VARIATION OF LINE WIDTHS IN POLAR OFF-LIMB REGIONS

D. Banerjee[(1)], E. O'Shea[(2)], and J. G. Doyle[(2)]

[(1)]Indian Institute of Astrophysics, II Block, Koramangala, Bangalore 560 034, India
[(2)]Armagh Observatory, College Hill, Armagh BT61 9DG, N.Ireland

ABSTRACT

Using measurements from the Coronal Diagnostic Spectrometer (CDS) on board SOHO we seek to examine the relative roles of radiative and collisional excitation in regions far off-limb at the Northern pole of the Sun. We study the line width variation with height. It is found that above 1150 arcsec the ratio of two coronal Mg X resonance lines reduces to values that we might expect for a radiatively dominant excitation mode. A comparison of line widths with the Mg X ratios shows that the line widths start to show a decrease in their values at the same location where the dominant excitation changes from being collisionally to radiatively dominant. This is considered to be evidence for a sudden drop in the electron density at this location, and, therefore, the reported decrease in the line widths above 1150 arcsec can be attributed to a reduction in the measurable contribution of waves/turbulence to the non-thermal velocity component of the line widths. This result suggests that the reported decrease of line widths in coronal ions at large altitudes off-limb may not simply be related to the dissipation of wave energy. Implication to the acceleration of the fast solar wind will be discussed.

1. INTRODUCTION

A number of recent papers, e.g., Harrison et al. (2002) and O'Shea et al. (2003), have found evidence for line width decreases off-limb in the equatorial and polar regions, respectively. These line width decreases are taken as evidence for magnetic wave dissipation and, hence, heating of the corona. However, other papers, notably Wilhelm et al. (2004), have found no evidence for a narrowing of line widths in either the equatorial or polar regions. Using CDS data we investigate the variation of line widths off-limb in the Northern polar region of the Sun. For these observations we use the Mg X lines at 609.79 and 624.94 Å, two resonance lines from the lithium isoelectronic sequence.

For transition region and coronal lines belonging to the lithium and sodium isoelectronic sequences the relative intensities of the collisonally and radiatively excited components can be determined from a ratio of their resonance lines, e.g., Mg X 609.79, 624.94Å; O VI 1031.91, 1037.62Å; Fe XVI 360.76, 335.41Å. The collisionally excited component of these resonance lines will be proportional to the ratio of their collision strengths, that is, 2:1. The disk or low coronal radiation that causes the radiative excitation is also formed due to collisional excitation and thus will also have a 2:1 ratio. The radiatively excited component of the intensities, which is proportional to the ratio of the collision strengths (2:1) times the ratio of the intensities of the disk/coronal radiation (2:1), has, therefore, a 4:1 ratio. In measuring the ratio of the Mg X resonance lines, therefore, a value of 2:1 will indicate a predominantly collisionally excited emission while a value of 4:1 will indicate a predominantly radiatively excited emission, with intermediate values pointing to a mix of both collisional and radiative excitation (Kohl & Withbroe, (1982)).

Table 1. A log of the datasets obtained using the 4 × 240 arcsec CDS slit in December 2002.

Date	Dataset	Pointing (X,Y)	Start/ End (UT)	Exp. Time (s)
17/12	s26478	59,1071	18:03	60
17/12	s26479	60,1213	20:54	120
27/12	s26542	0,1070	18:10	60
27/12	s26543	-1,1215	21:01	120

Using measurements of Mg X 609.79 and 624.94Å lines we seek to find evidence of line widths decreases far off-limb and to relate this to information provided by the Mg X ratios.

2. OBSERVATIONS AND DATA REDUCTION

2.1 Initial calibration and line fitting

For these observations we have used the normal incidence spectrometer (NIS), which is one of the components of the Coronal Diagnostic Spectrometer (CDS) onboard the Solar and Heliospheric Observatory (SOHO), see Harrison et al. (1995). The details of the observations, obtained during November/December 2003, including pointing and start times are summarised in Table 1. For the SER150W temporal series sequences the CDS slit was pointed in the North polar region in such a way that the bottom few pixels corresponded to the limb. For the SER75W sequences, the slit was shifted north to cover far off-limb regions, a sizable overlap of ∼100 arcsec being maintained between the SER150W and SER75W datasets. Using these two complementary sequences data was obtained for the coronal lines of Mg X 609.79 and Mg X 624.94 Å ($\sim 1.25 \times 10^6$ K). Note that we shall henceforth refer to the lines without the following decimal places, e.g., 624 in place of 624.94, etc.

The data reduction was carried out using the standard CDS routines. Further details of the data reduction will

Proceedings of the 11th European Solar Physics Meeting - The Dynamic Sun: Challenges for Theory and Observations, 11-16 September 2005 (ESA SP-596, December 2005)

be published in O'Shea et al. (2005).

Before fitting the lines, and in order to increase the signal-to-noise ratio, we binned by 2 along the 143 pixel long slit to produce 70 pixels (4×3.36 arcsec^2) in Y for the SER150W sequences, and by 4 to produce 35 pixels (4×6.72 arcsec^2) in Y for the SER75W sequences. We then also summed in time over the 150 time frames in SER150W and the 75 time frames in SER75W to produce the required high signal-to-noise line profiles along the Y slit direction.

Harrison et al. (2002) discuss the relative contributions expected in the line width of an observed CDS line; the instrumental width, the thermal width and the non-thermal width. For CDS lines, the instrumental width dominates. Unfortunately, this instrumental width is an uncertain quantity due to CDS being designed to measure and compare line intensities rather than line profiles. Harrison et al. (2002) estimate it to have a value of 0.28Å ($\sim$2 pixel widths) for a Mg X 624 line obtained using the 4 arcsec wide slit. It is, however, an unchanging component to the line widths. As the thermal width is also an unchanging component, we can state that any change in the width of a spectral line must be due solely to changes in its non-thermal velocity component. The widths presented in this paper are 1/e widths in units of CDS pixels.

Often scattered light contributions are significant while making observations off-limb. As reported in Young et al. (1999), scattering within the NIS/CDS instrument can occur at two locations: (i) within the spectrograph and, (ii) within the telescope section. Type (ii) scattering can be neglected as it is considered to take place only in the wavelength dispersion direction and not in the spatial direction.

The only factor we take into account in the analysis of these lines at high altitudes is their S/N ratio and if they still possess a recognizable Gaussian shape. We note that Harrison et al. (2002) have also discussed the contribution of the scattering to the intensity in the CDS/NIS Mg X 624 line and they also conclude that it is a very small effect. A detailed description on the scattering contribution has been discussed in O'Shea et al. (2005) and it was shown not be be significant.

3. RESULTS

In Fig. 1 we plot the results of line width measurements for the December 17 and 27 datasets. These plots combine the results from the SER150W and SER75W datasets obtained on the same day and, taking the CDS pointing error of $\approx$3 arcsec into account, at the same pointing locations (see Table 1). The data from the lower level SER150W observations are plotted up to an altitude of $\approx$1110 arcsec and from there the data is from the higher level SER75W observations; something reflected in the lower number of data-points present from that point on. There is a small overlap of 5 data-points allowed between the observations from the two datasets.

Note that for some of the datasets in Fig. 1, and, in particular, for the Mg X 624 line, the line widths are not plotted at higher altitudes due to the low values of intensity at these greater heights. We chose not to plot any line widths from summed profiles that have a measured flux of less than a lower limit of $\approx$2500 counts, i.e. a S/N of $\approx$4. Gaussians with these S/N are still recognizable as such and so we chose this as a lower limit. It will be noticed that the results from Mg X 609 and 624 lines, although formed from the same ion and at the same temperature, show significant differences in line width. That is, the Mg X 624 line shows consistently larger values. This may be due to the effect of blends at 624.78Å, a Si X line, and at 625.13Å, a O IV line. These blends on the blue and red wings of the Mg X line would have the effect of increasing the overall measured line width while only being responsible for, at maximum, 10% of the radiance of the blend, see, e.g., Wilhelm et al. , (2004).

Before discussing the line widths in Fig. 1 in more detail, we firstly draw the reader's attention to the fact that the two plots for Mg X 609 share many small-scale line width variations, e.g., between 1100 and 1200 arcsec and, more obviously, between 1240 and 1270 arcsec. We have discovered that these small-scale variations are not caused by real physical effects but are, in fact, due to an instrumental effect called 'Fixed Patterning Noise' (FPN) which is found in the CDS slit in the North-South, i.e., along the slit, direction. This fixed-patterning is constant in time and is present in intensity, velocity and line-width maps of CDS data (C.D. Pike, 2004, private communication). This FPN generally causes small-scale variations in the line width values at the 3% level. We further note that there is also a more general instrumentally induced line width variation of about 5-6% from South to North along the slit due to variations in the scan mirror position. This more general instrumental effect is, however, not constant in time and different datasets can show significant differences in the size of the effect. In general, though, for CDS datasets this more general effect can be expected to cause an instrumental width increase of about 5% from one end of the slit to the other.

In order to reduce the effect of FPN in the data we perform a box-car averaging smoothing of 7 pixels ($\sim$24 arcsec) along the slit for the SER150W datasets and a smoothing of 5 pixels ($\sim$34 arcsec) along the slit for the SER75W datasets. The results for this are shown as the over-plotted thick line in each of the plots. In Fig. 1, it is possible to see that the line widths of both the Mg X lines increase up to an altitude of $\sim$1150 arcsec before showing a general decrease above this height. As it is known that, for Alfvén waves, the energy flux is proportional to line width (Doyle et al. (1998)) the question we must ask is; are the decreases in the line widths at the higher altitudes above 1150 arcsec due to some form of wave dissipation? To examine this, we plot in Fig. 2 the ratio of the two Mg X lines versus height above the limb for each of the datasets. The values from the SER150W sequence are plotted up to a height of $\approx$1110 arcsec and after that the values come from the SER75W sequence, with an overlap of $\sim$15 arcsec. These ratios have also been smoothed

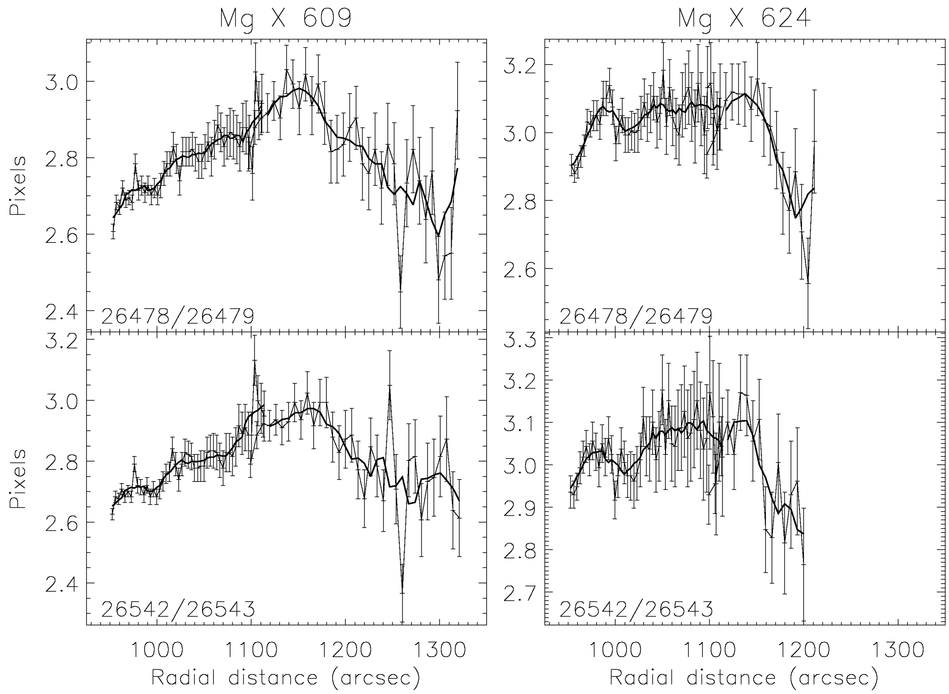

Figure 1. Variation of the 1/e line width versus radial distance for the 26478/26479 and 26542/26543 datasets as indicated by the numbers shown in each plot. The thick black lines show the result of a box-car averaging to remove the effects of the FPN. Radial distance locations where the intensity fell below a critical S/N value do not show the results of the line width measurements.

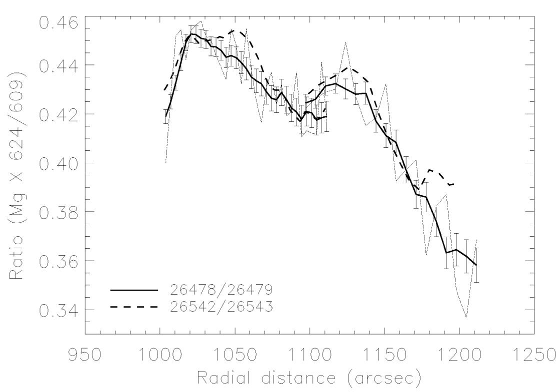

Figure 2. Ratio of Mg X 624/609 as a function of radial distance in arcsec for the 26478/26479 and 26542/26543 datasets. Representative errors bars for the 26478/26479 datasets are plotted. The original unsmoothed ratio values for the 26478/26479 datasets are shown in grey for comparison.

to remove the effects of the FPN discussed earlier.

Above the limb (>1000 arcsec) in Fig. 2, the ratio of the two Mg X lines have values that we would expect for a more collisionally dominant excitation mode, that is, values of almost two to one or 0.5 in the scale of this plot. There is a change, however, in the ratios at ≈1150 arcsec where they begin a decrease to values more expected for radiatively dominant excitation, i.e., towards values of 0.25. Similar results have been found previously by Singh (1985) for Fe X lines. Singh found that for R/R_O <1.2 collisional excitation is the dominant mode, for $1.2 < R/R_O < 1.4$ collisional excitation and radiative excitation are both equally important, while for $R/R_O > 1.4$ radiative excitation becomes dominant. We note that between ∼1000 and 1020 arcsec, in a region close to the limb, the Mg X ratios show an initial increase, before reaching maximum values of ∼0.45. This initial increase can be explained by the effect of a blend of O III and O IV lines at 609.70 and 609.83Å, respectively, with the Mg X 609 line. These lower temperature lines can account for as much as 15% of the total radiance of the blend (Wilhelm et al. , (2004)) at locations close to the limb. At higher altitudes off-limb the proportion of O III and O IV in the blend drops and the ratios return to their expected values of close to 0.5. As mentioned previously, the Mg X 624 line is also blended with a Si X line at 624.78Å and a O IV line at 625.13Å. This blending of the Mg X 624 line further complicates and alters the ex-

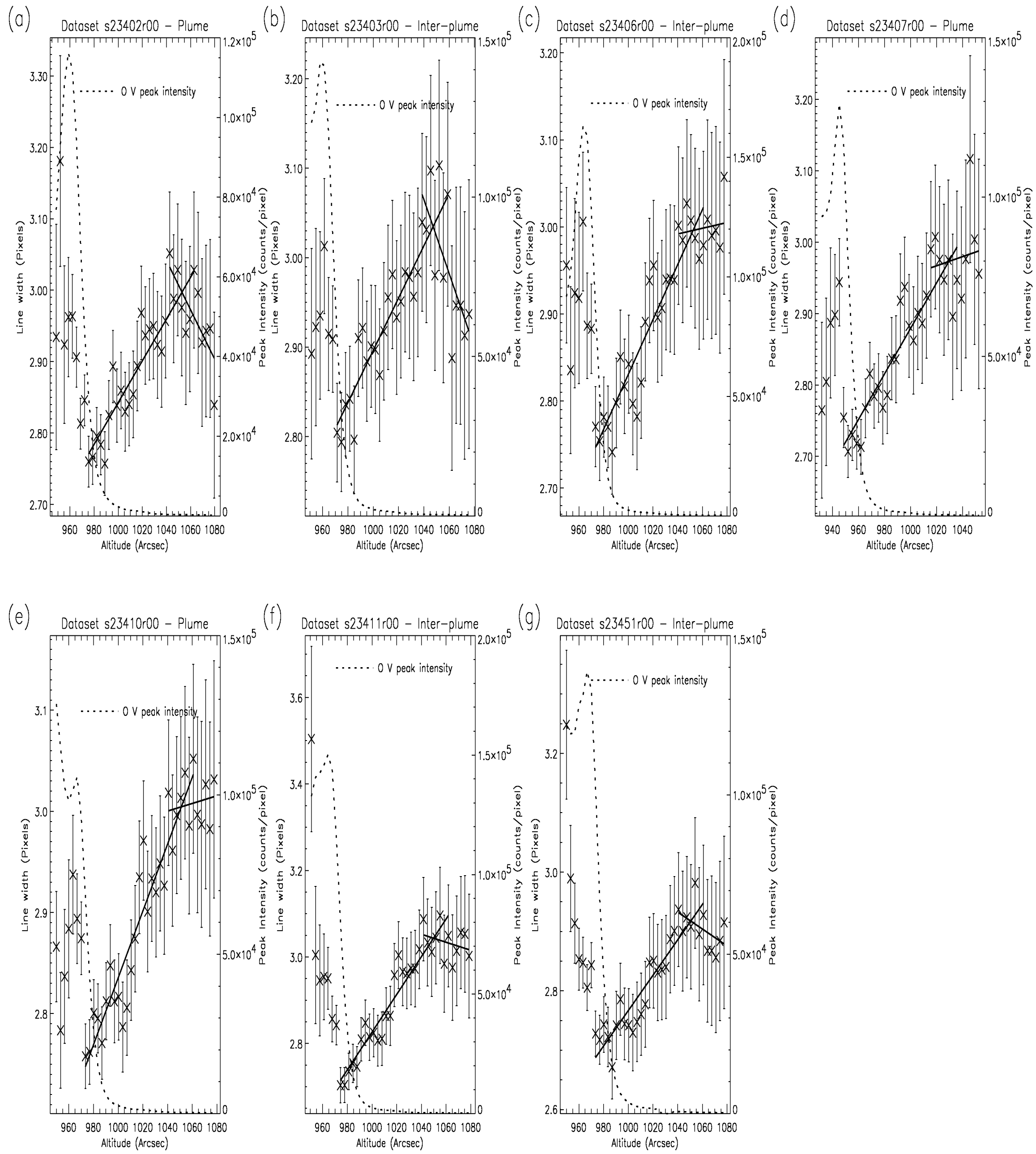

Figure 3. Variation of the Mg X *line width (half 1/e width) with altitude corresponding to the different datasets as labelled. The dotted lines in each plot show the variation of the O* V *intensity with altitude, which is useful for identifying the solar limb. The solid lines correspond to the best-line fit to the observed line widths.*

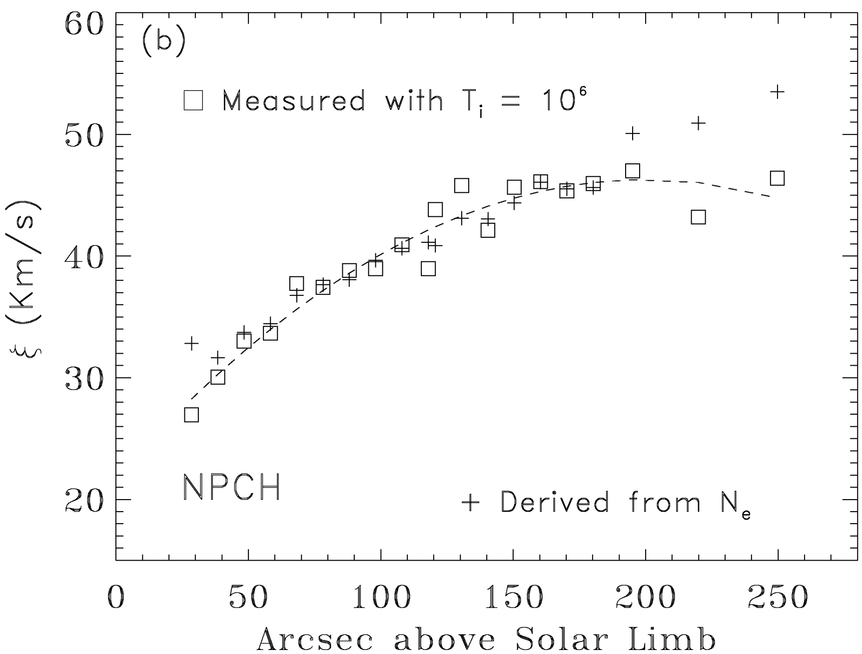

Figure 4. The non-thermal velocity as derived from Si VIII *using $T_i = 1\ 10^6$ K from a study of SUMER dataset. The dashed line is a second order polynomial fits, while the (+) symbols correspond to theoretical values (see Banerjee et al. 1998).*

pected ratio values of 0.5.

If we compare the ratios in Fig. 2 with the line widths in Fig. 1 it is clear that there is a decrease in the line width values at exactly the same location, i.e., ≈1150 arcsec. The change in the line ratios occurs at the location where the dominant excitation changes from being collisionally to radiatively dominant, strongly suggesting a drop in the electron density at and above this height. We note that November & Koutchmy (1996) found evidence for significant electron density depletion in light and dark threads above a small prominence just above the limb. Their results would suggest that electron densities off-limb may not always decrease smoothly but can have sharp variations over relatively small spatial scales. The decrease in the line widths above 1150 arcsec may then simply be related to a reduction in the measurable contribution of waves/turbulence to the non-thermal velocity component of the line widths, which is due to the lessened effect of the waves/turbulence on a more diffuse and less dense plasma. So, in answer to the question; is the decrease in line widths above 1150 arcsec found in this work due to wave dissipation; we can say, probably not. These results would suggest that caution must be taken in attributing decreases in line widths to wave dissipation, at least at high altitudes above the limb. For sake of comparison we show the earlier results from a similar CDS study as reported in O'Shea et al. (2003) in Fig. 4, note the location off-limb (around 1050 arc sec), where the line width shows a change of trend. Similarly from a SUMER dataset Banerjee et al. (1998), see Fig. 5, found that around 150 arc sec above the limb the width do not increase linearly with height any further out. Thus previously published results showing a decrease of line width with height far off-limb in the polar region (Banerjee et al. 1998; O'Shea et al. 2003) and in the equatorial regions, e.g. Harrison et al. (2002), may perhaps be explained by this new findings as reported in this paper.

4. CONCLUSIONS

We find evidence for a decrease in line widths at a certain height above the limb in polar regions. We attribute this decrease in line widths, above ∼1150 arcsec, to changes in the plasma, manifested as a reduction in Mg X 624/609 ratio values to those expected for a more radiatively and, hence, less collisionally dominated excitation. This suggests that the decrease in widths at a fixed height above the limb is linked to a decrease in electron density; the sudden decrease in electron density leading to a substantial fall-off in the non-thermal velocities which are assumed to cause the otherwise almost linear increase in the line widths off-limb. It must be noted that measurements of electron density in off-limb polar regions have found no evidence for a sudden large decrease above heights of ∼1150 arcsec, see, e.g., Banerjee et al., (1998), Doyle et al., (1998). These measured densities, however, are typically calculated using theoretical line ratios that only take collisional excitation into account. We, on the other hand, have seen there is a large change in the radiative excitation component off-limb at ∼1150 arcsec. This suggests that line ratio calculations of electron densities, using solely collision excitation calculations, may be incorrect in regions far off-limb where radiative excitation becomes stronger than collisional excitation. Further and fuller results from the off-limb polar region discussed in this paper will be presented in O'Shea et al. (2005)

ACKNOWLEDGEMENTS

We would like to thank the CDS team at RAL and at Goddard Space Flight Center for their help in obtaining the present data. CDS is part of SOHO, the Solar and Heliospheric Observatory, which is a project of international cooperation between ESA and NASA. This work was supported in part by a PRTLI research grant for Grid-enabled Computational Physics of Natural Phenomena (Cosmogrid). We thank the Royal Society London and the British Council, India for supporting visits between Armagh Observatory and Indian Institute of Astrophysics. We would also like to thank D. Pike and A. Fludra for their advice during the data reduction.

REFERENCES

Banerjee, D., Teriaca, L., Doyle, J.G., Wilhelm, K., 1998, A&A, 339, 208

David, C., Gabriel, A.H. & Bely-Dubau, F., 1997, Proc. 5th SOHO Workshop, ESA SP-404, 313

Doyle, J.G, Banerjee, D, & Perez, M.E., 1998, Sol. Phys., 181, 91

Doyle, J.G., Teriaca, L., Banerjee, D., 1999, A&A, 349, 956

Harrison, R.A., Sawyer, E.C., Carter, M.K., Cruise, A.M., et al. , 1995, Solar Phys., 162, 233

Harrison, R.A., Hood, A.W. & Pike, C.D., 2002, A&A, 392, 319

Kohl, J.L. & Withbroe, G.L., 1982, ApJ., 256, 263

November, L.J. & Koutchmy S., 1996, ApJ., 466, 512

O'Shea, E., Banerjee, D. & Poedts, S., 2003, A&A, 400, 1065

O'Shea, E., Banerjee, D. & Doyle, J.G., 2005, A&A, 438, L35

Singh, J., 1985, Solar Phys., 95, 253

Wilhelm, K., 2000a, A&A, 360, 351

Wilhelm, K., Dwivedi, B.N. & Teriaca, L., 2004, A&A, 415, 1133

Young, P.R., Klimchuk, J.A. & Mason, H.E., A&A, 1999, 350, 296