The Drivers of Active Region Outflows into the Slow Solar Wind

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Plasma outflows from the edges of active regions have been suggested as a possible source of the slow solar wind. Spectroscopic measurements show that these outflows have an enhanced elemental composition, which is a distinct signature of the slow wind. Current spectroscopic observations, however, do not have sufficient spatial resolution to distinguish what structures are being measured or determine the driver of the outflows. The High-resolution Coronal Imager (Hi-C) flew on a sounding rocket in 2018 May and observed areas of active region outflow at the highest spatial resolution ever achieved (250 km). Here we use the Hi-C data to disentangle the outflow composition signatures observed with the Hinode satellite during the flight. We show that there are two components to the outflow emission: a substantial contribution from expanded plasma that appears to have been expelled from closed loops in the active region core and a second contribution from dynamic activity in active region plage, with a composition signature that reflects solar photospheric abundances. The two competing drivers of the outflows may explain the variable composition of the slow solar wind.

Abstract

Plasma outflows from the edges of active regions have been suggested as a possible source of the slow solar wind. Spectroscopic measurements show that these outflows have an enhanced elemental composition, which is a distinct signature of the slow wind. Current spectroscopic observations, however, do not have sufficient spatial resolution to distinguish what structures are being measured or determine the driver of the outflows. The High-resolution Coronal Imager (Hi-C) flew on a sounding rocket in 2018 May and observed areas of active region outflow at the highest spatial resolution ever achieved (250 km). Here we use the Hi-C data to disentangle the outflow composition signatures observed with the Hinode satellite during the flight. We show that there are two components to the outflow emission: a substantial contribution from expanded plasma that appears to have been expelled from closed loops in the active region core and a second contribution from dynamic activity in active region plage, with a composition signature that reflects solar photospheric abundances. The two competing drivers of the outflows may explain the variable composition of the slow solar wind.

Unified Astronomy Thesaurus concepts: Solar corona (1483); Slow solar wind (1873)

1. Introduction

The source of the slow (~400 km s⁻¹) solar wind that fills the heliosphere remains elusive, and several possibilities have been suggested and debated (Abbo et al. 2016). One promising candidate during periods of high solar activity is outflows from the edges of active regions (Sakao et al. 2007; Doschek et al. 2008; Harra et al. 2008). At solar maximum, at least some fraction of the mass supply to the slow wind appears to originate low down in the solar atmosphere in these outflows (Sakao et al. 2007; Brooks et al. 2015) and is often able to escape into interplanetary space on open magnetic field lines (Sakao et al. 2007; Doschek et al. 2008; Harra et al. 2008). While the composition of the fast (>700 km s⁻¹) solar wind largely reflects solar photospheric abundances, the slow wind shows much more variability. The composition can also be close to photospheric but is often enhanced above those levels by factors of 2–4 (Meyer 1985; von Steiger et al. 2000; Stankov et al. 2016) due to the first ionization potential (FIP) effect, where the plasma is enriched with elements of low (<10 eV) FIP (Pottasch 1963; Feldman 1992). An enhanced composition, similar to the closed-field solar corona, is a distinct signature of the slow solar wind and has been detected in active region outflows using observations from the EUV Imaging Spectrometer (EIS; Culhane et al. 2007) on Hinode (Brooks & Warren 2011).

While the exact contribution of active region outflows to the slow wind is still under debate, they are scientifically interesting in themselves, as they form part of the basic structure of active regions (Del Zanna 2008). Active regions are typically composed of a hot core emitting at 3–4 MK temperatures, with peripheral “warm” 2 MK loops and bright fan structures dominated by downflows emitting at lower temperatures (0.9 MK) at the active region boundary. Active region outflows mix in and around the downflows on the bright fans and could be different structures or part of the chromospheric–coronal mass cycle (McIntosh et al. 2012). The outflows are more conspicuous and spatially extended at higher temperatures (~2 MK) and have lower intensities in EUV images than the active region core and bright fans. We show a summary of our observations, example intensities, and Doppler velocity maps from EIS observations made in support of the High resolution Coronal imager (Hi-C 2.1; Rachmeler et al. 2019) sounding rocket flight of 2018 May 29 in Figures 1 and 2 (see also Warren et al. 2011). The Hi-C target region is AR 12712. Downflows on the fans (red in the Doppler velocity maps) and outflows (blue) are marked with arrows. The velocity maps show the expected pattern of flows in solar active regions as described above. In particular, strong downflows (arrowed and labeled in the figure) are seen on the bright fan structures to the solar northeast (NE) and southwest (SW) in Fe IX 188.497 Å. These transition to

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downflows on the fans mixed with upflows in Fe XI 188.216 Å (labeled “mix”) and Fe XII 195.119 Å (labeled “outflow”) in the NE and purely upflows in the SW (also labeled “outflow”). At the higher temperatures of Fe XIII 202.044 Å and above, we see only upflows. So the structures seen at different temperatures (Fe IX 188.497 and Fe XIII 202.044 Å, for example) are not the same.

Here we report observations of two apparent drivers of the outflows observed in AR 12712. We use high spatial resolution observations of the base of an outflow area from the Hi-C 2.1 flight, together with plasma composition measurements inferred from Hinode/EIS spectroscopic data. We describe the details of the observations in Section 2.2. Plausible scenarios have been suggested for the formation of outflows into the fast solar wind in magnetic funnels in coronal holes (Tu et al. 2005). In contrast, it has been unclear where the outflows in active regions are originating from and what is driving them. One reason is their spatial extent in the corona, which is largest around 1.7 MK, where they encompass areas containing many structures. Another reason is that at lower temperatures, where they appear more confined, the bright fan structures in active regions obscure the view and make it difficult to understand which temperature represents the base of the outflows and where they are ultimately emanating from. Furthermore, in low spatial resolution spectroscopic data, it is difficult to cleanly separate emission from different structures superimposing along the line of sight. It is also difficult to clearly determine the structures that are contributing to the emission. This is a particular problem for plasma composition measurements that generally require some kind of spatial averaging to improve the signal-to-noise ratio of the key diagnostic spectral lines observed in these dark areas. The high spatial resolution (250 km) of the Hi-C narrowband images has allowed us to identify what features are contributing to the composition signature measured by EIS at lower spatial resolution (>2000 km) and therefore to separate emission from those features and determine their relative contributions.

2. Data Analysis and Results

2.1. Data Sources and Processing

Hi-C 2.1 launched on 2018 May 29 and obtained 5.5 minutes of data from 18:56:21 UT. We analyzed the complete Hi-C time series of images, which were obtained at a fixed cadence of 4.4 s. The Hi-C 2.1 bandpass is narrow (3 Å) and centered on 172 Å. The temperature response peaks at \(\log (T/K) = 5.9\) (Rachmeler et al. 2019) and is broader than that of the 171 Å filter of the Atmospheric Imaging Assembly (AIA; Lemen et al. 2012) on the Solar Dynamics Observatory (SDO; Pesnell et al. 2012). The Hi-C 2.1 data we use have been calibrated to level 1.0 through removing the dark current and applying a flat field from a master file obtained while the telescope was slewing to target during flight. Over scans bias pixels were removed and corrections for hot and dusty pixels applied. A total of 78 images were obtained. The instrument and performance of Hi-C during flight is discussed in a dedicated article (Rachmeler et al. 2019). We co-aligned each image to the nearest 171 Å image obtained by AIA. The AIA data we use were retrieved from the Joint Science Operations Center (JSOC) at Stanford and are also calibrated to level 1.0 following standard procedures (Boerner et al. 2012). The actual co-alignment was performed by first determining the Hi-C rotation angle and pointing offset from AIA using customized affine transformation software (Brooks et al. 2012) and then optimizing the alignment using cross-correlation.

We used the EIS on Hinode (Kosugi et al. 2007) for the spectroscopic analysis of the outflows. The EIS observes two wavelength bands from 171–211 Å and 245–291 Å with a spectral dispersion of 22.3 mÅ pixel\(^{-1}\). We processed the EIS data using standard calibration procedures available in SolarSoftware. These account for removal of hot, warm, and dusty pixels; CCD dark current; and strikes from cosmic rays. They also apply the radiometric calibration to convert the data from photon events to physical units (erg cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\)). To account for the evolving sensitivity of the instrument on orbit, we applied the updated calibration of Warren et al. (2014).

Several EIS observations were planned in support of the Hi-C flight, and we use two distinct data sets in this study. First, we make use of a wide field-of-view (FOV; 303" \(\times\) 384") scan we obtained prior to the Hi-C launch window starting at 14:54:11 UT. This scan uses the 2" slit to cover the FOV in 3" steps with 30 s exposures. The second EIS data set is from an observing program we designed specifically for observing during the rocket flight itself. It is a very coarse scan covering an FOV of 210" \(\times\) 512" by moving the 1" slit in 10" steps. The exposure time for this program was 15 s, so it was able to complete a full scan of the AR during the Hi-C flight. Both EIS data sets contain many diagnostic spectral lines covering a broad range of temperatures.

The EIS raster scan data we use for context from prior to the rocket flight are taken stand-alone, but we co-aligned the EIS coarse slit scan data obtained during the flight with the Hi-C images for detailed analysis. This was achieved by cross-correlating the EIS 195.119 Å intensities along the Y-direction of the slit with the intensities in the AIA 193 Å image taken closest in time to the EIS exposure and locating the best match.
After coalignment with AIA, the EIS data are automatically coaligned to the preprocessed Hi-C images. A further refinement to the coalignment of EIS and AIA is to determine the EIS roll angle using the technique of Pelouze et al. (2019). We have not applied this correction here, since our EIS measurements are made along the slit regardless of the roll angle, and the dynamic activity we study in the Hi-C data is not detectable at the spatial and temporal resolution of EIS.

2.2. Observations

In Figure 3, we show a Hi-C image taken at 18:56:21 UT with EIS slit positions from a rapid scan overlaid. These positions are coincident with upflows on the NE and SW (see Figure 2). We show the areas of upflow in blue in Figure 3. The velocities were determined using Fe XIII 202.044 Å (see Section 2.3). These blue regions highlight the boundaries of
The bulk upflows in the range of 5–30 km s\(^{-1}\) on either side of the active region. We do not show other isolated upflow patches or lower-velocity areas along the slit positions. Also, some patches within the upflows highlighted on the NE side (left panel) may include slight redshifts on the fans. In fact, unfortunately, because of the superposition of foreground loop emission, or simply due to missing appropriate features, we could only use two slit positions for a detailed analysis. In all the positions on the NE upflow, for example, the slit is crossing the bright fans. Figure 2 shows that these bright fans are strongly redshifted at lower temperatures. So even when upflows are detected near 1.7 MK in Fe XII 192.044 Å, the emission from lower temperatures is coming from different structures that show downflows. It is possible that there are outflows at these lower temperatures along the line of sight, but the bright fans block our view of what is below. So we cannot isolate any outflow component at low temperatures, and an emission measure (EM) analysis becomes inappropriate.

The situation is more promising on the SW side (middle panel). There the bright structures are more closely aligned with the large loops connecting the leading negative polarity to the trailing positive polarity of the AR. They also do not fan out so dramatically to obscure the view. So several EIS slit positions where upflows are detected cross the fans from the south and offer an unobstructed view of the root of the outflows. These are the key positions for our analysis.

The Hi-C bandpass is dominated by emission from the strong Fe IX 171.073 Å resonance transition formed at \(\sim 0.8\) MK. So images such as those in Figure 3 clearly show emission from fan structures and bright plage. The AIA 193 Å filter is dominated by emission formed at 1.6 MK, so the image in Figure 3 (right panel) provides context at higher temperatures. The EIS observations in Figure 2 show intensity images of the target active region prior to the Hi-C launch window and provide further diagnostic information from the extra wavelength dimension (used to construct velocity maps). To compliment the intensity and velocity maps in Figure 2, we show example spectral line profiles from one of the outflow areas in Figure 4. These are mean profiles from the white boxed area shown in the top panel of Figure 5. We fit the spectra for all of the lines we analyzed mostly using single Gaussian functions, but we also accounted for specific known blends using multiple Gaussian fitting. There are no strong asymmetries in the profiles indicating that a single Gaussian is a good fit in the areas of outflow we analyze here, but the profiles are not representative of all outflows in every active region. Other regions show a high-speed blue wing component, and the asymmetry increases as a function of temperature; see, e.g., Figure 2 in Brooks & Warren (2012). In other regions, a downflow component may be detectable. The strength of any red- or blueshifts also depends on the orientation to the observer’s line of sight (McIntosh et al. 2012).

2.3. Velocity Measurements

The EIS instrument does not have an absolutely calibrated wavelength scale. Therefore, we quote only relative Doppler velocities in this article. These were calibrated as follows. First, an artificial neural network model was applied to the data to remove the orbital drift of the spectrum on the detector (Kamio et al. 2010). This model uses satellite housekeeping temperature information to correct the drift and is expected to be accurate to \(\sim 4.5\) km s\(^{-1}\). Since the spectrum is moving on the CCD, and real plasma motions on the Sun are changing the positions of the spectral lines, a reference wavelength is needed to convert from the measured line centroids to Doppler velocities. The neural network model assumes that the Doppler shift of the strong Fe XII 195.119 Å line is zero when averaged over the entire mission data set. There is evidence from absolutely calibrated spectra, however, that in fact the corona is slightly blueshifted at the formation temperature of Fe XII (Peter & Judge 1999). Therefore, we determined reference wavelengths for the lines we use by averaging the fitted line centroids in the upper 100 pixels of the CCD as far away from the active region as possible within the EIS FOV. When quoting results, later in the discussion of Figure 5, we also apply a correction to the velocities to account for the calibrated on-disk coronal blueshift (Peter & Judge 1999). For the Fe XIII 202.044 Å line, this is at least 4.5 km s\(^{-1}\). In a final step, we removed a residual orbital drift that remained after the standard correction. This is discussed briefly in the Appendix.

The biggest uncertainty associated with this technique is the choice of the reference wavelength. Given the EIS FOV and the extent of the active region, the upper portion of the CCD could not realistically be classified as truly quiet Sun. Transition region emission from the strong Si VII 275.368 Å line in this region is about a factor of 2.4 higher than measured in the quiet Sun (Brooks et al. 2009). In this work, however, we are not overly concerned with the absolute values of the velocities. We only use the relative velocity maps to identify regions of upflow. Typical Doppler shifts in coronal lines such as Fe XII 195.119 Å in active regions are only 5–10 km s\(^{-1}\) (Del Zanna 2008), whereas the outflows typically show larger bulk velocities of 10–40 km s\(^{-1}\), with wings in the line profiles extending to much higher velocities (Brooks & Warren 2011, 2012).
We compute the plasma composition, commonly referred to as the FIP bias, by first determining the plasma electron density and temperature structure from the equation

\[ I_{ij} = A(Z) \int \phi(T) G_{ij}(T, n) dT, \]

where \( I_{ij} \) is the line intensity for a transition from level \( j \) to \( i \) within a particular ion, \( A(Z) \) is the elemental abundance of species \( Z \), and \( \phi(T) \) is the differential emission measure (DEM) as a function of temperature, \( T \), and defined as \( \phi(T) = n^2 ds/dT \), where \( n \) denotes the electron density and \( ds \) is the path length along the line of sight. Throughout our analysis, we refer to the emission measure (EM) distribution, which we define as \( \phi(T) dT \). Here \( G(T, n) \) is the contribution function that contains all of the necessary atomic physics coefficients (spontaneous radiative decay, upper level population, ion fraction, etc.). This equation definition makes several simplifying assumptions that have been discussed in great detail in the literature (Craig & Figure 5. Hi-C and EIS observations of the outflow area detected by the EIS slit. First panel: rotated Hi-C image of the outflow area detected at one EIS slit position (labeled S1 in Figure 3). The aspect ratio of the image is reduced from the original in order to better reveal the features. The Hi-C plate scale is eight times better than EIS, so a single EIS pixel in the E–W direction corresponds to at least eight Hi-C pixels (the actual value depends on the ratio of the EIS and Hi-C PSFs). The white box shows the plage region of interest. Second panel: normalized Hi-C intensity along the slit averaged in the solar E–W direction. The bright fan footpoint is highlighted by an arrow. The red dots show the locations chosen for background/foreground subtraction, and the red line shows the polynomial fit between these positions. Third panel: normalized EIS 195.119 Å intensity along the slit. The plage and background/foreground components are highlighted in blue and pink, respectively. Fourth panel: Doppler velocity measured in the EIS 202.044 Å spectral line, showing that this whole region is within the blueshifted outflow.

2.4. Composition Measurements and Emission Measure Distributions

We compute the plasma composition, commonly referred to as the FIP bias, by first determining the plasma electron density and temperature structure from the equation

\[ \frac{\partial}{\partial T} \int f(T) dT = \frac{1}{\Delta T} \int \frac{\partial}{\partial T} f(T) dT, \]

where \( f(T) \) is the differential emission measure (DEM) as a function of temperature, \( T \).
Table 1
Spectral Lines Used for Analysis

| Element  | Ion | λ/Å | T_f/MK | I_a | σ_a | I_b | σ_b | I_p | σ_p |
|----------|-----|-----|--------|-----|-----|-----|-----|-----|-----|
| Fe[7.9]  | IX  | 188.497 | 0.9 | 62.4 | 14.3 | 2845.8 | 672.1 | 1136.9 | 349.6 |
| Fe       | IX  | 197.862 | 0.9 | 40.5 | 9.2  | 1410.1 | 336.8 | 1089.6 | 273.2 |
| Fe       | X   | 184.536 | 1.1 | 371.7 | 83.1 | 17906.3 | 4038.7 | 5222.1 | 1453.4 |
| Fe      | XI  | 188.216 | 1.4 | 503.0 | 110.9 | 20397.9 | 4508.8 | 10286.2 | 2904.9 |
| Fe      | XII | 195.119 | 1.6 | 930.5 | 204.9 | 37523.2 | 8268.8 | 19238.0 | 4259.0 |
| Fe      | XIII| 202.044 | 1.8 | 596.3 | 131.8 | 28234.3 | 6258.4 | 8143.3 | 1947.7 |
| Fe      | XIV | 203.826 | 1.8 | 519.8 | 116.2 | 16201.0 | 3781.1 | 15538.3 | 3644.0 |
| Fe      | XV  | 264.787 | 2.0 | 688.4 | 151.6 | 34470.2 | 7596.7 | 8795.2 | 1986.3 |
| Fe      | XVI | 270.519 | 2.0 | 407.7 | 98.8  | 14001.8 | 3095.4 | 11101.0 | 2461.1 |
| Ca[6.4]| XV   | 284.160 | 2.2 | 4312.0 | 948.9 | 191643.7 | 42187.5 | 71489.0 | 15796.9 |
| Si[8.2]| X    | 262.984 | 2.8 | 300.1 | 66.3  | 14001.8 | 3095.4 | 11101.0 | 2461.1 |
| Si[10.4]| X   | 264.787 | 2.0 | 688.4 | 151.6 | 34470.2 | 7596.7 | 8795.2 | 1986.3 |

Note. Here, λ is the wavelength, T_f is the formation temperature, I_a is the intensity of the averaged bulk outflow, I_b is the total intensity in the background/foreground emission, and I_p is the total intensity in the active region plage. The uncertainties in the intensities are denoted by σ and include the calibration error added in quadrature. The FIPs for each element are given in brackets in eV. Intensity units are erg cm⁻² s⁻¹ sr⁻¹.

Brown 1976; Lang et al. 1990; Judge et al. 1997. In particular, since G(T, n) is dependent on both T and n, we estimate the electron density in order to compute this function to the highest accuracy for all of the spectral lines used in the EM analysis.

Here we use the Fe XIII 202.044/203.826 diagnostic ratio to measure the plasma density. This ratio varies by a factor of 120 in the range of log(n/cm³) = 7–10. This density is then used to compute the contribution functions using the CHIANTI v8.0 database (Del Zanna et al. 2015), assuming photospheric abundances (Grevesse et al. 2007) and the CHIANTI ionization fractions (Dere et al. 2009). We use spectral lines from Fe IX–XVI together with Ca XIV 193.874 Å and Si X 258.375 Å to determine the temperature distribution of the feature of interest. The specific lines used are listed with their formation temperatures in quiet Sun conditions in Table 1. With the exception of the Fe XIII 202.044 Å and Fe XIII 203.826 Å density-sensitive lines, the contribution functions for all of the other spectral lines are mostly insensitive to density; the G(T, n) peak magnitudes vary less than 25% for the typical density range of the outflows, log n = 8.4–9.0 (Brooks & Warren 2011).

We compute the EM using the Markov Chain Monte Carlo algorithm available in the PINTofALE software package (Kashyap & Drake 1998, 2000). This method reconstructs the temperature distribution by estimating the amount of EM needed to reproduce all of the observed line intensities. In our analysis, we compute 100 potential realizations of the EM distribution from the Monte Carlo simulations and use the solution that best fits the data. Since Fe, Ca, and Si are all low-FIP elements, we expect the temperature distributions derived from the spectral lines of these elements to be similar. Initially, we only use the Fe lines for the actual derivation—to minimize the influence of the choice of elemental abundances—with Ca XIV acting as a high-temperature constraint. We then make an adjustment to match the Si X 258.375 Å intensity, and the final temperature distribution is used to simulate the expected intensity of the S X 264.223 Å line.

The G(T, n) functions for Si X 258.375 and S X 264.223 Å are very similar. Brooks & Warren (2011) showed them in their Figure 1 and discussed the range of validity of the ratio in terms of densities and temperatures. To achieve the highest accuracy, the density should be measured and the G(T, n) functions convolved with the EM distribution, as we do here. The low- and high-FIP groups of elements are usually defined as having an FIP below or above 10 eV. With no enhancement of low-FIP elements, we expect the density and temperature distribution that reproduces Si X to be valid for S X. If the low-FIP elements are enhanced, however, the prediction for S X 264.223 Å will be too large because it is a high-FIP element. The ratio of the predicted to observed intensity of S X 264.223 Å then gives the FIP bias. Note that with an FIP of 8.2 eV, Si has the highest FIPs of the low-FIP group of elements, and with an FIP of 10.4 eV, S is very close to the boundary between groups. So these elements are not necessarily the best ones to use for detecting a strong FIP effect. In particular, S sometimes shows behavior that could be described as intermediate between low- and high-FIP elements (Reames 2018). In theoretical models, this depends on whether the magnetic field is open or closed and therefore whether Alfvén waves can achieve resonance (Laming 2015). We therefore stress here that the FIP bias we are measuring is, strictly speaking, the ratio of the Si and S coronal abundances. Note, however, that the EIS composition measurements made using this ratio have been quite successful in capturing the expected trends of the FIP effect. For example, a photospheric composition is detected in polar coronal holes (Brooks & Warren 2011), and an enhanced composition is detected in bright active region loops (see, e.g., Doschek & Warren 2019). Ideally, the results would be checked against measurements made with other elements, but useful spectral lines from other high-FIP elements are mostly emitted at higher temperatures (Feldman et al. 2009).

Our technique has been well tested for robustness in previous studies (Brooks & Warren 2011; Baker et al. 2015; Brooks et al. 2015) and specifically to assess the impact of potential cross-calibration problems between the short- and long-wavelength detectors, a significant difference in fractionation behavior between Fe and Si, unknown problems with the atomic data, and the uncertainties in the computed FIP bias measurements (Brooks et al. 2017). The conclusion was that the method works well even if the short-to-long-wavelength calibration, or Si/Fe fractionation, is in error because we are
only using Fe lines on the short-wavelength detector to determine the shape of the DEM, not the magnitude. The magnitude is determined by the intensity of Si X 258.375 Å. Furthermore, the most relevant part of the DEM (near 1.5 MK) is dominated by emission from lines of Fe XI, Fe XII, and Fe XIII, which are relatively close in wavelength. The effect of the test on atomic data uncertainties is to modify the DEM and produce a dispersion in FIP bias values of ±0.3. This is the estimated uncertainty. Since these were generic experiments on how the method handles input intensities and atomic data, they are applicable here. Of course, we also assume that the simplifying assumptions of the DEM method are valid. If that were not the case, for example, if the plasma were not in ionization equilibrium, then there could be significant systematic errors in the atomic data. We expect that these would be revealed as systematic deviations between observed and calculated intensities.

In Figure 5, we show the analysis of one of the EIS slit positions. The figure shows the structures observed by Hi-C in the upper transition region (formation temperature of the 172 Å filter) and corresponding features seen in the 195.119 Å spectral line in the low corona by EIS. In this case, the EIS slit (labeled S1 in Figure 3) is fortuitously positioned between the fans. The lower part of the slit does glance the footpoint of a bright fan loop around pixel positions 30–40 (highlighted with an arrow in Figure 5). The upper part of the slit, however, passes across an extended area of active region plage or mosslike emission around pixels 40–95. Moss is usually defined as the footpoints of high-temperature loops (Berger et al. 1999).

Analysis of the high-temperature emission in this AR suggests that the loops seen in Fe XVIII are not connecting to the regions we identify as outflow (Warren et al. 2020). So we refer to these mosslike areas as plage here. We see considerable structure in the plage in Hi-C, but it appears fairly homogenous at the higher temperature of Fe XII 195.119 Å. This is primarily due to the relatively lower spatial resolution of EIS (see Figure 6).

The Hi-C data enable us to understand what EIS is measuring and exclude, for example, the region around the fan footpoint that is not detectable in Fe XII 195.119 Å but gives a contribution to the 172 Å emission from downflowing plasma. Furthermore, the Hi-C data also play another important role in defining where to extract the background/foreground emission from the structures of interest. Until now, all outflow measurements have been made without treating this background/foreground emission when determining the temperature distribution and using it to infer the plasma composition. Yet this has proven to be critical in the analysis of the temperature distributions of coronal loops (Klimchuk & Porter 1995; Del Zanna & Mason 2003). Since the outflow has expanded above and around the plage and fan loops, emission from the outflow has itself become part of the background measured by EIS. So it is not clear how to isolate this contribution. The Hi-C data, however, clearly show where the plage is delineated, so the plage component can be extracted, and the outflow component is what remains. We show the positions of the boundaries of the plage as red dots in Figure 5. We fit a polynomial to these background positions.
and extract the plage emission above the linear fit (blue region in Figure 5). This is a simple approximation but similar to the analysis that has been done for coronal loops (Aschwanden & Nightingale 2005; Warren et al. 2008). The uncertainties will likely be larger here, since the fit is made over a greater distance, but the method is supported by previous observations that show that the background emission increases approximately linearly from the periphery to the core of active regions (Del Zanna 2013) with a gradient that is instrument-dependent. The background/outflow component (pink region in Figure 5) is the emission below the linear fit. We then use the approximate locations of the background positions to extract the intensities of the two components for all other EIS spectral lines used in the analysis. The intensities are totaled between the red dots. This procedure is done automatically to reduce any bias introduced by visual selection. Future observations with high spatial resolution at all wavelengths will help to confirm these measurements.

We show the resulting EM distributions for three examples in Figure 7. These distributions are for the outflow region analyzed in Figure 5, that is, the mean outflow, the background/foreground outflow, and the plage region. The electron densities measured using Fe XIII are log \((n/cm^{-3}) = 8.9, 8.7,\) and 9.3 for these regions, respectively, with an uncertainty on the measured ratio of \(\sim 30\%\) \((0.12–0.16\text{ dex})\) due to the instrument photometric calibration. In most cases, the differences between the observed and calculated spectral line intensities are within \(\sim 25\%: 11/12\) of the lines in the mean outflow, 10/12 in the background/foreground outflow, and 9/12 in the plage region. This indicates that the EM distributions are well constrained. Most of the few discrepant lines (including the worst—Fe XIV 270.519 Å—which is 50\% out in the plage region) emit at temperatures above 2 MK. This is considerably higher than the temperature of the Hi-C 172 Å filter where detailed features are observed in the plage and therefore may be emission coming from unconnected structures. It is also far from the temperature where the FIP bias is measured.

Our technique assumes that Si and Fe fractionate in a similar way due to the FIP effect because they are both low-FIP elements. It appears, however, that that might not always be the case (Heidrich-Meisner et al. 2018), and in making our composition measurements, we found some evidence that Si is fractionated more than Fe. For example, in the worst case in the plage region, the difference between the observed and calculated Si X 258.375 Å intensity is \(\sim 33\%\) before the Fe and Si EM distributions are matched. This is larger than the intensity calibration error (Lang et al. 2006), so the difference could be real. It is difficult to definitively pin down the reason for this difference, however. It could be that it just reflects a difference in the degradation of the intensity calibration between the short- and long-wavelength detectors. It is also possible that a small error in the atomic data is showing up here in the most marginal case. A fractionation split of this magnitude is also much smaller than the large difference in the composition signature we measure in the plage and outflow, so it does not affect this result.

Our measurements show that the FIP bias in the outflow region of interest (white box in Figure 5) is 1.8. That is, the outflows show a coronal composition, consistent with previous measurements in similar active regions and the expectation for the slow solar wind. The emission from the expanded background/foreground component of the outflow shows a higher FIP bias of \(\sim 2.5\). This is a new result because this component of the outflow has been separated from the plage emission.

The composition in the plage region is different. The FIP bias is \(\sim 1.0\), which indicates photospheric abundances. Plage regions are known to be sites of dynamic activity from chromospheric jets (de Pontieu et al. 2007; De Pontieu et al. 2009). The moss emission, however, generally shows lower variability when observed with lower spatial resolution in the corona (Brooks & Warren 2009), except around the edges where the magnetic field is changing or at the footpoints of the hottest loops (Testa et al. 2013). We might therefore expect an increased range of variability at the temperature and spatial resolution of Hi-C, and we do detect some evidence of this. The bright structures seen in the Hi-C image and intensity plot of Figure 5 show an average intensity variation of 30\% (range 9\%–86\%) on a mean timescale of 167 s (range 65–243 s).
These dynamic properties were measured using only the low-jitter images. We also show the variability of the emission in Figure 8. Without simultaneous lower-temperature observations, we cannot connect this activity to specific chromospheric features such as type II spicules or dynamic fibrils, but the lifetimes and spatial scales (widths of 232–692 km with an average of 503 km) are comparable to the lifetimes and widths of these chromospheric jets (De Pontieu et al. 2007; Pereira et al. 2012).

It is worth noting that one of our experiments showed that the uncertainty in the FIP bias could be greater than 30% if the errors in the atomic data are larger than ~40%. We do not expect the atomic data errors to be this large, but in any case, a 30% error is within the intensity calibration uncertainty for the Si/X/S ratio and is much smaller than the factor of 2.5 difference between the FIP bias measurements in the plage region and background-subtracted outflow. Our key result is that a photospheric composition is detected in the plague with an FIP bias of ~1.0. The value for the bulk outflow is an average and not uncorrelated with the other two measurements.

Del Zanna & Mason (2018) gave a thorough review of the current status of elemental abundance studies in the literature for different solar features. These measurements have been derived from a variety of methods, and they do not all agree. At least some of these discrepancies are due to differences in the EM analysis techniques and the assumptions associated with that.

2.5. Analysis of Other EIS Slit Positions

We also examined the two other EIS slit positions that cross into the plage (labeled S2 and S3 in Figure 3) using the same methodology as for S1. The slit position to the extreme right (S2) showed a similar coronal composition for the outflow region (FIP bias ~2), though greater variability in the S X 264.233 Å intensity distributions made the measurements of the separate components very sensitive to the background subtraction. Ultimately, we were not able to obtain a satisfactory solution for the two components simultaneously and could not confirm the presence of photospheric composition plasma in the plage for this case. Figure 9 is similar to Figure 5 and shows this example but without the separated components.

There is dynamic activity in the plage with similar intensity variations and lifetimes to those seen in Figures 5 and 8. This is shown in Figure 10. The widths of the brightening were more difficult to examine due to the smoothness of the emission in this slit position but are similar to those measured above. The third slit position (S3) proved even more problematic. Most of the emission comes from the fan loops to the south, and only the edge of the plage region is actually in the outflow.

Our Hi-C analysis reveals that a similar systematic study of many outflow regions may be possible with the lower spatial resolution AIA data. Analysis of data from the first Hi-C flight found evidence that some loops observed by Hi-C showed evidence of substructure, while others did not (Brooks et al. 2013; Del Zanna 2013; Peter et al. 2013). With hindsight, it appears that the AIA spatial resolution may be good enough to separate the EIS outflow components; though the properties of the dynamic features we discuss would be less well constrained.

2.6. Effect of the EIS PSF

The amorphous structure and relatively low EUV emission in the outflow regions make it difficult to identify any recognizable feature that contributes to the emission away from the plage area and bright fan loops. This raises an issue as to whether some part of the outflow might simply result from an instrumental effect, such as the spillover of photons to adjacent pixels on the detector due to the EIS point-spread function (PSF).

The EIS optical performance was investigated on the ground prior to launch, and the spatial resolution was measured to be close to the 2″ Nyquist limit expected for the detector pixel scale (Korendyke et al. 2006). On-orbit observations, however, suggest a lower spatial resolution. The smallest transition region brightenings detected by EIS have been used as pointlike sources to estimate a value of 3″−4″ by independent members of the EIS team (see the discussion on the EIS wiki at http://solarb.mssl.ucl.ac.uk/eiswiki/Wiki.jsp?page=TRbrightenings). Higher spatial resolution AIA
images were also convolved with a Gaussian PSF to see what values would best reproduce the EIS raster images (see EIS software note number 8; [http://solarb.mssl.ucl.ac.uk/SolarB/eis_docs/eis_notes/08_COMA/eis_swnote_08.pdf](http://solarb.mssl.ucl.ac.uk/SolarB/eis_docs/eis_notes/08_COMA/eis_swnote_08.pdf)). That investigation found that a Gaussian PSF with an FWHM of 3.6 produced the best match.

Some studies have also found evidence of an asymmetry and inclination to the PSF. It appears that in regions of strong intensity gradients, the effect is to introduce a systematic shift in Doppler velocity (on the order of a few km s\(^{-1}\)) across the feature (Young et al. 2012). This was most dramatically demonstrated for EIS observations of a thin off-limb current sheet that developed following an X8.3 flare in 2017 September (Warren et al. 2018). An asymmetric Gaussian PSF with an FWHM of 3" in the X-direction and 4" in the Y-direction was able to reproduce the reversed Doppler pattern observed around the current sheet. These values are consistent with measurements made during the 2012 Venus transit (I. Ugarte-Urra 2020, private communication).

We do not expect spurious velocity artifacts to affect observations in large homogenous areas of outflow such as we have analyzed here. We have, however, investigated the effect of a Gaussian and asymmetric Gaussian PSF on the distribution of intensities through the outflow region along the slit position analyzed in Figure 5. We show the results of this experiment in Figure 11. The figure contrasts the raw intensity distribution...
with the intensity distribution produced after deconvolution using a Gaussian PSF with an FWHM of $3''$, $3''$ (red line) and an asymmetric Gaussian PSF with an FWHM of $3''$, $4.5''$ (pink line). The raw and deconvolved data do not show any significant differences. Although small deviations are introduced by the PSF, the intensities remain highly correlated, and the general features we are interested in (the plage and background) are largely unaffected. The modeled PSF implies that the peak intensity in a feature should drop to its FWHM within $3''$–$4.5''$, whereas the background component is slowly changing and the standard deviation from the mean is less than $10\%$ over the lower $0''$–$40''$ of the slit.

### 2.7. Magnetic Topology Model

For magnetic topology modeling (see Section 3), we use a potential field source surface (PFSS) extrapolation made with the package distributed in SolarSoftware (Schrijver & De Rosa 2003). The package traces field lines from potential field models archived at 6 hr cadence for specified Carrington longitudes and heliographic latitudes. During Carrington rotation 2204, AR 12712 was on disk, and appropriate ranges to cover the region were Carrington longitudes $[108.6, 258.6]$ and heliographic latitudes $[-61.0, 59.0]$. The PFSS model extrapolates up to $2.5 R_\odot$. To illustrate the global structure and magnetic configuration of the active region, we drew a selection of 275 field lines on top of a magnetogram obtained by the Helioseismic and Magnetic Imager (HMI) on SDO. The selected field lines start from radial distances within a range of $1.02$–$1.5 R_\odot$. The HMI magnetogram was downloaded from the JSOC at Stanford University. It is a level 1 full disk magnetogram obtained during the Hi-C flight at 18:56 UT.

### 3. Discussion

Our outflow composition measurements, aided by high spatial resolution Hi-C images, identify two drivers of the outflows that went undetected at lower spatial resolution. Previous Hi-C observations show the presence of wave motions in both active region loops and moss (Morton & McLaughlin 2013, 2014), and theoretical knowledge of the FIP effect based on magnetohydrodynamic wave models (Laming 2004, 2015) provides a framework to understand our results. First, theory and observations of evolving active regions suggest that plasma needs to be confined for some time (at least several hours) before the plasma composition becomes enhanced (Widing & Feldman 2001). So the coronal component of the outflow is likely to be a signature of plasma that has been confined in closed magnetic loops after emergence, perhaps in the active region core, and then released into the
outflow when these loops open. Second, dynamic activity in the upper transition region in the plage studied here occurs on timescales (a few minutes) that modeling suggests are too short for the FIP effect to take place. Plasma is ejected rapidly through the region where the FIP effect is assumed to operate (the upper chromosphere) and injected directly into the outflow from the plage region with the observed unenhanced (photospheric) composition. As suggested by the coronal-contralflow model (McIntosh et al. 2012), there may be a draining phase detectable as downflowing plasma at lower temperatures. We have deliberately attempted to spatially isolate the upflow components here, since they are the only ones that produce plasma that can contribute to the solar wind.

The magnetic configuration of AR 12712 suggests how this picture could apply here (Figure 12). The closed AR core loops (sky blue) extend from positive polarities and converge in the negative polarity area where the plage (pink region) is located at the base of the outflows observed by EIS (dark blue). Open field lines and long loops that close distant to the AR (sky blue) also converge in this negative polarity region. As an example, the schematic cartoon in Figure 12 illustrates the process. Component reconnection can take place between the core loops and the open or closed long field lines. This can release material into the outflow from both the plage region (pink arrow) and the closed loops (sky blue arrow). The photospheric and coronal composition plasma then escapes and expands into the outflow (dark blue arrows).

This scenario can potentially explain the variability of the slow wind composition observed in situ. In this active region, the outflows show a coronal composition at the spatial scales measured by EIS, but a critical point is that plasma with a photospheric composition is also being injected, even though it went undetected until now. The coronal component dominates in this case (only about 1/3 of the emission between the red dots in Figure 5 is being contributed by the plage at the formation temperature of 195.119 Å; 1.6 MK), but this likely depends on the time, location, and active region. It is not hard to imagine a scenario where the photospheric component is the dominant contributor and the total outflow signature is photospheric.

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Appendix

As discussed in Section 2.3, we applied a nonstandard additional correction to remove a residual orbital drift that remained in the data after following the standard correction procedures. The standard correction is based on a neural network calculation performed early in the mission. Updates
were made following significant instrument configuration changes (e.g., slit and grating focus) but have not been made since 2008. So we often find that a residual orbital drift remains that needs further correction. After assessing the accuracy of the orbital drift correction for the observations used in this paper, we found that in fact this was true of the data sets presented in this paper. The residual drift was removed by averaging the velocities in the \( Y \)-direction in the upper 100 pixels of the CCD, smoothing the resultant curve over 5 pixels in the \( X \)-direction, and subtracting this smoothed velocity function from the data.

We illustrate the improvement in measurements achieved by this method in Figure A1. The red histogram shows the results after following the standard procedure. The Doppler velocity distribution is approximately bimodal, indicating a shift across the FOV with an amplitude of \( 10.5 \) \( \text{km s}^{-1} \) (the drift is red to blue in this case). The blue histogram shows the results after correcting for the residual drift. The apparent bimodality is removed, and we are left with a single-peaked distribution with a standard deviation of \( \sim 3.5 \) \( \text{km s}^{-1} \). This is comparable to the rms error of \( 4.4 \) \( \text{km s}^{-1} \) achieved by the standard method when applied to data earlier in the mission.

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