The Time Variable Solar Atmosphere - Dynamical and Variable Active Region Loops Observed with CDS on SOHO.

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Abstract.

The Coronal Diagnostic Spectrometer, CDS, on SOHO has detected an upper solar atmosphere that is much more dynamic and time variable than previously expected. Loops in active regions, particularly in emission lines formed at temperatures $10^5$ K to 1 MK, traditionally thought of as the transition region, are seen to change significantly over an hour. Loops appear or disappear, the emission along their length change, or they change shape or expand outward, all on time scales of 10-20 minutes. The structural variability is accompanied by high Doppler shifts, especially in the 2-5x$10^5$ K temperature range. Velocities corresponding to the shifts typically amount to $\pm 50-100$ km s$^{-1}$. We find that existing theoretical models for loops cannot explain the observations. However, models with extreme fine structure, combined with episodic heating and magneto-acoustic wave disturbances propagating in the loop legs seem promising. The rapidly changing conditions that we observe give a new conception of loop systems that has never before been seriously considered.

1. Introduction

Recent observations with CDS and EIT on SOHO show that the upper solar atmosphere is much more dynamic and time variable than previously accepted. This result is reached from a systematic investigation of active region loops at transition region and coronal temperature, that was carried out over the last year mainly with CDS. Starting point for the investigation was the result of Brekke, Kjeldseth-Moe and Harrison (1997) showing unexpectedly high Doppler shifts in active region loops in the O v line at $\lambda 629$. Shifts corresponding to line-of-sight velocities of $\pm 50$ km s$^{-1}$ were found. From September 1997 to May 1998 we observed 20 active region loop systems on the solar limb and found that high Doppler shifts are common in these loop systems. In addition we discovered, or perhaps re-discovered, that a strong and rapid time variability is the norm for these loops, giving an impression of the physical conditions in loops that has never before been seriously accounted for by any observations or models.
2. Observations

The observations reported here have used the CDS normal incidence spectrometer, NIS. The two wavelength bands of NIS allows simultaneous observations of lines formed over temperatures from the chromosphere to the hot corona at 3 MK. We have employed the 4" wide slit, giving an angular resolution of $4'' \times 4''$. We may then distinguish individual loops above active regions if there are not too many of them in the line of sight, causing them to overlap. The spectral resolution amounts to values of $\lambda/\delta \lambda$ between 3600 and 4500, and Doppler shifts may be measured with an accuracy corresponding to $\pm 10$ km s$^{-1}$ for lines with a good signal to noise ratio. Only relative shifts can be measured, since there is no absolute wavelength reference. Usually the value of zero line shift refer to a line profile from an area on the nearby quiet disk.

Monochromatic images are made by rastering with CDS, i.e. by moving the slit parallel to its long axis in steps of 4". The spectrograms retain their full spectral information, and intensities, line shifts, and line widths may be determined at any point. To detect rapid time variations, we have used observing sequences for times series of rasters with a cadence as high as possible. Since it takes time to build up a raster image, typically 10-20 min, we do not get a snapshot of the full loop system as it appears at a given time. For more details about the instrument, including observing and data reduction procedures, we refer to Harrison et al. (1995).

3. A Dynamic Transition Region

The high Doppler shifts in the O v line, found by Brekke, Kjeldseth-Moe and Harrison (1997), occurred only in parts of loops, not along their entire length. Typically, 20 Mm long sections showed the high shifts, while the rest of the loop was unaffected. Doppler shifts of opposite directions were found in different regions of the loop system. The shifts were furthermore observed in regions where the loop axis was not directed mainly in the line of sight, but was more perpendicular to it. Thus, true gas velocities along the axis of the loop would have to be considerably larger than the ones inferred from the observed Doppler shifts. The observation seemed difficult to reconcile with flows and Brekke, Kjeldseth-Moe and Harrison (1997) considered an alternative interpretation involving magneto-sonic waves causing the shifts. Such large shifts have been computed for magneto-sonic Alfvén disturbances by Wikstøl, Judge and Hansteen (1998). We shall not go into details here, but refer to Brekke, Kjeldseth-Moe and Harrison (1997), and references in their paper, for a discussion of the wave mechanism versus explanations involving flows.

The later systematic investigation has confirmed that the results of Brekke, Kjeldseth-Moe and Harrison are typical. Furthermore, we found that the high Doppler shifts are seen up to Ne vi, T=430 000 K, but generally not in Mg ix at 1 MK. Finally, the highest line shifts in a loop are often found at its outer edge.
4. Shape and Temperature Dependence of Active Region Loops

The systematic material on active region loops throws light on their morphology and on their time variability. We first describe results with regard to the appearance of loops, addressing the question of their co-location at different temperatures.

Loops at $T \lesssim 1.5$ MK are usual and exist most of the time above active regions. Commonly they reach altitudes of 20-90 Mm, but loops well over 100 Mm occur. For $T \gtrsim 1.5$ MK, emission is concentrated at low altitudes, but diffuse emission extend high above the cooler loops.

A loop often emit along its entire length, or a considerable fraction thereof. This property of active region loops was noted already by Foukal (1976) from Skylab data. Foukal constructed models that were isothermal along their length to explain this property. His loops consisted of sheaths of plasma at different temperatures that increased outward from a cool core towards the hot corona on the outside.

This loop model would imply that loops at different temperatures should exist in exactly the same region. And, indeed, loops at different temperature are often found to be co-located within their diameters. However, numerous counter-examples exist of loops at one temperature, that are not present at other temperatures. Often loops at different temperatures are slightly, but significantly shifted in position, and their size and shape may also differ slightly. Thus, we cannot accept the simple conceptual model of Foukal. Instead, loop properties may be better understood if the loops observed with CDS and other instruments with spatial resolutions of 1'' to 5'', in reality consist of much finer sub-structures or thin strands only a few km thick. We may also point to the time variability of loops: A loop “missing” in one place, may become present at another time.

5. Time Variability – the Inconstancy of Loops

The many rapid time series of rasters with CDS of active region loops at the solar limb revealed, perhaps surprisingly, that the loops were extremely time variable. This time variability was first briefly reported by Brekke (1998) and is thoroughly described by Kjeldseth-Moe & Brekke (1998). In Figure 1 we illustrate the variability with a typical example of a loop system observed with CDS in the O vii $\lambda 629$ line formed at 235 000 K.

We note the large loop appearing in image number 3 of the sequence. This loop seems fairly stable and can be followed for 3 hours. It is shifting in appearance, becoming more skewed after on hour, but then stays in place until it suddenly has disappeared around frame 14. This is a stable loop. Most of the time we see the the loops appearing and disappearing in 1-2 frames, i.e. in 15-30 min. The variability is equally clear at other transition region temperatures from He i at 15 000 K to Ne vi at 430 000 K. Also in Mg ii at 1 MK and in EIT images in the 195 Å band, formed at 1.5 MK, we see correspondingly rapid time variations. This means that “typical” life times for active region loops range from minutes to hours.
In the hot corona, e.g. in Fe xvi λ360, we also see changes, but they are less spectacular. Perhaps structures at these temperatures are more stable, but another possibility is that we have many overlapping optically thin loops and cannot distinguish individual structures.

6. Some Concluding Remarks

Time variability of loops in active regions have been observed previously by several investigators, see Kjeldseth-Moe & Brekke (1998) for references. However, except for the results of Sheeley (1980), from SO82A on Skylab in 1973, none of these investigations reported changes in individual loops that were nearly as rapid as the ones seen here. To some extent Sheeley’s results, based on a single
set of observations, were “forgotten” and were never seriously reflected in modeling efforts of coronal loops. A brief discussion of a few models of time variability in loops is given by Kjeldseth-Moe & Brekke (1998), but the conclusion is that we cannot at present explain their rapidly changing behavior.

These observations points to a revision of our concept of the transition region, and probably the corona as well. It is unlikely that we have a smooth physical transition from the chromosphere to the corona. Nevertheless there must be a close connection between regions of various temperatures, from $10^4$ K to 1.5 MK, i.e. we have no disjointed atmosphere. The connection is probably through the magnetic field and the dynamic processes in the solar atmosphere.

A promising picture is that loops consist of thin, thermally insulated strands or cords, much smaller than the 3-10 arc second loop diameters observed, cf. Dere et al. (1988). The individual strands, that may be episodically heated, are in different phases of development and evolve at different rates. A possible mechanism both for the heating and for producing the high Doppler shifts might be the transport and dissipation of magneto-sonic disturbances. The observed behavior of the loops will finally be the average of an ensemble of strands.

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References