Active region dynamics

L.K. Harra[1], S.A. Matthews[1], H. Hara[2] and K. Ichimoto[2]

[1] Mullard Space Science Laboratory, University College London,
Holmbury St. Mary, Dorking, Surrey RH5 6NT, U.K.
[2] National Astronomical Observatory,
Mitaka, Tokyo 181, Japan

Abstract. It has been frequently observed that in solar active regions the measured line widths are larger than those based on thermal equilibrium widths. This excess width (characterised as non-thermal velocity, V_{nt}) has been proposed as a signature of the heating mechanism. The behaviour of the V_{nt} at coronal temperatures has not produced consistent results with values ranging from 0 to 100 km/s. We investigate this problem by using joint observations from Norikura Solar Observatory, Japan and the Coronal Diagnostic Spectrometer (CDS) on SOHO. We find that values of V_{nt} range between 10 – 20 km/s. We analyse the dynamical behaviour of different temperature loops and find that for loops with Log T_e < 5.8, the variability $\propto T_e^{0.39}$. This is comparable to the dependence of non-thermal velocity on temperature which we have determined to be $V_{nt} \propto T_e^{0.35}$. This suggests that the excess line broadening is caused by highly dynamical behaviour in the transition region for active regions. These results have significant implications for potential heating mechanisms and these are discussed.

1. Introduction

It is well observed that in flaring and non-flaring active regions the line widths are found to be in excess of the thermal width. This excess width has been termed *non-thermal velocity* (V_{nt}) and it is thought to be an indicator of the coronal heating mechanism. Transition region observations in both active regions and the quiet Sun (e.g. Boland et al. 1975, Doschek et al. 1976 and Mariska et al. 1978) show that the non-thermal velocity

(V_{nt}) increases with increasing temperature ($V_{nt} \propto T_e^{1/4}$ for $\log T_e < 5.8$). This behaviour is predicted from an Alfvén or acoustic wave propagating without energy dissipation.

However as coronal temperatures are reached the relationship becomes less clear. For coronal active region observations a wide range of values of V_{nt} (10–100 km/s) have been derived for temperatures ranging between 1–6.2 MK. Although the dependence of V_{nt} with temperature below $\log T_e = 5.8$ has been verified, the behaviour above $\log T_e > 5.8$ is still not well understood. One of the assumptions that is generally made in the case of active regions is to assume that there is no temperature gradient and the active region is isothermal.

Another possibility to explain the excess line broadening is that there are multi-directional Doppler flows which could be a result of the superposition of flows in many magnetic flux tubes which are not spatially resolved. In active regions it has been found that cool transition region loops coexist with hot coronal loops (e.g. Orall 1981, Matthews and Harra-Murnion 1997). These various observations dictate that caution has to be used in assuming a link between the transition region emission and its relation to the coronal emission.

Different temperature loops in active regions have been found to show very different characteristics. The transition region cool loops (< 1 MK) are in general more dynamic than the hotter loops (> 1 MK). If this is the case then the dependence of V_{nt} with temperature in active regions may be due to the different classes of loops which exist, and cannot be due to a wave which travels through the different temperature layers.

In this paper, we determine the values of V_{nt} in an active region without assuming that the region is isothermal in the radial direction. This is achieved by making use of the temperature diagnostic and spatial information available from the Coronal Diagnostic Spectrometer (CDS), and the measurements of the line widths from the Norikura Solar Observatory. We investigate the behaviour of different temperatures loops and relate this to the dependence of V_{nt} with temperature.

2. Observations

For the calculation of the V_{nt} at coronal temperatures we employed data from an observing campaign which took place from the 23 August – 31 August 1997 using the 25 cm coronagraph at the Norikura Solar Observatory and the CDS. CDS observed in a variety of lines enabling us to calculate the spatial distribution of temperatures. The Norikura spectrograph provides high resolution spectral imaging data in the Fe XIV 5303 Å line which provides accurate line widths. Combining CDS and Norikura observations permits the determination of V_{nt} without assuming a single fixed temperature throughout the active region.

For the determination of the dynamical behaviour of loops as a function of temperature the CDS was used. A time sequence was carried out on 17th Jan 1998, which covered lines formed over a range of temperatures from the cool transition region to the hot corona.

3. Non-thermal velocity of coronal loops

The non-thermal velocity was derived from the temperature obtained from CDS and the line widths from Norikura coronagraph. Non-thermal velocity is defined as $V_{nt}=[2k(T_D-T_e)/m_i]^{1/2}$, where T_D is the Doppler temperature derived from the total observed line width, T_e is the electron temperature obtained from line ratio diagnostics and m_i is the mass of the ion considered. In all cases the total width of the lines (T_D) is larger than the thermal width as calculated from the electron temperature.

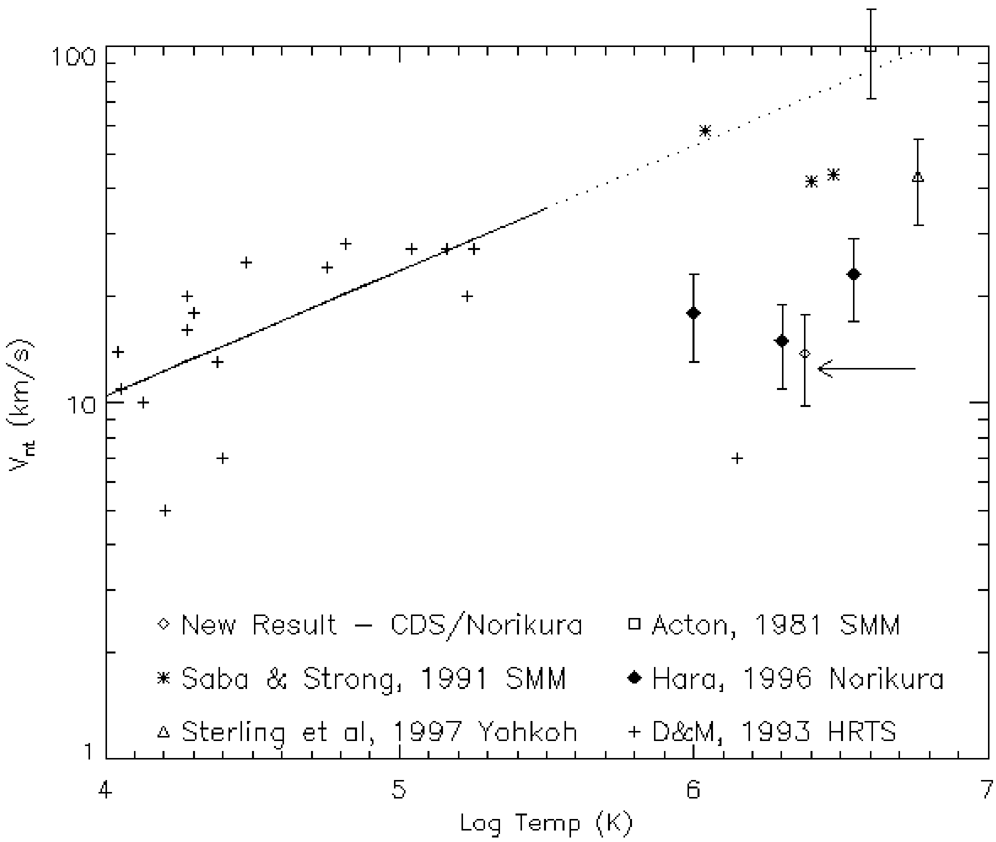

Figure 1: This plot illustrates the variation of V_{nt} with temperature. Values of V_{nt} from previous observations are shown alongwith our new result (indicated with an arrow). The errors from this result are derived from fitting the histogram of the spread of non-thermal velocities derived over the overlapping region of the Norikura and CDS FOV and deriving the FWHM of the spread of V_{nt}.

Fig. 1 illustrates the variation of the line broadening with temperature. The temperature plot shows data from previous observations alongwith our derived value. The behaviour below $\log T_e = 5.7$ has been shown many times to increase with increasing temperature. However as temperatures above $\log T_e = 6$ are reached, the relationship becomes less clear with a wide range of values being derived. Our averaged data shows a magnitude of V_{nt} = 13.8±1.2 km/s which is lower than previously calculated, suggesting that the V_{nt} reaches a maximum and starts to decrease as coronal temperatures are reached. The

V_{nt} value decreases when the assumption that the temperature is isothermal in the radial direction is removed. This is true for active regions at $\log T_e \approx 6.4$. Dmitruk, Gomez and DeLuca (1998) have carried out numercial simulations of an externally driven 2-D magnetohydrodynamic (MHD) system to model the dynamics of a coronal loop. Their derived value of V_{nt} is 16 km/s which is consistent with our results. They suggest that the larger values of V_{nt} observed by Saba and Strong (1991) correspond to hotter and larger active regions. Our observations could only be carried out for $\log T_e \approx 6.4$. Above this temperature, it is possible that the V_{nt} values may start to increase again. A large statistical study would be have to be carried out to determine whether the higher values derived at higher temperatures are due to poor (or no) spatial resolution, assumption of radial isothermality, or magnetically complex regions.

It has been well observed (e.g. Kjeldseth-Moe and Brekke 1998) that high-lying loops with temperatures below $\log T = 5.8$ are much more dynamic and unstable than loops with $\log T > 6$. This is expected since this particualr class of high-lying cool loops have heights which are larger than the scale heights predicted from their temperatures. In the next section we investigate the dynamical behaviour of active region loops at different temperatures and relate this to the dependence of V_{nt} with temperature.

4. Loop dynamics

As mentioned in the introduction it is now well observed that not only do cool (<1 MK) loops exist, but they are also more dynamic than their hotter counterparts. In this section we quantify how dynamic the behaviour is in each temperature regime. No previous attempt has been made to directly relate the dynamical behaviour of loops with $\log T_e < 5.8$ to temperature.

To achieve this, a CDS time series sequence (EPHAR_4 s10267) was carried out on the 17 Jan 1998 at a small active region on the limb in order to quantify the dynamics of the different temperature loops. Fig. 2 shows sample images in the OV and Mg X lines over a period of ≈ 5 hours with a cadence of ≈ 7 mins. As expected the OV loop shows rapid changes, whereas the Mg X loop stays relatively static.

To demonstrate the changes in the structures with time, the correlation (linear Pearson correlation coeffient, r) of each image relative to the first image observed has been calculated , where x is the intensity in the x direction and y is the intensity along the slit, where r=1 defines a complete positive correlation and r=0 defines no correlation. The correlation decreases with time for both the hot (Mg X) and the cool (O V) loops – however the O V loop fluctuates greatly. This behaviour has been observed in many active region studies with CDS. The variability is defined as the standard deviation (σ) of the derivative of the correlation with respect to time ($\sigma(dr/dt)$). Fig. 3 shows the variability with temperature. This provides a measurement of how much the loop structure varies in the different temperature loops.

The behaviour of the variability with temperature is similar to the behaviour of the line broadening with temperature (Fig. 1). Both relationships are linear with *variability* $\propto T_e^{0.39}$ and $V_{nt} \propto T_e^{0.35}$. Below $\log T_e = 5.8$, both the variability and the V_{nt} show positive

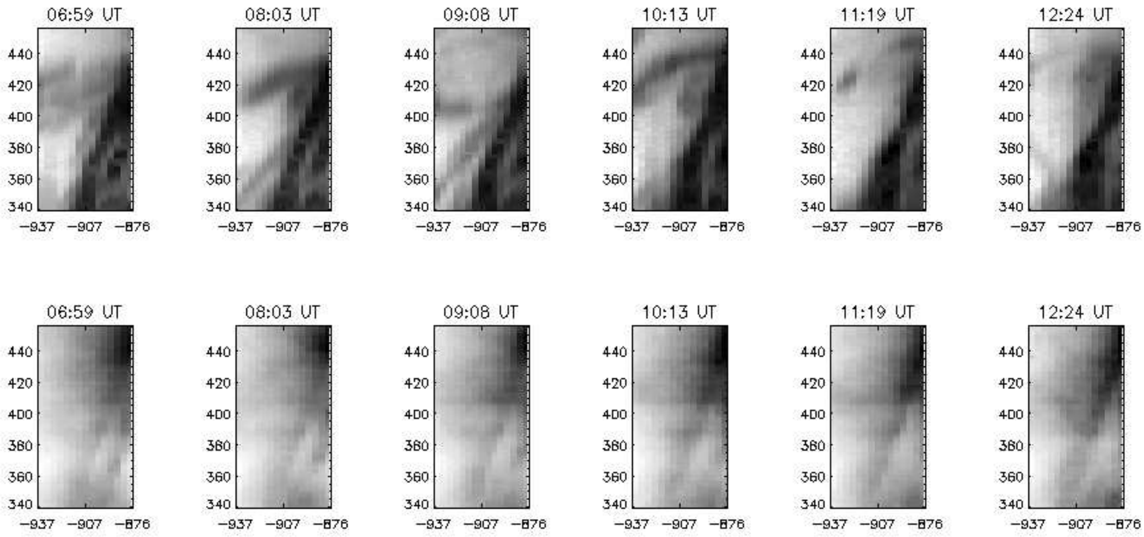

Figure 2: A time series of images in the O V line (top) and Mg X line (bottom). The scale is in arcsecs. The OV images show frequent changes in loops brightening and disappearing. The Mg X structure remain relatively stable throughout the time series.

gradients of approximately the same value suggesting that the line broadening is due to multi-directional flows. Consequently, the heating mechanism for the cool loops must be a transient, random mechanism, which produces flows in all directions.

5. Discussion

The behaviour of line broadening in the active region corona is not well understood. Making use of the diagnostic capabilities of CDS along with the accurate line widths from the Norikura Solar Observatory, Japan, we have been able to measure the non-thermal velocities accurately without assuming that the active region is isothermal throughout the loop structures. The results indicate that there is a distinct change in the behaviour of V_{nt} with temperature as coronal temperatures are reached. As coronal values are reached the V_{nt} does not continue to increase with temperature, but decreases dramatically, which is consistent with some previous observations. The values we have derived are consistent with values determined by Dmitruk, Gomez and DeLuca (1998) using 2D MHD simulations. They also expect V_{nt} to increase with increasing temperature for coronal loops. In Fig. 1 for $\log T_e > 6.4$, there is a trend for V_{nt} to increase with increasing temperature. However, this would need to be clarified by carrying out a large statistical study over a wide range of different temperature active regions using a range of different coronal lines for analysis.

There are two options to explain the dynamic cold loops. The first is that they exist as a progressive stage to the hotter loops and secondly that they are entirely separate entities. Both of these options are discussed in the following subsections in light of our results.

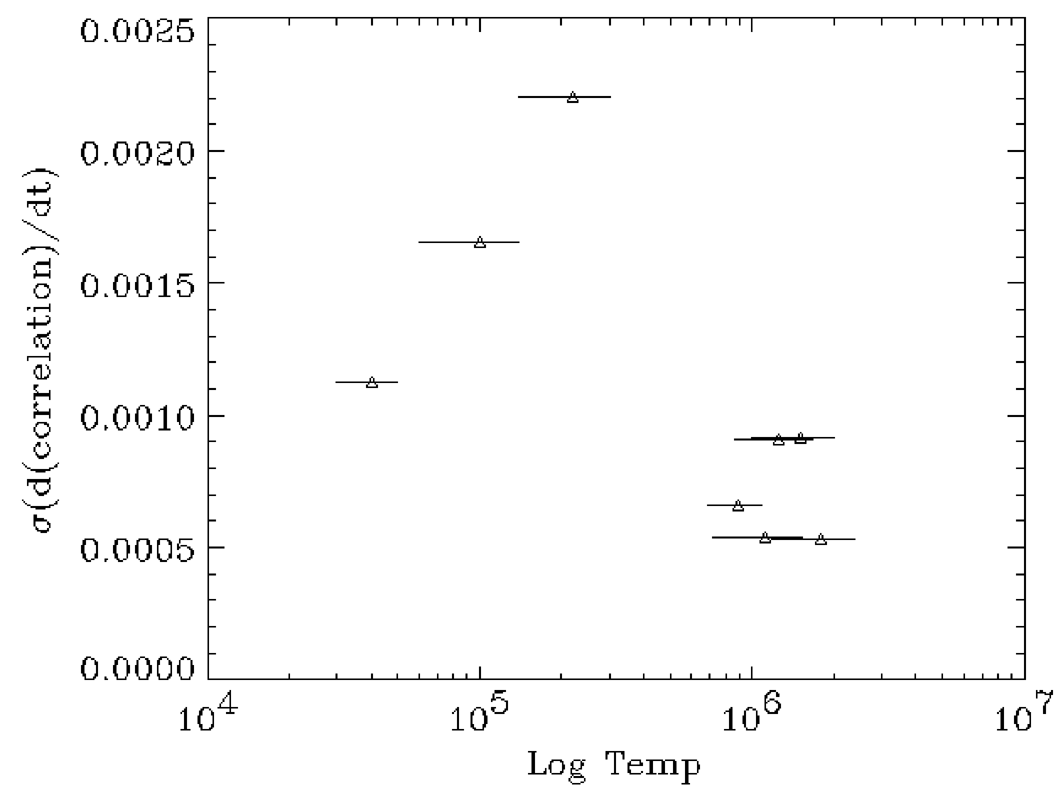

Figure 3: The time variability ($\sigma(dr/dt)$) of the different temperature loops.

6. Conclusion

In summary we found that the value of the V_{nt} at around 2 MK ranges between 10 – 20 km/s. This value was determined by using temperature diagnostics rather than assuming an electron temperature. This confirms that V_{nt} does not continue to increase with temperature beyond 1 MK, but decreases from 40 km/s at $\log T_e = 5.6$ to 15 km/s at $\log T_e = 6.3$. There is some evidence in other work that above $\log T_e = 6.6$ (see Fig. 1), that the V_{nt} starts to increase again with temperature.

With the recent observations from SOHO confirming the existence of cool transition region loops, we investigated the relationship that the behaviour of these loops have to the V_{nt} values. We can no longer assume that the transition region emission in active regions is a transitional layer between the surface and the hot coronal loops. We investigated one of the properties which would most likely affect the line widths - the dynamics of the different temperature loop systems. We found similar relationships between the variability and V_{nt} as a function of temperature ($\log T_e < 5.8$). This suggests that the V_{nt} is due to multiple Doppler flows which are superimposed. Above 1 MK the relationship was not as clear. It is possible that since there is no relationship between the variability and V_{nt} that a different heating mechanism exists. However there were a limited number of data points to confirm this.

Acknowledgements

LKHM and SAM would like to thank PPARC for postdoctoral funding. We are grateful to the referee for improving the clarity of the paper.

References

Boland, B.C., et al, 1975, MNRAS, 171, 697.

Dmitruk, P., Gomez, D.O., DeLuca, E.E., 1998, ApJ, 505, 974.

Doschek, G.A., Feldman, U., VanHoosier, M.E., and Bartoe, J.D.F., 1976, ApJS, 31, 417.

Kjeldseth-Moe, O., and Brekke, P., 1998, Solar Phys., accepted.

Mariska, J.T., Feldman, U. & Doschek, G.A., 1978, ApJ, 226, 698

Matthews, S.A. and Harra-Murnion, L.K., 1997, Solar Phys, 175, 541-551.

Orall, F.Q., 1981, 'A Monograph from Skylab Solar Workshop III', Colorado Associated University Press

Saba, J.L.R and Strong, K.T., 1991, ApJ, 375, 789

Discussion

S. Solanki: Did you determine the correlation coefficient over the whole CDs "image", or just over the off-limb part?

L. Harra: The correlation coefficient is determined just over the off-limb part of the active region.

S. Antiochos: Could it be that the observed T dependence of the Vnt is due to the cooling of hot loops?

L. Harra: What is clear is that there is some relationship between the cool and hot loops. Whether it is that the cool loops are dynamic enough and produce enough energy to heat the corona, or whether the hot loops are cooling down is hard to ascertain from the observations. The cooling times of the coronal loops have been measured and are too long to explain the cool loops.