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Coronal Loops: New Insights from EIS Observations

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Abstract. Multi-instrument observations of coronal loops of different active regions have been studied. The general features discussed in Del Zanna (2003) and Del Zanna and Mason (2003) based on *SOHO*/CDS are confirmed. *Hinode*/EIS high-cadence observations clearly show how dynamic loops are at all temperatures. This clearly reflects the fast changes in the photospheric magnetic fields measured by SOT over a minute timescale. Despite that, persistent patterns are present. In particular, the pattern of Doppler shifts and non-thermal widths, found for the first time in NOAA 10926 (cf. Del Zanna 2007, 2008), is actually a common feature in all active regions. It is likely that the majority of cool (0.5–1 MK) loops are observed during their radiatively cooling phase.

1. Introduction

Since the launch of *Hinode*, the EIS instrument has collected a number of observations of coronal active region loops. Here, we are interested in quiescent loops, i.e., not those related to flare activity. Earlier analyses (e.g., Del Zanna 2007, 2008) of NOAA 10926 have confirmed all the characteristics known from previous observations, mostly from *SOHO* CDS (cf., Del Zanna 2003 and Del Zanna and Mason, 2003), but have also brought new results: at $T < 1$ MK, red-shifts in loops are ubiquitous in both legs, and are larger toward lower T; at $T > 1$ MK, blue-shifts are ubiquitous; they are mostly located in a sharp boundary, are spatially confined in regions where the strongest magnetic fields are, and have a large coronal expansion; densities in the blue-shifted regions are low, a factor of 10–100 lower than densities in the hot loops (10^9 cm^{-3}); the boundary is located above the short hot (3 MK) loops of the core of an active region, and underneath the over-lying long cool (1 MK) loops; blue-shifts keep increasing in lines formed at $T > 1$ MK and always have associated large (> 50 km s^{-1}) non-thermal broadenings (line widths are mostly symmetric); the pattern of Doppler shifts and line widths follows the changes of the underlying magnetic fields and is generally long-lasting.

In order to study the temporal evolution of the coronal loops, we designed a multi-instrument campaign to test radiative cooling, described in the next Sec-

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tion. We also searched available observations of other active regions to confirm the above results.

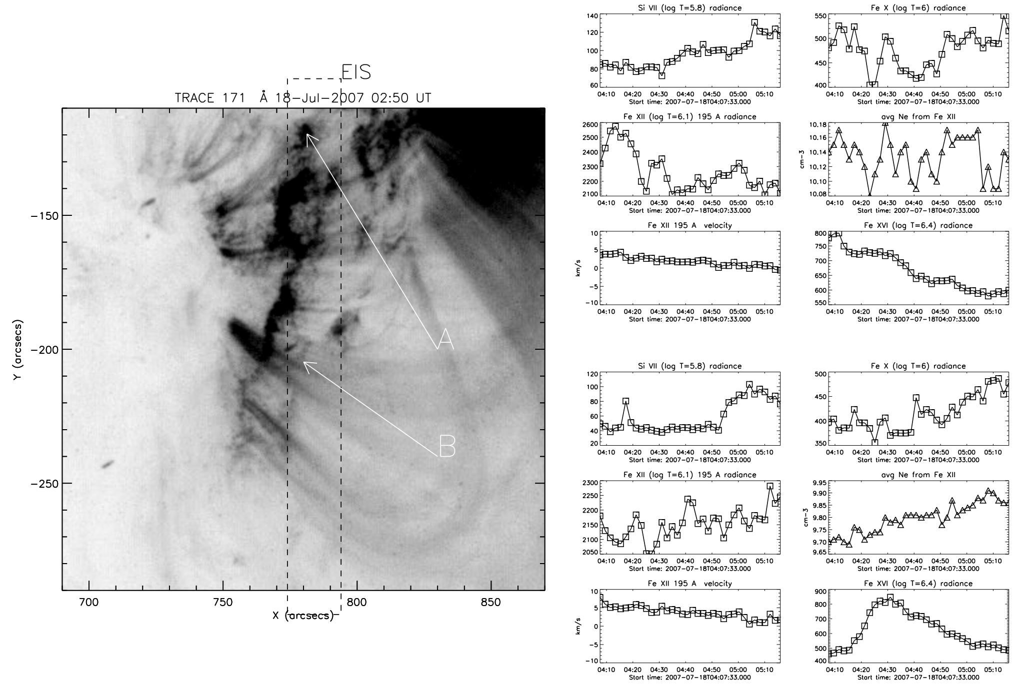

Figure 1. A negative *TRACE* 171 Å image with the field of view of the 'sit-and-stare' EIS study, with a moss area A and a hot loop area B. Temporal evolution from the EIS spectra in region A (upper right) and B (lower right).

2. Test of Radiative Cooling in Quiescent Active Region Loops

It is well-known that when a coronal loop undergoes radiative cooling with no heat input to partially balance the loss of energy, the temperature and density are related by $T \sim N^2$ (e.g., Serio et al., 1991; Bradshaw and Cargill, 2005). Accurate observations of T and N will reveal extremely valuable information regarding the cooling phase of coronal loops. For example, whether there is residual energy input during this period and, if so, how much and its decay time.

We designed an observational sequence based on two EIS studies and support from XRT and *TRACE*, to be run on an active region near Sun centre. *TRACE* data are essential, given its unsurpassed spatial resolution ($1''$), which allows us to observe structures which are not resolved by EIS, which has a resolution of about $4''$. Unfortunately, the spacecraft/instrument has a fast (time-scales of minutes) and random jitter. In order to correct for this jittering, we designed a 'sit-and-stare' EIS study (GDZ_DENS_20x240_ARL1) which scanned a small area, $20'' \times 240''$ using the $2''$ slit with a 10 s exposure time and 10 slit positions. We carefully chose which spectral lines to telemeter. To our knowledge, ours was the fastest (2 minutes cadence) 'sit-and-stare' EIS study. We note that in any strict ‘sit-and-stare’ observation, i.e., where the slit position is fixed, at any one time different regions of the Sun are observed.

Our sequence was never run as requested, however in one instance, on 2007 July 18, some useful observations were obtained of an active region near the limb. XRT data were unfortunately saturated. There were *Hinode* and *TRACE* eclipses which reduced the overlap in time. The EIS ‘sit-and-stare’ study was only run for two short periods of 1 hour each. Despite all the limitations, we have found some interesting features. We have found large and fast variability in radiances and Doppler shifts at all temperatures. The variability in hot ($T > 2$ MK) lines appears more evident than in the XRT high-cadence movies, perhaps due to the fact that any XRT filter is broad-band, i.e. the observed emission is multi-thermal (if there is multi-thermal plasma along the line of sight). The real variability is likely to be much larger, considering the smoothing effect of the EIS spatial resolution and the jittering.

Figure 1 shows the field of view of the EIS raster on a *TRACE* 171 Å image. Parts of 1 MK loops were observed, as well as moss regions and hot loops (not visible in the *TRACE* image). As an example, we show in the same figure the temporal evolution, in two areas, of some line radiances, Doppler velocities (positive values are red-shifts) and densities. In the second area (B) we found a possible case of a heating and cooling event, however in most areas it is not easy to find a clear relation between intensity variations in lines formed at different T. One problem is the limited information of flows along the structures, most of which are highly inclined.

3. New Active Region Observations

We have extensively searched the *Hinode* database for suitable high-cadence observations of active regions. We have found a few, and all of them showed similarities with those of NOAA 10926. For example, Figure 2 shows a 30-minute sequence of observations of NOAA 10938. Other ARs we studied in detail are 10956 and 10961. All the observations we have found were of limited use, however. Mostly because of short exposure times (5 s in the case shown), small fields of view ($4' \times 4'$), small count rates ($1''$ slit), and low cadence (15–30 minutes).

4. Discussion and Conclusions

Bradshaw (2008) derived an equation for the critical velocity $V_{\rm c}$ needed in order for an enthalpy flux to balance the transition region radiative losses given a loop of apex temperature $T_{\rm a}$ and transition region density n. The down-flow speeds are weakly dependent on $T_{\rm a}$ and strongly dependent on n. The $V_{\rm c}$ speeds are quite modest (a few km s^{-1}) even for a relatively high density ($n = 10^{10}$ cm^{-3}) and are consistent with the measured Doppler velocities, which provides strong evidence that the majority of observed 1 MK loops are radiatively cooling and their transition regions are supported by an enthalpy flux rather than by thermal conduction. It is still not clear where the chromospheric evaporation, which fills the loops with plasma, occurs. The large outflows in hot lines, combined with large non-thermal motions in localized low-height regions suggests that heating

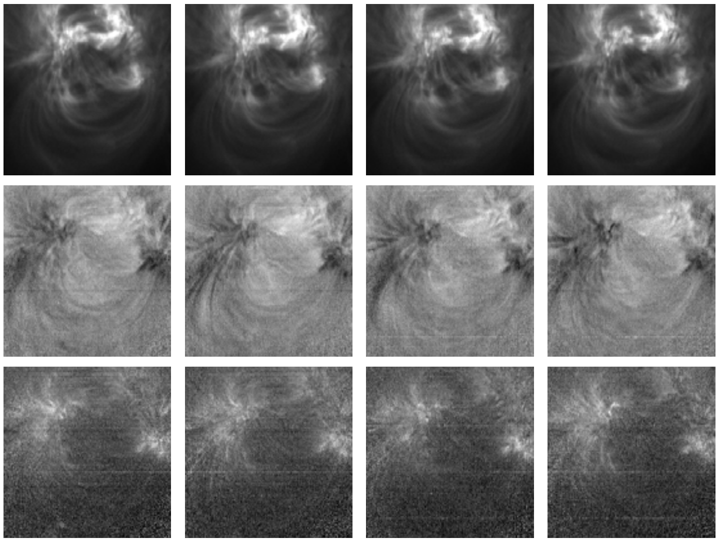

Figure 2. Radiances (top row), Doppler shifts (middle row; dark areas are blue-shifts) and non-thermal widths (bottom row) obtained from the Fe XII 195 Å line with EIS rasters starting at 01:57, 02:23, 02:50, 03:16 UT on 2007 Jan 17.

occurs in those locations. Del Zanna (2008) suggested that this heating is actually related to the down-flows, however substantial work and better observations are needed to confirm this.

Spectroscopic observations with EIS show variations in Doppler motions and intensities in active region loops, suggesting that some changes occur on timescales much shorter than 2 minutes. This is not surprising, given that SOT/NFI/FGIV images show restructuring of photospheric magnetic fields on shorter timescales. Temporal and spatial smoothing can give the false appearance of a quasi-static corona.

Despite various limitations (large variations in pointing and wavelength scale, low telemetry, eclipses, little useful observations, etc.), the EIS instrument has already provided new important insights (and challenges) into the physics of coronal loops. There is clearly a potential for good science when combining *Hinode*, *SOHO*, *TRACE* and *STEREO* observations.

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