FLARES OBSERVED BY THE NORMAL INCIDENCE X-RAY TELESCOPE ON 1989 SEPTEMBER 11

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ABSTRACT

We report observations of two solar flares seen in soft X-rays during a sounding rocket flight of the Normal Incidence X-ray Telescope (NIXT) payload on 1989 September 11. The rocket was launched at the onset of a two-ribbon event which reached a maximum intensity of C5 (GOES classification) slightly before the start of our X-ray observations. The flare in X-rays consists primarily of a single bright loop crossing the neutral line and having its footpoints at the southern ends of the ribbons; this loop accounts for more than two-thirds of the emission and is shown to have an electron density of ~6 × 10^10 cm^-3 at a temperature of ~6 × 10^6 K. However, within the remainder of each of the flare ribbons, we also observe complicated coronal structure which although energetically less important is clearly interacting with the main flare loop. A second event in an active region at the limb began during the flight: its most striking feature is a strong correlation with Hz images taken at the same time, which indicates the coexistence of chromospheric and coronal temperature material in close proximity. We give possible interpretations of this phenomenon as either a sheath of X-ray emitting material surrounding the Hz ejection or as an admixture of hot and cool magnetic flux tubes, each ejecting the material which they contain.

Subject headings: Sun: flares — Sun: X-rays

1. INTRODUCTION

The rocket-borne Normal Incidence X-ray Telescope (NIXT) flew on 1989 September 11 in a mission from which preliminary results were presented in Golub et al. (1990). As described in more detail in Spiller et al. (1990), the NIXT instrument allows high-resolution imaging of coronal features by a photographic camera located at the prime focus of an f/8, 2 m focal length system. The multilayer mirror which is used corresponds to a wavelength of 63.5 Å with a passband of 1.4 Å which includes the spectral lines of Fe xvi (maximum formation temperature 3 × 10^6 K) and Mg x (10^6 K). The rationale for choosing these particular lines as well as an analysis of the temperature response of the instrument is given in Golub, Hartquist, & Quillen (1989) and Golub & Herant (1989).

Without going into details, we wish however to point out that in contrast with grazing incidence instruments (e.g., on Skylab or Solar-A), per unit emission measure the response of the NIXT instrument peaks at 10^6 cm^-3 and then decreases with temperature. However, this is compensated by the increase of emission measure with temperature in most hot coronal loops. The intensity of active regions and flare loops, thus allowing us for the first time to observe both structures simultaneously and therefore to study the interactions between flaring and non-flaring regions in the same image.

One of the primary goals of this flight was to take advantage of the high level of solar activity near solar maximum by attempting to launch during a flare. To this end, the countdown was held at T = 2 minutes in order to wait for a possible flare, while real-time data from the GOES X-ray satellites were monitored. As shown in Figure 1, a rise in the 1–8 Å channel was seen beginning at 16:30 UT; examination of Hz from a telescope available on the launch site showed a flare in progress and the countdown was resumed. The launch took place at 16:35 UT, and the observation sequence began at 16:36 UT. Two flares were observed during the flight. The first was located close to Sun-center and had its X-ray peak (as shown by data from the GOES satellite) just prior to the start of our observations, while the other was situated on the limb and began its impulsive phase toward the end of the flight. These two flares will hereafter be referred to as the disk flare and the limb flare.

NIXT registered 38 photographic exposures of the full Sun with varying sensitivity and time resolution between 16:36:35 and 16:41:45 UT (Table 1). The object of this paper is to present an analysis of both the geometrical structure and the time evolution of these two flares using the NIXT data, and also comparisons with magnetograms, Hz, and GOES X-ray data. Finally, we discuss some of the implications of our observations for models of solar flares in general.

2. THE DISK FLARE

The initial rise of X-rays seen by the GOES satellite (which triggered the decision to launch) occurred at 16:25 UT while the peak intensity took place at 16:31 UT (Fig. 1). The flare classification is C5 and Hz observations put the flare in the two-ribbon category (Fig. 2 [Pl. 8]). A longitudinal magnetogram obtained by the National Solar Observatory (Kitt Peak) at 14:41 UT (Fig. 2) shows that the flaring area corresponds to a comparatively weak magnetic region; this is commensurate with the relative weakness of this flare in comparison with other events which occurred during the same day.

Because no transverse field data are available for this region, we cannot investigate a possible departure from potential field configuration which would have led to storage of magnetic energy in the corona. Big Bear Solar Observatory obtained a
Fig. 2.—Disk flare images: (a) X-ray, 63.5 Å, 16:37:50 UT (NIXT rocket), (b) magnetogram, 14:41 UT (NSO), (c) and (d) Hz 16:25 UT and 16:35 UT (USAF photograph, Holloman Solar Observatory). All images are coaligned.

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sequence of magnetograms before and after the flare in which no changes are apparent, therefore probably eliminating emerging flux as a possible trigger to the flare.

2.1. Morphology and Time Evolution

Most of the X-ray emission comes from a single loop connecting the southern parts of the two Hα ribbons; this loop also links the strongest opposite polarities of the region (Fig. 2). The spatial dimensions of the loop consist of a thickness of ~6000 km and a footpoint separation of ~23,000 km. As far as it is possible to estimate projection effects, the loop seems to assume the shape of a half doughnut. The total volume of the loop is then $V \sim 10^{27}$ cm$^3$. We do not detect any significant change in either the morphology or the intensity of the X-ray emission from this loop at any time scale for which we have data: blink comparisons of the main loop using a series of one second images as well as the 30 s and 1 minute exposures show remarkably little variation. The absence of fine structure and of variability in the loop probably indicates that not only has the flare energy input ended, but also that, 15 minutes after the impulsive phase, the loop has had the time to relax to a state of thermal quasi-equilibrium.

Complicated structure is visible in X-rays to the north of the main loop. Figure 3 is a composite drawing in which we indicate the location of this structure relative to the Hα and magnetic features of the region. Note that small X-ray loops lie within each ribbon, but careful examination of the magnetogram shows that they connect small regions of opposite polarity. The ratio of intensities between the main loop and

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<tr>
<th>Exposure Numbers</th>
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<tr>
<td>1-2</td>
<td>10</td>
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<td>3-7</td>
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<td>8-10</td>
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<td>38</td>
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Notes. Exposures 1–7 are on high-sensitivity, medium-resolution film (2′′). Exposures 8–38 are on medium-sensitivity, high-resolution film (0′′/8). One second is spent between each exposure to advance the film.
secondary loops is ~2, which corresponds to a fairly large difference in temperature and density when one takes into account the flattened response of the NIXT instrument (see § 1). However, the secondary loops are still ~5 times brighter than the strongest "normal" active region loops. This shows without ambiguity that they are somehow participating in the flaring process.

A time sequence of Hz images shows that at the beginning of the flare, the ribbon structure is of a complexity comparable to that seen in X-rays. At 16:25 UT, the eastern ribbon is forked toward the north, while the western ribbon is actually made up of two very close parallel features (Fig. 2). As the flare progresses, all these features merge to form two ribbons, and after 16:35 UT, the Hz aspect of the region stops changing almost completely except for a gradual dimming. Similarly, the NIXT images do not show any changes in the X-ray structures north of the flare.

It is somewhat unfortunate that the start of our X-ray observations nearly coincided with the end of the dynamical phase in Hz. However, there are several points worth noting in the data available to us. First, the initial Hz bright spots did not occur at the location of the footpoints of the main X-ray loop (see Fig. 2 for the Hz evolution). Second, the progression of the Hz brightenings affects what appear on the magnetogram and the soft X-ray images to be distinct coronal loops. Third, all the loops which belong to the local magnetic region (i.e., all the loops connected to the white polarity in Fig. 2) are affected. Fourth, the Hz event starts before the GOES satellites register an increased count rate.

All these points tend to show that the time evolution of the disk flare is the result of a complicated sequence of triggering and propagation of magnetic disturbances. The initial trigger of the event, probably an instability in a minor loop, appears to be distinct from the main site of energy release in the brightest loop. This would explain the lack of spatial coincidence between initial Hz brightenings and the main loop footpoints. Further, it would also explain the time delay between Hz and GOES detections of the flare. Our lack of spatially resolved X-ray observations of the flare prevents us from determining the propagation mechanism, but we can rule out heat conduction and beams since they are inefficient across magnetic field lines. This leaves the possibility of compressional Alfvén shocks or magnetic instabilities triggered by changes in the neighboring field structure.

### 2.2. Temperature and Density

As described in detail by Thomas, Starr, & Crannell (1985), data from the GOES satellites can be used to calculate flare temperature and total emission measure. Because the GOES satellites integrate flux over the whole solar disk, it is difficult to discriminate between limb flare and disk flare contributions. Reliable values can therefore only be obtained for the beginning of the event when the limb flare is not yet a factor. At 16:36 UT, the temperature of the flaring loop is estimated to be $T = 5.9 \pm 0.3 \times 10^6 \text{K}$ and the total emission measure to be $EM = 5.5 \pm 1.0 \times 10^{48} \text{cm}^{-3}$. The uncertainties were obtained by comparison of estimates derived from the GOES 7 satellite versus the GOES 6 satellite. If we use the volume estimate obtained in § 2.1, we obtain the average electron density: $n_e = (EM/V)^{1/2} = 7 \times 10^{10} \text{cm}^{-3}$.

Despite the fact that the NIXT instrument was primarily designed for imaging purposes, it has the capability to give reasonable estimates of intensities. This is done by measuring photographic densities in regions of interest on the flight film and matching to a calibrated curve of energy versus density. We have determined in this manner that the energy flux at the focal plane of NIXT in the flare region was $0.3 \pm 0.1 \text{ergs s}^{-1} \text{cm}^{-2}$. The rather large error bracket is due mainly to uncertainties in the film response function. This flux is approximately constant (less than 30% variation) along the main flare loop (Fig. 2).

For the optical parameters appropriate to the NIXT instrument (200 cm focal length, 15 cm² effective collecting area with 7% overall transmission of the filters; Spiller & Golub 1989) this corresponds to a coronal intensity: $I_{\text{NIXT}} = 1.6 \pm 0.5 \times 10^3 \text{ergs s}^{-1} \text{cm}^{-2}$. Contributions to this brightness include bremsstrahlung emission, free-bound emission, and line emission. The plasma is optically thin.

Rybicki & Lightman (1979) give the emission for thermal bremsstrahlung:

$$\frac{dW}{dV dt dv} = 6.8 \times 10^{-38} Z^2 n_e n_i T^{-1/2} e^{-h\nu/kT} \times G_{\text{ff}} \text{ergs s}^{-1} \text{cm}^{-3} \text{Hz}^{-1}. $$

Integrating along the line of sight and across the passband of NIXT:

$$I_{\text{NIXT}}^{\text{brems}} = 6.8 \times 10^{-26} \left(\frac{10^6 \text{K}}{T}\right)^{1/2} \exp \left[-2.3\left(\frac{10^6 \text{K}}{T}\right)\right] \times \frac{Z^2 n_e n_i G_{\text{ff}}}{\text{ergs s}^{-1} \text{cm}^{-2}},$$

where we have used the fact that the multilayer mirror used by NIXT has an effective passband width of $\Delta \nu = 1.0 \times 10^{15} \text{s}^{-1}$ (Δλ = 1.4 Å) centered at $\nu_0 = 4.7 \times 10^{16} \text{s}^{-1}$ ($\lambda_0 = 63.5 \mu\text{m}$). We then assume that the loop temperature and density are close to uniform so that it is possible to take the temperature $T$ and densities $n_e, n_i$ out of the integrand. This is a reasonable assumption within the context of our ~30% estimate, and takes into account the efficiency of thermal conduction along the magnetic field and the fact that the uniformity of the overall loop brightness should indicate fairly homogeneous conditions. We then obtain:

$$I_{\text{NIXT}}^{\text{brems}} = 1.6 \times 10^{-25} n_i^2 \left(\frac{10^6 \text{K}}{T}\right)^{1/2} \exp \left[-2.3\left(\frac{10^6 \text{K}}{T}\right)\right] \times L \text{ergs s}^{-1} \text{cm}^{-2},$$

where the Gaunt factor $G_{\text{ff}}$ was averaged to 1.2 (Rybicki & Lightman 1979), $Z^2$ was averaged to 2, and $n_i^2$ substituted for $n_i, n_i^2, L$ is the line-of-sight thickness of the loop.

Bound-free emission is generally negligible (Landini & Montignori Fossi 1990). However, line emission may not be negligible, depending on whose emission calculation we use. Raymond & Smith (1977; see also Raymond 1988) compute the line emission of Fe xvi at $5.9 \times 10^6 \text{K}$ to be log $P/n_i^2 = -25.26$, where $P$ is the power emitted per unit volume in cgs. Similarly, for Mg x, Raymond & Smith give log $P/n_i^2 = -25.49$. Since the line widths are much smaller than the NIXT passband this yields the following contribution to the brightness:

$$I_{\text{NIXT}}^{\text{Mg x}} = 8 \times 10^{-26} n_i^2 \times L \text{ergs s}^{-1} \text{cm}^{-2},$$

where we have folded in a factor of 0.9 corresponding to the wavelength offset of the lines from the peak response of our multilayer primary mirror.
Computations by Landini & Monsignori Fossi (1990) give much smaller values: \( \log (P/n_e^2) = -26.37 \) for Fe xvi and \( \log (P/n_e^2) = -25.89 \) for Mg x. These lead to contributions which are negligible (at our level of approximation) compared to the bremsstrahlung emission.

Since we would like a conservative estimate of the electron density, we have used the Raymond and Smith data as an upper limit to the line emission. For \( T = 6 \times 10^6 \) K we then obtain a total

\[
I_{\text{NXT}} = 1.2 \times 10^{-25} n_e^2 \times L \text{ ergs s}^{-1} \text{ cm}^{-2}.
\]

This estimate can then be used to get a relation for the electron density:

\[
\frac{n_e}{10^{10} \text{ cm}^{-3}} = 3.8 \left( \frac{10^6 \text{ km}}{L} \right)^{1/2}.
\]

Taking \( L = 6000 \) km, we obtain the electron density for the loop: \( n_e = 5 \times 10^{10} \text{ cm}^{-3} \) which, taking into account the various uncertainties, is in excellent agreement with our first estimate. Also, this confirms that the main loop is energetically dominant when compared to the secondary flare X-ray structure since we have shown that it accounts for most of the GOES X-ray emission.

We have assumed that the lack of spatial and temporal variations in the intensity of the main flare loop is a sign of quasi-uniform pressure and temperature. This is partly justified by the fact that the pressure scale height (for an isothermal atmosphere at \( 6 \times 10^4 \) K) is \( RT/\mu g \sim 10^5 \) km. Conversely, for an adiabatic atmosphere, the corresponding temperature scale height of \( RT/\mu g (\gamma - 1) \sim 2 \times 10^5 \) km. Since these distances are much larger than the height of the loop (10\(^4\) km), one can expect a high degree of uniformity along field lines.

On the other hand, the assumption of homogeneity transverse to the loop is more difficult to justify. An electron density of \( n_e = 6 \times 10^{10} \text{ cm}^{-3} \) corresponds approximately to a molar density \( [n_e] = 2 \times 10^{-12} \text{ mol cm}^{-3} \) with all species confined. This means that the pressure in the loop is \( P = [n_e]RT \sim 50 \text{ dyn cm}^{-2} \). Note that this pressure is in good agreement with flare observations by Bruner (1987), while the fairly large loop diameter adds plausibility to the shell structure proposed in that paper. Measurements of photospheric field strengths yield \( B \sim 200 \) G over areas of size comparable to the cross section of the main flare loop. This implies a magnetic pressure of order 1500 dyn cm\(^{-2}\), much larger than the gas pressure. Therefore, we cannot verify the assumption of transverse homogeneity.

### 3. THE LIMB FLARE

Because the limb flare started during the decay phase of the disk flare, the relevant GOES X-ray data are difficult to interpret. In particular, we cannot derive reliable values for either temperature or total emission measure as we did for the disk flare. The flare can be approximately rated as importance C2, based on extrapolation of the disk flare decay curve under the limb flare peak. Detection by the GOES satellite starts at 16:38 UT (Fig. 1), while in patrol Hx data the event begins at 16:35 UT. Magnetogram data from the previous day, before the region went over the limb, show the area to be very magnetically active. Also notable is a large filament, visible only in overexposed Hx, which is located \( \sim 15,000 \) km above the flaring region (Fig. 4). No changes are apparent in the filament during the flare event.

### 3.1. Morphology and Time Evolution

In both X-ray and Hx the flare starts out as a small spot brightening on the limb, which then extends upward along a curved arch. The velocity of the upward motion is \( \sim 75 \) km \( s^{-1} \), to be compared with a sound speed ranging from \( \sim 5 \) km \( s^{-1} \) in the chromosphere to \( \sim 100 \) km \( s^{-1} \) in the corona. At 16:41 UT, which is the time of our last X-ray images, the surge has extended along a length of 6000 km with a width \( \sim 6000 \) km at its base. At 16:47 UT, the surge has mostly faded away in Hx, remaining clearly visible only on saturated Hx images.

Presumably, by that time all of the ejected material has become so diluted and heated that it stops emitting in Hx.

The Hx and X-ray images were coregistered with great care by lining up the limbs and neighboring features in which we do not observe any time evolution. The alignment of the data set, which should be accurate to the 1" level, clearly demonstrates that the Hx surge lies within the X-ray feature (Figs. 5 & 6 [PI 9–10]). Figure 4 shows the relative location of the principal Hx and X-ray features of the flare. The curvature of the surge is clearly of magnetic origin: it would correspond to a coronal loop of diameter at least 50,000 km. Such giant arches commonly flare at one of their footpoints (Martin & Svestka 1988).

This is not the first observation of the association of X-ray emitting material with an Hx ejection: such events were seen by the HXIS experiment on board the Solar Maximum Mission satellite in conjunction with ground-based observatories; see Svestka, Farnik, & Tang 1990, for a review. However, it is the first time such an event is observed with an X-ray spatial resolution (\( \theta \) at 16° off-axis) comparable to or better than the available Hx images. As a result, we are able to assert that material at a temperature of order \( 10^6 \) K coexists with material at a temperature of order \( 10^9 \) K on very short distance scales.

### 3.2. Discussion

Two questions need to be answered simultaneously: how is chromospheric material suddenly heated up to coronal temperature, and how is cool chromospheric material ejected outward at supersonic velocities? The most natural explanation would have been that some mechanism (e.g., proton beams, magnetic energy release in the chromosphere) heats up material deep in the chromosphere which would then adiabatically expand and push out cooler material above it. However, this explanation is not supported by our observations, which show cooler material to be co-spatial with the X-ray-emitting region. The observations also do not support shock heating, since in that case, hot material would be expected to be located behind the shock front.

Two geometries are possible to explain these observations. The first is a sheath geometry, in which case the rising Hx surge is enveloped by a layer of dense, hot material. In this case the interpretation of the phenomena would be that the ejection of chromospheric material is accompanied by intense heating of the outer layers via some dissipation at a boundary layer. Note that if this were the case, one would expect a greater X-ray intensity at the edges of the surges, due to line-of-sight integration. This we do not observe, although our data are not of such resolution and sensitivity that we can definitively claim that this effect is absent. What makes this scenario appealing is that the presence of thin transition regions between cool chromospheric material and hot coronal material is an omnipresent phenomenon in the solar atmosphere. Further, the dissipation of a bulk velocity of 75 km \( s^{-1} \) into thermal energy yields a temperature close to \( 10^6 \) K, as required by the observations.
Fig. 5.—NIXT images of the limb flare

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Fig. 6.—The limb flare in Hα (USAF photographs, Holloman Solar Observatory)

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The other geometry is one in which the cool component is intimately mixed with the hot component on subarcsecond scales. However, since heat conduction along field lines is efficient in a matter of seconds on a length of order 1", this scenario assumes the existence of hot and cool field lines mingled over very short distances. This is not as unreasonable as it may seem at first: it has long been known that any magnetic energy release in the corona has to take place on extremely short length scales because of the very high conductivity of the plasma. Also, photospheric motions will lead to a tangle of field lines which can be very different at the chromospheric and at the coronal levels, i.e., field lines which are bundled together in the corona may originate in widely diverging locations at the solar surface.

The model we propose is as follows: some energy release takes place in the corona and is channelled down along field lines to many discrete points spread over a wide area of the chromosphere. Explosive chromospheric heating takes place at the bottom of these field lines generating a surge of hot material while also sending compressional Alfvén waves through the chromosphere. Unheated field lines close to the hot field lines are then violently compressed and send upward and downward surges of cool chromospheric material, much in the manner of a toothpaste tube. Naturally, this model can only be validated by further observations, and a theoretical analysis of explosive chromospheric evaporation with a magnetic field. Such an investigation would probably have to be carried out through numerical simulations.

IV. CONCLUSIONS

The observations which are presented in this paper have little statistical significance since "every flare is different." Thus 5 minutes of X-ray data on two flares (three if one counts the one observed in the previous flight of NIXT of 1988 September), can hardly be said to constitute a complete sample. However, our observations raise some puzzling questions. First, the observations of the disk flare show that although there are hints of arcade-like structure, a single loop is responsible for most of the flare X-ray emission within the NIXT passband, as was also the case for the two-ribbon flare observed during the 1988 flight (Herant, Golub, & Neidig 1989). At the same time, both flares showed complicated structures involving connections from near the flare site to more distant regions, albeit at lower intensity than the main flare loop. All this puts some doubt on the validity of the magnetic arcade picture for two-ribbon flares and the translational symmetry along the neutral line which most models assume. It may be that two-ribbon flares are really single loop flares with some transverse energetic spill-over. Our observations also show that Hα and magnetogram data are by themselves misleading for inferring the coronal topology and luminosity, in part because Hα saturates easily. Coronal observations with good spatial resolution are therefore a necessity for a comprehensive picture of flare events.

It is clear that attempts to understand the mechanism of chromospheric evaporation, which by itself is an important diagnostic for the validity of flare theories, require combined...
Our observations of the limb flare bring home the critical importance of achieving the highest possible spatial resolution and good time resolution, in order to understand the internal structure of a flaring loop during the dynamical stage of the event.

We are grateful to Don Neidig and Jack Harvey for making available to us, respectively, Hα and magnetogram images corresponding to the time of our flight. We thank Roger Thomas for temperature and emission measure calculations from the GOES satellites data. We also thank John Raymond for an enlightening discussion. George Nystrom and Janus Wylczynski made major contributions to the development and flight of the NIXT payload. The NIXT program has benefited from the support of Dave Bohlin, Harjit Ahluwalia and Sharad Kane at NASA Headquarters. Funding for the program is provided under NASA grant NAG5-626 to the Smithsonian Institution.

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