The relation between hot and cool loops

N.V. Nitta

Lockheed Martin Solar and Astrophysics Laboratory,
O/L9-41, B/252, Palo Alto, CA 94304, U.S.A.

Abstract. In order to trace the origin of the hot ($\gtrsim$ 2.5 MK) corona above active regions, we compare images from *Yohkoh*/SXT and TRACE. A typical SXT snapshot of an active region shows the bright core surrounded by diffuse emission. In time sequence SXT images, bright X-ray structures easily recognized as loops are often found to follow minor brightenings and to undergo structural changes on time scales that can be shorter than the expected cooling times. These loops do not show up in TRACE coronal images before, during or after they are seen in SXT images, indicating their origin to be different from 1-2 MK loops. The data suggest that heating and cooling of the diffuse loops may occur dynamically.

1. Introduction

From space-bourne observations, it has been known for three decades that the solar corona is structured into closed loops, which are believed to delineate magnetic field lines. How these loops are heated is still a mystery, even though various types of theory have been proposed. A serious ambiguity on testing theory against observations comes from the multi-thermal nature of the corona, as obvious from images that are taken by instruments with different temperature sensitivities (e.g., Yoshida et al. 1995; Di Matteo et al.). The hot ($T \gtrsim$2.5 MK) corona appears quite different from the cooler ($T \sim$1 MK) corona. Does the cooler emission represent only the bases of hot loops and their transient (heating or cooling) states, or do cool loops exist on their own? If the latter is the case, theory must explain the heating of both hot and cool loops. Therefore it is important to study the spatial and temporal relationships between hot and cool loops, by analyzing images with different temperature sensitivities over times that are longer than the life times of the loops.

In this paper, we compare images from the *Yohkoh* Soft X-ray Telescope (SXT; Tsuneta et al. 1991) with those from TRACE (Handy et al. 1999). The initial results from TRACE can be found in Golub et al. (1999) and Schrijver et al. (1999). Besides the higher spatial resolution, a major advantage of TRACE over the Extreme-Ultraviolet Imaging Telescope (EIT; Delaboudinière et al. 1995) on the *Solar Heliospheric Observatory* (*SOHO*) is the availability of images in multiple EUV wavelengths at a good cadence. EIT observations normally concentrate on one wavelength (typically 195 Å), taking images in other channels only four times a day. As we see in Section 3, the temperature response of the TRACE 284 Å channel somewhat overlaps that of SXT compared with other channels. The 284 Å images, not extensively analyzed up to now, may be important for understanding the different appearances of the corona in SXT and TRACE 171 Å/195 Å images.

2. High-temperature loops

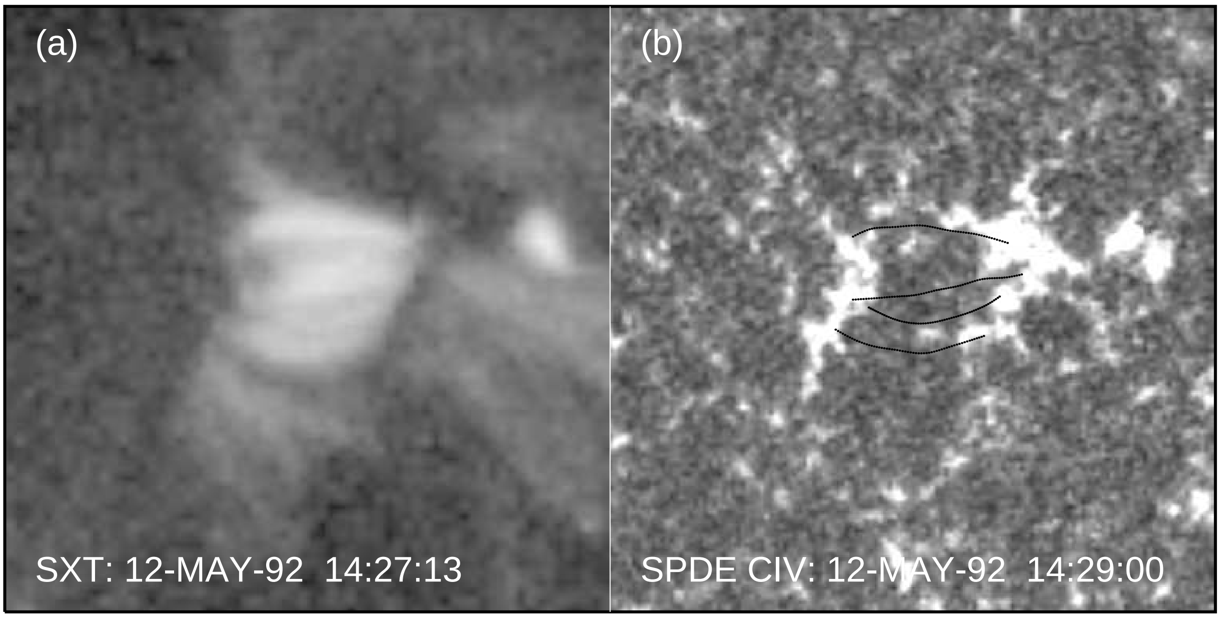

Figure 1: (a) Example of well-defined but steady loops in an SXT image. The loops are traced, and overplotted on a UV image that includes the C IV doublet at 1550 Å, as shown in (b). They appear to anchor at areas that are bright in the UV image.

Steady or quasi-steady loops in SXT images have been extensively studied (e.g., Porter & Klimchuk 1995; Kano & Tsuneta 1996) and their heating and cooling have been discussed in terms of simple models that put the measurements in the context of the well-known scaling law (Rosner, Tucker, & Vaiana 1978). An example of such loops is given in Figure 1(a), in which individual loops are readily recognizable. Their bases seem to be on bright patches in a broadband UV image (Figure 1(b)) from the Solar Plasma Diagnostic Experiment (SPDE) rocket payload (Damé et al. 1996) that includes the C IV doublet at 1550 Å. The bright areas in the UV image is considered to be due to heat conduction from the upper part of the loops. Based on a quick look at SXT time sequence images, these loops existed without significant changes for a few hours. We need to make some assumptions as to their geometry, however, to estimate how long these loops are (an important parameter for the scaling law), because we do not know how much they are inclined with respect to the vertical (c.f., Nitta, van Driel-Gesztelyi, & Harra-Murnion 1999).

We looked for steady and clearly defined loops in 15 active regions that had reasonably good TRACE 284 Å coverage between June 1998 and June 1999. We found that there were not many clearly defined loops in these regions. Most of these loops showed high or decreasing brightness. This indicates that these loops were preceded by small flarings that might have been identified with so-called transient brightenings (Shimizu et al. 1992). Indeed, it turns out that some of the loops studied by Kano & Tsuneta (1996) show significant variations in the X-ray intensity and even structural changes during the intervals of a few hours. Given longer decay times than rise times of the brightenings, it is likely that at least some SXT loops correspond to "postflare" loops of transient brightenings that happened during data gaps.

As in an example shown in Section 4, an active region often consists of a bright core, which appears to be due to occasional brightenings, surrounded by diffuse and fainter emission, which probably represents unidentifiable loops. Because we cannot easily trace the loops, it is hard to locate their bases. We will come back to these diffuse loops in Section 5.

3. Response

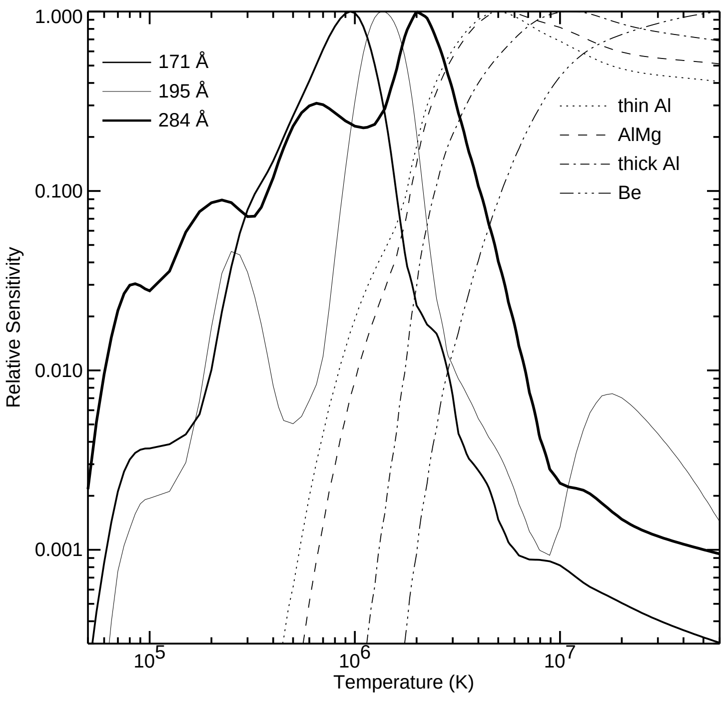

Figure 2: Comparison of normalized responses of SXT and TRACE with temperature.

In Figure 2, we compare the responses with temperature of SXT and TRACE in different filters and channels. As well known for the difference between grazing incidence and normal incidence telescopes, SXT has broader and less peaked responses than TRACE. The plot also confirms that SXT, even in the thinnest (thin aluminum or Al 1265 Å) filter, is more sensitive to hot plasma than all the coronal channels of TRACE. The 284 Å channel is closest to SXT, and its overlap with SXT may depend on the amount of (2.5–3) MK plasma relative to ~2 MK plasma along the line of sight. The 284 Å channel has substantial sensitivities to temperature below 1 MK. The 195 Å channel has enhanced sensitivity above 10 MK, but it is not relevant for usual active region loops. The different appearance of the solar corona in SXT and TRACE (or EIT) images comes from these different responses with temperature.

4. Coalignment of SXT and TRACE images

In Figure 3, we show what we believe to be coaligned SXT and TRACE 171 Å images of an active region (AR 8518). As of September 1999, we could not automatically coalign these images because the pointing information for either instrument appeared to be not consistent. Therefore, we used an EIT (195 Å) full-disk image taken close in time, with which both an SXT full-disk image and a TRACE 195 Å image were coaligned by matching various features. Relative offsets among TRACE images in different wavelenghts are well understood.

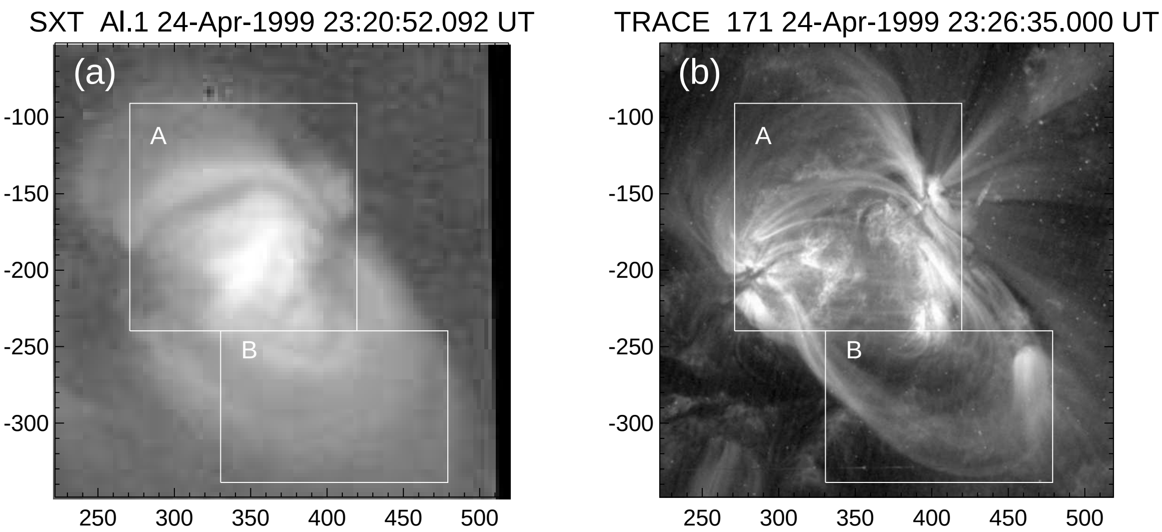

Figure 3: SXT and TRACE 171 Å images of AR 8518. Sub-regions A and B are expanded in Figures 4 and 5. The coordinates are in arcseconds from disk center.

In the course of this exercise, we also confirmed that the pixel sizes of these three instruments are consistent with the official values; 2.62″ for EIT (uncorrected for the fact that *SOHO* is orbiting around the L1 point), 2.46″ for SXT and 0.50″ for TRACE. There is a plan of generating a new pointing database for TRACE images within SolarSoftware,

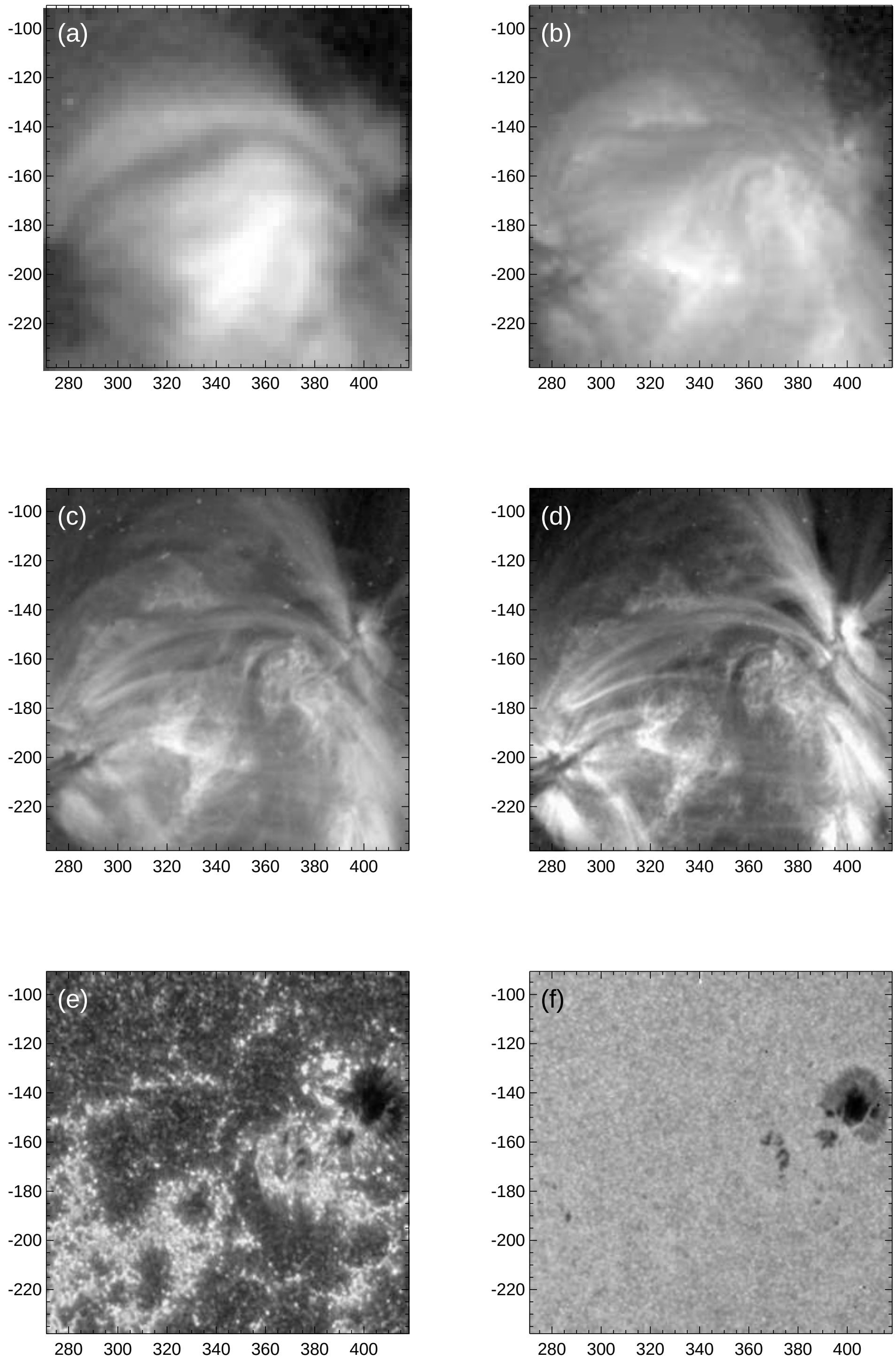

Figure 4: Images of sub-region A. (a) SXT thin Al filter (23:20:52 UT), (b) TRACE 284 Å (23:26:09 UT), (c) TRACE 195 Å (23:27:07 UT), (d) TRACE 171 Å (23:26:35 UT), (e) TRACE 1600 Å (23:25:30 UT), and (f) TRACE white-light (23:25:34 UT).

on the basis of cross correlations with EIT images taken close in time (Freeland 1999, private communication).

5. Comparisons of SXT and TRACE images

The SXT image in Figure 3 shows that the region consisted of the bright central part and the surrounding part of diffuse emission. Although the SXT and TRACE images have different bright regions, the overall shape of the active region in these images is quite similar. We make closer comparisons of two areas as indicated in Figure 3.

Figure 4 replicates the images in Figure 3 extracted and blown up for sub-region A, together with TRACE images in other channels, taken between 23:20 UT and 23:30 UT. The western legs of the bright SXT loops seem to be anchored at small pores to the southeast of the main spot (Figure 4(f)). These loops are not seen even in the 284 Å image, in which the bright patches appear to represent their bases, as in the 195 Å and 171 Å images. Part of these patches may be regarded as "moss" (Berger et al. 1999; Fletcher & De Pontieu 1999), which is likely to be low-lying structures at the base of high-pressure loops (Peres, Reale, & Golub 1994). Concerning the larger loop structure to the north, its appearance is similar but not quite the same in the SXT and 284 Å images. Note that moss in the 171 Å image (Figure 4(d)) exists even under the middle of this loop structure. The 195 Å and 171 Å images reveal different E-W loops, probably lower in height. These images also show legs of a few large-scale loops, including the one that emanates from the main sunspot (c.f., Schrijver et al. 1999), which never show up in SXT images. The bases or footpoints of all these loops seem to be bright in the 1600 Å broadband image.

Images of the southern part (sub-region B) are shown in Figure 5. This completely spot-free area (Figure 5(f)) is characterized by diffuse emission in the SXT image. It probably represents ensemble of low density loops or loops with small filling factor. Its appearance is quite different in images of Figures 5(a)–(d). Bright areas do exist in the 1600 Å image, which appear to be associated with the 171 Å moss. However, we cannot tell whether there are shorter loops beneath the diffuse emission in the SXT image, whose bases may match the moss. More detailed study of the moss may shed light on the issue of the filling factor of the SXT loops (Porter & Klimchuk 1995).

6. Evolution of loops

According to the SXT time sequence images, the central part of AR 8518 repeatedly brightened, but the bright loops of Figure 4(a) (not as readily recognizable as those in Figure 1) were formed between 22:24 UT and 23:18 UT. The time of their disappearance is not known due to a long (~2 hours) data gap, but based on the past activity the loops seen in the images of 25 April 01:25 UT were probably different ones. In Figure 6, we show TRACE time sequence images of the central part of the region (approximately matching sub-region A) over three hours. We do not identify the bright loops in any of

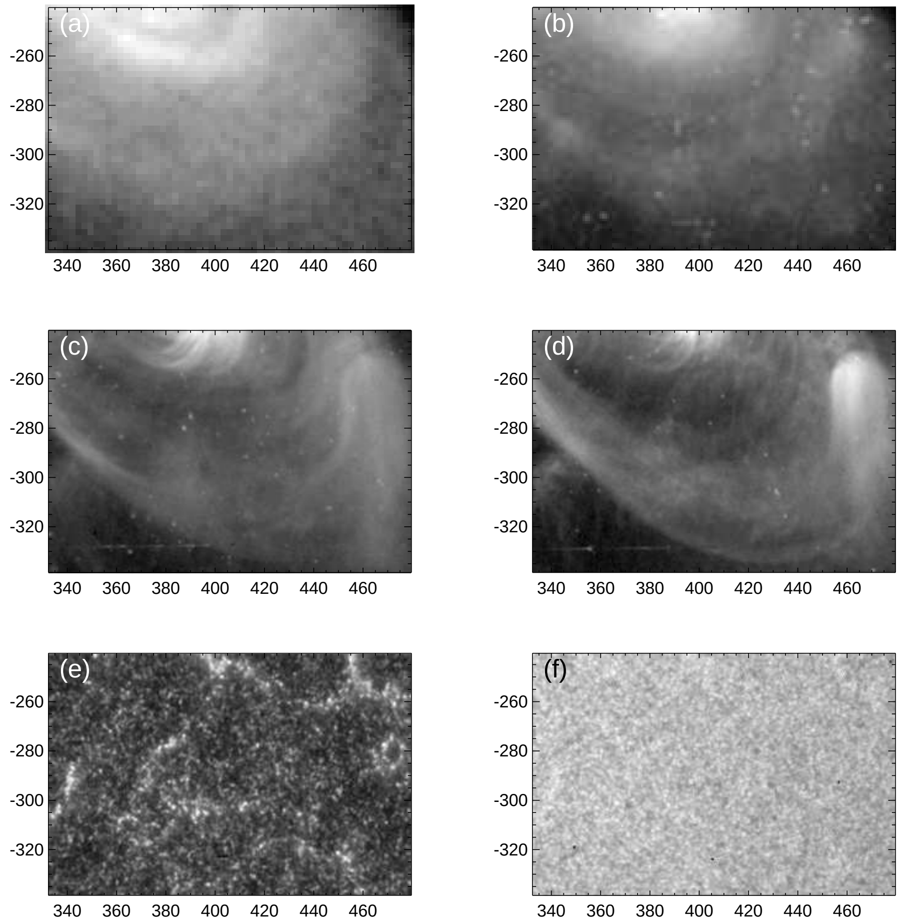

Figure 5: Images of sub-region B. The image types are same as Figure 4.

these images. This is also further confirmed in the high cadence (30–40 s) movie in the 171 Å channel.

The changes of the southern part of the region seemed to be slower. For example, the diffuse loops in SXT images became brighter over a few hours. Figure 7 compares SXT images with TRACE 284 Å and 171 Å images during the period of increasing brightness. At the same time, the volume filled with hot plasma was increasing. But the corresponding or underlying loop structure in TRACE 171 Å images appeared to shrink. This can be more readily seen in a movie representation. In the northern part of the region, another set of loops (including those in Figures 4(a)–(d) north of the bright SXT loops) were also found to be in motion, as studied by Priest & Schrijver (1999). These observations indicate that heating and cooling of loops can take place dynamically (c.f., Wang et al. 1997).

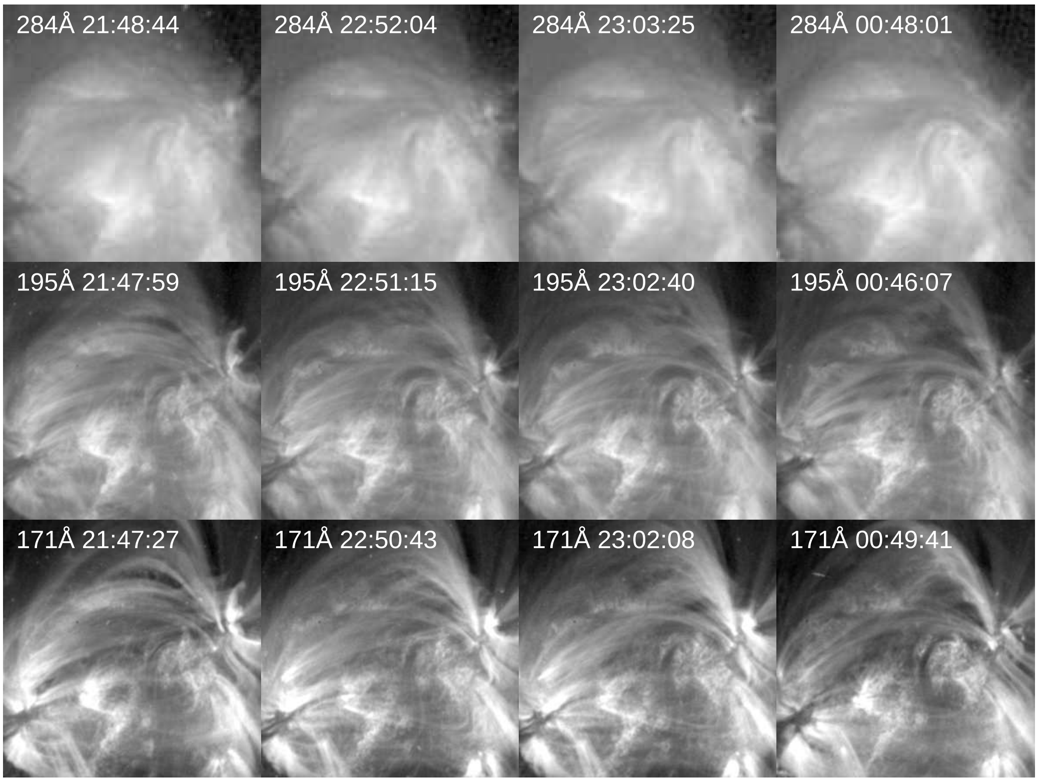

Figure 6: TRACE 284 Å, 195 Å, and 171 Å images (from top to bottom) of the central part of AR 8518. No counterparts of the bright SXT loops in Figure 4 are found.

7. Discussion

In spite of the fact that SXT and EIT have been operational for more than eight years and 3.5 years, respectively, there has not been much work (but see Nagata 2000) to discuss the relation between the $\gtrsim$2.5 MK and (1-2) MK coronae or coronal loops including their temporal variations. Our study presented more observational evidence that hot and cool loops are physically independent, which was recently discussed by Aschwanden et al. (1999) and Lenz et al. (1999) in terms of the much smaller conductive loss in cool loops than the radiative loss, indicating that they are not in steady state.

We found to our surprise that a clearly defined SXT loop tends to be not steady, often observed while it is becoming fainter. This implies that the loop corresponds to the post flare loop of a small flare or transient brightening (Shimizu et al. 1992), whose (fast) rise may not be observed by SXT. If the SXT loop results from large-scale magnetic reconnection as does a flare, according to many investigators, the same loop may not have to be seen *earlier* at lower temperatures. The reason we do not see the loop *later* may indicate that heating is turned off relatively early. If we consider a flare-like heating scenario in terms of the temperature-density diagram (Jakimiec et al. 1992; Brown 1996), the temperature rises first, followed by an increase in density due to chromospheric evaporation provided the heat input continues. Then the steady state is established, and the loop will be found to follow the scaling law (Rosner, Tucker, & Vaiana 1978). However, without the sustained heat input, the loop may cool down quickly to be invisible even to TRACE.

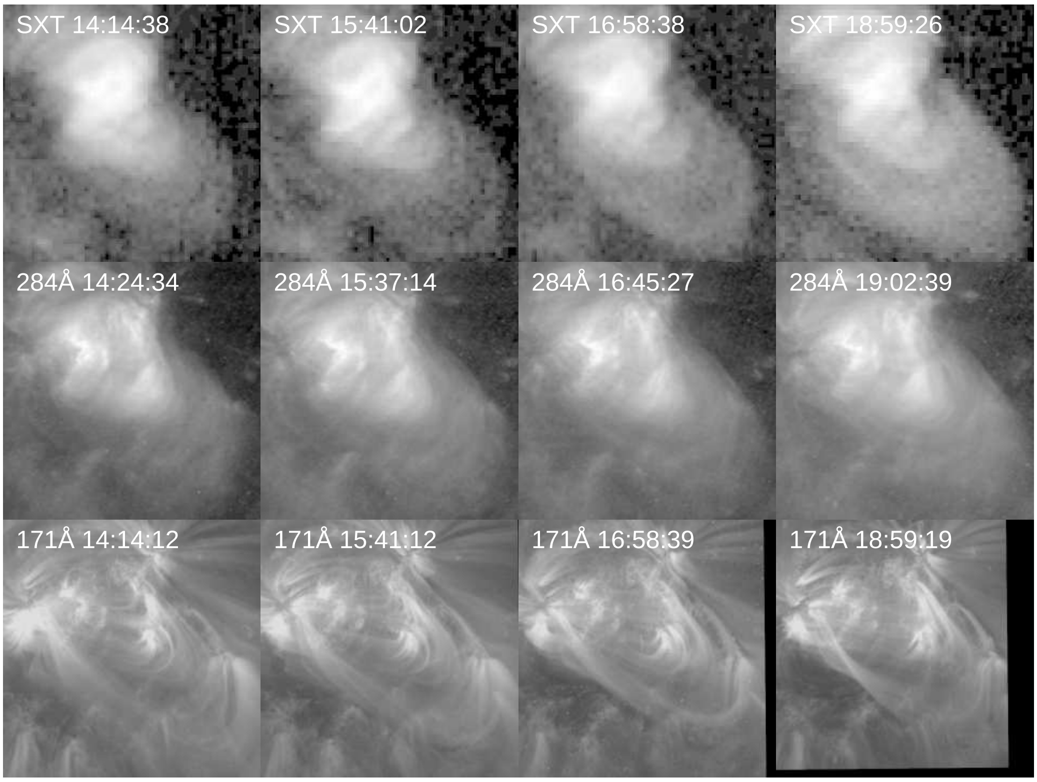

Figure 7: SXT thin Al, TRACE 284 Å, and 171 Å images (from top to bottom) of the southern part of the region (field of view of $2.5' \times 2.5'$), while the SXT diffuse loops were gradually brightening.

The flare origin of the active region loop was indeed suggested in a high temperature region cospatial with a mini cusp as discovered by Yoshida & Tsuneta (1996).

Acknowledgements

The work by NVN has been supported by NASA contract NAS 8-40801. The author is grateful to the organizers of the workshop "The Sun and Sun-like stars" for their hospitality.

References

Aschwanden, M.J., Newmark, J.S., Delaboudinière, J.-P., Neupert, W.M., Klimchuk, J.A., Gary, G.A., Portier-Fozzani, F., & Zucker, A. 1999, ApJ, 515, 842

Berger, T.E., De Pontieu, B., Schrijver, C.J., & Title, A.M. 1999, ApJ, 519, L97

Brown, S.F. 1996, A&A, 305, 649

Damé, L., Martić, Brown, W.A., Bruner, M.E., Strong, K., Suematsu, Y., Tsuneta, S., and Schmieder, B. 1996, Adv. Space Res., 17 (4/5), 189

Delaboudinière, J.-P. et al. 1995, Sol. Phys. 162, 291
Di Matteo, V., Reale, F., Peres, G., & Golub, L. 1999, A&A, 342, 563
Fletcher, L. & De Pontieu, B. 1999, ApJ, 520, L135
Freeland, S.L. & Handy, B.N. 1998, Sol. Phys., 182, 497
Golub, L. et al. 1999, Phys. of Plasma, 6, 2205
Handy, B.N. et al. 1999, Sol. Phys., 187, 229
Jakimiec, J., Sylwester, B., Sylwester, J., Serio, S., Peres, G., & Reale, F. 1992, A&A, 253, 269
Kano, R. & Tsuneta, S. 1996, PASJ, 48, 535
Lenz, D.D., Deluca, E.E., Golub, L., Rosner, R., & Bookbinder, J.A. 1999, ApJ, 517, L155
Nagata, S. 2000, PhD thesis, Univ. Tokyo
Nitta, N., van Driel-Gesztelyi, L., & Harra-Murnion, L.K. 1999, Sol. Phys., 189, 181
Peres, G., Reale, F., & Golub, L. 1994, ApJ, 422, 412
Porter, L.J. & Klimchuk, J.A. 1995, ApJ, 454, 499
Priest, E.R. & Schrijver, C.J. 1999, Sol. Phys., in press
Rosner, R., Tucker, W.H., & Vaiana, G.S. 1978, ApJ, 220, 643
Schrijver, C.J. et al. 1999, Sol. Phys., 187, 261
Shimizu, T., Tsuneta, S., Acton, L.W., Lemen, J.R., & Uchida, Y. 1992, PASJ, 44, L147
Tsuneta, S. et al. 1991, Sol. Phys., 136, 37
Wang, J., Shibata, K., Nitta, N., Slater, G.L., Savy, S., & Ogawara, Y. 1996, ApJ, 478, L41
Yoshida, T., Tsuneta, S., Golub, L., & Strong, K. 1995, PASJ, 47, L15
Yoshida, T. & Tsuneta, S. 1996, ApJ, 459, 342

Discussion

S. Antiochos: Isn't the "moss" observed by TRACE the footprints of the SXT loops?

N. Nitta: First of all, the same feature was already identified by previous observations including NIXT and EIT. TRACE revealed it very clearly. Yes, it is almost always associated with X-ray emission with a wide range of intensity and concentration, but I personally consider it difficult to say that it is located at the footpoints of X-ray loops. The reason is partly that the ends of SXT loops should be considerably higher than the real footpoints and more importantly that individual loops are not recognized where X-ray emission is diffuse.

P. Démoulin: An increase in coronal heating induces an increase in the loop density (through chromospeheric evaporation) more dramatically than an increase in the maximum temperature (and temperature in most of the loop): It is then difficult to bring a "TRACE loop" to a YOHKOH loop.

N. Nitta: Although I am not completely sure how much truth the so-called scaling law tells us (given huge uncertainty in the measured temperature and length), the density of a steady loop is proportional to square of the temperature. Therefore, to bring a 1 MK loop to 4 MK, one needs to provide 16 times as much mass. This will happen only in non-steady state, e.g., in a flare-like heating. The loop's repsonse to such a heating is well described in a T-N diagram. When the heat input goes back to the level of steady heating, the loop will cool very fast, and it may stay the TRACE temperature range only for a short time. This is probably why we do not see the cooled SXT loop in TRACE images.