The Solar Flare of 1992 August 17 23:58 UT

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Abstract

A small flare (C4.3 in the GOES X-ray class) was well observed by all of the instruments on board Yohkoh. The X-ray light curves have double peaks which are about 5 min apart. Until the first peak from flare onset, four compact areas brighten up in the soft X-ray region, which are aligned almost on one straight line. We regard them as being footpoints of two sets of loops, which are identifiable in soft X-ray images, since their locations match those of hard X-ray sources. Indeed, after the second peak, the temporal behavior of the temperature and emission measure at each point is consistent with the existence of two such loops. Comparing our results with recent MHD simulations, we propose a possible scenario for this flare that is based on the coalescence of two loops.

Key words: Sun: corona — Sun: flares — Sun: magnetic fields — Sun: X-rays

1. Introduction

Solar flares sometime show quasi-periodic oscillations at high energies. Their best example is the 1980 June 7 flare, in which a quasi-periodicity appeared in the hard X-ray and γ-ray light curves (Chupp 1983; Forrest, Chupp 1983; Nakajima et al. 1983; Kiplinger et al. 1983). Another example of quasi-periodic oscillations is seen in the hard X-ray and microwave (17 Ghz) time profiles of the 1982 November 26 flare (Tajima et al. 1987). These flares appear to be consistent with an interpretation that a flare is excited by quasi-periodical collisions of two current loops, which would finally coalesce after several collisions (Sakai, Ohsawa 1987). However, since these arguments have been based purely on non-imaging observations, it is important to compare the plasma parameters obtained from spectroscopic observations with morphological information from simultaneous imaging observations.

In this paper, we present an analysis of the X-ray data for a flare which has double-peaked intensity time profiles. The flare of 1992 August 17 23:58 UT was well observed by all of the instruments on board Yohkoh (Ogawara et al. 1991), i.e. the Hard X-ray Telescope (HXT) (Kosugi et al. 1991), Soft X-ray Telescope (SXT) (Tsuneta et al. 1991), Wide Band Spectrometer (WBS) (Yoshimori et al. 1991), and Bragg Crystal Spectrometer (BCS) (Culhane et al. 1991). The soft X-ray images reveal highly localized emissions at four areas that are aligned on a straight line. This flare was also observed by the magnetograph of the Solar Flare Telescope (SFT) at the National Astronomical Observatory, Mitaka (Ichimoto et al. 1991). Although the location of the flare (N19W01) is not suitable for studying the height structure, it allows the magnetogram to place the polarity dividing lines unaffected by the projection effect.

In the following we discuss the loop configuration of this flare and a possibility that magnetic interactions of two parallel loops triggered it.
2. Observations

Yohkoh observed the flare from 1992 August 17 23:58 UT to August 18 00:16 UT in which most SXT images of the flare were taken in the 2.5' x 2.5' field of view with three X-ray filters (Be 119 μm, Al 12 μm, and Al 0.1 μm) and an optical filter. The pixel resolution is 2''45 and the time resolution is 2 s.

HXT images are synthesized using the maximum entropy method (MEM). Although the time resolution of the raw data is 0.5 s, in order to ensure adequate counting statistics we selected intervals 6–8 s long. Maps with a good signal-to-noise ratio were obtained only in the Low-band (14–23 keV). The angular resolution is about 5''.

BCS employs bent germanium crystals and has four channels for different ions. Here, we concentrate on data from one channel that observes the line spectra of He-like Fe XXV ions. The wavelength resolution is 0.53 mA and the full time resolution is 3 s. The field of view is about the solar full disk. Spectra averaged over 60 s intervals are used for a better determination of plasma parameters.

SXS, which is one instrument of WBS, is a xenon-gas proportional counter with a time resolution of 0.25 s for pulse-count data of two energy bands: 2 to 15 keV and 15 to 30 keV.

SFT simultaneously observes the Fe I 6337 Å and 6303 Å lines with Lyot filters and polarizers in order to measure the photospheric velocity and magnetic fields. The field of view is 7.3' x 5.5' and the pixel resolution is about 1''35. The magnetogram used in this paper was obtained on August 18 between 01:50:15 and 01:51:21 UT.

2.1. X-Ray Light Curves

X-ray light curves are shown in figure 1. The upper panel comes from the 2–15 keV channel of SXS, whereas the middle panel shows a light curve from the Low-band (14–23 keV) of the HXT. For a reference, the GOES light curve (0.5–4.0 Å) is shown in the lower panel. The SXS counting rate started increasing at 23:57 UT; the level was then about fifty-times the quiescent level at 00:00 UT. The SXS light curve had double peaks at 00:00 UT and 00:05 UT. The HXT light curve also had double peaks at 23:58 UT and 00:05 UT. Such a double-peak nature of temporal variations is also recognized in the GOES data. There is a delay of 2 min in the first SXS peak with respect to the HXT counterpart. This delay may reflect the time for a non-thermal plasma to be thermalized.

2.2. SXT Images

Figure 2 (Plate 25) shows a time series of SXT images taken in a Be 119 μm filter. Each image is scaled to its maximum intensity. Four areas brightened in a straight line from northeast to southwest at 23:58:46 UT. We call these four areas as Points 1, 2, 3, and 4, counting from top to bottom. They are gradually replaced by loop emissions. For example, images after 23:59 UT reveal a bright loop connecting Points 2 and 3.

The only available preflare SXT image (23:56:10 UT) shows that a loop connecting Points 2 and 3 is already bright about 2 min before the impulsive phase of the flare [figure 3 (Plate 26)]. The upper three images in figure 2 (Plate 25) also show a southward shift of the brightest part of this loop. Note that the second peak in the light curves at 00:05 UT was seen most prominently at Point 1.

We have tried various ways to scale the images in order to obtain a better idea of the connectivity of other emission patches, i.e. Points 1 and 4. Figure 4 (Plate 27) is another sequence of SXT images (in Al 12 μm filter) displayed in the logarithmic scale. These images are suggestive of a connection between Points 1 and 4, especially well after the impulsive phase.
2.3. Comparison between SXT and HXT Images

In figure 5 (Plate 28) we show an HXT image of 23:58:44-23:58:50 UT as a contour map superimposed on the simultaneous SXT image. We coaligned two images, using the method of Masuda (1994) which has an accuracy of about 1". The two images are remarkably similar, except that the hard X-ray image suggests an additional source between Points 3 and 4. Based on this similarity, we regard the four soft X-ray bright points as being footpoints. A similar example of soft X-ray emission from footpoints has been reported by Hudson et al. (1994). Unlike the flare described by Hudson et al., the present flare lacks a sharp increase in soft X-ray brightness at the footpoints simultaneously with the hard X-ray spikes during the early phase. This is probably because we observe the flare face-on and what appears to be footpoints may be contaminated with loop emission of a thermalized plasma.

2.4. Co-alignment between SXT Images and a Magnetogram

Unfortunately, no simultaneous magnetogram is available. The magnetogram closest in time to the flare is that obtained by SFT on August 18 01:50 UT. Using the well-known relationship between SXT X-rays and white-light images, we are able to coalign an early soft X-ray image on the magnetogram [figure 6 (Plate 29)].

It is found that Point 1 and Point 2 have an N-polarity, and that Point 3 and Point 4 have an S-polarity. A magnetic neutral line runs between Point 2 and Point 3, which is consistent with the existence of two sets of loops, as shown in subsection 2.2. Since Point 4 is in the penumbra of the nearby sun spot, the magnetic field around Point 4 is considered to be stronger than the other points.

2.5. BCS Spectra

In figure 7, from top to bottom we show the count rate in the Fe XXV channel, the electron temperature, the emission measure, and the turbulent velocity derived from the Fe XXV spectra. The parameters were unavailable before 23:58:36 UT due to noise. In the early phase of the flare, during which four soft and hard X-ray sources and another hard X-ray source between Points 3 and 4 can be seen, the electron temperature and turbulent velocity have maximum values. They then decrease, while the intensity and emission measure gradually increase as a loop brightened up between Points 2 and 3 on the SXT images. Both the intensity and emission measure have maximum values at around 00:00 UT. As expected, the intensity had double peaks, like SXS light curves, at about 00:00 UT and 00:05 UT. Note that the temperature has a small hump at around the time of the second peak (00:05 UT).

3. Discussion

3.1. Thermal Evolution in the Flare Decay Phase

Using the ratio of the SXT images in Be 119 μm and Al 12 μm filters, we obtained temperatures and emission measures at the four bright areas. In order to improve the signal-to-noise ratio we averaged the intensity over a unit-area, defined as 3 x 3 pixels centered at each area. Figure 8 shows a scatter diagram of the emission measure vs electron temperature at four points. It is easily seen that the trajectories of Point 1 (2) and those of Point 4 (3) almost overlap with each other in the decay phase of the flare (00:08-00:16 UT). We thus regard the behavior of the emission measure vs electron temperature of Points 2 and 3 as belonging to one group and that of Points 1 and 4 as belonging to another group. Let us denote the emission measure of Points 2 and 3 in the
decay phase $EM_{23}$ [cm$^{-3}$/unit-area], and of Points 1 and 4 $EM_{14}$ [cm$^{-3}$/unit-area]. Because of evaporation, we believe that in the decay phase the parameters obtained at a footpoint also represent those at the loop top.

For each of the groups of Points (2, 3) and Points (1, 4) we find a good fit to the data points that were taken in the decay phase, assuming that the emission measure is proportional to the fourth power of the electron temperature. We obtain the following relations:

$$EM_{23} = 1.6 \times 10^{20} T^4$$  \hspace{1cm} (1)

and

$$EM_{14} = 6.1 \times 10^{19} T^4.$$  \hspace{1cm} (2)

where $T$ is the electron temperature in unit of K. The ratio of $EM_{23}/EM_{14}$ at a given temperature is found to be 2.7. Based on the SXT image taken at 23:58:46 UT, the distance between Points 2 and 3 ($L_{23}$) is $1.8 \times 10^{6}$ cm, whereas the distance between Points 1 and 4 ($L_{14}$) is $5.0 \times 10^{8}$ cm, and their ratio ($L_{14}/L_{23}$) is 2.8. Therefore, the ratio of the emission measure is comparable to that of the loop length, resulting in the relation

$$\frac{EM_{23}}{EM_{14}} \sim \frac{L_{14}}{L_{23}}.$$  \hspace{1cm} (3)

Finally, the following formula is obtained from equations (1), (2), and (3):

$$T^4 \propto EM \cdot L.$$  \hspace{1cm} (4)

Base on the assumption of a constant heat input per unit volume along the loop, Rosner, Tucker, and Vaiana (1978) derived the famous scaling law for coronal loops,

$$T \sim 1.4 \times 10^3 (pl)^{\frac{1}{3}}.$$  \hspace{1cm} (5)

where $T$ [K], $p$ [dyn cm$^{-2}$], and $l$ [cm] are the maximum temperature at the loop top, the constant loop pressure, and the semi-loop length, respectively. We find that the scaling law (5) leads to relation (4) for a circular loop with a constant cross-section, as long as the loop width is proportional to the separation of the footpoints. Therefore, the result of our fit to the scatter diagram strongly suggests two connections in the decay phase: Points 2–3 and Points 1–4.

We can estimate the magnetic energy using the SFT magnetogram. The photospheric magnetic-field strength at the four foot points is about 10$^5$ Gauss. The magnetic-field strength in the corona may not be much different from that in the photosphere, since the width of the loops is found to be nearly constant in the SXT.
images (Klimchuk et al. 1992). In our case, the loop radius is $\sim 3 \times 10^8$ cm for both loops. If a circular-shaped loop is assumed, the volumes of the loops 2–3 and 1–4 are $V_{23} \sim 1 \times 10^{27}$ cm$^3$ and $V_{14} \sim 3 \times 10^{27}$ cm$^3$, respectively, and the total volume of the two loops is $V \sim 4 \times 10^{27}$ cm$^3$. Therefore, the total magnetic energy of the loops amounts to $\sim 10^{30}$ erg.

Using the electron temperature, $\log T_e$ [K] = 6.95, and emission measure, $\log EM$ [cm$^{-3}$] = 49.05, at 00:05 UT, which are derived from the SXT filter ratio method, the total thermal energy is estimated to be $3 N_e k T_e V \sim 10^{29}$ erg, where $N_e = \sqrt{EM/V}$ ($\sim 5 \times 10^{10}$ cm$^{-3}$), $k$ is Boltzmann constant. It follows that the magnetic field of the loops is capable of providing the entire energy used for heating the soft X-ray thermal plasma of the flare.

### 3.2. Magnetic Loop Interaction

Based on these observations, a hypothetical scenario of this flare could be as follows. At 23:58 UT, the first collision between the two loops occurred. The non-thermal electrons were accelerated and hit the chromosphere. As a result, four foot-points of the two loops brightened in both the SXT and HXT images. HXT observed an additional hard X-ray source (14 keV–23 keV) between Points 3 and 4, which may correspond to the interaction region of the two loops. Thus, the shape of the Points 1–4 loop is thought to be very sheared.

The second collision of the two loops took place at around 00:05 UT, creating the second peak in the light curves. Because the emission measure of Point 1 was about half that of Points 2 or 3 just before the second peak, its brightness increased more prominently than Points 2 and 3. We also speculate that the magnetic field of Point 1 gradually weakened after the first collision, while the magnetic field at Point 4 did not change during the two collisions due to the stronger magnetic field of the penumbra. Note that the magnetic field of Point 4 was also two or three times as much as that of Point 1 (about 200 Gauss) based on the SFT magnetogram. Thus, more than at Point 4, non-thermal electrons produced in the second collision precipitate at Point 1, resulting in the observed contrast between Points 1 and 4 at 00:05 UT.

Theoretical simulations (Charmeixvili et al. 1993; Zhao et al. 1993) support this view of the flare. These simulations are based on the collision of two parallel loops (I-type reconnection). The SXT images suggest that their two loops are approximately parallel with each other. The simulations show that the time interval between the two peaks is $3 \tau_1$, where $\tau_1$ is the Alfvén transit time. The length of the interaction region may be approximated by the sum of the thickness of each loop, and it is estimated to be $1.5 \times 10^9$ cm in the SXT image. Assuming an $\alpha$ ratio of 0.1 of the magnetic-field for the current flowing in the magnetic flux tube to the magnetic field strength along the loop, the combination of an electron density on the order of $10^{10}$ cm$^{-3}$ as discussed above, and a magnetic-field strength of 100 Gauss along the loop (from the magnetogram), the Alfvén transit time is estimated to be 68 s, and hence a collision time interval of 3.4 min. This is consistent with the interval of the two peaks in the X-ray light curves and time profiles of the electron temperature. The simulations by Zhao et al. (1993), using the same set of parameters ($\alpha$ and 100 Gauss), show that particles can be accelerated to about 30 keV within a second in the magnetic reconnection region and that a thermal plasma up to $10^8$ K can be produced in parallel-loop collisions. It is noted that the highest electron temperature ($\log T_e$ [K] $\sim 7.1$) is obtained in the area between Points 3 and 4 in the SXT images [figure 2 (Plate 25)], where an additional hard X-ray source (14 keV–23 keV) is also seen in the HXT image at 23:58:44.

### 3.3. Configuration of the Flaring Loops

An understanding of the loop configuration is essential for identifying the trigger mechanism of this interesting flare observed close to the disk center. The key observational facts to be explained are that four distinct points in soft X-rays and hard X-rays brightened simultaneously and co-spatially at the onset of a flare, and that the flare had clear and distinct flux enhancements twice in soft and hard X-rays. Those four points are actually considered to be the loop foot points, since they correspond to the hard X-ray sources in the initial phase as well. In addition to them, the energetics of the coronal parts of flaring loops and a comparison with photospheric magnetograms deduce the thermal evolution of flaring loops and the foot point magnetic polarity.

Yokoh found some events of flares triggered by a loop–loop interaction. A similar magnetic configuration in NOAA 7360 is drawn by Hanoka (1996). He shows that the magnetic-field structure in the region causes a recurrence of the loop–loop interactions for producing homologous flares, microflares, and plasma flow. Akioka et al. (1994) show an event on 1992 April 22 03:48 UT in NOAA 7137 as an example of a successive reconnection of compact brightening loops and a preexisting overlying coronal loop. These flares are triggered by the interaction of small and large loops across common magnetic neutral lines. Loop–loop interactions are often observed in X-rays (de Jager et al. 1995) or at visible wavelengths (Smartt et al. 1993), but are rather difficult to be identified on the solar disk because of low contrast of the interacting region. This event is considered to be a good example of two parallel-loop interactions observed near the disk center, though there is no definite evidence for the second collision based on X-ray images.

The connection of Points 2 and 3 is clear, as can be seen
in soft X-ray images during the later phases as well as in
the pre-flare image at 23:56:10 UT in figure 3 (Plate 26).
The magnetic polarity in the photosphere also supports
this idea. Although the overall spatial resolution of the
instruments and their co-alignment lead to a discussion
of the global structure of the flaring loops or bundle of
loops, no fine details nor filamentary structures in those
loops can be discussed.

Regarding the connectivity of Points 1 and 4, the only
supporting evidence is a similarity of the thermal evolu-
tion of these points in the decay phase. Faint loop-like
structures can be traced in soft X-ray images, though an-
other morphological possibility might be that it actually
consisted of three loops connecting Points 1 and 2, 2 and
3, 3 and 4. Options for the involvement of multiple
loops in the flare might not be verified by an argument
concerning the overall spatial resolution. We have less
confidence in the connectivity of Points 1 and 4, since
the supporting evidence is just indirect observational
results.

All of the radio sources from Points 2, 3, and 4 have
the same polarization at 17 GHz (Enome et al. 1994),
and thus an additional interpretation may be required to
explain the radio data consistently with the Yohkoh and
optical observations.

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References

Akioka M., Acton L.W., Hudson H.S. 1994, in X-ray Solar
Physics from Yohkoh, ed Y. Uchida, T. Watanabe, K.
Shibata, H.S. Hudson (Universal Academy Press, Tokyo)
p241

Culhane J.L., Hiei E., Doschek G.A., Cruise A.M., Ogawara
Phys. 136, 89
Phys. 158, 391
Enome S., Nakajima H., Shibusaki K., Nishio M., Takano T.,
Hanaoka Y., Torii C., Shiomi Y. et al. 1994, PASJ 46, L27
Hanaoka Y. 1996, PASJ 48, 275
Hudson H.S., Strong K.T., Zarro D., Inda M., Kosugi T.,
Ichimoto K., Sakurai T., Yamaguchi A., Kumagai K., Nishino
Y., Suematsu Y., Hiei E., Hirayama T. 1991, in Flare
Physics in Solar Activity Maximum 22, Lecture Notes in
Physics 387, ed Y. Uchida, R.C. Canfield, T. Watanabe,
E. Hiei (Springer Verlag, Berlin) p320
Kiplinger A.L., Dennis B.R., Frost K.J., Orwig L.E. 1983,
ApJ 273, 783
Klimchuk A.J., Lemen J.R., Feldman U., Tsuneta S., Uchida
Y. 1992, PASJ L181, 44
Kosugi T., Makishima K., Murakami T., Sakao T., Dotani T.,
Nakajima H., Kosugi T., Kato K., Enome S. 1983, Nature 305,
292
Ogawara Y., Takano T., Kato T., Kosugi T., Tsuneta S.,
Sakai J.-I., Ohsawa Y. 1987, Space Sci. Rev. 46, 113
Tajima T., Sakai J.-I., Nakajima H., Kosugi T., Brunel F.,
Tsuneta S., Acton L., Bruner M., Lemen J., Brown W.,
Phys. 136, 37
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Galactic Structure and Stellar Dynamics


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