strong EUV emission. Previous work (e.g., Gurman et al., 1974; Schrijver 1987; Fisher et al. 1998; Fludra and Ireland 2003a) found power-law relations between the total magnetic flux, \( \Phi \), and total intensities of a few chromospheric, transition region and coronal emission lines in active regions, e.g., \( I_{X-ray} \propto \Phi^{1.2} \).

Data from the Coronal Diagnostic Spectrometer (CDS) on SOHO together with the SOHO/MDI magnetograms provide an excellent material to make a substantial advance in the study of the coronal heating. Using four spectral lines from the CDS synoptic data set: He I 584.3 Å (2 × 10⁶ K), O V 629.7 Å (2.2 × 10⁵ K), Mg IX 368.00 Å (9.5 × 10⁴ K), and Fe XVI 360 Å (2.5 × 10⁷ K), Fludra and Ireland (2002a,b; 2003b) found power laws between the total line intensities, integrated over an active region area, and the total unsigned magnetic flux \( \Phi \). For the two best diagnostics, the coronal Fe XVI 360.8 Å line and the transition region O V 629.7 Å line, they find that the total Fe XVI intensity is proportional to \( \Phi^{1.2} \), and the total O V intensity is proportional to \( \Phi^{0.78} \). Since the total unsigned photospheric magnetic flux in the 50 – 500 G range is nearly proportional to the magnetic area (Fludra and Ireland, 2003b), a large part of the global dependence, \( I_{\text{tot}} \propto \Phi^{\delta} \), can be explained by the variation of the active region area. However, there exists an underlying local \( I \propto B \) dependence that can be used as a diagnostic of the coronal heating.

Fludra and Ireland (2003a) show for the first time that the equation describing how the observed total line intensity integrated over an active region area arises from the magnetic field, can be approximated by a Laplace integral:

\[
I_\infty / H_0 = \int_0^\infty I(\phi) \exp(-\beta \phi) d\phi
\]

(1)

where \( \beta \) is the slope of the histogram of the unsigned magnetic flux density \( \phi \) above 50 G, \( H_0 \) is the normalisation of the histogram, and \( I_\infty \) is the intensity that would arise if the histogram extended from \( \phi = 0 \) to infinity (\( I_\infty \) can be determined iteratively). They use this property to solve an inverse problem and derive a function relating the line intensity from individual loops, \( I(\phi) \), to the photospheric magnetic flux density at their footpoints. They propose a simple model in which the intensity of a coronal line Fe XVI 360.8 Å in an individual coronal loop is proportional to the footpoint magnetic flux density to the power of \( \delta \):

\[
I(\phi) = Q_1 L_\phi \phi^\delta
\]

(2)
where $Q_1$ is a constant and $L$ is the loop length, and explore how well the value of the power index $\delta$ is constrained by the observations. For the coronal line Fe XVI, they obtain $\delta = 1.3$, where $1.0 < \delta < 1.6$ with 90% confidence.

Our simulations (Fludra and Ireland 2003b) using static loop models show that the intensity of the coronal Fe XVI line is proportional to $P^2$, where $P$ is pressure, for loop-top temperatures in the range $2.0 - 2.5$ million K. Thus, using scaling laws, we have $I_{Fe} \propto E_{\nu}^{3/2}$. Combining this with $I_{Fe} \propto \phi^{1.3}$, we obtain the heating rate $E_h \propto \phi^{0.75}$.

In this paper we extend the analysis to another spectral line, O V 629.7 Å, which is emitted at transition region temperatures ($2.2 \times 10^6$ K) and thus its intensity in loops that reach coronal temperatures is always proportional to pressure $P$ (Martens et al. 2000). This is a convenient property for the study of the coronal heating because for static loops it relates the intensity and the volumetric heating rate $E_h$, $I_{loop} \propto E_h^{2/3} I_{Fe}^{5/7}$.

First results of this analysis are presented by Fludra and Ireland (2003c). Here we extend that work to include a different example and give a more detailed discussion.

First, we assess whether we can use the Laplace transform to invert Equation 1 for the O V line intensity in the same way as Fludra and Ireland (2003a) did for the Fe XVI line intensity. We find that the parameter $\delta$ is not too well constrained by the global relationship ($\delta = 0.8 \pm 0.3$ for all 45 active regions considered, and $\delta = 0.7 \pm 0.5$ for 26 active regions without sunspots). Therefore, in this paper we will use a spatially-resolved comparison between the OV intensity and the magnetic field, instead of the global relationship of integrated quantities. However, that global relationship gives us an indication of the dependence of the intensity on the average active region size: when we approximate an average loop length $L_{av}$ in each region as the square root of the projected area of the coronal Fe XVI emission, the goodness-of-fit criterion $\chi^2$ is minimised for $L_{av}^3$, $\lambda = -0.5 \pm 0.1$.

2. COMPARISON OF SPATIALLY RESOLVED DATA

We adopt the following procedure of aligning the CDS OV rasters with the MDI magnetograms:

Following Fludra and Ireland (2003a), we assume that a majority of magnetic field lines have both footpoints in the same active region, and that a spectral line intensity emitted from a loop depends on the magnetic flux at its footpoints. In other words, each magnetic pixel, with the unsigned magnetic flux density $\phi$, is located at a footpoint of some coronal loop with length $L$ and contributes intensity $I(\phi, L)$ to the emission from that loop, where the function $I(\phi, L)$ may be different for different spectral lines. Moreover, for lines emitted at transition region temperatures ($10^6 - 4 \times 10^5$ K) we assume that their emission is located so close to the loop footpoints that, for practical purposes, the projection of the emission onto the photosphere overlaps the magnetic field concentrations at the footpoint for active regions observed at the solar central meridian.

To align the MDI and CDS data, a simulated intensity image in the OV 629.7 Å line is calculated from the magnetogram by assuming a model $I = |B|^\delta$ at each magnetogram pixel, for $\delta = 0.5$. This simulated intensity map is smeared out by convolving it with a spatial point spread function (PSF) representing the PSF of the CDS (a 2D gaussian with FWHM= 1.7", FWHMY = 8").

The observed CDS raster is corrected for the effect of the solar rotation which makes the distance between features (in the E-W direction) appear shorter than it really is. Although the effect is small, less than a few arcseconds for a raster duration of 40 minutes, it may lead to a misalignment of the magnetic and EUV features by up to 6". Therefore, the CDS raster is 'stretched' to a spatial grid that is free from the effect of the solar rotation, so that the distance between various features in the E-W direction becomes a true distance on the solar surface.

Subsequently, the observed, 'stretched' CDS OV raster and the simulated OV intensity map are interpolated to a finer step of $0.5"$ and co-aligned by performing a 2D cross-correlation. After the co-alignment, both images are rebinned to a coarser pixel size of $4" \times 4"$.

Assuming the relationship from Equation 2, $I(\phi) = Q_0 \phi^\delta$ at each pixel, we vary $\delta$ from 0 to 1.2 with a step of 0.1. For each value of $\delta$, $Q_0$ is calculated to minimise $\chi^2$ that compares the log of observed and simulated intensities for all pixels with the magnetic flux density greater than $20$ G:

$$\chi^2 = \sum_{i,j} (1. - \log(I_{sim,i,j})/\log(I_{obs,i,j}))^2$$

(3)

Here, $I_{obs,i,j}$ and $I_{sim,i,j}$ are local intensities observed and simulated, respectively, in pixel $(i,j)$. The optimum $\delta$ is that which gives the global minimum of $\chi^2$. Fig. 1 shows an example how $\chi^2$ varies with $\delta$ for one of the

![Figure 1. The dependence of $\chi^2$ on the power index $\delta$ for one of the active regions.](image-url)
active regions. In this analysis, $Q_0 = Q_1 L^3$ is held the same for all pixels as we do not measure the lengths of individual loops within the active region.

Fig. 2a shows the comparison of simulated and observed OV intensities for one of the active regions, for the optimum value of $\delta$. Fig. 2b compares the observed OV intensities with a 5-point boxcar average of the simulated intensities which significantly reduces the scatter. Clearly, on small spatial scales ($4'' \times 4''$) the relationship between the line intensity and the magnetic field is more complex and has greater scatter than it would appear from spatially integrated $I - \Phi$ plots (e.g., Fludra and Ireland 2003b). We attribute the scatter to a combination of statistical noise, a distribution of loop lengths inside active regions, and the time variability of the EUV emission.

The errors of the SOHO/MDI magnetic flux density measurements are of the order of 30% (T. Tarbell, private communication). The statistical errors of CDS OV intensities depend on the slit used, the exposure time, and the observed intensity. The synoptic rasters analysed in this paper are taken with the $2\,'' \times 240''$ slit and exposure time of 15 s. Estimating the intensity errors according to a procedure given by Thompson (1998), we obtain relative errors in the range 4 – 8% for the active region intensity levels.

Another reason for the difference between the predicted and observed OV intensities is a variable nature of the transition region emission. The CDS raster takes 40 minutes to complete. Moreover, sometimes there is a difference of up to several hours between the time of the magnetogram and the start of the CDS raster. Therefore, it is likely that the line intensities change in this time period. In particular, the OV emission can be quite variable on time scales of the order of minutes to tens of minutes. Figure 3 shows an example of a time series taken in the OV line in an active region plage (AR8249 on 23 June 1998). This region was previously analysed for the presence of oscillations in a sunspot plume (Fludra 1999). Here we present a time series in a plage area near a sunspot, recorded in a $4'' \times 3.4''$ pixel. In this two-hour interval the O V intensity shows both a slow 70% increase and bursts by up to 100% on shorter time scales of several minutes. This is quite a typical behaviour of the O V intensity in brighter areas of many active region plages. For this time series, the statistical error calculated from the formulas given by Thompson (1998) is in the range 4 – 6%, so the variations are real. Another example of variable O V emission in active regions in given by Fludra et al. (1997; see their Fig. 9).

Applying the analysis described at the beginning of this Section to six active regions, we have obtained the following values of $\delta$: 0.5, 0.7, 0.6, 0.6, 0.9, 0.7, each with a range of $\pm 0.1$. The uncertainty reflects a range of values of $\delta$ that give $\chi^2$ close to its minimum value. The average value is $0.7 \pm 0.2$. The dependence on $L$ cannot be determined for individual active regions because we do not measure loop lengths inside active regions.

The intensity of a transition region line emitted from a static loop is:
\[ I_{OV} = cP \int_{T_1}^{T_2} G(T) dT \]  \hspace{1cm} (4)

where \( P \) is plasma pressure and \( G(T) \) is the line emissivity. Combining this with the relationship \( I_{OV} \propto \phi^{0.7} \) derived from the observations, we obtain \( P \propto \phi^{0.7} \), independent of the active region size. For static loops, where \( P = E_h^{6/7} L^{5/7} \), we obtain the heating rate \( E_h \propto \phi^\beta L^{-5/6} \), \( \beta = 0.8 \pm 0.2 \). This is close to the value of \( \beta = 0.75 \) obtained for the Fe XVI line in Section 1. The power index of 0.8 in this relationship is comparable to the index of 1.0 obtained by Schrijver and Aschwanden (2002) from simulations of solar and stellar soft X-ray emission, and to the index of 0.9 obtained by Yashiro and Shibata (2001) based on the data from the Yohkoh Soft X-ray Telescope. We assume, as indicated by Yashiro and Shibata (2001), that the loop length is not correlated with the photospheric magnetic flux density at the loop footpoint.

3. THE HEATING MECHANISM

To see how this result constrains the heating mechanism, we refer to Mandrini et al. (2000); in this work, the authors review many heating models, characterising the heating rate as \( E_h \propto B_0^\beta L^\gamma \), where \( B_0 \) is the coronal magnetic field. Among the 22 models reviewed by Mandrini et al. (2000), only two models predict \( E_h \propto B_0^\beta L^\gamma \) proportionally to \( B \). The first one (model 4 in Table 5 of Mandrini et al. 2000) is a direct current (DC) model considering magnetic reconnection in current sheets. The second model is in the alternating current (AC) class, with high-frequency boundary excitation (referred to as model 21 in Mandrini et al. 2000). These two models are closest to our result. Most other models predict \( \beta \) equal to \(-1, 0, 1.5, \) and \( 2 \). Our result, \( E_h \propto B_0^{0.8} \), is in contrast with most DC coronal heating models which predict the volumetric heating rate proportional to \( B^2 \). However, we point out that should a significant relationship between \( L \) and \( \phi \) exist, it would change the overall dependence of \( E_h \) on \( \phi \). Therefore, confirming the independence of the loop length of its footpoint magnetic flux density is a high priority task in the coronal heating studies.

ACKNOWLEDGMENTS

This work was supported by the UK Particle Physics and Astronomy Research Council. SOHO is a project of international cooperation between ESA and NASA.

REFERENCES


