Plasma flows in active region fan loops

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1. Introduction

- Fan loops are found at the periphery of active regions, and emit most prominently at temperatures of 0.8-1.0 MK.
- Plasma flows as a function of temperature within fan loops have not previously been characterized, but are crucial to determining the energy balance within the loops.
- Imaging instruments such as TRACE revealed upward *propagating intensity perturbations* at temperatures of 0.8-1.0 MK that have been interpreted as magnetoacoustic waves rather than plasma upflows (De Moortel et al. 2002, Wang et al. 2009).
- Downflows of 15-40 km/s were observed in a fan loop with the Ne VIII λ770 line (0.7 MK) by Winebarger et al. (2002) using the SOHO/SUMER instrument.
- EIS has access to emission lines in the temperature range 0.2-2.0 MK. *What velocities are found?*
- A fan loop aligned at ≈20° to the line-of-sight was selected (**Figures 1, 2 & 3**).
- The loop is clearly seen in Fe VIII λ185.21 (0.7 MK) and Fe X λ184.54 (1.0 MK), but less so in Fe XII λ195.12 (1.5 MK).

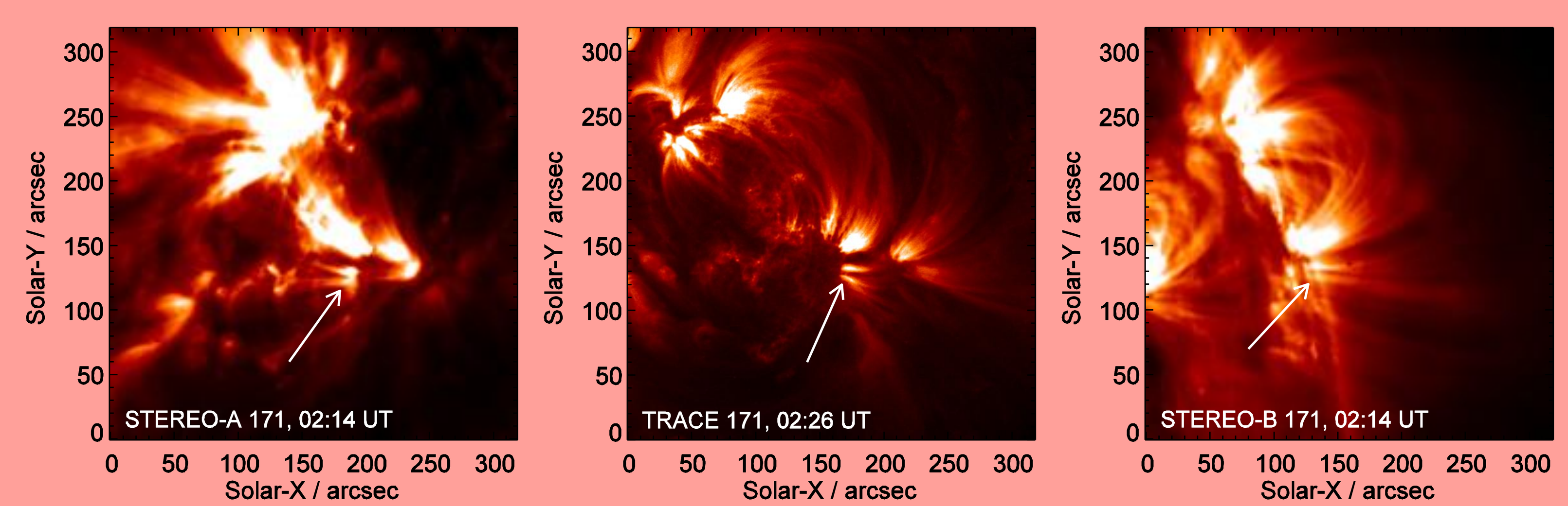

Figure 1. Three images of AR 11032 obtained by the STEREO-A and B spacecraft, and TRACE on 2009 November 22. The fan loop studied here is indicated with arrows on each image.

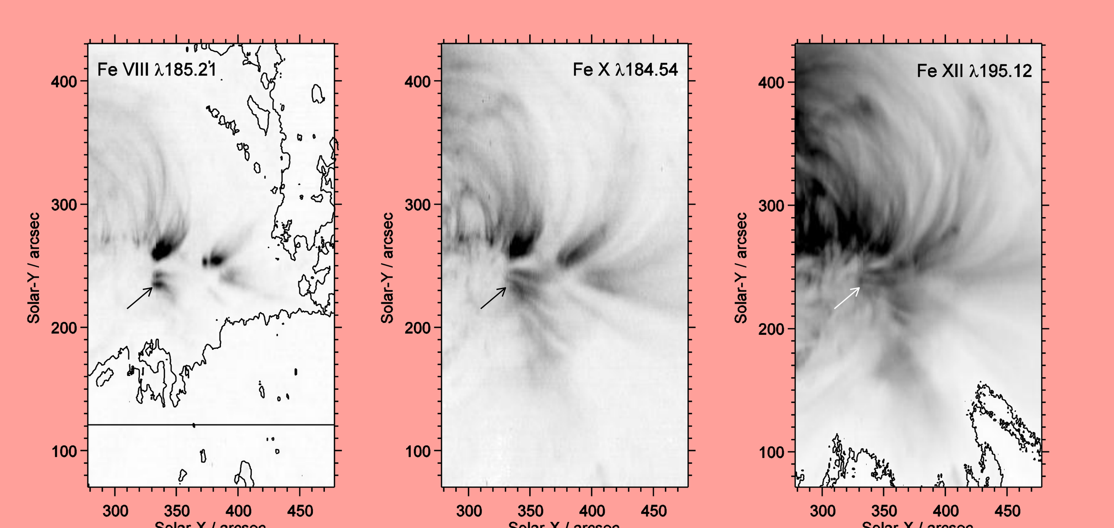

Figure 2. EIS images of a section of AR 11032. The Fe VIII, X and XII lines are formed at 0.7, 1.0 and 1.5 MK, respectively. The fan loop is indicated with an arrow on each image. The contours indicate regions consistent with quiet Sun intensity. The horizontal line on the left panel indicates the region used for wavelength calibration (Section 2).

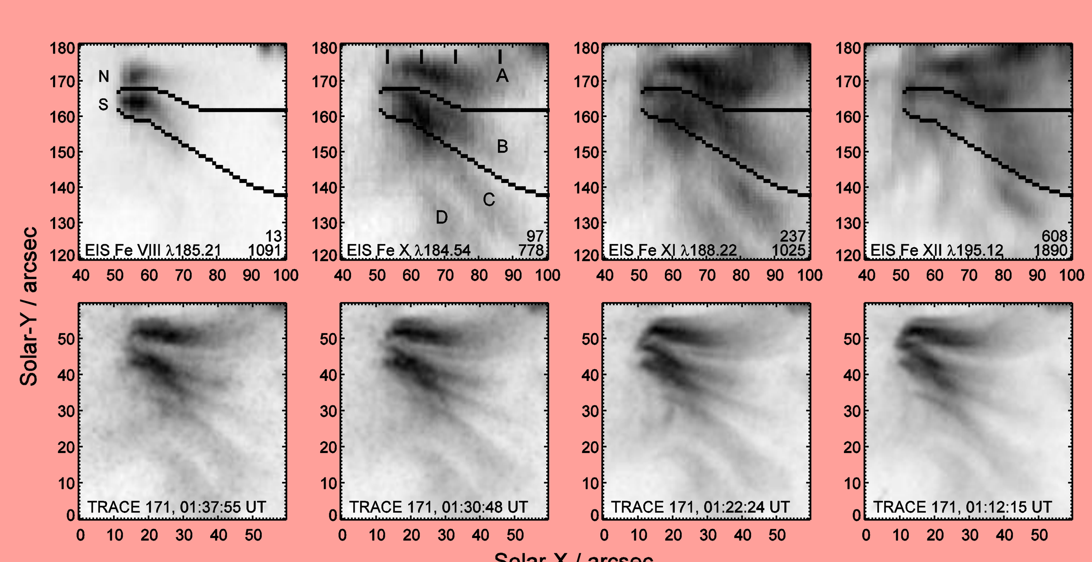

Figure 3. A close-up of the fan loop as seen in four EIS emission lines (top panels). A time sequence of TRACE images (bottom panels) shows that the loops remain fairly stable over the EIS raster. The solid lines in the EIS images demark the boundaries of the fan loop, identified by S and B in the Fe VIII and Fe X images.

2. Absolute velocity measurements with EIS

- Absolute velocity measurements require comparison with a reference wavelength scale.
- EIS does not have a calibration lamp, nor does it observe photospheric lines that can act as wavelength fiducials.
- The method used here is to determine a reference wavelength for Fe VIII λ185.21 from quiet Sun observed simultaneously with the fan loops (see left panel of **Figure 2**).
- The active region has a much smaller spatial extent in Fe VIII λ185.21 than it does for a hotter line such as Fe XII λ195.12 (consider images shown in **Figure 2**), making it more suitable as a wavelength calibration line.
- Reference wavelengths for other lines in the EIS SW band (171-212 Å) are obtained from λ185.21 using the off-limb wavelength separations of Warren et al. (2011), which assumes that off-limb, quiet Sun plasma is at rest.
- Reference wavelengths for lines in the EIS LW band (246-292 Å) are obtained by assuming that Si VII λ275.37 has the same velocity as Fe VIII λ185.21 (empirically the velocities of the two lines mimic each other).
- The method described above leads to absolute velocity uncertainties of ±5 km/s.

References

De Moortel, I., et al. 2002, Solar Physics, 209, 61.

Wang, T. J., Ofman, L., & Davila, J. M. 2009, ApJ, 696, 1448

Winebarger, A. R., et al. 2002, ApJ, 567, 89.

3. Velocity results

- Line-of-sight velocities along the length of the fan loop are shown in **Figure 4** for various ion species.
- Ions formed at temperatures of 0.7 MK and below (O IV, O VI, Mg VI, Fe VIII) show redshifts (downflows) of around 10-20 km/s.
- Ions formed at temperatures of 1.0 MK and above (Fe X, Fe XI, Fe XII) show no net flow in the higher portions of the fan loop, and blueshifts (upflows) near the base.
- A velocity image from Fe XII λ195.12 (**Figure 5**) shows that the blueshifts in the hotter lines are actually due to the loop being embedded in an outflow region. The loop itself does not show blueshifts.
- A key result is that over a projected distance of 9 Mm (pixels 58 to 70 in **Figure 4**) the Fe VIII and Fe X ions show a velocity difference of ≈15 km/s.
- *This can only be explained if the fan loop consists of two types of structure: one that is cool (0.7 MK) and downflowing, and one that is hot (1.0 MK) and stationary.*

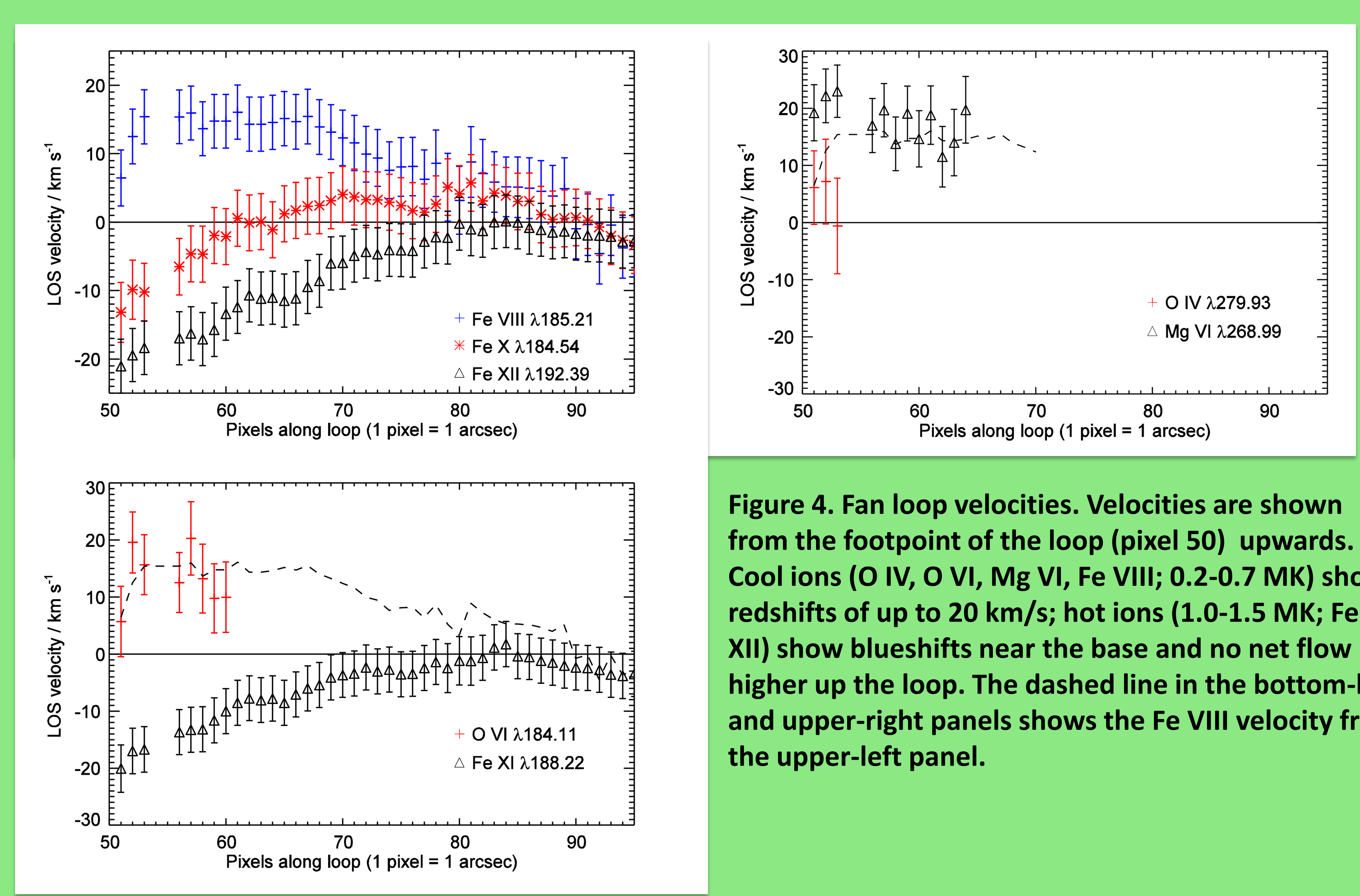

Figure 4. Fan loop velocities. Velocities are shown from the footpoint of the loop (pixel 50) upwards. Cool ions (O IV, O VI, Mg VI, Fe VIII; 0.2-0.7 MK) show redshifts of up to 20 km/s; hot ions (1.0-1.5 MK; Fe X-XII) show blueshifts near the base and no net flow higher up the loop. The dashed line in the bottom-left and upper-right panels shows the Fe VIII velocity from the upper-left panel.

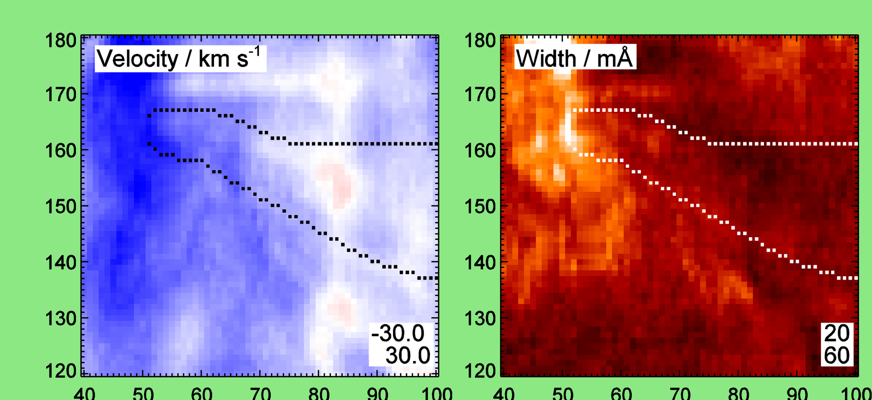

Figure 5. The left panel shows a velocity map derived from Fe XII λ195.12 near the loop footpoints (the fan loop is indicated by the two solid lines). The right panel shows the Fe XII λ195.12 line width. The blueshifts and large line widths indicate an active region outflow region. The loop itself is redshifted at the footpoints (Figure 4), showing it is a distinct structure from the outflow region.

4. Density and filling factor

- The Mg VII λ280.75/λ278.39 density diagnostic allows the filling factor of the Fe VIII emitting region to be determined.
- The location where Fe VIII and Fe X have different velocities has a filling factor of 0.2 (**Figure 6**), consistent with the Fe VIII emitting region occupying only a fraction of the loop volume.

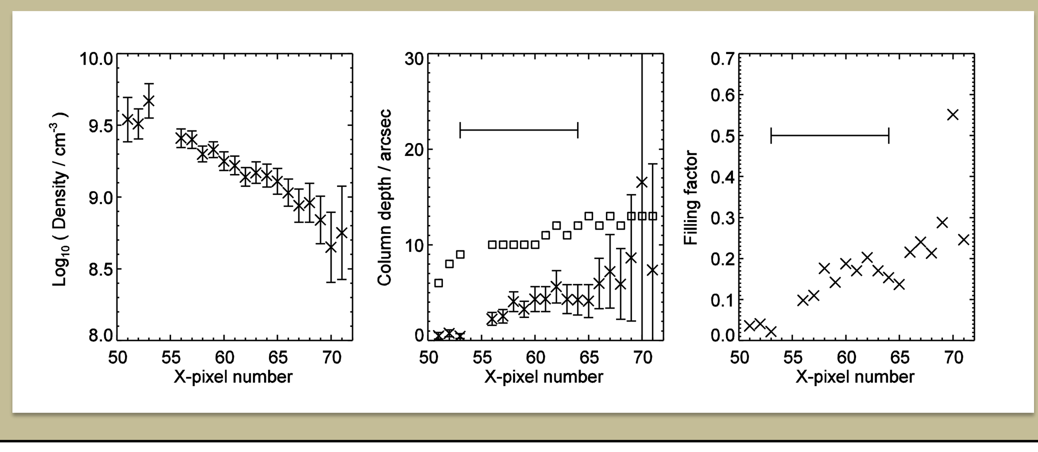

Figure 6. Density, column depth and filling factor variation along the loop, as derived from the Mg VII λ280.75/λ278.39 ratio. The bar in the middle and right panels shows the region in which the Fe VIII velocity is different to the Fe X velocity (Figure 4).

5. Summary

- The fan loop shows downflows of around 15-20 km/s at its base, at temperatures of 0.2-0.7 MK.
- At larger heights the plasma is close to being stationary.
- Fe VIII and Fe X (formed at 0.7 and 1.0 MK) maintain a velocity difference of 15 km/s over 9 Mm along the loop, implying there are two distinct types of "strand" within the loop. The velocity properties of the strands are indicated in **Figure 7**.
- The Type 2 strand may be a later evolutionary stage of the Type 1 strand.

Figure 7. A schematic illustrating how the velocity results can be interpreted in terms of two types of loop strand. Type 1 principally emits Fe X along its length and is stationary, while Type 2 principally emits Fe VIII along its length and is downflowing.