ESTABLISHING A CONNECTION BETWEEN ACTIVE REGION OUTFLOWS AND THE SOLAR WIND: ABUNDANCE MEASUREMENTS WITH EIS/HINODE

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ABSTRACT

One of the most interesting discoveries from Hinode is the presence of persistent high-temperature high-speed outflows from the edges of active regions (ARs). EUV imaging spectrometer (EIS) measurements indicate that the outflows reach velocities of 50 km s\(^{-1}\) with spectral line asymmetries approaching 200 km s\(^{-1}\). It has been suggested that these outflows may lie on open field lines that connect to the heliosphere, and that they could potentially be a significant source of the slow speed solar wind. A direct link has been difficult to establish, however. We use EIS measurements of spectral line intensities that are sensitive to changes in the relative abundance of Si and S as a result of the first ionization potential (FIP) effect, to measure the chemical composition in the outflow regions of AR 10978 over a 5 day period in 2007 December. We find that Si is always enhanced over S by a factor of 3–4. This is generally consistent with the enhancement factor of low FIP elements measured in situ in the slow solar wind by non-spectroscopic methods. Plasma with a slow wind-like composition was therefore flowing from the edge of the AR for at least 5 days. Furthermore, on December 10 and 11, when the outflow from the western side was favorably oriented in the Earth direction, the Si/S ratio was found to match the value measured a few days later by the Advanced Composition Explorer/Solar Wind Ion Composition Spectrometer. These results provide strong observational evidence for a direct connection between the solar wind, and the coronal plasma in the outflow regions.

Key words: solar wind – Sun: abundances – Sun: corona

Online-only material: color figures

1. INTRODUCTION

Recent observations by the Extreme-UV Imaging Spectrometer (EIS; Culhane et al. 2007) and X-ray Telescope (XRT; Golub et al. 2007) on Hinode (Kosugi et al. 2007) have detected the presence of high-temperature outflows at the edges of active regions (ARs; Sakao et al. 2007; Doschek et al. 2007; Harra et al. 2007). These outflows show velocities on the order of tens of km s\(^{-1}\) and the high spectral resolution EIS data have revealed that the line profiles have asymmetries that reach several hundred km s\(^{-1}\) (Bryans et al. 2010; Peter 2010). Similar outflows have been observed previously at lower temperatures as intensity perturbations in TRACE images (Schrijver et al. 1999), or Doppler shifts in SUMER spectra (Marsch et al. 2004), but the relationship between the cool and hot flows is only now being established through comprehensive studies using the broad temperature coverage of EIS (Del Zanna 2008; Warren et al. 2010). ARs are thought to be possible sources of the slow solar wind, especially during solar maximum, and there have been several studies pursuing this connection (Neugebauer et al. 2002; Schrijver & De Rosa 2003; Liewer et al. 2004). It is important, however, to determine exactly where the slow speed wind is originating from in an AR. Wang et al. (2009) have stressed that the conditions at the base of open field lines greatly influence the properties of the wind in hydrodynamic models. The persistence of the outflows for several days has led to the suggestion that they specifically could be the most significant contributors (Sakao et al. 2007; Harra et al. 2008; Doschek et al. 2008). A direct link has been difficult to establish, however, and further studies are needed, together with observational and theoretical investigations of the origin and driver of the outflows (Baker et al. 2009; Murray et al. 2010).

One capability of EIS that has not yet been fully exploited could help in establishing a connection is the ability to measure the chemical composition of the outflows. It is known from in situ measurements of the ion composition in the slow speed solar wind that elements with a first ionization potential (FIP) below about 10 eV are enhanced by factors of 3–4 relative to their photospheric abundances (von Steiger et al. 2000; Feldman & Widing 2003). In contrast, the fast speed solar wind shows only a small enhancement, perhaps a factor of 1.5 (von Steger et al. 2000), and this is also consistent with spectroscopic measurements in the coronal hole source regions that show abundances that are close to photospheric (Feldman & Laming 2000). For a discussion of explanations for the FIP effect see, e.g., Laming (2004). The magnitude of the FIP effect also appears to be related to the coronal plasma confinement time (Feldman & Widing 2003), so the source of the plasma that flows to the slow wind must be confined long enough to reach an enhancement factor of 3–4 and then must be released to the solar wind along open field lines.

Since the magnitude of the FIP effect varies substantially between different solar features (Feldman & Widing 1993; Sheeley 1995, 1996; Raymond et al. 1997), the possibility exists that measurements of the magnitude of the FIP effect could identify the source location of the slow wind. Some previous work measuring the FIP bias (ratio of coronal abundance of a low FIP element to that of a high FIP element) in the boundary between an AR and a coronal hole has been undertaken by Ko et al. (2006), who found that this could be a possible source location of the solar wind. Similar studies are rare, however, and
to date there have been no measurements of relative abundances in the high speed outflows near ARs. Recently, Feldman et al. (2009) outlined how EIS observations of Si and S lines could be used to measure the FIP bias at temperatures near 1.5 MK, the peak temperature for the AR outflows. They did not study the outflows, but gave a few illustrative calculations for a number of targets. They also noted that accurate measurements would require differential emission measure (DEM) analysis. In this Letter, we present the methodology needed to account for the temperature and density sensitivity of the emission lines involved and calibrate it with measurements in several polar coronal holes. We then measure the FIP bias in the outflow regions of AR 10978 over a period of 5 days in 2007 December and show that the results are consistent with the in situ measurements.

2. DATA PROCESSING AND METHODOLOGY

The EIS instrument observes in two wavelength bands: 171–212 Å and 245–291 Å. It has 1″ spatial pixels and a spectral resolution of 22.3 mÅ. The instrument is described in detail by Culhane et al. (2007). In this Letter, we analyze observations of AR 10978 obtained between 2007 December 10 and 15. This region has previously been studied in detail by several authors (Doschek et al. 2008; Brooks et al. 2008; Warren et al. 2009; Ugarte-Urra et al. 2009; Bryans et al. 2010). The data we use were obtained with the 1″ slit in scanning mode. The observing sequence covers a large field of view (FOV) of 460″ × 384″ with 40 s exposures at each position and we use data from five runs of this sequence. Calibration and processing of the data were performed using standard procedures in SolarSoft. In addition, the orbital drift of the spectrum on the detector due to instrument thermal variations and spacecraft revolution were corrected using the artificial neural network model of Kamio et al. (2010). This model also corrects the spatial offsets between detectors and the spectral curvature caused by the grating tilt. It uses instrument temperature information and spacecraft housekeeping data to perform the correction, and the residual uncertainty of the wavelength positions is expected to be ∼4.5 km s⁻¹. The reference wavelength is taken from an average of all the mission data for the Fe xii 195.119 Å line, but we make an additional correction for Fe xiii 202.044 Å using the average value obtained in a relatively quiet area of the rasters. We use the lowest 50 pixels for this purpose.

The high spectral resolution of EIS enables observation of coronal emission line profiles in detail. In previous work, we have found the line widths in the core of an AR to be narrow (Brooks & Warren 2009), however, several studies have identified blue-wing asymmetries associated with different solar features including the outflows (Hara et al. 2008; De Pontieu et al. 2009; Bryans et al. 2010; Peter 2010). A Gaussian function tends to broaden and shift toward the wings to account for this asymmetry, but here we mainly use the derived velocities to identify the outflow regions and are more concerned with the accuracy of the intensity measurements. Since the contribution of the asymmetry to the total line intensity is generally small, we fit the spectral features with single and multiple Gaussians. A number of methods can be used to determine the FIP bias (fFIP) in the outflows and a detailed discussion of diagnostic ratios in the EIS wavelength range is given by Feldman et al. (2009). They show that the Si x 258.375 Å/S x 264.233 Å ratio is constant to within ∼30% in the log (T_e/K) = 6.0–6.2 range, which makes it useful for analysis of the outflows. We recomputed the ratio using the CHIANTI v6.0.1 database (Dere et al. 1997, 2009), and show it as a function of temperature and density in Figure 1. With these data we find that the ratio varies by ∼40% in the log (T_e/K) = 5.7–6.2 range, but deviates strongly at high temperatures. In regions with a significant high-temperature emission measure then, the ratio should properly be convolved with the DEM distribution. We also find a significant sensitivity of the ratio to the electron density (factor of 2.3 between log (N_e/cm⁻³) = 8 and 10). So, the density in the target region also needs to be measured and accounted for. As we will show below, the densities determined for the outflows do not vary sufficiently to cause a greater than 30% change in the ratio.

We adopt the following procedure for our analysis. First, we measure the density in the outflow region using the Fe xii 202.044 Å/Fe x 264.233 Å diagnostic ratio. Then, we derive the DEM distribution using a series of Fe viii–xvi lines to minimize uncertainties due to elemental abundances. The specific lines used are Fe viii 185.213 Å, Fe ix 188.485 Å, Fe x 184.536 Å, Fe xi 188.216 Å, Fe xii 195.119 Å, Fe xiii 202.044 Å, Fe xiv 274.203 Å, Fe xv 284.160 Å, and Fe xvi 262.984 Å. The DEM is reconstructed using the Markov Chain Monte Carlo (MCMC) algorithm distributed with the PINTo-fALE spectroscopy package (Kashyap & Drake 1998, 2000). For all the calculations we adopted the photospheric abundances.
Figure 2. North polar coronal hole observation used as a test of the method for deriving the FIP bias. The derived values within the boxes are shown. (A color version of this figure is available in the online journal.)

of Grevesse et al. (2007). The atomic data for this calculation were computed using the CHIANTI database at the fixed electron density previously measured for each outflow. Once the DEM is computed, the Si x 258.375 Å and S x 264.233 Å line intensities are calculated. Since Si and Fe are both low FIP elements, the calculated Si x 258.375 Å intensity should be well matched, but we scale the Fe DEM (if necessary) to make sure that it is. We find, however, that the difference is less than 20% for all the outflow regions we investigate. The ratio of the calculated to observed intensity for the high FIP S x 264.233 Å line is then the FIP bias, fully accounting for the temperature and density dependence of the emissivities.

As an independent check of the method, we derived $f_{\text{FIP}}$ values for eight polar coronal hole observations. Since the polar coronal hole is the presumed source of the fast speed solar wind, and the chemical composition there is close to photospheric, we should obtain values close to one if the method is working correctly. Figure 2 shows an example for observations taken on 2007 November 3. The EIS scan used the 2″ slit to cover an area of 300″ by 512″ in around 1 hr. The exposure time was 50 s. The FIP bias was derived using spatially averaged line profiles from the indicated areas, and found to be 1.0 and 1.1, respectively. In all eight regions, $f_{\text{FIP}}$ was found to be $1.2\% \pm 15\%$. This agreement with expectations gives us confidence that the method is working correctly.

3. RESULTS

Figure 3 shows context images of AR 10978 for December 12 when it was near disk center (top row). A SOHO EUV Imaging Telescope (EIT; Delaboudiniere et al. 1995) full Sun image is shown with the EIS raster FOV overlaid as a box. Note that the preceding and following coronal holes are located outside of this FOV, so this region is a good target for examining the outflow regions in isolation from any interaction with the coronal hole boundaries where previous measurements of $f_{\text{FIP}}$ have been made in other ARs (Ko et al. 2006). The figure also shows intensity, Doppler velocity, and non-thermal velocity.
maps all derived from Gaussian fits to the Fe xiii 202.044 Å line profile. The non-thermal velocity is computed by subtraction in quadrature of the thermal and instrumental widths. The thermal width is calculated assuming the peak temperature of each outflow ($T_p$ in Table 1). The on-orbit instrumental width is assumed to be 56 mÅ (Brown et al. 2008).

One can generally associate the dark intensity areas at the east and west side of the AR with the blueshifted emission and regions of large non-thermal velocity, though careful comparison would be needed to understand if they are related to each other in detail. Doppler velocity maps are also shown for December 10–15. These maps are used to select outflow regions for further analysis, and the chosen regions are shown by the small boxes. Since the S x line is weak in the outflows, averaging over a small area is necessary to increase the signal-to-noise ratio. We selected 40 locations in total in both the solar east and west outflow regions over the 5 days.

In making this selection, we only chose regions of outflow along the line of sight. For example, on December 10, the solar east side of the AR presumably has an outflow, and this rotates into view on December 11. On December 10, however, this region shows only redshifts and low non-thermal velocities, presumably due to line-of-sight effects. On this day, we only chose areas in the blueshifted west side outflow.

To ensure that our selected locations were really in the outflows, we measured the Doppler velocities. These and the non-thermal velocities are noted in Table 1. The results indicate that this AR shows bulk outflows of 9.8–41.7 km s$^{-1}$ and non-thermal mass motions of 31.6–59.4 km s$^{-1}$.

We then used the Fe xiii line ratio to measure the electron density and the results are also shown in Table 1. We find values in the range log ($N_e$/cm$^{-3}$) = 8.4–9.0. These are broadly consistent with the results found by Doschek et al. (2008).

The DEM distributions at fixed electron density were used to determine the peak temperatures of the outflows. The results are also shown in Table 1 and fall in the range log ($T_e$/K) = 5.6–6.3. Finally, the calculated $f_{\text{FIP}}$ measurements are also shown in Table 1 and fall in the range 2.5–4.1. This indicates that the

Table 1
Properties of AR 10978 Outflows Measured in EIS Slit Scans

| Date       | Start Time | Location | \(v\) (km s$^{-1}$) | \(\eta\) (km s$^{-1}$) | log ($N_e$/cm$^{-3}$) | log ($T_p$/K) | $f_{\text{FIP}}$ |
|------------|------------|----------|---------------------|------------------------|----------------------|---------------|-----------------|
| 2007 Dec 10| 00:19:27   | West     | −18.3               | 41.9                   | 8.6                  | 6.1           | 3.0             |
|            |            |          | −23.9               | 51.6                   | 8.5                  | 6.1           | 2.8             |
|            |            |          | −19.1               | 42.0                   | 8.5                  | 6.0           | 2.7             |
|            |            |          | −20.4               | 46.9                   | 8.5                  | 6.2           | 3.0             |
|            |            |          | −17.5               | 35.9                   | 8.4                  | 6.2           | 2.9             |
|            |            |          | −16.8               | 38.6                   | 8.5                  | 6.2           | 2.7             |
|            |            |          | −17.4               | 37.1                   | 8.5                  | 6.2           | 2.8             |
|            |            |          | −17.8               | 39.4                   | 8.5                  | 6.2           | 2.5             |
| 2007 Dec 11| 10:25:42   | East     | −10.9               | 33.0                   | 8.8                  | 6.3           | 3.7             |
|            |            |          | −10.9               | 34.8                   | 8.8                  | 6.2           | 3.8             |
|            |            |          | −9.8                | 31.7                   | 8.7                  | 6.3           | 3.5             |
|            |            |          | −14.2               | 38.1                   | 8.8                  | 6.2           | 3.9             |
|            |            | West     | −26.8               | 50.7                   | 8.5                  | 6.2           | 3.7             |
|            |            |          | −17.9               | 39.2                   | 8.4                  | 6.2           | 3.3             |
|            |            |          | −24.1               | 45.6                   | 8.6                  | 6.2           | 3.2             |
|            |            |          | −21.4               | 45.8                   | 8.5                  | 6.2           | 3.3             |
| 2007 Dec 12| 11:43:36   | East     | −16.6               | 39.7                   | 8.7                  | 6.2           | 4.0             |
|            |            |          | −12.6               | 32.9                   | 8.6                  | 6.2           | 3.5             |
|            |            |          | −17.3               | 39.0                   | 8.6                  | 5.6           | 3.8             |
|            |            |          | −20.4               | 41.0                   | 8.7                  | 6.3           | 4.1             |
|            |            | West     | −18.1               | 40.4                   | 8.5                  | 6.2           | 3.1             |
|            |            |          | −20.8               | 43.3                   | 8.5                  | 6.2           | 3.7             |
|            |            |          | −21.8               | 45.8                   | 8.5                  | 6.2           | 3.4             |
|            |            |          | −22.3               | 47.3                   | 8.5                  | 6.2           | 3.8             |
| 2007 Dec 13| 12:18:42   | East     | −20.7               | 35.5                   | 8.7                  | 6.2           | 3.6             |
|            |            |          | −21.1               | 41.9                   | 8.8                  | 5.9           | 3.6             |
|            |            |          | −21.2               | 35.9                   | 8.7                  | 6.2           | 3.4             |
|            |            |          | −26.4               | 47.8                   | 8.7                  | 5.6           | 3.9             |
|            |            | West     | −17.2               | 37.0                   | 8.4                  | 6.2           | 3.5             |
|            |            |          | −12.5               | 35.6                   | 8.4                  | 6.2           | 2.9             |
|            |            |          | −15.3               | 35.0                   | 8.4                  | 6.2           | 2.7             |
|            |            |          | −21.9               | 43.4                   | 8.5                  | 6.2           | 2.8             |
| 2007 Dec 15| 00:13:49   | East     | −41.2               | 57.5                   | 8.7                  | 6.0           | 4.0             |
|            |            |          | −27.5               | 41.5                   | 8.8                  | 6.2           | 3.9             |
|            |            |          | −41.7               | 57.4                   | 8.8                  | 6.0           | 3.7             |
|            |            |          | −33.2               | 47.2                   | 8.8                  | 6.2           | 4.1             |
|            |            |          | −40.0               | 59.4                   | 8.7                  | 5.6           | 3.9             |
|            |            |          | −35.1               | 53.1                   | 9.0                  | 6.0           | 3.9             |
|            |            |          | −32.7               | 47.4                   | 8.7                  | 6.0           | 3.8             |
|            |            |          | −24.8               | 46.3                   | 8.8                  | 6.0           | 3.7             |

Notes. $v$: Doppler velocity; $\eta$: non-thermal velocity; $N_e$: electron density; $T_p$: temperature of emission measure peak; $f_{\text{FIP}}$: FIP bias.
FIP enhancement factors in the outflows are in agreement with expectations from the in situ measurements in the slow wind.

4. SUMMARY

Using data from Hinode EIS we have studied the outflow regions of AR 10978 over 5 days in 2007 December. We find that the outflows show Doppler velocities of \(-22\ \text{km s}^{-1}\) and mass motions of 43 km s\(^{-1}\) on average. We also measured the electron density and temperature in the outflows and found average values of \(\log (N_e/\text{cm}^{-3}) = 8.6\) and \(\log (T_e/\text{K}) = 6.2\), respectively. Combining an emission measure analysis with the modeling of Si\(x\) and S\(x\) lines, we measured the FIP bias in the outflows of the AR away from any surrounding coronal holes. We found that Si is always enhanced over S by a factor of 2.5–4.1, with a mean value of 3.4. These results generally agree with the enhancement factors of low FIP elements measured in situ in the slow solar wind by non-spectroscopic methods, and the enrichment was consistent throughout the observations.

The fact that plasma with a similar composition to the slow speed wind was continuously flowing out from the edge of the AR for several days lends strong support to the suggestion that the outflows contribute to the slow wind. We therefore show new evidence of a direct connection between the slow speed solar wind, and the coronal plasma in the outflow regions.

To conclusively prove this connection, however, one should directly compare the EIS Si/S ratio in the outflows with that measured in the slow wind three days later (the travel time to Earth). If the plasma flowing from the AR really reaches the Earth, the in situ measurements should match the EIS results are thus within 20% of the SWICS measurements.

Note that no connection could be established before or after December 10 and 11 the EIS averages are 2.8 and 3.4, respectively. The EIS observations indicate that the western outflow was near central meridian and favorably oriented toward Earth on December 10 and 11. The best dates for the SWICS comparison are therefore December 13 and 14. We examined the SWICS Si/S measurements on these dates and found average values of 2.3 and 3.5, respectively. From Table 1, we see that for December 10 and 11 the EIS averages are 2.8 and 3.4, respectively. The EIS results are thus within 20% of the SWICS measurements.

Note that no connection could be established before or after these dates, indicating that the influence of the outflows is only seen when they are near disk center. Further work will be needed to determine if AR 10978 is a rare case, and also to quantify whether the outflow contribution to the slow wind is dominant or not.

Finally, we note that there may be other areas of an AR which could contribute to the solar wind and larger more systematic studies are needed. We have made some preliminary measurements in several locations in the core of the 2007 December region and find the FIP bias to be similar to that of the outflows. It is difficult to see how these closed field regions could contribute directly to the solar wind since no blueshifted Doppler signatures are seen there. They could, however, contribute indirectly, for example, by reconnecting with open field lines. At present the outflows are the only regions that are known to meet the two necessary conditions for direct contribution to the wind: upflow and composition.

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