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OBSERVATIONS OF THE STRUCTURE AND DYNAMICS OF CORONAL LOOPS

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Abstract

The most striking thing about the SXT images is the range of loop sizes and shapes. Active regions are bright tangles of magnetic field lines, surrounded by a network of large-scale quiet coronal loops stretching between regions or to the quiet-Sun areas over distances in excess of 100,000 km. Often quite exotic loop geometries are seen, particularly cusped, sheared, and twisted loops. All of these magnetic structures show changes on timescales from seconds to months, depending on the nature of the coronal structure. The question of how these structures become bright and fill with hot plasma is still open. While we see the propagation of brightenings along the length of loops with velocities of several hundred km/s in active regions, particularly during flares, much higher velocities are seen in the quiet Sun. In X-ray bright point flares velocities of over 1000 km/s have been observed. X-ray jets with complex structure are also seen. The active-region loops themselves seem to be in constant motion, moving slowly out, carrying plasma with them.

1. Introduction

When we look at an image of the solar corona, the eye is naturally drawn to the brightest or largest structures. However, focusing on these rare and peculiar events may tell us little about how the general corona forms, evolves, and dissipates. We need to investigate the more common phenomena that are not so spectacular but make up a mojority of the structures in the corona, because it is these that hold information on the physical process that dominate the corona. We need to study these structures on a statistical basis rather than reading too much into one-off events. The Soft X-ray Telescope (SXT) on Yohkoh has provided us with a huge, long-term data base that is unique in its coverage, detail, and easy access by the solar community. In this paper I will summarize some of the surprising results that have come from SXT so far and are helping us build a new view of the dynamic and complex coronal structure in active regions. This will build on the review given by Hudson (1994) at this symposium.

All magnetic structures seem to show changes on timescales that range from seconds to months. The question of how these structures are formed, become filled with hot plasma, and are maintained is still open. Active-region loops seem to be in constant motion, moving slowly outward, carrying plasma with them. During flares, loops often produce localized brightenings at the base and later at the apex of the loop. Reliable alignment of the ground-based data with the X-ray images makes it possible to perform a detailed intercomparison of the hot and cold plasma structures over extended periods. Hence we are able to follow the long-term evolution of these structures and see how they become destabilized and erupt.

2. Coronal Structure and Dynamics

The corona is dominated by magnetic fields that originate in the photosphere, where the plasma and magnetic field are more or less in balance. Hence the chaotic photospheric motions can move the position of the legs of coronal loops, causing them to collide and interact. A relatively small displacement in the photosphere can be the cause of major reconfiguration in the corona. By observing any extended sequence of active-region images in movie form, several general characteristics become plain:

Active regions are far more dynamic than we expected. We knew from spectroscopic studies made by the Solar Maximum Mission (SMM) that there is a significant nonthermal energy in the coronal plasma (Saba and Strong 1991). However, SXT observations that show the loops in active regions seem to be continuously in motion, forming and reforming. Observing active regions near the limb has revealed that the magnetic field lines seem to be generally expanding outward, as was first pointed out by Uchida et al. (1992). Are thes the same nonthermal motions observed by SMM? It seems not to be the case, as several basic characteristics are different. In particular, the velocity signature is different. In the Saba and Strong study, line broadening of about 40 – 60 km/s was found in quiescent active regions, whereas the loop expansion would be seen as a line shift of 10 – 20 km/s the the SMM spectrometers, which is below their velocity resolution in soft X-rays. It is believed that the X-ray line broadening is the result of turbulent motions or plasma waves which could be associated with coronal heating. The most energetic active regions seem also to contain a large number of transient brightenings, which seem to be the result of various types of loop interactions (Shimizu et al. 1992). However, the initial studies of the frequency of transient brightenings do not seem to indicate that they are sufficiently numerous to heat the corona. Their non-uniform distribution within active regions does not seem to support their ability to maintain the heating of the active-region loops; i.e., not all hot, bright loops seem to be associated with recent transient brightenings. To counter this, it should be pointed out that Yohkoh gets data for only 46% of an orbit under optimum conditions. So Yohkoh can quite easily miss such events. Porter et al. (1994) link these soft X-ray transients with the far more numerous UV brightenings observed by SMM and the HRTS rocket, which could make up the energy deficit. Flows and jets of several hundred km/s are often seen in active region structures (Shibata et al. 1992, 1994) to complete the highly dynamic picture of active regions that we are forming. While we see the propagation of brightenings along the length of active-region loops and in X-ray jets with velocities of several hundred km/s, much higher velocities are seen in the quiet Sun. In XBP flares, for example, velocities of over 1000 km/s have been observed.

Active regions have a complex magnetic structure. If we were to ignore the dynamic aspect of active regions and merely compare the coronal structure with a high-resolution magnetogram, we find that many of the bright interconnections are not what one might expect from simple potential extrapolations. Many models represent the field by a submerged dipole which gives a loop geometry that has a large Γ (ratio of loop diameters at the base and apex of the loop). Instead, SXT observes that many loops have a near-constant cross-section in the corona. Klimchuk et al. (1992) put an upper limit of about $\Gamma = 1.1$. Exotic loop geometries such as twisted, sheared, kinked, and cusped loops are much more common than we expected. Sheared and twisted loop structures seem relatively stable lasting from an hour to several days. Kinked loops (see Figure 2 in Strong 1994) seem to be relatively unstable and short lived. However, cusped loops are more widespread and seem to have several different manifestations in the corona:

- Large-scale, helmet-streamer-like structures. These are quite rare and are often associated with the eruption of polar-crown filaments. They grow slowly to be over a solar radius in length and can last for days.
- Cusped loops associated with long-duration flares. These usually have bright emission at the apex of the cusp and last for several hours, growing at a rate of 1 – 10 km/s, and are part of an extended arcade.
- Cusped loops formed in quiet active regions. These tend to be relatively stable structures, evolving over periods from hours to days. They seem to be thin structures, i.e., not part of an extended arcade.
- Small jet-like structures. These are small, exceedingly dynamic and short-lived structures often associated with flares in X-ray bright points or "anemone" active regions (Shibata et al 1994). Propagation velocities of over 1000 km/s have been observed in these events (Strong et al. 1992), but flows of several hundred km/s are the norm.

Active regions interact with each other and the quiet Sun. Active-region loops often make connections to quiet-Sun sites several arcmin away, and clear interactions with other distant regions are quite common. It is often hard to distinguish from the X-ray images where one active region starts and another stops. From the integrated flux variation in soft X-rays we find that activity seems to peak for several weeks, implying that the activity is increased globally rather than just being a local phenomenon associated with single active regions (where one would expect activity to last for no more than 2 weeks).

3. Conclusions

The geometry of coronal loops implies that coronal currents are playing a major role in determining their shape. A field-parallel current will provide a toroidal field that will act to restrict the natural expansion of the field with height, explaining the observed near-constant loop cross section. This conclusion is supported by a recent result by Lang et al. (1993), who compared microwave radio maps from the VLA and RATAN 500 with SXT images to measure the coronal magnetic field strength. They found the field strength to be much higher than that expected from magnetic field models extrapolated from photospheric magnetograms. They proposed the present of strong coronal currents to explain the lower field divergence. Further evidence of coronal currents comes from the common twisted and sheared geometries seen in SXT images. If currents are so important in determining the geometry of these loops, are they also causing the heating that maintains high coronal temperatures? The answer, at the moment, seems to be that there is no evidence to support this. In fact, a recent result comparing the location of vertical currents in the photosphere from vector magnetograms with the location of the hot, bright coronal loops shows no significant correlation.

The solar corona is a rich and varied environment. It is hard to see how a single mechanism can produce such variety on so many different spatial and temporal scales even when the basic structure is similar (e.g., cusped loops). Rather, the general structure we observe seems to be a dynamic balance between competing mechanisms such as magnetic flux emergence, flux cancellation, photospheric motions, reconnection, and electric currents. The factor that determines which combination of these mechanisms is dominant may well depend on small-scale, local conditions that Yohkoh cannot observe.

During flares we find loops to be asymmetric, often showing localized brightenings at the base and the apex of the loop (Acton et al., 1992, Feldman et al. 1994). The problem of confinement of these volumes of concentrated emission is one of the most interesting problems to come out of flare studies by Yohkoh so far.

The Sun continues to provide us with a complex set of problems, and Yohkoh by itself cannot provide all the answers. In fact, it seems to be creating more thorny questions! However, it should be remembered that Yohkoh has several practical limitiations.

- High-rate data are available only for less than half of any given orbit even under the best of circumstances.
- There is no information available on the lower-temperature material in the chromosphere and transition region.
- SXT does not resolve the smallest-scale structures. From coordinated observations between Yohkoh and HRTS it is clear that the cool and hot plasma seems intimately mixed in fine filamentary structure and isolated from each other by the magnetic field. This implies that we need yet higher resolution over a broad range of wavelengths simultaneously.

We will have to wait for SOHO and the Transition Region and Coronal Explorer to provide such data, hopefully simultaneously with Yohkoh. As the corona is optically thin we have no information on the true 3-D structure of the phenomena that we see. Rotational tomography does hold some hope for providing 3-D information, but the highly variable nature of most coronal sources introduces large uncertainties into such calculations. Only simultaneous multiple spacecraft observations can solve this problem.

The way to fill some of these gaps in the short term is to coordinate observations by Yohkoh with optical and radio ground-based observatories, other spacecraft, and sounding rockets. We have held several very successful observing campaigns duirng the first two years of Yohkoh operations. While these are very time consuming operationally they do provide unique information. Several of these collaborations are discussed elsewhere in this volume but as the focus of the conference is the Nobeyama Radioheliograph, it should be pointed out how well these data are being merged with the Yohkoh data. The ease by which these different data sets can be compared and analyzed now gives us some hope that we can untangle the complexities of the solar activity cycle and the Sun's outer atmosphere.

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