Observations of the Variability of Coronal Bright Points by the Soft X-Ray Telescope on Yohkoh

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Abstract

We present the initial results of a study of X-ray bright points (XBPs) made with data from the Yohkoh Soft X-ray Telescope. High temporal and spatial resolution observations of several XBPs illustrate their intensity variability over a wide variety of time scales from a few minutes to hours as well as rapid changes in their morphology. Several XBPs produced flares during their lifetime. These XBP flares often involve magnetic loops, which are considerably larger than the XBP itself, and which brighten along their lengths at speeds of up to 1100 km s$^{-1}$. We speculate on the origin of the XBP variability and flares.

Key words: Sun: corona — Sun: flares — Sun: X-rays — X-ray bright points

1. Introduction

X-ray bright points (XBPs) were first observed by a rocket-borne grazing-incidence soft X-ray telescope (van Speybroeck et al. 1970) and extensively studied by Skylab (Golub et al. 1974, 1976, 1977). Until Yohkoh was launched in 1991 August, only a few sounding rockets have sampled the XBP population on the Sun.

Our current view of the origin, structure, and evolution of XBPs comes from studies of the Skylab data. Golub et al. (1974) first pointed out the occurrence of flares in XBPs in $\leq 10\%$ of these structures. Nolte et al. (1979) observed impulsive ($\leq 5$ min) brightenings and rapid decays in a small sample of XBPs with 90-s time resolution data. They suggested that the fluctuations were driven by episodic heating superimposed upon a continuous input of energy. Webb (1981) showed a light curve of an XBP that included a large flare. Habbal and Withbroe (1981) found more rapid and larger-amplitude variations in EUV lines formed in the chromosphere, transition region, and lower corona than had been noted in soft X-rays. The largest fluctuations were seen in the C II data. The link between XBPs, He I 10830 dark structures, and small-scale magnetic bipoles has been established from the comparison of these earlier X-ray or radio data with ground-based optical observations using He I 10830 or magnetograms (Harvey et al. 1974; Harvey 1985). We adopt the somewhat arbitrary definition of an XBP, based on the Skylab studies (Webb 1981), as being an area of enhanced emission no larger than 1' in diameter and with a lifetime of up to 48 hr.

The Soft X-ray Telescope (SXT) on Yohkoh offers a unique opportunity to study XBPs over an extended period at high spatial and temporal resolution. The SXT has a larger linear dynamic range than the earlier film-based instruments owing to the unique shutter/filter/CCD combination and low-scatter mirror (Tsuneta et al. 1991). Improvements in data access through rapid digital data processing, interactive software, and large-volume on-line storage media make the SXT data, with the more extensive supporting ground-based images that are currently available, an ideal new tool for studying XBPs.

2. Observations and Results

During nonflaring times the SXT takes full-Sun full-frame images (FFIs), typically at a rate of one every 128 s. In this study we will use only the FFIs which
Fig. 1. The evolution of the four XBPs marked by the arrows in the initial frame. The intensity variations shown on the right are derived by summing the signal in a box surrounding the XBP core and including all of the enhanced emission, excluding that of the large scale structures seen during flares. The individual image frames are 128 x 128 half resolution (~5") pixels or about 460,000 km.

consist of either 512 x 512 half-resolution (5") pixels or 256 x 256 quarter-resolution (10") pixels using the Al 1400 Å filter. The SXT typically takes images at three different exposure durations to extend the dynamic range: for example, 15.108, 2.668, and 0.078 s in half-resolution mode. This gives it an effective dynamic range of about 200,000. With thousands of examples of XBPs in the current Yohkoh data archive to choose from, we describe here mainly the data from 1992 February because it is the most complete available and the Sun was rather quiet, so there are few interruptions of the FFI observations by flares.

Figure 1 illustrates the evolution of four XBPs that show different types of intensity variations and struc-
Coronal Bright Points

3. Discussion

The Yohkoh data provide an opportunity to delve more deeply into XBP phenomena than has been possible to date and to determine their connection to the large-scale magnetic field structure. The SXT data already have shown that rapid, large-amplitude fluctuations are a common property of XBPs as seen in soft X-rays. The amplitude variations are more in agreement with the EUV results of Habbal and Withbroe (1981) than with the soft X-ray results from Skylab. The original EUV/X-ray discrepancy may be a selection effect overcome by the higher cadence of Yohkoh, which is better able to sample the fluctuations. However, it is possible that the XBs observed by SXT during the current more active phase of the solar cycle do not have the same properties as those observed by Skylab. The fluctuations observed by SXT are typically 30 to 200% of the slowly varying component of the XBP flux. The SXT time resolution in this mode of operation is insufficient to exclude the possibility that the slowly varying baseline signal is itself made up of even shorter-duration fluctuations.

The SXT data also show that XBPs tend to produce small flares with an intensity increase of between one and two orders of magnitude, but we have investigated too few examples of these to be able to conclude that they...
are fundamentally different phenomena from the lower-level fluctuations. Several flaring XBP\textsc{s} appear only for a single frame, implying a lifetime of a few minutes at most. While some of these could be short-lived XBP, it seems likely that most are flares in XBP\textsc{s} which are normally too faint to be detected by SXT.

It seems most significant that XBP flares usually involve not only a large increase in the area and integrated flux of the XBP, but also a corresponding increase in the brightness of a long, nearby loop, implying the involvement of the ambient field in the process. Following such a flare, the XBP either disappears rapidly or is much...
reduced in its X-ray output, indicating that something fundamental has changed in the structure and/or heating process of the XBP. An interesting question remains to be answered, namely whether these XBP flares are the same phenomenon as the microflares observed in hard X-rays, UV, and radio wavelengths (Lin et al. 1984; Porter et al. 1987). Whether this increase in intensity in the XBP and large loop structure reflects an increase in emission measure (density or emitting volume) or an increase in the X-ray emissivity as a result of an increase in temperature or a combination of the two may be answered following a more detailed examination of the SXT calibration.

The large-scale loops that brighten as a result of the XBP flare could be filled by hot, dense plasma that originates within the small XBP loop or plasma produced from the energy released in the reconnection process forced by the collision of opposing field lines as new magnetic flux emerges or moves to interact with the existing coronal fields. Similarly, they could represent the propagation of a conduction front or some other heating phenomena such as plasma waves or particles. The velocity of the brightening may be a clue to which of these it could be. Typically, we see velocities in the range of a few hundred to just over 1000 km s$^{-1}$. These velocities are generally lower limits, as we are measuring only the translational velocity and not the full-velocity vector.

3.1. Waves and Particles

Plasma waves would propagate with the Alfvén velocity, $v_A$, which is given by:

$$v_A = 2.8 \times 10^{11} B n_e^{0.5}$$

where $B$ is the strength of the magnetic field and $n_e$ is the electron density. In the quiet corona, the electron density is likely to be low ($\leq 10^6$ cm$^{-3}$) and $B$ is likely to be only a few gauss (e.g., $\leq 5$ G), which would give a velocity of $\leq 1400$ km s$^{-1}$. While this is consistent with the observed motions in the loops, there remains the difficulty of dissipating the energy that they might carry under these conditions. Alternatively, particles accelerated in the XBP flare would traverse the loop in a few seconds and be absorbed into the cool, dense chromosphere at the far end. They would not produce significant brightening along the length of the loop unless the large-scale loop was very dense, in which case it should be plainly visible in soft X-rays before the flare, which it is not.

3.2. Conduction Fronts

Brown et al. (1979) and Smith and Lilliequist (1979) investigated the properties of a conduction front and showed that its propagation rate is the sound speed, $c_s$, given by:

$$c_s = 0.166 T^{0.5}$$

where $T$ is the electron temperature. This expression was used by Batchelor et al. (1985) to show that conduction fronts were a viable alternative to the chromospheric evaporation model for large flares, where high temperatures could be assumed and much lower velocities were required. However, for XBPs the temperature is lower (about 1.8 MK, Little and Krieger 1977) and the velocities are significantly higher than seen in most flares. Using this value for $T$ would give a propagation speed of about 220 km s$^{-1}$, which is clearly inconsistent with the velocities that are seen in these flaring XBP events. Even if the temperature is higher, it would have to approach 50 MK to produce velocities over 1000 km s$^{-1}$, which is clearly impractical for XBPs.

3.3. Plasma Flows

Is it possible that a plasma expanding along a loop can attain the velocities observed in the XBP flares? In such a situation the hotter and denser plasma in the XBP loop is released into the large-scale loop as they reconnect. For an adiabatically expanding plasma moving in a simple one-dimensional flow the velocity, $v$, is given by:

$$v = 3c_s[1 - (p_e/p_0)^{1/5}]$$

where $p_e$ and $p_0$ are the plasma pressures of the large-scale and XBP loops, respectively. For a large-scale loop where the initial pressure is negligible (i.e., $p_e = 0$) the maximum velocity is $3c_s$, and if $T = 1.8$ MK then the maximum velocity is about 650 km s$^{-1}$. If there is any significant plasma pressure in the large-scale loop, this velocity would be reduced further, becoming arbitrarily small as $p_e$ approaches $p_0$. It should be remembered that these enhanced loops are created as a result of a flare in the XBP, and so the temperature is likely to be considerably higher. For example, if $T = 5$ MK, the flow velocity would be over 1100 km s$^{-1}$, i.e., consistent with the fastest flows measured to date.

Some of the short-lived XBPs do not seem to be the result of a flare at the XBP site itself but, rather, reflect the impact of such a flow or propagating front at a remote site. Thus, we might be seeing the effects of the plasma flowing along closed field lines and impacting the steep temperature and density gradient of the transition region at the footpoint at the far end of the loop. This would compact the plasma, increasing the emission measure, and thermalize the kinetic energy of the flow, increasing the plasma temperature; consequently a flarelike event would be produced. The dense, cool region where this energy is released would aid the rapid dissipation of the energy by both conduction and radiation, explaining the rapid decay of such events.
4. Conclusions

From this study of XBPs, we conclude:

1. The longer-lived XBPs exhibit significant fluctuations on time scales of minutes to hours, which does not alter the overall structure or radiant energy from the XBP. It is possible that the "steady-state" component of XBPs is made up of many such short-term fluctuations.

2. Occasionally XBPs flare, producing an increase in X-ray flux of over an order of magnitude. Such events result in a reduction or elimination of the heating in the region.

3. A major new result is that substantial XBP flares are associated with the enhancement of larger-scale structures connected with the XBP, lending considerable weight to the idea that the fluctuations in XBP intensity are due to magnetic reconnection of emerging flux with the ambient coronal fields. The degree to which we see interconnections and communication between different coronal structures has been one of the most surprising aspects of Yohkoh so far.

4. The magnitude of the inferred velocities strongly supports the notion that the large-scale structure is being filled by a flow of hot, dense plasma and not by the propagation of a conduction front. However, we can not exclude plasma waves or compressional mechanisms.

5. We have found a new type of XBP, one that is transitory and possibly caused by the impact of a plasma flow or a propagating front at a remote site.

With a life expectancy of several years, Yohkoh should be able to follow the changes in the numbers, distribution, and nature of XBPs as a function of the phase of the solar cycle. A detailed comparison of the temperature response of the SXT compared with that of Skylab remains to be completed before we can draw more detailed comparisons. We hope to use the high-time resolution modes of SXT to look at the variability of XBPs at 10 times the cadence that has been possible to date. SXT data should enable us to understand the true nature of these "simple" objects, which, in turn, may give us some clues to understanding the far more complex processes involving magnetic flux emergence and reconnection occurring on a larger scale in active regions and flares.

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