THE OFF-LIMB BEHAVIOUR OF THE FIP EFFECT IN THE SOLAR ATMOSPHERE OBSERVED BY SUMER ON SOHO

Bhola N. Dwivedi\textsuperscript{1,2}, Werner Curdt\textsuperscript{2}, Klaus Wilhelm\textsuperscript{2}

\textsuperscript{1}Department of Applied Physics, Banaras Hindu University, Varanasi 221005, India
Tel: +91 542 317722 Fax: +91 542 313965 e-mail: dwivedi@banaras.ernet.in

\textsuperscript{2}Max-Planck-Institut für Aeronomie, D-37191 Katlenburg-Lindau, Germany

ABSTRACT

We present results from a study of EUV off-limb spectra. These were obtained on 1996 August 9, with the Solar Ultraviolet Measurements of Emitted Radiation (SUMER) instrument on the spacecraft Solar and Heliospheric Observatory (SOHO). With the capabilities of SUMER, we rastered the emitting source from 2.9 arcsec off the limb outwards, and secured a unique, high-quality set of high-resolution EUV spectra. The scientific objective of this observing sequence was to record Ne\textsuperscript{VI} and Mg\textsuperscript{VI} intercombination/forbidden lines which provide good possibilities to study the relative element abundance of Ne (high FIP) and Mg (low FIP) in transition region emission in the corona, and the electron density in the solar atmosphere. We also investigate the variation of the FIP effect as a function of height above the limb. We compare and re-discuss our results with a similar observation obtained with the SUMER spectrometer on 1996 June 20, but from 40 arcsec off the limb outwards.

Key words: EUV spectroscopy, line identification, plasma diagnostics, corona, abundances

1. INTRODUCTION

Abundances are often suggested to be correlated with the first ionization potential (FIP). Many studies show that a 'FIP bias' does exist (e.g., Widing and Feldman 1993, Sheehy 1996, Young and Mason 1997, and references therein). Classically, a step function increase by a factor of four is assumed for elements with increasing FIP.

We carried out an observing sequence, based on a theoretical study by Dwivedi and Mohan (1995), with intercombination/forbidden lines from Ne\textsuperscript{4+5} and Mg\textsuperscript{4+5} ions which are formed at essentially the same temperature (4 \times 10\textsuperscript{5} K) according to Arnaud and Rothenflug (1985), in such a way that changes in the relative intensities of their spectral lines must be caused by changes in the relative amounts of neon and magnesium. The first ionization potential of Ne and Mg are 21.6 and 7.6 eV, respectively: They form a high-FIP/low-FIP pair. Intercombination lines of the Ne\textsuperscript{VI} spectrum and forbidden lines of the Mg\textsuperscript{VI} spectrum are potential density-diagnostic tools. Thus, we measure the electron density from Ne\textsuperscript{VI} and Mg\textsuperscript{VI} lines and use this information to study the relative elemental abundance Ne/Mg and to see if the classical FIP fractionation values are also found in active region loops observed off-disk. We also investigate the variation of the FIP bias as a function of height above the limb.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{f1.png}
\caption{The SUMER raster superimposed on a section of the Fe\textsuperscript{XV} 284 Å EIT image taken at 14:07 UT showing the active region NOAA 7981 on the limb in photo-negative representation. (EIT image by courtesy of EIT consortium).}
\end{figure}

\textit{Proceedings 8\textsuperscript{th} SOHO Workshop 'Plasma Dynamics and Diagnostics in the Solar Transition Region and Corona', Paris, France, 22-25 June 1999, (ESA SP-446, October 1999)}

© European Space Agency • Provided by the NASA Astrophysics Data System
The observation of the FIP effect in transition region emission in the corona is a new observational fact (cf. Dwivedi et al. 1999). Laming et al. (1999) have also investigated the behaviour of the solar FIP effect with height above the solar limb in a region of diffuse quiet corona and found a low FIP bias of a factor of 3 to 4 with no significant height variation.

2. OBSERVATIONS AND DATA REDUCTION

The observations were made with the spectrograph SUMER on 1996 August 9 above the active region NOAA 7981 on the west limb, starting at 14:07 UT. Fig.1 shows the position and extension of the SUMER raster superimposed on the Fe XV 284 Å image of the western limb of the Sun taken at 14:07 UT with the EIT extreme ultraviolet imager (Delaboudinière et al. 1995).

A full description of SUMER and its performance are given in Wilhelm et al. (1995), Wilhelm et al. (1997), and Lemaire et al. (1997). Briefly, the instrument is an ultraviolet telescope and spectrograph with a wavelength resolution element of 42 to 44 mÅ over the range 800–1610 Å (in first order). Along the N–S directed slit the spatial resolution element is about 1 arcsec (≈ 715 km at the Sun). In the E–W direction the resolution depends on the slit width and the raster step size. In the observation presented here, we used the slit 4 arcsec × 300 arcsec with a raster step of 3.75 arcsec to a total of 17 positions in the E–W direction.

The raster started 3.9 arcsec above the west limb, above the position of the bright Fe XV protrusion seen in the EIT image. With a step size 3.75 arcsec compatible with the slit width of 4 arcsec, the spectrograph slit was stepped westwards for 64.5 arcsec. At each position two 40 Å wide spectra were obtained. The first spectrum was centered on the Ne VI 1000 Å line (Fig.2) while the second spectrum was centered on the Mg vii 1192 Å line (Fig.3). The integration time per spectrum increased exponentially with position from 180 s at 3.9 arcsec to 500 s at 64.5 arcsec in order to get adequate count statistics. The total time for the raster was about 4 hours.
The spectra presented here have been recorded with detector 'A'. After decompression, the data set has been corrected for detector non-uniformities using the standard procedure for flat-field correction described in Wilhelm et al. (1997). For this exercise, the flat-field exposure from 1996 July 25 has been employed.

Electric field inhomogeneities in the detector MCP anode lead to a cushion-type deformation of the images. This geometrical distortion has been corrected using the SUMER standard destretching procedure (T.G. Moran 1996, private communication), which also contains a compensation for the small inclination of the slit image relative to the detector pixel direction.

The efficiency of the detector is wavelength dependent and different for the KBr coated area and the bare MCP areas. A radiometric calibration is required for a comparison of line intensities. We have used the laboratory calibration and the standard SUMER procedures to derive intensities in physical units.

3. PLASMA DIAGNOSTICS

The power $P$ (in energy units) emitted in an optically thin spectral line issued from a transition between upper level $u$ and a lower level $l$ is given by

$$P(\lambda) = \int \frac{hc}{\lambda} A_{ul} N_u dV$$  \hspace{1cm} (1)

where $A_{ul}$ is the transition probability, $N_u$ is the number density, and $V$ is the volume of the emitting plasma. $N_u$ can be further parametrized as:

$$N_u = \frac{N_u(X^{+p})}{N(X^{+p})} \frac{N(X)}{N(H)} \frac{N(H)}{N_e} N_e$$  \hspace{1cm} (2)

where $N(X)/N(H)$ is the abundance of the element X relative to hydrogen which varies in different astrophysical plasmas and also in different solar features; $N(H)/N_e$ is the hydrogen abundance which is usually assumed to be around 0.8 for a fully ionized plasma. Combining Equations (1) and (2) and taking the mean values of atomic parameters and integrating over $V$, we can write
Figure 4. Intensity maps in N III 992 Å, Ne VI 1005 Å, and Mg VI 1191 Å. Each image is displayed 60 arcsec across and 195 arcsec along the slit. For the study of line intensity ratios we have taken account of encompassed plasmas indicated by bars.

\[ P(\lambda) = 0.8 \frac{hc}{\lambda} A_{ul} \frac{N(X)}{N(H)} \beta \frac{N(X^{+p})}{N(X)} \frac{N_u(X^{+p})}{N(X^{+p})} N_e V \]  

where \( N(X^{+p})/N(X) \) is evaluated at the temperature of maximum ionic concentration, the factor \( \beta \) expresses the fact that the average value of \( N(X^{+p})/N(X) \) is less than the maximum value, and \( N_u(X^{+p})/N(X^{+p}) \) is evaluated at the electron density corresponding to the temperature at which the contribution function is maximum.

Following Jordan and Wilson (1971), \( \beta \) is evaluated from the average value of the contribution function over a constant logarithmic temperature width (=0.3 dex) around the peak temperature of formation of the line. The Ne VI and Mg VI lines have almost identical contribution functions. In order to obtain relative abundances of elements X and Y, ratios of respective spectral line intensities are used. The line intensity ratio \( R \) of two lines, or ratio of the power in the lines, is given by

\[ R = \frac{\lambda_{kl} A_{ji} A_{ik} \beta_1 N_j(X^{+p})/N(X^{+p})}{\lambda_{ij} A_{lk} \beta_2 N_l(Y^{+p})/N(Y^{+p})} \times \frac{N(X^{+p})/N(X)}{N(Y^{+p})/N(Y)} \frac{N(X)/N(H)}{N(Y)/N(H)} (N_e V)_1 (N_e V)_2 \]  

If the intensity or power of the two lines has essentially the same temperature dependence (similar contribution functions), then the lines are formed presumably in the same plasma volume and at the same density, and the quantities \( N_e \) and \( V \) are the same for each line and drop out of Equation (4). This is the case for the Ne VI and Mg VI combination. Substituting these values and \( N_e \) for X and Mg for Y in Equation (4) and for equal elemental abundances of Ne and Mg \( (N_{\text{theo}}(Ne) / N_{\text{theo}}(Mg) = 1) \), we can
compute a theoretical line intensity ratio $R_{\text{theo}}$ and subsequently deduce the relative abundance Ne/Mg from the observed line intensity ratio $R_{\text{obs}}$. From Arnaud and Rothenflug (1985), we find the ratio of the Ne vi to Mg vi ionization fraction to be 0.83 at $T_{\text{max}}$ and $\beta_1/\beta_2$ to be 0.89. With this correction, we have:

$$\frac{N_{\text{obs}}(\text{Ne})}{N_{\text{obs}}(\text{Mg})} = 1.35 \times \frac{R_{\text{obs}}}{R_{\text{theo}}}.$$ (5)

Atomic data used for ions in the present study are the same as discussed by Dwivedi et al. (1999).

4. RESULTS AND DISCUSSION

Spectra shown in Figures 2 and 3 are similar to those obtained on 1996 June 20. However, there is a significant variation in the relative line intensities. While we see emission from cold plasmas, e.g. from FeIII lines (not observed in the previous data set), we note that coronal emission lines are comparable or even more enhanced. Intensities of Ne vi and Mg vi lines are, however, found to be lower than those of previous ones.

Line ratios from Ne vi intercombination lines are density insensitive in the relevant range from $10^7$ to $10^{15}$ cm$^{-3}$ and are useful only for densities less than $10^7$cm$^{-3}$ or greater than $10^{10}$ cm$^{-3}$. However, the line ratio from the forbidden Mg vi lines is a good density monitor for plasma densities from $10^8$ to $10^{10}$ cm$^{-3}$. Here, we deduce a value of $10^9$ cm$^{-3}$ or even more from the observed ratios. This line ratio is rather insensitive of temperature variation over a logarithmic temperature width of 0.3 dex, thereby providing a potential density diagnostic tool for the emitting plasma.

The Ne vi/Mg vi line ratios as shown by Dwivedi and Mohan (1995) are density sensitive, although they do not vary much in the density range from $10^7$ to $10^9$ cm$^{-3}$ which is the case of the emitting plasma under investigation. It is to be noted that the logarithmic photospheric abundance of Ne is 8.08 (Grevesse et al. 1992) on a scale where the hydrogen abundance is 12.0, while that of Mg is 7.58 (Anders and Grevesse 1989), so giving a photospheric Ne/Mg relative abundance of 3.16.

In order to study the radiation signature from these lines, we have shown in Fig.4, N III, Ne vi and Mg vi line intensities 60 arcsec across and 195 arcsec along the slit, which is part of the emitting source. As shown in this Figure, we have taken account of 20 pixels for the first 11 raster positions and 15 pixels further out to estimate line intensity ratios. The Ne vi and Mg vi line emission radiation signatures look very similar, thereby confirming that these lines are formed essentially in the same plasma volume, as expected from our theoretical arguments presented in Section 3.

To analyze the spatial variation and height dependence of the FIP bias, we selected the stronger Ne vi and both Mg vi lines. The FIP bias versus height derived from our line ratios is displayed in Fig.5. Consistently, the FIP bias increases from about 4 to a value of 8 within 40 arcsec. At 49 arcsec off-limb the behaviour of the emitting plasma seems to be completely different and the FIP fractionation there falls to a value of 3 or so. Then again it rises to a value of 10
and falls back to a value of about 5. We are, therefore, led to believe that FIP fractionation strongly depends on solar plasma structures. It must, however, be noted that a depletion of Ne (enhancement of Mg ?) consistently results from all combinations of line pairs.

The inference of FIP fractionation at an electron density of $10^9$ cm$^{-3}$ cannot be entirely justified for the obvious reason that the plasma is both, non-isothermal and inhomogeneous. Moreover, Mg vi line ratio yields densities greater than $10^9$ cm$^{-3}$ at several raster positions. Since the Ne vi/Mg vi line ratio is more sensitive at densities greater than $10^9$ cm$^{-3}$, the FIP fractionation reported in this paper will only be enhanced at higher densities.

The treatment outlined in Section 4 for transition region lines is appropriate for a reasonably flat emission measure (EM) distribution at the temperatures of the line formation. Such a treatment may not be adequate for off-limb spectra where the EM is likely to have a steeper gradient. Consequently, the correction factors in Equation (5) may range from 1.35 for flat EM to about 1.9 for a power law EM $\sim T^3$. This will reduce the degree of FIP fractionation reported in the present paper by a factor of 1.4.

In conclusion, this observing sequence provides new observational facts of FIP effect in transition region emission in the corona; on a similar pattern as reported by Dwivedi et al. (1999).

REFERENCES

Young, P.R. and Mason, H.E. 1997, Solar Phys. 175, 523

ACKNOWLEDGEMENTS

The SUMER project is financially supported by DLR, CNES, NASA and the ESA PRODEX Programme (Swiss contribution). SUMER is part of SOHO, the Solar and Heliospheric Observatory, of ESA and NASA.