ELECTRON DENSITY OF ACTIVE REGION OUTFLOWS MEASURED BY THE EUV IMAGING SPECTROMETER ON BOARD HINODE

N. Kitagawa1 and T. Yokoyama2

1 National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan; kitagawa@solar.mtk.nao.ac.jp
2 Department of Earth and Planetary Science, School of Science, The University of Tokyo, 7-3-1 Hongo, Bunkyō, Tokyo 113-0033, Japan

Received 2014 July 24; accepted 2015 February 24; published 2015 May 26

ABSTRACT

In order to better understand the nature of active region outflows, the electron density was measured by using a density-sensitive line pair, Fe xiv 264.78 Å/274.20 Å. Because coronal line profiles of the outflow region are composed of a major component with a Doppler shift of $\lesssim 10$ km s$^{-1}$ and a minor component (enhanced blue wing, EBW) blueshifted by up to 100 km s$^{-1}$, we extracted EBW from the line profiles through double-Gaussian fitting. We tried applying the simultaneous fitting to those two Fe xiv lines with several physical restrictions. Electron density for both components ($n_{\text{Major}}$ and $n_{\text{EBW}}$, respectively) was calculated by referring to the theoretical intensity ratio as a function of electron density as per the CHIANTI database. We studied six locations in the outflow regions around NOAA AR10978. The average electron density was $n_{\text{Major}} = 10^{9.16_{-0.29}^{+0.16}}$ cm$^{-3}$ and $n_{\text{EBW}} = 10^{8.74_{-0.29}^{+0.16}}$ cm$^{-3}$. The magnitude relationship between $n_{\text{Major}}$ and $n_{\text{EBW}}$ was opposite in the eastern and western outflow regions. The column depth was also calculated for each component, which leads to the result that the outflows possess only a small fraction (~0.1) in the eastern region, whereas they dominate over the major component in the line profiles by a factor of five in the western region. When taking into account the extended coronal structures, the western region can be thought to represent the mass leakage. In contrast, we suggest a possibility that the eastern region actually contributes to mass supply to coronal loops.

Key words: Sun: corona – Sun: transition region – Sun: UV radiation

1. INTRODUCTION

Spectral coverage sensitive to the coronal temperature and the unprecedented high signal-to-noise ratio (S/N) of Hinode EIS enabled the existence of upflows at the edge of active regions (ARs) to be revealed (Doschek et al. 2008; Harra et al. 2008). These upflows have been called “AR outflows” and are considered to be ejected from the bottom of the corona. It has previously been confirmed that these outflows persist for several days in the images taken by the X-ray Telescope on board Hinode (Sakao et al. 2007). Some authors interpreted AR outflows as the source of the solar wind (Harra et al. 2008; Baker et al. 2009; Brooks & Warren 2011).

Doschek et al. (2008) analyzed emission line profiles of Fe xii 195.12 Å and revealed that the outflows are observed at the dark region outside an AR core. A preliminary result from EIS has shown that there is a clear boundary between closed hot loops in the AR core ($\sim 3 \times 10^{6}$ K) and extended cool loops ($\lesssim 1 \times 10^{6}$ K) where the blueshift was observed (Del Zanna 2008). The upflows were seen in the low-density and low-luminance area. Meanwhile, the redshift was observed in the AR core for all emission lines (Fe vii–xv). The existence of a strong major component near the rest wavelength hinders the signal of upflows and it leads to the apparent lack of signatures of any upflows at AR corors (Doschek 2012), but this has not yet been proven. The magnetic configuration of the outflow region has been modeled by magnetic field extrapolation from the photospheric magnetogram (Harra et al. 2008; Baker et al. 2009), and it was revealed that AR outflows emanate from the footpoints of extremely long coronal loops on the edge of an AR (Harra et al. 2008). Close investigation revealed that AR outflows are located near the footpoints of quasi-separatrix layers, where changes in the connectivity of the magnetic fields from closed coronal loops into open regions are formed (Baker et al. 2009; Del Zanna et al. 2011).

The velocity of the outflow lies within the range of a few tens up to $\sim 100$ km s$^{-1}$. These velocities were derived by subtracting the fitted single Gaussian from raw line profiles (Hara et al. 2008) and by double-Gaussian fitting (Bryans et al. 2010). Using extrapolated magnetic fields, the actual velocity was derived from the Doppler measurement and found to have a speed of 60–125 km s$^{-1}$ (Harra et al. 2008). The upflow velocity of AR outflows increases with the formation temperature that the emission lines Si vii–Fe xv represent (Warren et al. 2011). The blueshift becomes larger in the hotter emission line, 5–20 km s$^{-1}$ for Fe xii (formed at $\sim 1 \times 10^{6}$ K) and 10–30 km s$^{-1}$ for Fe xv (formed at $\sim 3 \times 10^{6}$ K) (Del Zanna 2008). The appearance of the blueshifted regions often seems to trace loop-like structures. However, it is not completely understood whether the AR outflows are related to fan loop structures (Tian et al. 2011; Warren et al. 2011; McIntosh et al. 2012).

AR outflows are observed as an enhanced blue wing (EBW) component in the emission line profiles of Fe xii–xv. By fitting the line profiles with a single Gaussian, it was revealed that there is a negative correlation between blueshifts and line widths (Doschek et al. 2008; Hara et al. 2008), which indicates the existence of an unresolved component in the blue wing emitted from the upflowing plasma. The intensity of this EBW is 25% in the maximum compared to that of the major component. (Doschek 2012).

Previous observations have revealed properties of the outflow from the edge of ARs such as (1) location: less bright region outside the AR core, (2) magnetic topology: boundary between open magnetic fields and closed loops, and (3) velocity: reaching up to $v \sim 100$ km s$^{-1}$ in the coronal
temperature. Although a number of observations have revealed those physical properties, there remains one missing quantity: the electron density of the outflow itself. The density of an outflow region derived using the line ratio of Fe xii 186.88 Å/195.12 Å was $\sim$7 $\times$ 10$^8$ cm$^{-3}$ (Doschek et al. 2008), which is slightly lower than the typical value in the AR ($n_e \geq 10^9$ cm$^{-3}$). Recently, Brooks & Warren (2012) carried out differential emission measure (DEM) analysis at the outflow regions. It was revealed that the properties of DEM and also the chemical abundance are rather close to those of the AR, from which the authors concluded that the outflowing plasma originates in the AR loops. The interchange reconnection was considered to be a candidate for accelerating the plasma into the outer atmosphere (Baker et al. 2009; Del Zanna et al. 2011).

The electron density of the outflow itself should help us to better understand the nature of the outflows. However, there have been few intensive attempts to do so until present (Patsourakos et al. 2014). One point of view is that those outflows are directly linked to the coronal heating in such a way that the outflowing plasma fills the outer atmosphere and forms the corona (De Pontieu et al. 2009; McIntosh et al. 2012). The impulsive heating in a coronal loop induces an upflow from its footpoint, which may account for what we see as the outflow (Del Zanna 2008; Harra et al. 2008). Outflows can also be caused by the sudden change of the pressure environment in a coronal loop (Bradshaw et al. 2011).

A theoretical estimate was recently proposed in terms of the ratio of the electron density between the major component ($n_{\text{Major}}$) and the EBW component ($n_{\text{EBW}}$) in the coronal emission line profiles (Klimchuk 2012). It was shown that if the tips of the chromospheric spicules supply the coronal plasma (De Pontieu et al. 2011), that ratio (hereafter denoted as $n_{\text{EBW}}/n_{\text{Major}}$) takes a value of an order of 10–100, whereas tiny impulsive heating (i.e., nanoflare) creates the ratio of 0.4–1 (Patsourakos et al. 2014). Thus, it was suggested that the ratio $n_{\text{EBW}}/n_{\text{Major}}$ can be used as a diagnostic tool, which enables us to discriminate these two mechanisms in the corona. Patsourakos et al. (2014) showed that this ratio peaks at the order of unity and suggested that type II spicules (De Pontieu et al. 2007) cannot be the primary source of the coronal plasma.

In this study, we used the spectroscopic data obtained with EIS on board Hinode in order to measure the electron density of the outflows. As a line pair suitable for our purpose, Fe xiv 264.78 Å and 274.20 Å were chosen because (1) these emission lines have a distinct EBW at the outflow region, which leads to better S/N; (2) they consist of relatively clean emission lines, and their line wings on the shorter-wavelength side do not overlap with other emission lines, different from the cases for Fe xii 186.88 Å/195.12 Å and Fe xiii 202.04 Å/203.83 Å; and (3) the Fe xiv line pair is sensitive to the density range of $n_e = 10^8$–$10^{12}$ cm$^{-3}$, as shown in Figure 1, which is wider than the other line pairs. The analyzed AR was the same as in Patsourakos et al. (2014), and one of our advantages is the spatial information (i.e., the east/west edges), which they did not focus on in their study.

This paper is structured as follows. Section 2 describes the EIS observation and wavelength calibration. The density of the outflows is derived in Section 3, and the results are shown in Section 4. We propose a new technique for line profile analysis ($\lambda$–$n_e$) in Section 5. We discuss the nature of the observed outflows in Section 6. Section 7 provides a summary of this paper. Two appendices describe some details of our analysis.

2. OBSERVATION AND CALIBRATION

In this study, we analyzed a raster scan obtained with Hinode/EIS, which observed AR NOAA AR10978 (hereafter AR10978) at the center of the solar disk. The scan with the narrow 1″ slit started on 2007 December 11 00:24:16 UT and ended at 04:47:29 UT. Field of view (FOV) was 256″ × 256″, and exposure time was 60 s. The EIS data were processed through the standard software, which detects the cosmic ray hits on the CCD pixels, subtracts the dark current bias, and corrects the digital number (DN) at warm pixels. The DN is converted into units of intensity, erg cm$^{-2}$ s$^{-1}$ sr$^{-1}$ Å$^{-1}$. This quantity should be called spectral intensity in the literature. However, we use the term intensity for the sake of simplicity. One complicated point in the calibration is the thermal drift of the projected location on the CCD pixels due to the orbital motion of Hinode. We calibrated the absolute wavelength through the method developed by Kamio et al. (2010). Because the relative position of the two emission lines Fe xiv 264.78 and 274.20 Å is the most important factor in this

![Figure 1. Theoretical line ratio calculated by CHIANTI database version 7 (Dere et al. 1997; Landi et al. 2012). (a) Fe xiv 264.78 Å/274.20 Å. (b) Si vii 274.18 Å/275.35 Å.](image-url)
analysis, we carried out relative wavelength calibration, details of which are described in Kitagawa (2013).

3. DENSITY DIAGNOSTICS OF UPFLOWS

One of our main achievements is the density measurement of the AR outflows. Previous observations have revealed that the density of the outflow region measured using a line pair, Fe xiii 186.88 Å/195.12 Å, indicates $7 \times 10^8$ cm$^{-3}$, which is close to that of coronal holes, rather than that of ARs (Doschek et al. 2008). However, the density of the outflow itself, measured by separating its component from the major component in the line profiles, has not yet been investigated.

There are three reasons for the difficulties in the analysis of spectroscopic data obtained by Hinode/EIS. First, the signals from an upflow are detected as an EBW component in the emission line profiles. Examples are shown in Figure 2. In each panel, the line profiles at the footpoint of a core loop (red histogram) and at the outflow region analyzed here (blue histogram) are shown in the upper half. Residuals from single-Gaussian fitting for each histogram are shown in the lower half. For example, the EBW component is significantly weaker in most cases, as shown in the spectra indicated by the blue histograms shown in Figure 2. In addition, the EBW component is significantly weaker in most cases, as shown in the spectra indicated by the blue histograms shown in Figure 2. The green histogram in panel (c) shows the estimated spectrum of Si vii 274.18 Å.

Figure 2. Line profiles of the active region, AR10978. (a) Context image of AR10978 obtained on 2007 December 11 00:24:16–04:47:29 UT. Intensity of Fe xiv 264.78 Å is shown. Boxes numbered 1 (red) and 2 (blue) indicate the footpoint of core loops and the outflow region, respectively. (b) Fe xiv 264.78 Å spectra. (c) Si vii 274.20 Å spectra. In each panel, the line profiles at the footpoint of the core loops (red histogram) and at the outflow region analyzed here (blue histogram) are shown in the upper half. The spectra were normalized by integration. Residuals from single-Gaussian fitting for each histogram are shown in the lower half. The green histogram in panel (c) shows the estimated spectrum of Si vii 274.18 Å.

Second, the density measurement of the outflow itself needs the accurate determination of the rest wavelengths of the emission lines from which we fit the two emission lines simultaneously and deduce the intensity. This is often laborious because we do not have the absolute measure of the wavelength corresponding to each of the observational spectral pixels.

Third, the density measurement needs at least two emission lines from the same ion (e.g., Fe xiv, as used in this paper). This means that the two emission lines should be fitted simultaneously using the same parameters, such as Doppler velocity and line width. No previous studies on the outflows from the edge of ARs have dealt with such fitting.

Our procedure for the density diagnostics is as follows: (1) integration of neighboring multiple pixels in order to reduce the noise; (2) determination of the wavelength position corresponding to the same Doppler velocity; (3) removal of the blending Si vii 274.18 Å from Fe xiv 274.20 Å, using Si vii 275.35 Å as a reference; (4) simultaneous fitting of the blended lines Fe xiv 264.78 Å and 274.20 Å; and (5) density inversion using a theoretical curve from CHIANTI as a function of the intensity ratio. In the following sections, each procedure will be described in detail.

3.1. Integration of Observational Pixels

The outflows from the edge of ARs are usually detected as an EBW in the emission line profiles. Its intensity does not exceed $\sim$25% of that of the major component (Doschek 2012). This makes analysis difficult because the photon noise of the major component affects the emission from EBW. In addition,
the region where the outflows can be seen is usually dark (i.e., small S/N). In order to improve the S/N, we integrated over multiple observational pixels in space using a square box with the size of $5'' \times 5''$. A larger integration box generally results in better S/N. However, we chose that particular size of integration box so as not to lose the information of the outflow region. In the integration, the pixels with instrumental problems (i.e., hot or bad pixels) were excluded.

3.2. Deblending of Si vii from Fe xiv 274.20 Å

Fe xiv 274.20 Å potentially has a contribution from Si vii 274.18 Å, which may become significant in the vicinity of an AR because Si vii emission often comes from the footpoint of cool loops extending from the edge of the AR. We need to subtract this blend from Fe xiv 274.20 Å. In this study, the spectrum of Si vii 274.18 Å was calculated by using the observed line profile of Si vii 275.35 Å, which is known to be clean (i.e., without any significant blend). The intensity ratio of Si vii 274.18 Å/275.35 Å is at most 0.25, as calculated from CHIANTI version 7 (Dere et al. 1997; Landi et al. 2012). The value has a dependence in the density range $10^9 \text{ cm}^{-3} \leq n_e \leq 10^{10} \text{ cm}^{-3}$, and it varies, 0.06–0.27 (monotonically increasing), as shown in Figure 1. First we removed the blending Si vii 274.18 Å for the case $n_e = 10^9 \text{ cm}^{-3}$ (Si vii electron density), and after that we considered three cases of the ratio corresponding to the density of $10^8$, $10^9$, and $10^{10} \text{ cm}^{-3}$. In order to make our analysis more robust, we excluded the location where the estimated intensity of Si vii 274.18 Å exceeds 5% of the Fe xiv intensity. Using the theoretical ratio, the intensity of Si vii 275.35 Å was converted into that of Si vii 274.18 Å. The spectrum of Si vii 275.35 Å was then placed at Si vii 274.18 Å, taking into account the shift of Si vii 275.35 Å from the rest wavelength using the relative difference between wavelengths of Si vii 274.18 and 275.35 Å (i.e., 1.1808 Å) given by the CHIANTI database. Note that because there were no locations where Si vii 274.18 Å dominates Fe xiv 274.20 Å in the data, we could not determine the relative wavelength position of the two Si vii lines; therefore we used the wavelength difference given by CHIANTI for the Si vii lines. The data points of the estimated Si vii 274.18 Å in the wavelength direction were interpolated into the data points of Fe xiv 274.20 Å by cubic spline. Thus, we removed the blended Si vii 274.18 Å from Fe xiv 274.20 Å.

Concerning Fe xiv 264.78 Å, there are two possible blend lines: Fe xvi 264.77 Å and Fe xvi 265.01 Å. As for Fe xvi 265.01 Å, it is sufficiently far enough from Fe xiv 264.78 Å in nonfaint situations. Moreover, the estimated peak intensity of Fe xvi 265.01 Å was around 100 erg cm$^{-2}$ s$^{-1}$ sr$^{-1}$ Å$^{-1}$ in the observed outflow region, which is no greater than the background level of Fe xiv 264.78 Å, as seen in Figure 3. Unfortunately, our data set did not have any isolated Fe xvi emission line, which makes it difficult to remove the blending Fe xvi from Fe xiv 264.78 Å. Nevertheless, our crude estimation of the intensity of Fe xvi 264.77 Å from Fe xvi 188.21/188.30 Å ($I_{264.77 \text{ Å}}/I_{188.21 \text{ Å}} \lesssim 0.03$) leads to its potential influence on Fe xiv 264.78 Å by up to 5% in maximum. It is inferred in Appendix B that the error in our results can be considered to lie within $\sim 3\%$.

3.3. Simultaneous Fitting of the Two Fe xiv Emission Lines

In order to make the fitting more robust, the two emission line profiles of Fe xiv 264.78 Å/274.20 Å were fitted simultaneously. This is based on the consideration that the emission line profiles coming from the same ion species must have the same Doppler shift and the same Doppler width. As seen in Figure 2, the emission line profiles of Fe xiv 264.78 and 274.20 Å from the AR core (red histogram) are obviously symmetric, whereas those from the outflow region (blue histogram) have an EBW, from which it is not likely that a strong major component hinders any signals of the upflows in the AR core. This EBW did not exceed the major component anywhere in the outflow region ($\leq 30\%$). Previous observations have never shown such emission line profiles whose EBW dominates over the major component (Doschek 2012).

In this study, the emission line profiles of the outflow region are assumed to be composed of two Gaussian components. Most previous analyses on the outflows at the edge of an AR assumed that the main component and EBW have the same line width in order to avoid an unrealistic solution in the fitting parameter space, but the assumption could strongly affect the fitting (Bryans et al. 2010; Brooks & Warren 2012). Brooks & Warren (2012) mentioned that this assumption may lead to the underestimation of the intensity of the EBW. The line profile with EBW often shows a rather longer tail in the line wing than could be represented by a Gaussian, which has the same line width as the major component. Moreover, the assumption that the major component and EBW have the same line width is not based on physical principles.

In order to examine the differences in the fitting result between different constraints on the fitting parameters, we applied three fitting models to a line profile pair of Fe xiv 264.78 Å. The line centroid and line width are denoted by $\lambda$ and $\lambda_W$, respectively. The suffixes “1” and “2” below represent Fe xiv 264.78 Å and Fe xiv 274.20 Å, followed by either the component “Major” or “EBW.” The first model (model 1) assumes $W_{1,\text{Major}} = W_{1,\text{EBW}}$ and $W_{2,\text{Major}} = W_{2,\text{EBW}}$, and fits the line profiles of Fe xiv 264.78 and 274.20 Å separately with double Gaussians that have the same line width for each component. The second model (model 2) also fits the two Fe xiv line profiles separately, but with double Gaussians that do not necessarily have the same line width for each component. The third model (model 3) fits the two Fe xiv line profiles simultaneously by applying $\lambda_{2,\text{Major}} = \alpha \lambda_{1,\text{Major}}$, $\lambda_{2,\text{EBW}} = \alpha \lambda_{1,\text{EBW}}$ ($\alpha = 1.0355657$, Kitagawa 2013), $W_{1,\text{Major}} = W_{2,\text{Major}}$, and $W_{1,\text{EBW}} = W_{2,\text{EBW}}$. We adopted model 3 for the electron density measurement in this study because it is the most physically reasonable in the sense that the model calculates the parameters (line centroids and thermal widths) consistently for both emission lines and does not impose artificial restrictions on the line widths.

The results for those three models are shown in Figure 3. We obtained a smaller and more blueshifted second component (EBW) with model 1, as seen in panels (a) and (b), which confirms the suggestion in Brooks & Warren (2012). In contrast, larger and less blueshifted EBWs were obtained with models 2 and 3, as clearly seen in panels (c)–(f). In addition to this, the line widths of the EBW component were much broader.

\footnote{We estimated the intensity from Fe xvi 262.98 Å included in the EIS data. The line ratio, Fe xvi 265.01 Å/262.98 Å, was determined in the raster scan that started from 10:25:42 UT because it included the spectra of both Fe xvi 262.98 Å and 265.01 Å, and it resulted in the ratio of 0.083.}
It is not clear at present whether the increased widths may indicate superposition of multiple upflow components, which will be another point to be revealed in the future. The comparison among those three models shows that the results in previous analyses probably underestimate the intensity of EBW with an artificial assumption that the two components in the line profile have the same line width. Moreover, independent fitting applied to the two emission lines causes a discrepancy, as seen in panels (c) and (d). The Doppler velocity of the EBW component was $-81.4$ km $s^{-1}$ for Fe XIV 264.78 Å, whereas it was $-70.1$ km $s^{-1}$ for Fe XIV 274.20 Å. Note that the rest wavelengths were determined from a limb observation on 2007 December 6, so these Doppler velocities have an uncertainty of 10 km $s^{-1}$ at most.

### 3.4. Density Inversion

Now the densities of the EBW and the major component can be obtained by referring to the theoretical intensity ratio of Fe XIV 264.78 Å/274.20 Å as a function of the electron density shown in Figure 1. The intensity ratio monotonically increases within the density range of $10^9$ cm$^{-3} \leq n_e \leq 10^{12}$ cm$^{-3}$. The electron density in the solar corona generally falls between $10^9$ cm$^{-3}$ (for coronal holes) and $10^{11}$ cm$^{-3}$ (for flare loops), so the intensity ratio of Fe XIV 264.78 Å/274.20 Å is quite useful. The error in the density was calculated by using the 1σ error in the intensity ratio. The electron density is obtained from

$$n_e = F^{-1} \left( \frac{I_{264}}{I_{274}} \right),$$

where $F^{-1}$ is the inverse function of the theoretical intensity ratio and $I_{264}$ and $I_{274}$ are the observed intensity of Fe XIV 264.78 Å and 274.20 Å, respectively. Using $\sigma_{264}/I_{274}$ as the error of the observed intensity ratio, we estimate the error of the density, $\sigma_n$, as

$$n_e \pm \sigma_n = F^{-1} \left( \frac{I_{264}}{I_{274}} \pm \sigma_{264}/I_{274} \right).$$

The error $\sigma_n$ was not dealt with symmetrically in this definition, which comes from the fact that the function $F$ has a curvature that cannot be negligible compared to $\sigma_{264}/I_{274}$.

### 4. DENSITY DERIVED FROM FE XIV 264.78 Å/274.20 Å

#### 4.1. Results from Single-Gaussian Fitting

First we describe the results deduced from single-Gaussian fitting. As described above, the line profiles at the outflow
regions are known to have a distorted shape, which cannot be represented well by a single Gaussian. Nonetheless, the results deduced from single-Gaussian fitting may be useful because the fitting is much more robust in terms of the freedom of the variables (e.g., four parameters for a single Gaussian with constant background and seven parameters for double Gaussians). Figure 4 shows the map of the intensity, Doppler velocity, line width of FeXIV 264.78 Å, and electron density derived from the line ratio FeXIV 264.78 Å/274.20 Å. The blending of Si VII 274.18 Å was taken into account and subtracted by referring to SiVII 275.35 Å. It is clear from panel (b) that the outflow regions are present (i.e., blueshift) at the east/west edge of the AR core around \((x, y) = (–280", –120")\) and \((-175", –125")\). Panel (c) shows that the line width at those outflow regions is larger than that at other locations by \(\Delta W = 0.020–0.027\) Å (square root of the difference of the squared line width), equivalent to \(dv = 20–30\) km s\(^{-1}\), which is similar to results reported previously (Doschek et al. 2008; Hara et al. 2008). The electron density at the outflow regions is \(n_e = 10^{8.5–9.5}\) cm\(^{-3}\), which is lower than that at the core \((n_e \geq 10^{9.5}\) cm\(^{-3}\)).

We defined the outflow regions as the locations (1) where the line width of Fe xiv 264.78 Å is enhanced and (2) which can be separated from the fan loops seen in the Si vii intensity map (not shown here). The six selected regions are indicated by white boxes in each map (numbered U1–U6, as written in panel (a)), whose size is \(8" \times 8"\). Those regions are located beside the bright core, as seen in the intensity map (panel a). We hereafter refer to U1–U2 as the eastern outflow region and U3–U6 as the western outflow region.

4.2. Density of the Upflows

The electron density of the EBW component was measured through the analysis described in Section 3. Figure 5 shows the distributions of the electron density for the major component \(n_{\text{Major}}\) in panel (a) and the EBW component \(n_{\text{EBW}}\) in panel (b). Pixels where the peak intensity of the major component \(I_{\text{Major}}\) did not exceed \(\eta = 2.0 \times 10^3\) erg cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\) Å\(^{-1}\) were masked in black. This threshold was determined by using the scatter plot of the intensity and electron density of the major component, shown in Appendix A. Pixels falling into the next three conditions were displayed, and others were masked in black. (1) \(I_{\text{Major}} > 2.0 \times 10^3\) erg cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\) Å\(^{-1}\). (2) The

*Figure 4.* Physical quantities deduced from single-Gaussian fitting for Fe xiv 264.78 Å obtained on 2007 December 11 00:24:16–04:47:29UT. (a) Intensity of Fe xiv 264.78 Å. (b) Doppler velocity of Fe xiv 264.78 Å. (c) Line width of Fe xiv 264.78 Å. (d) Electron density derived from the line ratio, Fe xiv 264.78 Å/274.20 Å.
intensity of the EBW component ($n_\text{EBW}$) exceeds 3% that of the major component ($n_{\text{Major}}$). (3) The difference between the Doppler velocity of the EBW component ($v_{\text{EBW}}$) and that of the major component ($v_{\text{Major}}$) satisfies $v_{\text{EBW}} - v_{\text{Major}} < -30 \text{ km s}^{-1}$ (i.e., the two components are well separated).

The relationship of the electron density between the major component and the EBW component is shown in Figure 6. The scatter plot in panel (a) shows the electron density for the outflow regions U1–U6 (colored symbols) and for the entire western outflow region indicated by the white dashed box in Figure 5 (black dots). The eastern outflow regions (U1–U2) and the western ones (U3–U6) exhibit different characteristics. The scatter plots for U1–U2 indicate $n_{\text{Major}} \lesssim n_{\text{EBW}}$, whereas those for U3–U6 indicate $n_{\text{Major}} \gtrsim n_{\text{EBW}}$. Panels (b) and (c) show the same data, but in histograms for which the colors again indicate the selected outflow regions. The gray (major component) and turquoise (EBW component) histograms in the background are made for the entire western outflow region. Those two histograms are multiplied by 0.1.

Figure 5. Electron density map deduced from two-Gaussian fitting of an emission line pair, Fe xiv 264.78 Å/274.20 Å, obtained by the raster scan on 2007 December 11 00:24:16–04:47:29UT. (a) Electron density of the major component. (b) Electron density of the EBW component. The same color contour is used in the two panels. Pixels where the peak intensity of the major component ($I_{\text{Major}}$) did not exceed $2.0 \times 10^4 \text{ erg cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ Å}^{-1}$ were masked in black. White boxes numbered U1–U6 are the same as those in Figure 4. The white dashed box indicates the entire western outflow region.

Figure 6. (a) Scatter plot for the Fe xiv electron density of the major component vs. that of the EBW component. Colors show the selected region indicated by white boxes in Figure 4. Triangles (Diamonds) represent the data points in the eastern (western) outflow regions. Numbers beside data points correspond to the name of the white boxes. Black dots show the electron density for the western outflow region indicated by a white dashed box in Figure 5. The dashed line indicates the point where two densities equal each other. (b) Histograms for the electron density of the major component (dotted) and the EBW component (solid) in the eastern outflow region. (c) Histograms for the electron density of the major component (dotted) and the EBW component (solid) in the western outflow region. The gray (major component) and turquoise (EBW component) histograms in the background are made for the entire western outflow region. Those two histograms are multiplied by 0.1.
consistent with those of Patsourakos et al. (2014; i.e., $n_{\text{EBW}}/n_{\text{Major}} \lesssim 1$).

### 4.3. Column Depth

Using the electron density obtained for each component in the Fe xiv line profiles, the column depth of each component can be calculated. We use the equation for the column depth including the filling factor,

$$h^* = hf = \frac{I}{n_e^2 G(n_e, T)},$$

where $f$ is the filling factor, $I$ is the intensity of an emission line, $n_e$ is the electron density, and $G(n_e, T)$ is the contribution function of an emission line. The quantity $h^*$ physically represents the plasma volume per unit area along the line of sight (LOS). Here the temperature substituted in Equation (3) was simply assumed to take a single value $T_f$, at which the contribution function $G(n_e, T)$ becomes maximum ($\log T_f [\text{K}] = 6.30$ for the Fe xiv lines used here). Panel (a) in Figure 7 shows a scatter plot for the column depth of the major component ($h_{\text{Major}}$) and that of the EBW component ($h_{\text{EBW}}$). The colored symbols indicate the studied regions (U1–U2 for the eastern outflow region and U3–U6 for the western outflow region). Similar to the result for the electron density, the eastern and western outflow regions exhibit different characteristics: $h_{\text{Major}} \gtrsim h_{\text{EBW}}$ in the eastern region and $h_{\text{Major}} \lesssim h_{\text{EBW}}$ in the western region. Panels (b) and (c) display the same data in the form of histograms for the eastern and western outflow regions, respectively. The gray and turquoise histograms in the background of panel (c) show the results for the entire western outflow region indicated by a white dashed box in Figure 5. Table 1 shows the column depths averaged in each studied region.

The result, $h_{\text{Major}} \lesssim h_{\text{EBW}}$, in the western outflow regions (U3–U6) means that the upflow dominates over the major component in terms of volume; this is opposite the composition ratio of the emission line profile itself. The value of $h_{\text{EBW}} \approx 10^{8.0} \text{ cm}$ can be understood by considering that the inclination of the magnetic field lines in the western outflow region was $30^\circ-50^\circ$ (given the potential field calculation), and the horizontal spatial scale of the region was on the order of $10^9 \text{ cm}$, which leads to a vertical height of nearly the same amount. On the other hand, it is clearly indicated that $h_{\text{EBW}}$ is smaller than $h_{\text{Major}}$ by up to one order of magnitude in the eastern outflow region (U1–U2). This means that the upflows possess only a small fraction compared to the plasma characterized by the major component in the line profiles. The Doppler velocities, derived electron densities, and the column depths for the studied outflow regions are listed in Table 1.

Note that in the line profile analysis, we assumed that the electron density corresponding to the temperature of Si viii (i.e., the transition region; hereafter $n_{\text{Si viii}}$) was $10^9 \text{ cm}^{-3}$. We discuss this assumption and its influence on our results in Appendix B.

### 5. $\lambda$--$n_e$ Diagram

We modeled the spectra as the composition of the two Gaussians in the above analysis. However, it is difficult to prove whether or not this assumption is suitable for the outflow regions. There are two alternative approaches to dealing with such a spectrum consisting of more than two Gaussians. One way is to adopt multiple-Gaussian functions (more than two components) and resolve multiple flows existing in an emission line. The more free parameters we use, the lower the $\chi^2$ of the fit to the spectra will be. But this does not mean that we extracted a great deal of useful physical information from the spectra. The number of local minima increases with the complexity of the fitting model, and the fitting process becomes an ill-posed problem.
The derived \( n_e^* (\nu_{\text{Dop}}) \) can be converted into a function of the wavelength in either spectrum, \( n_e (\lambda) \), by the Doppler effect equation. The function \( R(n_e) \) is the ratio of the intensities from the two emission lines, which is a function of the electron density; therefore when we know the intensities of the two emission lines, which are represented as

\[
I_i = \int \phi_i (\lambda) d\lambda, \tag{5}
\]

\[
I_2 = \int \phi_2 (\lambda) d\lambda, \tag{6}
\]

the electron densities can usually be derived as

\[
n_e = R^{-1} \left( \frac{I_2}{I_1} \right). \tag{7}
\]

Note that we used the same curve as shown in panel (a) in Figure 1 for the function \( R(n_e) \). This assumes that \( R(n_e) \) is the same for all wavelengths in the range of interest, which we have not investigated in detail.

As shown in the above equations, the \( \lambda-n_e \) diagram represents the density of particles which move with that speed; in other words, we do not obtain the electron density of the whole plasma as an ensemble of the Maxwellian distribution. We emphasize that the advantage of our method using Equation (4) is that even if we do not know the precise functional form of the spectra, it gives us the electron density as a function of the Doppler velocity without any modeling.

5.1. Method

To make the \( \lambda-n_e \) diagram we use the following processes: (1) subtraction of the blending emission line, (2) adjusting the wavelength scale of Fe XIV 264.78–274.20 Å by interpolation, and (3) density inversion at each spectral pixel. Because the blending of an emission line, Si XIV 274.18 Å, into Fe XIV 274.20 Å was already described in Section 3.2, here we explain only processes (2) and (3).

Because the EIS instrument does not have an absolute wavelength scale, the corresponding wavelength location of the same velocity in Fe XIV 264.78 and 274.20 Å must be determined from the data itself, as described in Kitagawa (2013). Using the obtained relation, \( \lambda_{\text{obs,274}} / \lambda_{\text{obs,264}} = 1.0355657 \pm 0.0000044 \), each wavelength value imposed on the spectral window of Fe XIV 264.78 Å was projected onto the values on the spectral window of Fe XIV 274.20 Å by the scaling

\[
\tilde{\lambda}_i = \alpha \lambda_{264,i} (\alpha = 1.0355657), \tag{8}
\]

where a number \( i \) indicates the \( i \)th spectral pixel in a spectrum of 264.78 Å.

Because the wavelength values of each bin of projected Fe XIV 264.78 Å do not generally coincide with those of Fe XIV 274.20 Å, the projected spectrum was interpolated by cubic spline in order to align the two Fe XIV spectra in identical wavelength bins.

We can calculate the ratio of the spectral intensity, Fe XIV 264.78 Å/274.20 Å, at each spectral bin. Now we are able to derive the electron density in the same way described in

| Table 1 | Doppler Velocities, Electron Densities, and Column Depths of the EBW Component and the Major Component Derived Through the Double-Gaussian Fitting Applied to Fe XIV 264 Å/274 Å |
|---------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|
|         | EBW Component                                   | Major Component                                 | EBW Component                                   | Major Component                                 | EBW Component                                   | Major Component                                 |
|         | \( \nu_{\text{Dop}} \) (km s\(^{-1}\)) | \( \log n_e \) (cm\(^{-3}\)) | \( \log h \) (cm) | \( \nu_{\text{Dop}} \) (km s\(^{-1}\)) | \( \log n_e \) (cm\(^{-3}\)) | \( \log h \) (cm) |
| U1      | \(-92.4 \pm 2.4\)    | \(9.17 \pm 0.09\) | \(7.03 \pm 0.22\) | \(-4.7 \pm 0.9\)    | \(9.10 \pm 0.04\) | \(8.38 \pm 0.05\) |
| U2      | \(-84.8 \pm 21.4\)   | \(8.95 \pm 0.09\) | \(7.67 \pm 0.34\) | \(-3.6 \pm 1.7\)   | \(8.93 \pm 0.09\) | \(8.64 \pm 0.12\) |
| Ave.    | \(-88.8 \pm 15.2\)   | \(9.06 \pm 0.14\) | \(7.36 \pm 0.43\) | \(-4.2 \pm 1.4\)   | \(9.01 \pm 0.11\) | \(8.51 \pm 0.16\) |

Note. Note that the Doppler velocities listed in the table are calculated by using limb spectra observed independently on 2007 December 6 as a reference of zero velocity, which leads to errors of up to 10 km s\(^{-1}\) at most, mainly originating in the absolute wavelength calibration.
Section 3.4. Because the intensity at each spectral bin has larger errors compared to the integrated intensity (e.g., double-Gaussian fitting), the estimated errors for the electron density in the $\lambda-n_e$ diagram become large, especially for the line wing.

5.2. Verification of the Method

In order to test the validity of the $\lambda-n_e$ method, we synthesized spectra of Fe XIV 264.78 and 274.20 Å, taking into account the spectral resolution of EIS and instrumental broadening. The spectra were composed of two components, which represent plasma at rest and an upflow. While the physical parameters for the major rest component (peak, Doppler velocity, and width) were fixed, those for the minor blueshifted component (i.e., upflow) were taken as variables. We made $\lambda-n_e$ diagrams for the minor component with

1. electron density of 8.50, 8.75, 9.00, 9.25, and 9.50 in the units of log cm$^{-3}$,
2. intensity of 1%, 5%, 10%, 15%, and 20% (ratio to the major component in Fe XIV 274.20 Å),
3. Doppler velocity of 0, –50, –100, –150, and –200 km s$^{-1}$, and
4. thermal width of 2.0, 2.5, 3.0, 3.5, and 4.0 MK.

The nonthermal width was not considered in this test because essentially it does not produce any differences. In this paper, only the tests for electron density and Doppler velocity will be given below because the dependence on them is significant. The other two variables (i.e., intensity and thermal width) do not have strong effects and are described in the author’s PhD thesis (Kitagawa 2013).

5.2.1. Dependence on Electron Density

The most important point on the $\lambda-n_e$ diagram is whether it reflects the electron density of the components, which comprise the spectrum properly or not. In order to test this, we synthesized the spectra, composed of the major component at rest, which has a fixed electron density of log $n_e$ [cm$^{-3}$] = 9.0, and the minor component, which has a variable electron density. Five cases (log $n_e$ [cm$^{-3}$] = 8.50, 8.75, 9.00, 9.25, and 9.50) were analyzed, where the peak ratio of the minor/major component was 15%, with fixed upflow speed $v = –100$ km s$^{-1}$. Panels (a) and (b) of Figure 8 show the spectra of Fe XIV 264.78 Å and 274.20 Å, respectively. The colors (blue, turquoise, yellow, green, and red) indicate the five cases calculated here. After converting the wavelength scale of 264.78–274.20 Å, $\lambda-n_e$ were obtained, as shown in panel (c) of Figure 8. The triangles in panel (c) indicate the centroid and electron density of the given minor component. It is clear that those $\lambda-n_e$ diagrams clearly reflect the changes of the electron density from log $n_e$ [cm$^{-3}$] = 8.50–9.50. Despite the spectra being composed of only two components, the $\lambda-n_e$ diagrams do not become a step function but a smooth function. This is natural because the two Gaussians in the spectra contribute to each other by their overlapping wings. We claim that the method proposed here ($\lambda-n_e$) is a good indicator of the electron density of the components in the spectrum.

5.2.2. Dependence on Velocity

The dependence of the $\lambda-n_e$ diagram on the Doppler velocity of the minor component is obvious. The spectra of Fe XIV 264.78 and 274.20 Å and the $\lambda-n_e$ diagrams are shown in panels (d), (e), and (f), respectively, of Figure 8. Colors indicate the five cases calculated for variable Doppler velocity (blue: 0 km s$^{-1}$, turquoise: –50 km s$^{-1}$, green: –100 km s$^{-1}$, yellow: –150 km s$^{-1}$, and red: –200 km s$^{-1}$). The major rest component was at rest (0 km s$^{-1}$), with the electron density of log $n_e$ [cm$^{-3}$] = 9.0. The triangles in panel (f) indicate the centroid and electron density of the given minor component. The relative intensity of the minor component is 15% of that of the major component, and the electron density of the minor component set was to log $n_e$ [cm$^{-3}$] = 8.5 in all five cases here. The location of the dips in the $\lambda-n_e$ diagram represents the centroid position of the input minor component when the two components are separated, so that the spectrum is dominated by EBWs near their centroids. This is not the case for $v = –50$ km s$^{-1}$, where those two components are not separated so clearly. In this case, the $\lambda-n_e$ diagram gradually decreases from longer to shorter wavelength. One advantage of the method described here is that we are able to know the tendency of the electron density of the upflow/downflow without fitting the spectrum, which might produce spurious results occasionally.

The tests for the four variables (i.e., density, intensity, velocity, and thermal width) indicate that the method proposed here ($\lambda-n_e$ diagram) is a powerful diagnostic tool for coronal plasma, which may be constituted of several components along the LOS and form a non-single-Gaussian line profile. In the next section, we exploit this $\lambda-n_e$ diagram so that the result obtained by double-Gaussian fitting would be confirmed (i.e., upflows are more tenuous than the rest component).

5.3. $\lambda-n_e$ Diagram in AR10978

The electron density of the outflow region in AR 10978 is investigated through the $\lambda-n_e$ diagram here. Figure 9 shows the intensity map of Fe XIV 264.78 Å obtained with EIS. Orange contours indicate the line width of 0.035 Å, which becomes an indication of the outflows. Five horizontal arrays of colored diamonds (red–violet), which cut across the AR core and the outflow region, are the locations where we made the $\lambda-n_e$ diagrams. First, we look at the location indicated by black plus signs named C (core) and U (outflow).

In Figure 10, the line profiles of Fe XIV 274.20 Å, interpolated 264.78 Å, and estimated Si VII 274.18 Å (see Section 3.2) are shown by the solid, dashed, and dotted spectra, respectively, in panel (a) for the AR core and (b) for the outflow region. We can see an EBW in the line profiles of Fe XIV in the outflow region. The vertical dashed lines indicate a rough reference of the rest wavelength position, $\lambda = 274.195$ Å, which was the average line centroid above the limb in the 2007 December 18 data (possible error up to 0.01 Å).

Panels (c) and (d) in Figure 10 show the $\lambda-n_e$ diagram for the AR core and the western outflow regions, respectively. The horizontal green dotted line in each plot indicates the electron density averaged in the neighboring three spectral bins, which are nearest to $\lambda = 274.20$ Å (i.e., the rest wavelength). Those $\lambda-n_e$ diagrams in the two locations exhibit a different behavior at the shorter-wavelength side, around $\lambda = 274.00–274.20$ Å: the diagram in the AR core is roughly constant, whereas that in the western outflow region slightly decreases at the shorter wavelength. The number written in the upper left corner of each plot indicates the linear slope fitted within the wavelength...
range $\lambda \leq 274.20\,\text{Å}$. This implies that the electron density of the outflows (i.e., the shorter-wavelength side) is smaller than that of the major component closer to the rest wavelength.

In order to confirm the above implication more robustly, we see the variation of the $\lambda-n_e$ diagram along the $x$ direction from the AR core to the outflow regions. The selected region spans from the AR core (red diamond) to the outflow region (violet diamond), as seen in Figure 9. The boundary of the AR core corresponds to the color between yellow and light green. The $\lambda-n_e$ diagrams at each cut (1–5) are plotted in Figure 11. We can see clear changes of the $\lambda-n_e$ diagrams with color. The $\lambda-n_e$ diagrams for cut 1 show a small hump around 274.00–274.10 Å, showing that the EBW component has a larger electron density than the major component, although with the hump being at almost all locations (red–black) might mean that it was caused by an anomalous pixel (e.g., warm pixel). For both cuts 1 and 2, the diagrams show flat or slightly decreasing behavior as a function of
wavelength at all locations. These behaviors are consistent with the result obtained in Section 4 (regions U1 and U2), which indicated that the electron density of the outflows in the eastern edge is almost the same or slightly larger. On the other hand, in the western outflow region (cuts 3–5), those for the outflow region show a dip around 274.10 Å. This wavelength corresponds to \( v = -110 \, \text{km s}^{-1} \) for the emission line, Fe XIV 274.20 Å, from which it is implied that the outflows in the western edge are composed of less dense plasma compared to the plasma characterized by around 274.20 Å existing along the LOS. Note that this velocity does not mean that of the upflows because no fitting was applied in the \( \lambda - n_e \) diagram.

The electron density of the EBW component evaluated from the \( \lambda - n_e \) diagrams around \( \lambda = 274.10 \, \text{Å} \) was \( \log n_e \, [\text{cm}^{-3}] = 9.0–9.2 \) in the eastern outflow region and \( \log n_e \, [\text{cm}^{-3}] = 8.5–9.0 \) in the western outflow region, which also coincides with the result obtained through the double-Gaussian fitting. By exploiting the \( \lambda - n_e \) diagram as a new diagnostic tool, we can now support the results obtained in Section 4.

6. DISCUSSION

6.1. Theoretical Estimation of the Electron Density

De Pontieu et al. (2011) proposed that the tip of the spicule is heated up to the coronal temperature (although the heating mechanism has not been revealed) and is injected to the higher atmosphere, where the heated plasma forms the corona. The electron density of upflows from the tips of the spicules is estimated using Equation (10) in Klimchuk (2012), which considers the mass conservation,

\[
    n_{\text{UP},s} \delta h_s = n_c h_c A,
\]

where \( n_{\text{UP},s} \) is the electron density of an upflow (a suffix, \( s \), denotes spicule), \( \delta \) is the fraction of the spicule that is heated to coronal temperatures, \( h_s \) is the height of the spicule, \( n_c \) is the coronal density after the tip of the spicule expands into the corona, \( h_c \) is the length of the coronal loops, and \( A \) is the expansion factor of the cross section of the coronal loops from the chromosphere to the corona. Using typical coronal values, \( n_c \approx 10^9 \, \text{cm}^{-3} \), \( h_c \approx 5 \times 10^9 \, \text{cm} \), \( \delta \approx 10\% \) (De Pontieu et al. 2011) would suggest an electron density \( n_{\text{UP},s} \).
Pontieu et al. 2011, $h \sim 10^9$ cm in the maximum height, and $A \sim 10$ (this factor has not yet been determined precisely, but is larger than unity), the electron density of the upflow is estimated as

$$n_{\text{upf}} \simeq 5 \times 10^{11} \left( \frac{n_e}{10^9 \text{ cm}^{-3}} \right) \left( \frac{h_c}{5 \times 10^9 \text{ cm}} \right) \times \left( \frac{A}{10} \right)^{-1} \left( \frac{\delta}{0.1} \right)^{-1} \left( \frac{h_s}{10^9 \text{ cm}} \right)^{-1} \text{ cm}^{-3}. \tag{10}$$

For impulsive heating, giving the typical energy content of nanoflares (i.e., $10^{24}$ erg) and considering the enthalpy flux as a response of the transition region below the corona leads to

$$\frac{5}{2} \rho v_{\text{upf},i} = \frac{E_i}{\pi r_{\text{at}}^2 q}, \tag{11}$$

where $\rho$ is the gas pressure of the upflow, $v_{\text{upf},i}$ is the speed of the upflow, $E_i$ is the released energy by the impulsive heating, $r_{\text{at}}$ is the radius of the coronal strand (i.e., the thin coronal loop as an elemental structure), and $q$ is the duration of the impulsive heating. Kinetic energy flux can be neglected because the upflow speed is around half the speed of sound ($\sim 200$ km s$^{-1}$ at $T \text{ [K]} = 6.3$), which means the ratio of the kinetic energy flux to the enthalpy flux is on the order of

Figure 11. $\lambda-n_e$ diagrams at the locations indicated by the colored diamonds in Figure 9 (cuts 1 and 2, including the eastern outflow region, and cuts 3–5, including the western outflow region).
0.1. Typical parameters $E_i \sim 10^{24}$ erg, $\nu_{UP,i} \simeq 100$ km s$^{-1}$, $r_i \sim 10^{-8}$ cm, and $\tau \sim 10$–$100$ s (this value contains a large degree of uncertainty because of a lack of knowledge at present) imply

$$n_{UP,i} \simeq 5 \times 10^{8}$$(10 cm$^{-3}$ (100 s)$^{-1}$ $E_i$$^{12}$ $r_i$$^{12}$ $\nu_{UP,i}$ $T_e$$^{-1}$ $\tau$$^{-1}$ $10^9$ K $10^8$ cm s$^{-1}$ $10^9$ K $10^8$ cm s$^{-1}$ cm$^{-3}$, \tag{12}

for which we used $p = 2n_{UP,i} k_B T_e$, where $n_{UP,i}$ is the electron density of the upflow and $T_e$ is its temperature. Recent observation by Hi-C (Kobayashi et al. 2014) indicated that the width of the coronal strands is around 450 km (Brooks et al. 2013). Note that $E_i$ and $\tau$ have not been observationally well constrained so far, although we used values that are considered to be reasonable at present. It is clear that the predicted electron density estimated by adopting the typical coronal values from the spicule and impulsive heating significantly exceeds the derived upflow density ($n_{EBW} \lesssim 10^9$ cm$^{-3}$ in our analysis). Equation (12) can be used to estimate the parameter range where the predicted upflow density becomes similar to the observed value because there is much uncertainty in the parameter $\tau$. For example, if the heating continues for $\tau = 500$ s, Equation (12) leads to $n_{UP,i} \simeq 10^{10}$ cm$^{-3}$ (i.e., near the obtained upflow density) for the case in which other parameters keep their typical value.

6.2. Mass Transport by the Outflow

We estimate the mass flux of the outflowing plasma $F_{out}$ in the western outflow region by using the Doppler velocity and electron density of the EBW component. The electron density was $n_e \simeq 10^8$ cm$^{-3}$, and the Doppler velocity was $-60$ km s$^{-1}$. The total area ($S$) of the entire western outflow region was roughly $30' \times 40'$ ($S \simeq 6 \times 10^{18}$ cm$^2$). Considering the inclination angle of the magnetic field of $30'–50'$ as calculated by potential field extrapolation of a Michelson Doppler Imager (MDI) magnetogram (mentioned in Section 6.3), the speed of the outflow is roughly thought to be $v \simeq 70–90$ km s$^{-1}$. Thus, $F_{out}$ can be estimated as $F_{out} = 2n_e \mu S = (4–5) \times 10^{10}$ g s$^{-1}$, where $\mu$ is the mean mass of ions, which was set to $1 \times 10^{-24}$ g. For a comparison, we also evaluate the total mass contained in the AR. Using the volume of $V = (100)^3 = 4 \times 10^{29}$ cm$^3$ and typical density $n_e = 10^{10}$ cm$^{-3}$, the total mass $M_{AR}$ is evaluated as $M_{AR} = 2n_e \mu V = 8 \times 10^{14}$–$15$ g.

This implies that if the mass in the AR is actually lost by the outflow (Brooks & Warren 2012), the timescale of the mass drain becomes $\tau_{out} = M_{AR}/F_{out} = 2 \times 10^{4}$ s (i.e., several hours to a couple of days). Because the lifetime of ARs is much longer than this timescale, up to several weeks, the AR needs a certain mechanism to provide the plasma continuously. We note that the outflow region is localized at the edge of the AR, which means that a limited part of the AR is involved in the outflow. In contrast to this mass drain scenario, the extrapolated magnetic field lines rooted in the outflow region were connected to the opposite edge of the AR, according to the potential field calculation. The opposite side of the outflow region exhibits almost zero velocity, which indicates that the mass would accumulate from the outflow region. This leads to the picture that the outflow actually provides the AR with the plasma. However, the Doppler velocity map shows a blueshifted pattern extending to the northwest from the western outflow region, which may indicate that it is connected to a far higher atmosphere. We must take into account the temporal evolution of the magnetic field in order to confirm the validity of these scenarios, which will be studied in the near future.

6.3. Eastern and Western Outflow Regions

Here we discuss some implications for the coronal formation (i.e., heating) from the viewpoint of the outflows. The differences of the derived quantities in those two outflow regions are listed in Table 1. The topology of the magnetic field lines can be inferred from the extrapolated field lines and the Doppler velocity map. We calculated the potential magnetic field from an MDI magnetogram taken during the EIS scan, which started from 10:25:42UT, because its FOV is larger than that of the EIS scan used for the density diagnostics and is large enough to include the entire AR. In order to confirm the connectivity of the magnetic field lines rooted at the studied locations, we drew projected field lines onto the intensity map of Fe xiv 264.78 Å, as shown in Figure 12. The outflow regions U1–U6 are indicated by white boxes. Note that because the intensity map was derived from the EIS scan, which started from 10:25:42UT, we took into account the solar rotation to identify the locations of those boxes. The orange (turquoise) contours indicate a magnetic field strength of $+250$ ($-250$) G in the MDI magnetogram.

Two solid white lines trace coronal loops; therefore we regarded the topology of the eastern outflow region as closed, which can also be seen as a coherent pattern tracing the coronal loops in the Doppler velocity maps. Four dashed white lines rooted at the western outflow region are connected to the opposite polarity around $(x, y) = (-160', -150')$, but the Doppler velocity maps clearly show that the blueshifted feature extends into the far west, from which we suspected the topology of the western outflow region would be open. The closed loops rooted at the eastern outflow region are brighter.
than the open structures extending from the western outflow region by one order of magnitude. This might reflect the length of each structure, in the sense that the upflow easily fills a closed loop, while it flows without obstacles in an open structure, which produces denser plasma in the closed loop. Note that Culhane et al. (2014) suggested that the eastern outflow region is actually connected to the heliosphere through a two-step reconnection process. We may need further observations (e.g., statistical) in the future mission to clarify this point.

As a consequence, this leads to the implication that the upflow from the bottom of the corona becomes dense in the closed loop because of the pressure balance between the corona and the transition region, which is consistent with our result that the electron density of the EBW component was larger in the eastern region than in the western region (see Table 1). Although the difference in the electron density of the major component would not be insignificant, the relationship of the column depth (i.e., $h_{\text{Major}}$ larger in the eastern outflow region than in the western outflow region) may mean that the eastern outflow region consists of more coronal loops than the western outflow region.

We have evaluated the mass leakage from the western outflow region in Section 6.2. A study of the first ionization potential bias in the AR by Brooks & Warren (2011) also suggested that the western outflow region connects to the slow solar wind. In contrast, the closed topology of the eastern outflow region may actually imply mass supply to the AR. If this is the case for a portion of the outflow region, it means that the outflow plays a crucial role in the coronal heating by supplying hot plasma into the coronal loops. We suggest a possible picture in Figure 13 as a summary of this discussion.

7. SUMMARY

The electron density of the outflow from the edges of NOAA AR10978 was measured by using an emission line pair, Fe XIV 264.78 Å/274.20 Å. The upflow component was extracted from an EBW in the Fe XIV line profiles through double-Gaussian fitting. We fitted those two Fe XIV emission lines simultaneously with the physical restriction that corresponding components in two emission lines must have the same Doppler velocity and thermal width, which previous EIS analysis on the density diagnostics have not tried. The results were listed in Table 1.

The derived electron density for the major component ($n_{\text{Major}}$) and that for the EBW component ($n_{\text{EBW}}$) had opposite relationship in their magnitudes at the eastern and western outflow regions. There are several possibilities for the cause of the difference in the magnitude relationship between the eastern and western outflow regions as follows. (1) The major component and EBW in the Fe XIV line profiles are not directly related (e.g., superposition of structures along the LOS). The electron density of the EBW component just reflects the energy input amount. (2) The eastern outflow regions consist of the footpoints of the corona loops extending to the north and connected to the opposite magnetic polarity around $(x, y) = (-170^\circ, -70^\circ)$, whereas longer coronal loops emanate in the western outflow regions and extend to the

**Figure 13.** Schematic picture of active region outflows.

**Figure 14.** Peak intensity of Fe xiv 264.78 Å vs. electron density deduced from the major component of Fe xiv 264.78 and 274.20 Å in the double-Gaussian fitting.
northwest; consider the appearance in Figure 4. The difference in length may influence the plasma density of the same driving mechanism for the outflow because it is easier for the upflows in an open structure to flow without condensation than those in a closed loop.

We also calculated the column depth for each component ($h_{\text{Major}}$ and $h_{\text{EBW}}$). In the eastern region, $h_{\text{EBW}}$ was smaller than $h_{\text{Major}}$ by roughly one order of magnitude, which implies that the upflows possess only a small fraction (~0.1). Considering this implication with the result for the electron density ($n_{\text{EBW}} > n_{\text{Major}}$), this leads to a picture that the upflows may play a role in supplying hot plasma ($\log T [K] = 6.2–6.3$) into the coronal loops. On the other hand, in the western outflow region, the upflows have a volume a factor of five to six larger than the plasma characterized by the major component, from which we consider the western outflow region as a structure composed of extending tubes with unidirectional upflows.

We introduced the density diagnostics from a new point of view in Section 5. The electron density derived in our method is a function of the Doppler velocity or wavelength (Equation (4)), referred to as a $\lambda$-$n_e$ diagram, which was found to be a good indicator of the electron density of the minor components in a line profile. This method has the advantage that it does not depend on any fitting model that might be ill-posed in some cases. Our aim was to evaluate the electron density of the outflow seen at the edge of the AR and reinforce the result obtained in Section 4.

Using a density-sensitive emission line pair, Fe xiv 264.78 Å/274.20 Å, we studied $n_e(\lambda)$ by making $\lambda$-$n_e$ diagrams at the AR core and the outflow regions. The increase in the diagrams was seen on the longer-wavelength side for both structures, but we could not ascertain whether that behavior actually implies a physical situation at present. The diagrams for the AR core were flat around $\log n_e [\text{cm}^{-3}] \approx 9.5$, whereas those for the outflow regions exhibit some characteristic behaviors at the shorter-wavelength side. They show a small hump around $v = -110 \text{ km s}^{-1}$ in the eastern region (cuts 1 and 2 in Figure 9) and a decreasing trend from $\log n_e [\text{cm}^{-3}] = 9.0$ to $\log n_e [\text{cm}^{-3}] = 8.5$ in a velocity scale of $100 \text{ km s}^{-1}$ in the western outflow region (cuts 3–5 in Figure 9), as seen in Figure 11. Thus we confirmed the results obtained in Section 4 through our new method independent of the double-Gaussian fitting.

As for the case where intermittent heating is responsible for the outflows, the duration of heating was crudely estimated to be longer than $\tau = 500 \text{ s}$ for the energy input of $10^{24} \text{ erg}$ (i.e., nanoflare), so that the density of the upflows from the footpoints becomes compatible with that of the observed outflows. The electron density and column depth of the upflows in the eastern and western outflow regions were different, which was considered to be due to the magnetic structure above the outflow regions. Mass leakage occurs at the western outflow region (small $n_{\text{EBW}}$ and large $h_{\text{EBW}}$). On the other hand, there is a possibility of mass supply to the AR loops at the eastern outflow region (large $n_{\text{EBW}}$ and small $h_{\text{EBW}}$), which may be related to the coronal-heating process.

Hinode is a Japanese mission developed and launched by ISAS/JAXA, with NAOJ as domestic partner and NASA and STFC (United Kingdom) as international partners. It is operated by these agencies in cooperation with ESA and NSC (Norway). We extend our gratitude to Hirohisa Hara and Toshifumi Shimizu who made a large number of insightful comments with their expertise in spectroscopy. We are also thankful to the GCOE program for proofreading/editing assistance.

Facility: Hinode

**APPENDIX A**

**Fe xiv 264.78 Å INTENSITY AND ELECTRON DENSITY**

We can see a clear positive correlation between the peak intensity and electron density in the intensity range larger than $I_{\text{Major}} = 2.0 \times 10^3 \text{ erg cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ Å}^{-1}$ in Figure 14 (indicated by a vertical dashed line), whereas the plot is more scattered below that intensity. It is not only the photon noise that contributes to this large degree of uncertainty, but, the unidentified blended emission lines could also do so. Therefore we analyzed the data points with $I_{\text{Major}}$ larger than the value which the vertical dashed line indicates.
APPENDIX B
UNCERTAINTY IN $n_{\text{Si VII}}$ DENSITY

Because the electron density is not the same for emission lines with different formation temperatures, there is an uncertainty in $n_{\text{Si VII}}$ that cannot be determined from the data used in this analysis. In order to evaluate the error in the electron density derived for Fe XIV ($n_{\text{Fe XIV}}$) coming from this uncertainty, we removed the blending Si VII at Fe XIV 274.20 Å in three cases for $n_{\text{Si VII}}=10^8$, $10^9$, and $10^{10}$ cm$^{-3}$—and derived $n_{\text{Fe XIV}}$ for each case. Panel (a) in Figure 15 shows scatter plots for the electron density of the EBW component within the entire western outflow region derived for the case $n_{\text{Si VII}}=10^9$ cm$^{-3}$ versus $10^8$ cm$^{-3}$ ($10^{10}$ cm$^{-3}$) in blue (red). The $n_{\text{Fe XIV}}$ of the EBW component derived by assuming $n_{\text{Si VII}}=10^8$ ($10^{10}$) cm$^{-3}$ becomes smaller (larger). Panel (b) in Figure 15 shows those relative differences, $\Delta n_{\text{Fe XIV}}/n_{\text{Fe XIV}}$, where $\Delta n_{\text{Fe XIV}}$ is the difference between $n_{\text{Fe XIV}}$ and different $n_{\text{Si VII}}$ ($10^8$ and $10^{10}$ cm$^{-3}$) measured for the case where $n_{\text{Si VII}}=10^9$ cm$^{-3}$. Colors (red and blue) are the same as in panel (a). Solid and dashed histograms indicate the western outflow region (the white dashed box in Figure 5) and the entire FOV, respectively. These relative differences were calculated in log scale. The histograms show that the error coming from the difference of $n_{\text{Si VII}}$ does not exceed 5%. This means that the error is around $10^{0.4-0.5}$ at most for the density range, $10^8$ cm$^{-3} \leq n_e \leq 10^{10}$ cm$^{-3}$, and roughly becomes a factor of 3 (i.e., comparable to the error originated in the photon noise).

REFERENCES

Baker, D., van Driel-Gesztelyi, L., Mandrini, C. H., Démoulin, P., & Murray, M. J. 2009, ApJ, 705, 926
Bradshaw, S. J., Aulanier, G., & del Zanna, G. 2011, ApJ, 743, 66
Brooks, D. H., & Warren, H. P. 2011, ApJL, 727, L13
Brooks, D. H., & Warren, H. P. 2012, ApJL, 760, L5
Brooks, D. H., Warren, H. P., Ugarte-Urra, I., & Winebarger, A. R. 2013, ApJL, 772, L19
Bryans, P., Young, P. R., & Doschek, G. A. 2010, ApJ, 715, 1012
Culhane, J. L., Brooks, D. H., van Driel-Gesztelyi, L., et al. 2014, SoPh, 289, 3799
De Pontieu, B., McIntosh, S., Hansteen, V. H., et al. 2007, PASJ, 59, 655
De Pontieu, B., McIntosh, S. W., Hansteen, V. H., & Schrijver, C. J. 2009, ApJL, 701, L1
De Pontieu, B., McIntosh, S. W., Carlsson, M., et al. 2011, Sci, 331, 55
Del Zanna, G. 2008, A&A, 481, L49
Del Zanna, G., Aulanier, G., Klein, K.-L., & Török, T. 2011, A&A, 526, A137
Dere, K. P., Landi, E., Mason, H. E., Monsignori Fossi, B. C., & Young, P. R. 1997, A&AS, 125, 149
Doschek, G. A. 2012, ApJL, 754, 153
Doschek, G. A., Warren, H. P., Mariska, J. T., et al. 2008, ApJ, 686, 1362
Hara, H., Watanabe, T., Harra, L. K., et al. 2008, ApJL, 676, L67
Harra, L. K., Sakao, T., Mandrini, C. H., et al. 2008, ApJL, 676, L147
Kamio, S., Hara, H., Watanabe, T., Fredrik, T., & Hansteen, V. H. 2010, SoPh, 266, 209
Kitagawa, N. 2013, PhD thesis, Univ. Tokyo
Klimchuk, J. A. 2012, JGRA, 117, 12102
Kobayashi, K., Curtain, J., Winebarger, A. R., et al. 2014, SoPh, 289, 4393
Landi, E., del Zanna, G., Young, P. R., Dere, K. P., & Mason, H. E. 2012, ApJ, 744, 99
McIntosh, S. W., Tian, H., Sechler, M., & de Pontieu, B. 2012, ApJ, 749, 60
Patsourakos, S., Klimchuk, J. A., & Young, P. R. 2014, ApJ, 781, 58
Sakao, T., Kano, R., Narukage, N., et al. 2007, Sci, 318, 1585
Tian, H., McIntosh, S. W., de Pontieu, B., et al. 2011, ApJ, 738, 18
Warren, H. P., Ugarte-Urra, I., Young, P. R., & Stenborg, G. 2011, ApJL, 727, 58