Coronal Plasma Motions in Active Region Loops
Observed with Hinode EIS

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Abstract. The Hinode EUV Imaging Spectrometer (EIS) has revealed the presence of high-velocity upflow components of nearly coronal sound speed near the footpoints of active region loops in a quiescent active region. The upflow is detected as subsonic line shifts with enhanced line broadenings when the emission line fitting by a Gaussian function is applied to the line-profile analysis for hot coronal emission lines, and it contributes to the line broadening because of the multiple components within the EIS spatial resolution, suggesting the presence of spatially unresolved upflows and the smallness of each heating volume.

1. Introduction

As a result of heat input to the solar upper atmosphere a million-degree corona is created above the photosphere. We try to find a signature of the heating process from observing some plasma properties in the upper solar atmosphere. Among various properties, one signature is that the hot plasma temperature there may be much $\sim 10^7$ K than the normal coronal temperature of $\sim 10^6$ K. Since the heat input is episodic with smaller energy than solar flares and microflares, and since the cooling is taking place simultaneously, $\sim 10^7$ K plasmas are rarely observed because they will quickly cool down. Another signature to detect is fast flows associated with the heating. The EUV Imaging Spectrometer (EIS) aboard Hinode has the capability to investigate the plasma motion in coronal loops that are regarded as elemental structures of the solar corona for closed magnetic field structures. This paper introduces the study presented in Hara et al. (2008) and supplemental interpretations.

2. Coronal Upflows in Active Regions

Figure 1 shows an EIS raster scan observation of active region (AR) 10938 located near the disk center of the Sun observed on 2007 Jan 18. The observation was performed by a slit scanning mode with 1$''$ wide slit, 1$''$ step size in the scanning direction, the spatial sampling along the slit is 1$''$, and exposure duration of 30 s. Eight other emission lines were simultaneously obtained. No other active region was observed on that day, and there was no micro-flaring activity during the raster scan from the GOES soft X-ray observation. Each panel in Figure 1 is made using a line profile analysis based on fitting the coronal emission line under a single Gaussian approximation. For estimating the Doppler velocity $V$, instrumental effects and spacecraft Doppler motion to the Sun are corrected.
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Figure 1. EIS raster scan observation (2007 Jan 18 18:12–20:26 UT) in Fe XIV at 274 Å for active region 10938 located near the disk center showing (a) intensity $I$ in photon units, (b) Doppler velocity $V$, and (c) line width $W$ in FWHM.

Figure 2. Nonthermal velocity map from Fe XIV 274 Å observation (a) near disk center and (b) near the west limb. (c) Histograms of nonthermal velocity values in enclosed footpoint areas denoted by C and L in panels (a) and (b).

The line width $W$, the Full Width at Half Maximum (FWHM), is $\sqrt{W_{\text{obs}}^2 - W_1^2}$, where $W_{\text{obs}}$ and $W_1$ are the observed and instrumental line widths in FWHM. Many loop structures are identified in Figure 1a, and blueshifted components are also seen near footpoints of coronal loops in the Doppler velocity map (Figure 1b). Subsonic upflows along coronal loops from their bottom ends have been reported from feature tracking in TRACE 171 Å band images (Winebarger et al. 2001). As similarly shown in Fe XII 195 Å observations with EIS by Doschek et al. (2007), the blueshifted areas also show enhanced line broadening (Figure 1c).

3. Unresolved Upflows Observed as Nonthermal Line Broadening

Nonthermal widths of emission lines in velocity units are $V_{\text{NT}} = \sqrt{2k(T_D - T_i)/m_i}$, where $T_i$ and $T_D$ are ion and Doppler temperatures and $m_i$ is the ion mass. In normal coronal conditions, the ion temperature is considered to be equal to the electron temperature $T_e$ that is estimated by the line intensity ratio between Fe XIV 274 Å and Fe XV 284 Å in this study. Figure 2a (Figure 2b) shows the nonthermal velocity map from an observation near disk center (at the west limb). Histograms in Figure 2c demonstrate a difference of nonthermal velocity
values in the same footpoint region of coronal loops, denoted by C and L, in the same active region. Enhanced nonthermal velocities observed near the disk center are not found in the limb observation in which the footpoint region of interest is not on the far side of the west limb. A possible cause of enhanced $V_{NT}$ near the footpoints in the disk center observation is due to the superposition of upflow structures in a spatial resolution element and in the line-of-sight structures. Note that the maps and histograms are made from the data with spatial sampling of $1'' \times 1''$. A possibility of high-velocity upflows in a high-altitude part of the foreground corona is unlikely because higher values in Doppler velocity and FWHM systematically appear at the bottom end of coronal loops.

If the enhanced nonthermal velocity is due to the superposition of multiple flows, there will be a strong correlation between Doppler velocity $V$ and nonthermal velocity $V_{NT}$. This trend is clearly shown in Figure 3a. Since a single Gaussian approximation is applied to estimate Doppler velocity and nonthermal velocity in Figures 1b and 1c, a high velocity component will be hidden in the spectral line profile if the enhanced line broadening is due to the effect of multiple components. An example of such multiple components in a line profile is
shown in Figure 3b and the residual after subtraction of a fitted Gaussian function in Figure 3c indicates an additional component. This line profile found at a loop footpoint in the disk center observation ($X_{EIS} = -72, Y_{EIS} = 34$ in Figure 1a) contains a high-velocity upflow component exceeding 100 km s$^{-1}$ at the blue wing. Since the loop axis near the footpoint appears to be largely tilted to the line-of-sight direction, the high-velocity component may have the coronal sound speed for a temperature of $\sim$2 MK. Similar line profiles are found in Fe XV 284 Å observations. A simple estimate of the thermal energy $E_{TH} (= 3n_e k_B T_e V)$ of this high-speed component is $6 \times 10^{23}$ ergs using the Fe XIV 274 Å observation for electron temperature $T_e = 2 \times 10^6$ K, electron density $n_e = 2 \times 10^9$ cm$^{-3}$, and associated volume $V = (725 \times 10^5$ cm$)^3$.

4. Discussion

The property of $V$-$V_{NT}$ relation is qualitatively reproduced by two independent line profiles, each of which has a different upflow component. Figure 4a is an example of a line profile consisting of two Doppler velocity components. When one has a range of upflow velocity of 0–10 km s$^{-1}$ and the other has a velocity of 0–40 km s$^{-1}$ along the line-of-sight direction, the scatter plot of $V - V_{NT}$ expected from observations at disk center (near the limb) is shown by black (grey) dots in Figure 4b. The blue-side enhanced line profile is expected when an additional high-velocity upflow component is given (Figure 4d), and the residual from a Gaussian line profile is reproduced (Figure 4e). Figure 4c is a line profile having an ideal zero instrumental width for the case of Figure 4d, which shows that the high-velocity component that is completely separated from the low-velocity component is observed as a blue-side enhancement smeared by the EIS spectral resolution. The low-intensity enhancement at the blue wing suggests the smallness of each heating volume.

This type of blue-side enhanced line profile is found near footpoints of coronal structures, and it is not seen at low part of coronal structures located near the limb. The blue-side enhancement is consistent with estimated line profiles from the nanoflare heating model in Patsourakos and Klimchuk (2006). Their model treats a coronal loop as a collection of small-scale bundles that cannot be resolved by the EIS spatial resolution. Fast upflows exceeding 100 km s$^{-1}$ near footpoints of coronal loops are favored by a footpoint-concentrated nanoflare heating model in Antolin et al. (2008) among different heating cases that they calculated. We are investigating the typical scale size of heating events that are smaller than the EIS spatial resolution, the temporal behavior of such small-scale heating events near the bottom of coronal loops, and the energy budget for coronal heating.

References