Solar activity studies through coronal X–ray observations

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Solar activity studies through coronal X-ray observations

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The solar corona consists of high-temperature plasma that is contained by a wide range of magnetic field structures. The cyclic behaviour of solar activity results in continuing evolution of these structures. This evolution can be well studied by observing the X-ray and extreme ultraviolet (EUV) emission from the hot plasma which delineates the magnetic field in the corona. In this review, the X-ray images obtained from the Yohkoh mission over more than half a solar cycle and the information they provide about coronal evolution will be discussed. A variety of short-term transient brightenings observed by Yohkoh, and at EUV wavelengths by the SOHO mission, will be described and their relevance for coronal heating evaluated. Yohkoh observations have advanced our understanding of solar flares. These important results will be summarized and discussed. Finally, the current view of the nature of coronal mass ejections as deduced by Yohkoh and SOHO is presented.

Keywords: solar physics; X-ray; solar activity; Yohkoh; SOHO; EUV

1. Introduction

A clarification of what is happening in the spectacularly dynamic and complex solar atmosphere has widespread implications for understanding stellar coronae, galaxies and the intracluster medium, all of which have million-degree plasma.

Since the launch of the Yohkoh spacecraft (Ogawara *et al.* 1991) in 1991, many of the previously accepted pictures of the Sun have been overturned. The Yohkoh spacecraft has provided, for the first time, high-cadence soft X-ray imaging, enabling a deeper understanding of many time-varying phenomena. Our understanding of some of the long-standing problems in solar physics, such as solar flare energetics and coronal heating, have been advanced dramatically in the past decade.

The most commonly accepted method of converting magnetic energy into kinetic and thermal energies is that of magnetic reconnection (see, for example, Priest & Forbes 1999). This occurs not only in solar plasmas but also in astrophysical and magnetospheric plasmas. Many recent observations of the solar corona provide support for magnetic reconnection as a heating source both on large and small scales. There exists a wide range of dynamic phenomena ranging from network flares (the smallest measurable events) to X-ray bright points, solar flares, and the largest being coronal mass ejections. Figure 1 shows a Yohkoh soft X-ray image depicting the wide range of activity which occurs on the Sun at any one time. The bright regions distributed predominantly in a band 30° above and below the equator are called active regions. These are the hottest regions on the Sun and the locations of the largest

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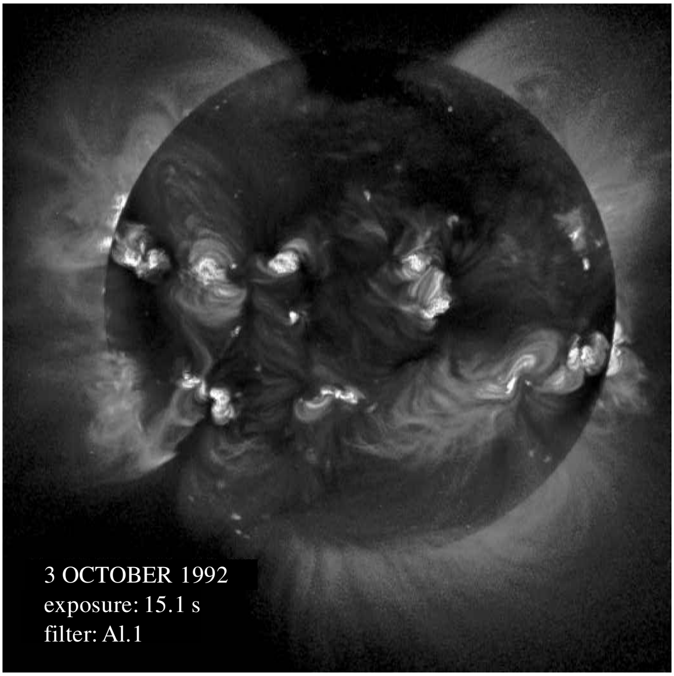

Figure 1. A Yohkoh soft X-ray image showing the wide range of structures that exist on the Sun at any one time.

energy releases—solar flares. The north pole shows a clear example of a coronal hole. In this region the field lines are open and hence, in the absence of contained plasma, there is little soft X-ray emission. Smaller bright regions are seen all over the disc, which are known to be X-ray bright points. On an even smaller scale than bright points, network brightenings exist. These are difficult to see clearly in figure 1 but will be discussed later. There is also a more diffuse component in between the active regions, which is quasi-static. The dynamics and heating of this wide variety of structures have to be explained. The Yohkoh spacecraft has been providing unprecedented observations of the X-ray corona. This extensive dataset was enhanced in 1995, when the ESA/NASA SOHO mission was successfully launched. SOHO has 12 instruments—results from three will be described in this review: the EUV Imaging Telescope (EIT) (Delaboudiniere *et al.* 1995), the Large Angle Spectroscopic Coronagraph (LASCO) (Brueckner *et al.* 1995) and the Coronal Diagnostic Spectrometer (CDS) (Harrison *et al.* 1995).

2. Active regions

One of the possible sources for heating the active region corona is the occurrence of numerous microscopic energy releases (microflares or nanoflares). This suggestion was put forward by Parker (1988). Hard X-ray microflares, with an energy in the range 5×10^{28}–10^{30} ergs, were first measured using a balloon-borne hard X-ray detector (Lin *et al.* 1984). The soft X-ray equivalent of hard X-ray microflares displays itself as intense transient brightenings. The soft X-ray telescope on board Yohkoh has provided us with the ability to measure energies as low as 10^{27} ergs.

The energy–frequency distribution of flaring behaviour can be used as a diagnostic for determining whether the transient events observed can supply sufficient energy to heat the active region corona. This has been done in the case of standard flares with energies of *ca.* 10^{32} ergs, and it has been found that the power law has an index of less than 2, which means that standard large flares do not supply enough energy to heat the corona. An investigation into the energy supplied by soft X-ray transient brightenings has been carried out by Shimizu (1995). A total of 291 brightenings were measured from one active region. The energy distribution was determined to be approximately the same as that for major flares (power-law index of 1.5–1.6). A significant increase in the slope of the energy distribution was not found for the lower-energy brightenings observed by the Soft X-ray Telescope (SXT). The total estimated energy input for flare and the smaller transient brightenings was determined to be a factor of five lower than that required for heating active regions. Events with energies smaller than those observed with SXT and with a higher occurrence rate would need to be found in order to explain the heating of the corona.

Another new discovery in terms of active regions is that in general they are not rigidly restrained by the strong magnetic fields. The active regions have been found to have sometimes continual expansions with speeds of up to a few tens of km s^{-1} (Uchida *et al.* 1992). The expansions occur even outside major flaring activity. It is hypothesized that the transient brightenings described in the previous paragraph are directly related to the phenomena of expanding active region loops.

Observations of transequatorial coronal loops which join two separate active regions have also been observed (Tsuneta 1996). It has been suggested that magnetic reconnection is triggered by the active region expansion, which was observed by Uchida *et al.* (1992). The large loops which are formed after the reconnection can heat large areas of plasma in between the active regions. It is suggested that the coronal regions outside active regions (the quiet corona) can be heated continuously as the result of reconnection between active region magnetic fields.

The Yohkoh data provide information on coronal temperatures. Since the launch of SOHO in 1995, it has been possible to combine the X-ray information with UV data to obtain spectral and imaging information not only for hot coronal temperatures (greater than 10^6 K), but also for lower-temperature emission (10^4–10^6 K). Until now the view of an active region magnetic loop structure has been the following: the footpoints are anchored in the photosphere (the surface of the Sun); the loop legs rise up through the subsequent layers of the solar atmosphere (chromosphere, transition region) with the loop top ending up in the corona (at heights less than 50 000 km above the surface). The transition region has been traditionally considered as a thin layer separating the cooler surface (6000 K) from the high-temperature corona (2 MK). However, it has recently been found that transition-region emission does not in fact exist as a thin layer but mainly as dynamic loop structures which extend high into the atmosphere—well into the traditional corona (Matthews & Harra-Murnion 1997; Fludra *et al.* 1997). These cool loop structures coexist spatially with the hot coronal structures (see figure 2).

The different temperature loop structures also behave in a very different manner depending on their temperature. Cool (250 000 K) loops are extremely dynamic, whereas the hot (2 MK) loops are quasi-static over time-scales of an hour (see figure 2). High flow velocities (*ca.* 100 km s^{-1}) have been observed in the cool loops (Brekke *et al.* 1997), whereas flows of only *ca.* 2 km s^{-1} have been observed in hot

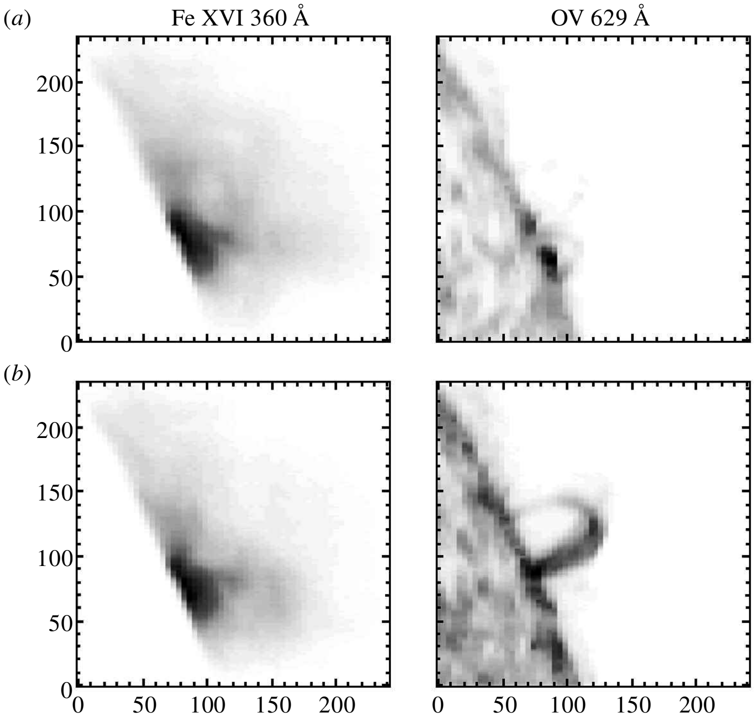

Figure 2. (*a*) Images of an active region on the west limb taken simultaneously in a coronal line Fe XVI (2 MK) and transition region line O V (250 000 K). (*b*) The same active region an hour later. The dramatic changes in structure in the transition region line are obvious. There is no evidence for the transition region behaving as a transitional layer between the cool surface and the hot corona.

loops. It is possible that the cool loops represent a stage in the heating of the hot loops (Harra-Murnion *et al*. 1999).

3. Flares

Our understanding of the flare process has improved dramatically with the data from the Yohkoh spacecraft. The hot, dense, thermal emission as measured in soft X-rays by the SXT shows the response of the plasma to a flare. The hard X-rays are produced by electron–ion Bremsstrahlung from highly energetic electrons during the impulsive phase of flares. The existence of hard X-ray sources (greater than or equal to 30 keV) at the footpoints of the soft X-ray loop has been confirmed from Yohkoh observations by Sakao *et al*. (1994). No significant time lag was found in the intensity variation of the footpoint kernels, and hence it is reasonable to assume that the energetic electrons are moving down both loop legs simultaneously. This observation represents a common characteristic of the impulsive phase, and is due to the accelerated electrons streaming down through the loop legs, from the reconnection point, to the footpoints.

In addition to the hard X-ray footpoint sources, a high-energy source can also exist well above the loop top during the impulsive phase (Masuda *et al*. 1995). The three hard X-ray sources can be seen in figure 3. The loop-top source is weaker than the

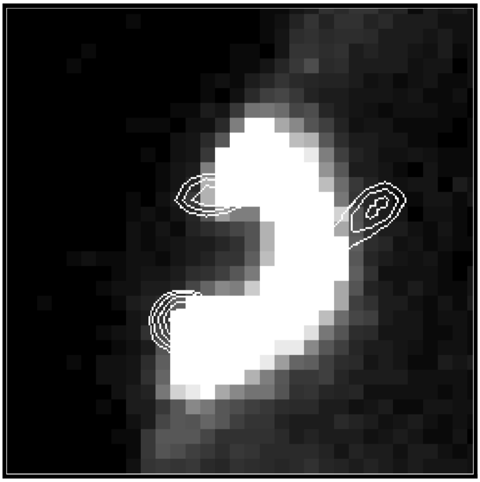

Figure 3. Hard X-ray image (33–53 keV) in contours overlaid on a soft X-ray image of the flaring loop. The flare occurred at the west limb on the 13 January 1992. The hard X-ray footpoint and loop-top sources can be clearly seen (Masuda *et al.* 1995).

footpoint sources by a factor of approximately five. The discovery of a loop-top source has implications for the understanding of the flare energy release mechanism. There are two possible explanations for this loop-top source. The first is that the source represents the reconnection site itself. Secondly, it could be that the reconnection point is far above the source, and that outflow ejected from the reconnection point is colliding with the higher-density magnetic loops and forming a shock. A cartoon of the reconnection configuration derived from the observations is shown in figure 4.

Another characteristic of the compact flares described above is the frequent observation of a hot plasma ejection (plasmoid). These plasmoids were observed to be very faint and have velocities of the order of hundreds of km s^{-1} (Shibata *et al.* 1995). Magnetic reconnection theory predicts (see, for example, Priest 1982) two oppositely directed high-speed jets at the Alfvén speed (*ca.* 3000 km s^{-1}). The observed velocities of the moving plasmoids are much lower.

Hard X-ray loop-top sources have also been observed in the decay phase of long duration events (LDEs). These flares tend to be associated with systems of loops called post-flare loops, and can last up to 12 h. It has been well observed that these post-flare loops expand and can last for many hours. The process of expansion is believed to be due to ongoing magnetic reconnection. The newly formed hot loops cool down to appear eventually as Hα loops. Schmieder *et al.* (1995) and van Driel-Gesztelyi *et al.* (1997) found that the cool Hα loops lie tangentially below the hot loops and rise with a velocity of *ca.* 1 km s^{-1} upwards. The hard X-ray sources were found to lie above and slightly overlapping the soft X-ray loop. As time progresses the hard X-ray source and the soft X-ray loop become further apart, with both the hard X-ray source and the soft X-ray loop rising with time (Harra-Murnion *et al.* 1998). This suggests that the mechanism which allows the flare to persist for so many hours is ongoing reconnection.

Observations of an LDE have also shown that the rise speed of the inner loop and the speed of the footpoint separation is *ca.* 10 km s^{-1} (Tsuneta *et al.* 1992). The movement of the loop and footpoints is thought to be due to the rise of the

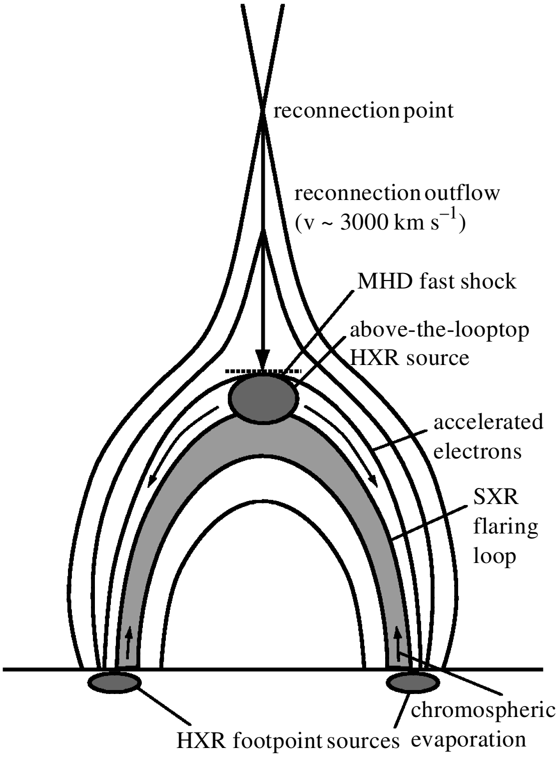

Figure 4. A cartoon of the reconnection configuration derived from the observations for a compact flare (Masuda *et al.* 1995).

reconnection point (X-point location). The loop-top region has a sharp cusp-like structure suggestive of the reconnection site being located at the top of the flare loop. The outer loops tend to have a larger temperature than the inner loops following the rise phase of the flare. This is consistent with the idea that the recently reconnected outer loops are hot whereas the inner loops are now cooling and are no longer being heated (Tsuneta 1996).

The imaging techniques described here have been enhanced by the availability of high-sensitivity spectroscopic information. The emission lines are broadened in excess of their thermal width and occasionally exhibit excess emission on the blue side of the rest wavelength during the rise phase of flares. A study of 190 solar flares observed by Yohkoh was carried out by Mariska (1994). He found that 25% of flares show spatial shifts of the emitting plasma, and there is a trend in the average value of the velocity with distance from the Sun centre which suggests radial mass motions. This is explained by the release of energy heating the plasma, and the change in pressures which induce plasma flow.

The excess line-broadening above the thermal width is also observed and is ascribed to non-thermal velocity. The physical process which produces this effect is not well understood. Before the results from Yohkoh, it was surmised that the large non-thermal velocities observed during the rise phase of flares were due to the evaporation of hot plasma early in the flare. Alexander *et al.* (1998) have examined the relationship between the time of the maximum in the non-thermal velocity and the time of the first significant hard X-ray burst (which determines the flare start). They found that the non-thermal velocity was at its peak or else declining from the peak at the time of the first hard X-ray burst. This suggests that the non-thermal velocity measurements may not be due to evaporation of the plasma, but can provide information on the flare initialization.

Although there is plenty of evidence to support magnetic reconnection providing energy input in many different aspects of coronal activity, there are also some who argue against it (Hudson & Khan 1997). For example, as mentioned earlier, the reconnection jets that have been described are not as fast as the jets which are predicted by simple Petschek theory, which suggest they move at approximately the Alfvén speed. However, more sophisticated theory (Priest & Forbes 1999) gives outflow and inflow speeds much slower than the Alfvén speed. Reconnection theory also requires inflow towards the reconnection site. Various forms of outflow have been observed and inflow has never been observed. Hudson & Khan (1997) also mention the frequent occurrences of homologous flares, which occur in the same location and have many similarities, although this may be explained in a reconnection model that first produces a change in the topology of the field, after which a slow shearing of the field returns it to the original configuration.

4. Coronal mass ejections

Many of the transient events described in the previous sections may add to the solar wind content. For example, the expanding active regions and jets mentioned above will all add to the mass loss of the corona. Most of our knowledge about coronal mass ejections (CMEs) is derived from white light coronagraph data. Pre-Yohkoh it proved difficult to assign any strong connection between the soft X-ray corona and the white-light CMEs. Yohkoh SXT, with its high-time cadence and sensitivity, has provided the opportunity to study some of the X-ray phenomena related to CMEs in much more detail. The coronagraph LASCO onboard SOHO is now providing continuous observations of white-light data providing the ability to observe the outward flows that may be related to soft X-ray features.

The first Yohkoh event, which was directly related to white-light observations of a filament eruption and a CME, was a streamer reformation (Hiei *et al*. 1993). The prominence eruption and coronal mass ejection occurred before the streamer appeared. Subsequently, the X-ray coronal helmet streamer slowly expanded. This event also showed strong evidence of coronal depletion (Hudson 1996), which permitted a determination of the CME launch time. The coronal 'dimming' observations provide one of the best X-ray signatures of CMEs.

There are a number of examples in which dimming appears above LDEs. This tends to be the most obvious type of dimming (Hudson *et al*. 1996), although an observational constraint is that they must be observed at the limb. LDEs have been associated with CMEs for many years.

The first example of dimming associated with a halo CME was found by Sterling & Hudson (1997). Halo CMEs which are directed along the Sun–Earth axis are characterized by a diffuse cloud of material lying symmetrically around the solar occulting disc. There was a flare observed in X-rays at 14:00 on the 7 April 1997. From the dimming measurements an estimate of the mass loss could be made. It was found that the dimming occurred over a projected area of 10^{20} cm^{-2} suggesting

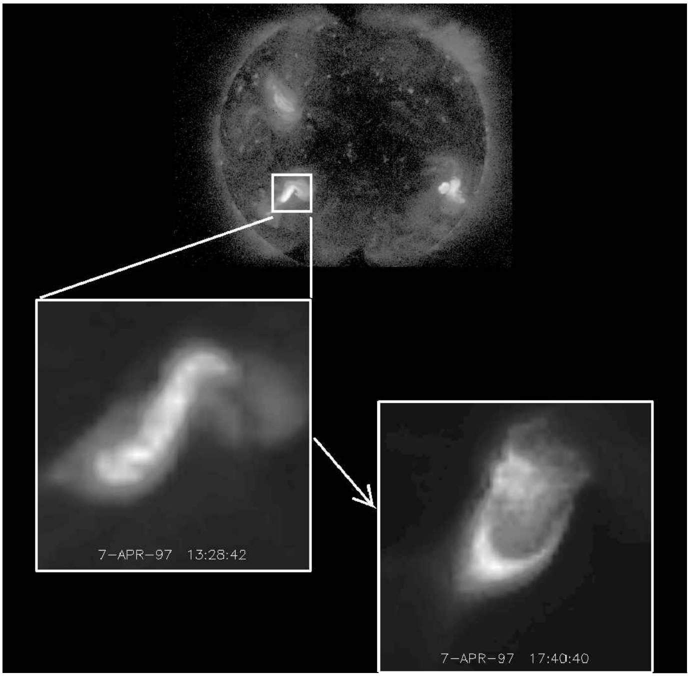

Figure 5. A full Sun soft X-ray image showing the source of a CME. The panel on the left shows the preflare S-type structure, and the panel on the right shows the cusp-shaped structure which developed following the CME (courtesy A. C. Sterling).

that a mass of *ca.* 10^{14} g was ejected. It is surmised that at least part of the CME mass is detected via the X-ray dimming measurements. Most of the ejected mass comes from two regions which lie close to the ends of the preflare S structure. This S structure changes morphology dramatically into a cusp-shaped structure following the flare (see figure 5). The levels of dimming remain high for roughly three days. It is suggested that the two areas of dimming represent a magnetic flux rope which erupts. The cusp shape which develops is thought to be due to the reconnection of the magnetic field lines following the eruption.

Following this work which showed the sigmoidal (S-shaped or inverse S-shape) morphology related to a CME, a statistical study has been carried out by Canfield *et al.* (1999). It was found that, from a study of 117 active regions, those which have sigmoidal structures are 68% more likely to be eruptive than those with non-sigmoidal structures. The other factor which increases the likelihood of eruption is the size of the sunspot area. Other factors such as the level of twist in the sigmoid will improve the prediction of eruptions in the future.

5. Bright points

It has been well established that there is an association of coronal X-ray bright points with bipolar magnetic features. The relationship between the magnetic field and the overlying atmosphere has been examined in detail by the Michelson Doppler Interferometer (MDI) onboard SOHO, and EIT. The magnetic field outside of active regions is continuously replenishing. From the MDI movies the flux concentrations

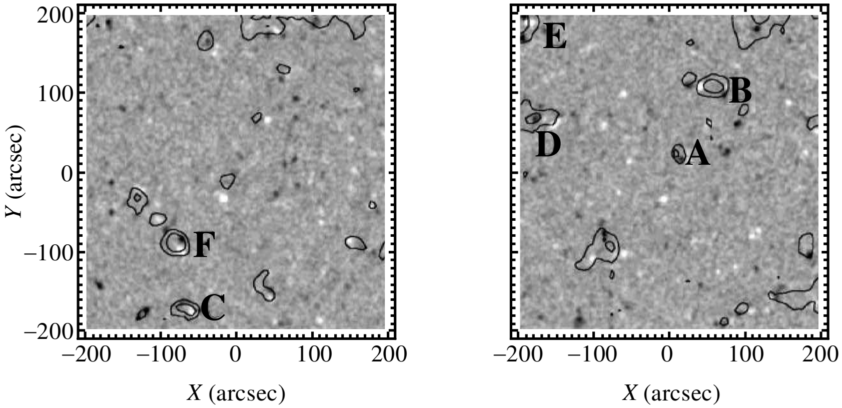

Figure 6. Two magnetograms of a quiet Sun region taken a day apart. The white areas show positive polarity and the black areas show negative polarity. The contours show coronal emission in Fe XII from EIT (Pres & Phillips 1999). A–F mark the regions of coronal emission.

frequently break into small fragments and collide with other flux fragments. Pres & Phillips (1999) have followed the time evolution of magnetic flux from birth to decay and found that it is very well correlated with the coronal emission. Figure 6 shows two magnetograms showing the bipolar field with coronal emission above it. Calculations of the total radiative and conductive flux are comparable to the magnetic energy available from the associated magnetic field.

Non-thermal processes have also been investigated in flaring bright points. Some bright points have a tendency to show brightness variations. Kundu *et al.* (1994) investigated whether these variations have any similarity to the standard flares which take place in active regions. One of the most important aspects of this question is whether there is any evidence of non-thermal emission. Even in the cases of long-lasting LDEs there is always some evidence of non-thermal processes. A joint campaign was carried out with the Nancay radioheliograph and Yohkoh SXT in 1992. The Nancay data are obtained at five frequencies ranging between 150 and 450 MHz. It was confirmed that the X-ray bright point flares give rise to non-thermal radio emission in addition to the soft X-ray emission. The duration of the radio emission is shorter than the soft X-ray emission. The existence and behaviour of the relationship between the non-thermal radio emission and the thermal soft X-ray emission has many similarities and strengthens the relationship between flaring bright points and standard flares. This suggests that the processes involved are similar in both cases.

Yohkoh has provided the perfect opportunity to determine whether there is a cycle dependence of the number of X-ray bright points. There has been some dispute about whether the number of bright points would increase, decrease or stay the same during the cycle. Nakakubo & Hara (2000) investigated the number of bright points seen with the SXT using an automated technique during the period from December 1992 (close to solar maximum) to August 1997 (close to solar minimum). The number of X-ray bright points did not change significantly until approximately 1995. As sunspot minimum approached, the number of bright points reached a maximum when the sunspot number was at its lowest. However, an investigation into the effects of the background intensity showed that the observed increase in the number of bright

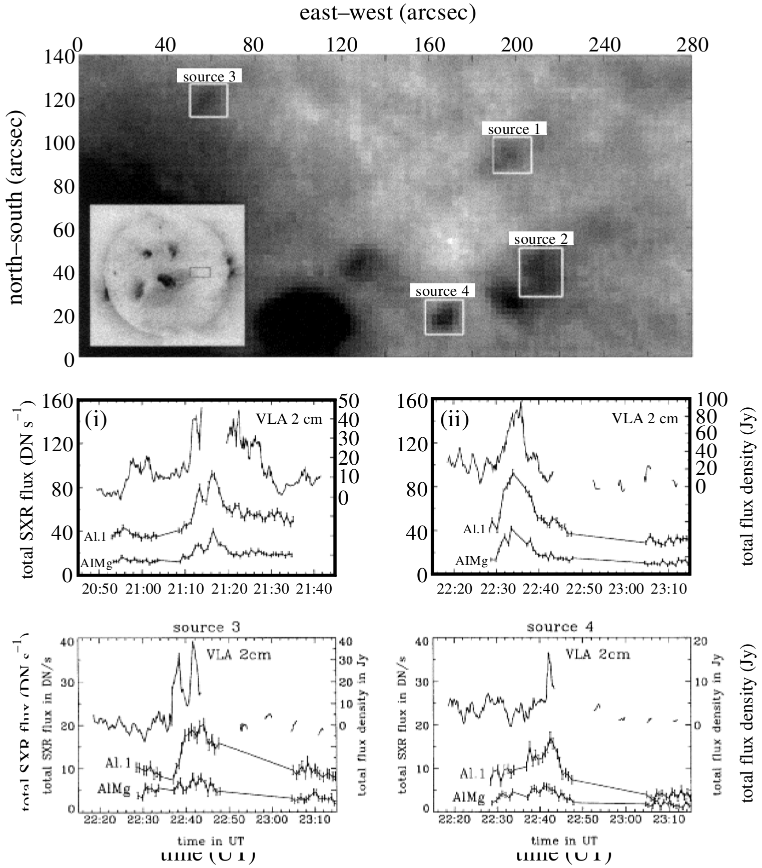

Figure 7. Temporal variation of network flares observed in soft X-ray and radio emission. The image at the top shows the soft X-ray image with network brightenings marked by white boxes. The four figures below show examples of the radio and soft X-ray brightenings (Krucker *et al.* 1997).

points was due to the drop in background intensity. When this effect is allowed for, it appears that there is no correlation between the number of bright points and the solar cycle.

6. Network brightenings

As mentioned previously there has been an investigation into whether active regions are heated by numerous flarings on small scales. The number of brightenings in an active region in the energy range 10^{27}–10^{29} ergs is too small to provide all the heating for the active region. The heating of the quiet corona has also been investigated. For a direct link between soft X-ray brightenings and the Parker model of nanoflares/microflares, there should be evidence of the release of non-thermal electrons, which are also observed during standard solar flares. Krucker *et al.* (1997) carried out a joint VLA/Yohkoh campaign in February 1995 to examine this question.

The soft X-ray enhancements found are smaller than recorded X-ray bright points by at least an order of magnitude. For all of the SXR events measured there was a radio event which correlated in space and time (see figure 7). The observations are very similar to solar flare observations but on a much smaller scale, and have hence been given the name network flares or network brightenings. The extrapolated frequency is one brightening every three seconds on the total solar surface, with each event having an energy between 10^{25} and 10^{27} ergs. There are some differences between the network flares and standard flares. The temperatures observed are much lower and the durations are shorter.

The variable nature of brightenings at the network junctions has also been observed in the UV by Harrison (1997) using the coronal diagnostic spectrometer (CDS) onboard SOHO. There appear to be more brightenings in the cooler transition region emission than in the coronal emission. The energy distribution of the heating in the quiet Sun has been determined by Krucker & Benz (1998) using the EIT onboard SOHO. The energy of the events measured in this case ranged between 8×10^{24} and 1.6×10^{26} ergs. The brightenings were measured as 3σ above the background level. These brightenings were found to have a frequency distribution of the form $f(E) = F_0 E^{-\delta}$, with δ having a value between 2.3 and 2.6. Since the power law is greater than 2, there is a strong possibility that the microflaring is the dominant heating mechanism for the quiet corona. The low-energy cut-off is due to sensitivity limitations, and hence there could be many more smaller energy events. Indeed Parnell (this issue) describes recent work with TRACE data going an order of magnitude lower in size of event and obtains a similar value of power law.

Gallagher *et al*. (1999) have analysed rapid-time cadence data of quiet Sun EUV emission observed by the CDS. The transient brightenings are observed both in the transition region line (O V) and in the chromospheric line (He I) suggesting a coupling between the chromosphere and the transition region. There is a clear association of brightenings in the network with downflows of the order of 20 km s^{-1}. The properties of the network regions are different to the cell region, which is suggestive of different heating mechanisms for the cell and network regions.

7. Diffuse corona

The diffuse component of the corona has very different characteristics from the more dynamic features that have been described above. Priest *et al*. (1998) have investigated the heating mechanism of this component. The diffuse emission consists of large-scale diffuse loops. The temperature profile along such a loop is measured and this is compared with various models. There are several possible heating mechanisms. Firstly, Alfvén waves may dissipate either by phase mixing releasing energy or resonant absorption. Another option, as mentioned earlier, is reconnection in many small current sheets scattered throughout the structure that form in response to twisting or braiding of the magnetic field lines. This may in turn lead to an MHD turbulent state. From this particular example it is found that the heating is uniform throughout the diffuse loops, and is not focused at the footpoints or loop-top (see figure 8).

8. The future

All the structures that have been described in this paper are magnetic in origin. To increase our understanding further we need to address the relationship between

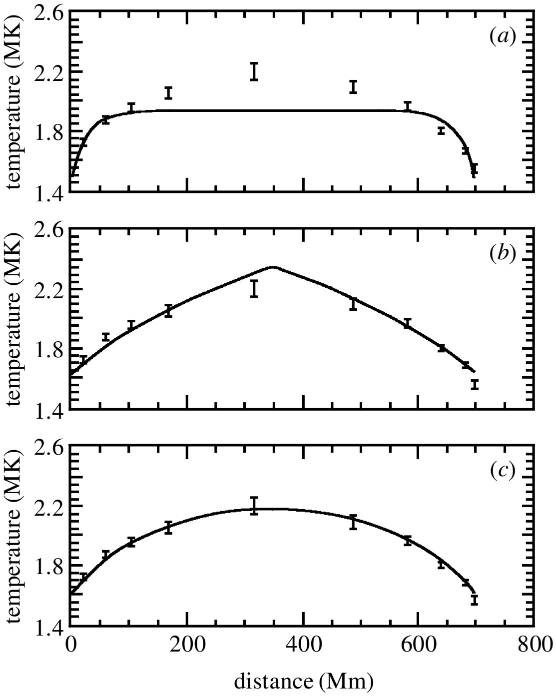

Figure 8. Comparison of the temperature profiles for different theoretical mechanisms (solid curves) with the observed temperature profile determined from SXT of a large coronal loop (Priest *et al.* 1998). (*a*) Exponential decay over $0.1L$; (*b*) localized at top; (*c*) uniform.

the magnetic field and the solar atmosphere. The mission which will follow from the success of the Yohkoh mission is the Japanese solar-B mission. The launch date will be in 2004. Solar-B will place the first optical telescope in space. The emphasis of the Yohkoh mission was to focus on energetic phenomena. Solar-B will concentrate on understanding the connection between the fine-scale magnetic field in the photosphere and the structure and dynamics in the entire solar atmosphere.

There will be three instruments onboard: a 0.5 m optical telescope with the ability to measure photospheric magnetic and velocity fields at 0.2 arcsec (150 km); an EUV imaging spectrometer, which will have velocity resolution of *ca.* 10 km s^{-1}, and spatial resolution better than 2 arcsec; and an X-ray/EUV imaging telescope to image the corona and transition region with better than 2 arcsec resolution.

9. Summary

The wide range of solar activity that has been observed by the Yohkoh mission since its launch in 1991 has been described. The characteristics of the small-scale structures such as bright points and network brightenings have shown similarities with larger flares. A direct relationship has been found between the variation of the magnetic flux at the surface and the coronal plasma above a bright point. The number of bright points has been found not to vary with solar cycle. Analysis of the larger active regions has shown that only some of the heating is provided by transient brightenings. Transequatorial loops connecting active regions can provide heating for the quiet

Sun. The active-region loop structures expand with velocities of the order of tens of km s^{-1}. The standard solar flares have shown many clues towards understanding the energetics and initialization. The main candidate is magnetic reconnection. The first soft X-ray signature for coronal mass ejections has been found. It takes the form of dimming or depletion of the coronal material, and is related to a sigmoidal-type structure.

The future of solar physics looks set to enhance these exciting discoveries with the next Japanese solar mission, solar-B.

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Discussion

L. Golub (*Harvard Smithsonian Center for Astrophysics, USA*). The word ‘diffuse’ occurs several times in this paper. I find it hard to believe that in a hot magnetized plasma, wherein the magnetic field is highly organized, there would be any diffuse corona. I prefer to use the word ‘unresolved’. Could you comment on the expected size scales transverse to magnetic field dissection?

L. Harra. Yes, I agree. In fact the work that I described assumes that the ‘diffuse’ structures take the form of loops. In the paper by Priest *et al.* (1998), there is an image showing the loop structure very clearly.

E. R. Priest (*University of St Andrews, UK*). The magnetic field in the corona of course dominates the plasma structure transverse to the field while its structure along the field is determined by purely (mechanical and thermal) plasma effects. If the magnetic field and plasma were static and the plasma pressure at the coronal base were uniform, the plasma pressure would be stratified purely vertically and would show no effect of the magnetic field. The fact that you see coronal loops implies the corona is much more complex than that! The expected transverse scales that Leon asked about are likely to be produced by two effects: the field-line footpoints moving around on granular scales would tend to produce coronal scales of the same size; and intrinsic coronal instabilities such as an MHD radiative instability would tend to produce variations *in situ* in the corona.

Y. Uchida (*University of Tokyo, Japan*). There is a possibility that those magnetically driven mass losses due to CME and active-region expansion may be more important than the usual Parker wind in magnetically active stars.

E. R. Priest. The solar wind itself has several components; a fast solar wind coming from the open coronal holes and a sporadic slow solar wind coming from mainly closed regions. The solar wind has a very complex structure: for example, the fast wind has both plume and interplume components and the slow wind has several parts to it, one of which you mentioned.

L. Harra. Yes, as well as the active-region expansion that I mentioned there are high speed jets.

R. E. Pudritz (*McCaster University, Canada*). Do your observations show any evidence for coronal heating by waves?

L. Harra. Most evidence that I have described has favoured heating by reconnection. There have been a few studies which have indicated evidence of wave heating by examining the line broadening (non-thermal velocity) as a function of temperature, and also looking for periodic motions. However, the evidence is not strong. Of course, there is strong evidence for the production of waves in other phenomena, such as Moreton waves associated with flares.

E. R. Priest. I think it's fair to say that, before the Yohkoh/SOHO era, theorists were equally divided: it could be waves or it could be reconnection. Now, in the light of SOHO observations, there's much more evidence in favour of reconnection, but substantial wave heating may still be occurring. I think you have to keep an open mind and not rule them out. There may well be several mechanisms at work heating the corona, but if there were only one then reconnection is most likely since it has been shown to be the probable cause of X-ray bright points.

D. Lynden-Bell (*Queen's University, Belfast, UK*). Certainly, magnetohydrodynamic waves are likely to be travelling upwards in the Sun. The question at issue is whether the heating due to their dissipation is the main source of coronal heating or microflaring causes the major heating source via superthermal particles generated at reconnections of the magnetic field. While I am a believer in reconnection as the major source, there is no doubt that wave heating does occur too.

L. Harra. I agree that wave heating also must occur. However, most of the observational evidence tends towards small-scale reconnection events as the dominant source of heating.