HIGH-RESOLUTION X-RAY SPECTRA OF SOLAR FLARES. VII. A LONG-DURATION X-RAY FLARE ASSOCIATED WITH A CORONAL MASS EJECTION

E.O. Hulburt Center for Space Research, Naval Research Laboratory, Washington, DC

Received 1984 March 20; accepted 1984 November 15

ABSTRACT
X-ray spectra from the P78-1 spacecraft are discussed for a long-duration X-ray flare (M8+) that occurred on January 18. The X-ray flare was associated with a large coronal mass ejection that was observed with the white-light coronagraph on P78-1. The X-ray emission region was at least 1'-2' above the solar surface, and extended over an angular distance of as much as 3'. These parameters are not typical for soft X-ray compact flares, which are much smaller and occur in closed-loop structures lower in the solar atmosphere. Emission measures for this flare vary between $10^{48}$ and $10^{49}$ cm$^{-3}$ and are probably larger, since part of the emission may have been occulted by the solar limb. The combination of emission measure and source size implies the existence of small, high-density structures within a considerably larger volume. The November 14 X-ray line profiles exhibit large widths and complicated structure on the red and blue wings. The source size appears to decrease as the flare progresses, and the event increases in height above the limb. The rising motion is at a rate of less than 30 km s$^{-1}$ near 0700 UT and decreases very shortly thereafter to low speeds of about 1.7 km s$^{-1}$ at 1300 UT. Data are not available after 1400 UT. The November 14 flare appears to be a very bright example of a class of spatially large, long-duration X-ray events originally recognized from the analysis of data obtained from Skylab.

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

I. INTRODUCTION
The ejection of mass from the Sun during solar flares has long been an intriguing subject. In the last several years it has been recognized that very long duration X-ray events (lasting several hours) are frequently associated with coronal transients. For example, Sheeley et al. (1983a) found that the probability of the occurrence of a coronal mass ejection (CME) increases monotonically with the X-ray event duration time.

The association of long-duration, or long-decay, X-ray events (LDEs) with CMEs was first recognized from analysis of solar images obtained by the X-ray telescopes on Skylab (the American Science and Engineering [AS&E] and Marshall Space Flight Center [MSFC] instruments) and the Naval Research Laboratory (NRL) slitless spectroheliograph. Sheeley et al. (1975) discussed coronal changes associated with a disappearing filament observed near solar disk center on 1974 January 18. They found that the disappearing filament was associated with a large, long-duration X-ray event with a spatial extent of about 50,000 x 100,000 km. The temperature of the X-ray-emitting plasma was estimated to be about 6 x 10^6 K, and the event occurred over a time interval of ~5 hr. Enlarging their study to the entire Skylab time interval, they noted the general association of LDEs with CMEs.

The subject was pursued further by Kahler (1977) and Pallavicini, Serio, and Vaiana (1977), using X-ray images recorded by the Skylab AS&E telescope. Kahler (1977) found that LDEs are typically ~$10^8$ km in height with small expansion rates of about 1 km s$^{-1}$ in the late decay phase. The typical X-ray-emitting structure consists of an arcade of loops with a bright region at the loop tops. Kahler (1977) also noted that LDEs were closely associated with CMEs and filament activations. Pallavicini, Serio, and Vaiana (1977) concluded that LDEs were sufficiently different to merit a distinct classification from compact flares (flares with sizes less than 1' and down to sizes less than 10'). Like Kahler (1977), they found that the LDEs are very large spatially (volumes ~$10^{28}$-$10^{29}$ cm$^3$) and tend to have bright regions at the tops of the loops. They concluded that LDEs are the result of heating the associated cool, erupted prominence material, whereas the compact events are produced by chromospheric evaporation.

Recently, high-resolution Bragg crystal X-ray spectrometers have been flown on three spacecraft: the Department of Defence P78-1 spacecraft, the NASA Solar Maximum Mission (SMM), and the Japanese Hinotori spacecraft. These instruments are capable of accurately determining electron temperatures of X-ray events (independent of the assumption of ionization equilibrium), emission measures, and dynamical information such as anisotropic bulk motion of gas and random nonthermal motions in the gas. In this paper we present P78-1 X-ray spectra of an LDE that had its origin behind the solar west limb on 1980 November 14. The P78-1 experiment package is described by Doschek (1983). From these data we are able to estimate temperatures of the hottest portion of the magnetic loops in which the emission arises, and we can extract dynamical information about the event from analysis of the line profiles and angular shifts. A large associated CME was observed by the P78-1 Solwind coronagraph.

There is one significant difference between our event and most of the LDEs discussed above. Of the six LDEs discussed by Pallavicini, Serio, and Vaiana (1977), two were X-ray class C2, two were class C5, one was class M1, and one was class X2. The Sheeley et al. (1975) January 18 event was of class C1, but their other Skylab events extended to X1. Of the 31 events tabulated by Kahler (1977), two were class X1, two were class M7, one was class M5, and two others were class M1 and M3. The rest were C-class events. Our event is class M8. However, this is a lower limit to the X-ray classification, because the event began behind the solar limb and therefore some of the...
II. THE 1980 NOVEMBER 14 EVENT

The event under discussion occurred near 0700 UT on 1980 November 14. The exact onset time is unclear because the event began behind the limb and because it was blended with another X-ray event. The GOES 1–8 Å X-ray flux for the flare is shown in Figure 1. It can be seen that the event was both large (class M8) and of long duration (> 6 hr).

There are four reasons for placing the origin of the event behind the west limb of the Sun. First, a large CME was associated with the X-ray event. This event can be traced backward to points on or behind the west limb (there was no observed source of the transient on the solar disk.) Second, a large active region near the equator had rotated around the west limb about 1.6 days before the event (from Solar-Geophysical Data 1981). This is the region (active region 244) in which we believe the flare and associated CME occurred. However, there were no reported Hα ejecta above the west limb at the time of the event. Third, there was no Hα flare reported for this event. Fourth, there was no Fe Kα emission due to transitions in very low iron ionization stages (i.e., mostly from Fe II). Such emission is produced by fluorescence and shows up in spectra of disk flares if the count rates are sufficiently large, but not in spectra of limb events (Doschek et al. 1971).

Because the Kα emission is weak, its absence could only be determined for times during the event when the iron emission was strong, e.g., at times around 0800 UT. For these times, the spectral region around the Kα lines was compared with the same spectral region for a known disk flare, for times during the disk flare at which the iron (Fe XX–Fe XXV) line count rates of the disk flare and limb flare are comparable. At these times the Kα lines are seen at a glance in logarithmic plots of the iron data for the disk flare, but not in those for the limb flare that appears in the November 14 data. Quantitatively, the November 14 Kα line is < 22% of the intensity of the Kα lines seen in the disk flare.

In Figure 1 there is a bump in the X-ray light curve just before 0700 UT that is due to a flare that was observed in Hα at the location S11-12, W34-38, i.e., active region 255. This event is unrelated to the much larger limb event we are discussing. Several other small SF and SN Hα events in active region 255 were also reported during the duration of the limb event, but these are all of short duration (~ 20 min) and clearly are not the dominant source of the X-ray emission we recorded. However, for early times during the rise phase of the event, the calcium spectra may be contaminated by emission from these events. This is discussed in the next section.

It is possible to place lower limits on the height of the X-ray-emitting region above the solar surface by assuming that the X-ray event occurred above active region 244. The extreme east and west boundaries of the active region had rotated 20° 3 and 27° 9 behind the limb respectively. Thus if the X-ray event occurred above this region, the height of the observed emission had to be between 4.6 x 10^4 and 9.2 x 10^4 km (or 1° 06 and 2° 1). These are the heights at which the X-ray emission would just graze the white-light limb, and of course the event could be higher than this. The range of heights results because the location of the event within the active region is unknown.

If we assume that the emission occurs in a semicircular loop, the loop lengths corresponding to the heights are at least 1.4–2.9 x 10^5 km or 3'–6'. Thus the size of this event, along with its duration, supports our contention that the November 14 event is in fact similar to the LDEs described by the investigators cited in § I.

Figure 1 also shows the count rates [counts (64 ms)^{-1}] for the resonance lines of Fe XXV and Ca XIX (1/2^1S_{0}-1/2^1P_{1}), obtained from the NRL solar flare X-ray (SOLFLEX) spectrometers. The gaps in the SOLFLEX data (dashed lines in Fig. 1) arise because of spacecraft night and other spacecraft priorities that preempted the spacecraft tape recorders. Note that the count rate in the calcium line is about a factor of 4 larger than for the Fe XXV line. However, iron is about an order of magnitude more abundant than calcium. Introducing the
Fig. 2.—Images of the November 14 CME recorded by the Solwind coronagraph on P78-1. The occulter radius is 2.5 $R_\odot$. The 0527 image is the background image subtracted as indicated from images showing the transient, in order to enhance contrast.
relative spectrometer efficiencies does not remove this apparent anomaly. We shall see shortly that it is the rather low electron temperature of the event (~10-14 x 10^8 K) that depresses the iron line relative to the calcium line.

Images of the CME associated with the November 14 event obtained by the Solwind coronagraph are shown in Figure 2. The CME was relatively large, massive, and fast compared to most CMEs and was associated with an interplanetary shock recorded by the Helios 1 spacecraft (Schwenn 1983; Sheeley, et al. 1983b). The position of the outer boundary of the CME is plotted in terms of solar radius in Figure 3, as a function of time. An eye fit of a straight line to these data yields an outward speed of the transient of roughly 900 km s^{-1} (solid line in Fig. 3). Strictly speaking, this speed is only applicable between about 0800 and 0900 UT, but such flare-associated CMEs often have constant speeds in the 1.2–6 solar radii field of view (MacQueen and Fisher 1983). Thus we assume that the outward motion of the CME was at approximately constant speed directed along a solar radius that passed somewhere through active region 244. Finally, we note that the start time of the CME, found by extrapolating the straight line in Figure 3, is very roughly 0700 ± 30 min. We have forced the start time to be at 0700 in order to achieve rough consistency with the onset of X-ray emission. The CME data are too limited in solar radius to rule out this interpretation, and therefore we may regard the speed of 900 km s^{-1} as a possible lower limit to the CME speed.

At radii less than the occulter radius, nothing is known about the speed or acceleration of the November 14 transient. However, for events that occur on the solar disk, and for which an onset time is known because the CME is associated with a flare observed in Hα, an average speed can be defined. As MacQueen and Fisher (1983) have found, this speed often agrees fairly well with the speed inferred from the position of the CME on the plane of the sky, indicating a quick acceleration of the event following onset.

### III. X-RAY SPECTRA OF THE NOVEMBER 14 EVENT

Typical iron and calcium spectra obtained during the rise phase (0700–0730) are shown in Figure 4. The first spectra recorded are shown in Figures 4a and 4b, and spectra recorded during the decay phase are shown in Figures 4c and 4d. In Figures 4a and 4b, the lines are much wider than in Figures 4c and 4d, and the count rates are lower, leading to larger statistical fluctuations, but relative line intensities otherwise appear rather similar. Before discussing the line widths and profiles in detail, we consider the effect of contamination of the lines due to flares in active region 255.

Flares occurring simultaneously in different solar regions produce the same spectral features at different fiducial angles of the crystal spectrometers, unless the different regions fortuitously lie precisely along a line at right angles to the line of dispersion of the crystals. That is, multiple spectral lines of the same spectral line will almost always appear in the data. The position of the line of dispersion of the spectrometers is known, as well as the angular separation between region 255 and the limb over region 244. This separation is about 3.9' at times near 0700 on 1980 November 14.

For a separation of 3.9', and considering the intrinsic line widths, region 255 iron lines should appear completely distinct from the limb-event iron lines, and should appear 4.0 mÅ to the red side of the limb-event lines. (See vertical arrows in Fig. 4.) On the other hand, the red wings of the calcium lines could be contaminated by region 255 emission (Fig. 4), since 3.9' for calcium only corresponds to 2.8 mÅ.

The resonance line of Fe xxv for region 255, which is the strongest line and one of the main diagnostic lines, should fall on the far blue shoulder of line x (Fig. 4). Therefore the resonance line from the limb event is uncontaminated. The other important diagnostic line, j, is contaminated in the spectrum shown in Figure 4b but should be only weakly contaminated in subsequent spectra. This follows from the weak emission of the Fe xxv resonance line emission from region 255 flares in subsequent spectra. Iron-line contamination is not significant for...
most of the parameters derived from the line widths and intensities. However, the calcium line contamination must be considered carefully. It is not possible to determine this contamination precisely and therefore some of our results must be expressed as upper or lower limits. The contamination should be worse for data obtained over the rise time interval between 0700 and 0730. Also, the contamination should primarily affect the clacium line profiles and not produce a large effect on peak line intensity. Finally, after about 0813 UT, the calcium profiles appear quite symmetric and appear no different from profiles obtained from events that are known not to be contaminated. Therefore, for times over which the calcium line intensities are large, the contamination must be quite small, and we neglect the possible effects of blending for these times.

The electron temperature can be derived using diagnostic line ratios. The ratios of the lines marked $j$ and $k$ to the line labeled $w$ in Figure 4 depend only on electron temperature $T_e$, and are insensitive to both electron density $N_e$ and to whether or not the plasma is in ionization equilibrium (Gabriel and Jordan 1972). Using the techniques described in Bely-Dubau et al. (1982a, b), temperatures are obtained for the November 14 event as a function of time. The line ratios and temperatures are shown in Figure 5, along with the count rates in the resonance lines, $w$. It can be seen that the temperature of the event is about $15 \times 10^6$ K or less at all times. Typical class M and X flares have temperatures considerably higher than $15 \times 10^6$ K, i.e., $20-25 \times 10^6$ K (Doschek et al. 1980; Feldman et al. 1980).

For the calcium data during the rise time, blending with region 255 may increase the intensity of line $k$, but should have only a small effect on the peak intensity of line $w$. This might tend to make the calcium temperatures appear somewhat lower than the actual temperature. However, this difference should be very small.

The temperatures obtained from iron line ratios are about $3 \times 10^6$ K higher than those obtained from calcium lines. Aside from a small effect due to the blending just mentioned (rise phase only), this reflects the sensitivity of the iron lines to higher temperature and the fact that the plasma is probably composed of more than one temperature region. As discussed by Doschek et al. (1980), the iron-line ratio is sensitive to the maximum temperature of the bulk of the emitting plasma, and
therefore the iron-line temperature is close to, or perhaps one or two million degrees less than, the maximum thermal temperature of the bulk of the high-temperature plasma. However, the calcium temperature is close to the average temperature of the high-temperature loops. The iron-line temperatures at maximum flux are higher than the temperatures derived by Pallavicini, Serio, and Vaiana (1977) for a variety of events, and by Sheeley et al. (1975) for a much less intense (C-class) X-ray event. These authors used methods that appear to be strongly weighted by the presence of cold loops that also may be part of the flare. But as noted in § I, most of the LDEs reported previously are of lower X-ray class, and most probably had lower temperatures than our event.

The excitation rates of the resonance lines are proportional to the Boltzmann factor, \( \exp(- \Delta E/kT) \), where \( \Delta E \) is the transition energy. At temperatures of \( 15 \times 10^6 \) K or less, this factor is much smaller for the iron line at 1.85 \( \AA \) than for the calcium line at 3.17 \( \AA \). Also, the excitation rates are proportional to the fractional abundance of the ion that emits the line, which is less for iron than for calcium at low temperatures. These two differences between the excitation of the calcium and iron lines account for the fact that the calcium lines are stronger than the iron lines, in spite of the much larger iron abundance.

By the end of our observations, the temperature of the event is about \( 9 \times 10^6 \) K, as determined from the calcium lines. This temperature is typical of the late decay phase of a flare as found from our spectrometer data. (For these times the iron lines are too weak to record with statistical significance.) The highest temperatures occur during the rise phase and at the time of peak flux in the X-ray lines.

However, the most interesting aspects of the spectra in Figure 4 are the large line widths and not the temperatures. The line widths are on the order of 3 m\( \AA \), and the line profiles are also quite interesting.

To understand the line widths, we note that the X-ray lines are broadened by the rocking curve of the crystals, by thermal and turbulent Doppler motions, and finally by the size of the source. Assume for simplicity that all broadening mechanisms are Gaussian, and consider the FWHM of a spectral line. In the case of Gaussian profiles the total FWHM is given by

\[
\text{FWHM} = (\Delta \lambda_D^2 + \Delta \lambda_S^2 + \Delta \lambda_t^2)^{1/2}, \tag{1}
\]

where \( \Delta \lambda_t \), \( \Delta \lambda_S \), and \( \Delta \lambda_D \), represent the FWHM due to instru-

mental broadening, source-size broadening, and Doppler broadening respectively. The Doppler broadening is given by

\[
\Delta \lambda_D = 2(\ln 2)^{1/2} \left( \frac{\lambda}{c} \right) \left( \frac{2kT}{M} + \xi^2 \right)^{1/2}, \tag{2}
\]

where \( \lambda \) is the wavelength, \( M \) is the ion mass, and \( \xi \) is a random, nonthermal motion that is usually present in solar plasmas (e.g., Doschek, Mariska, and Feldman 1981; Doschek et al. 1980). The instrumental broadening is much smaller than the Doppler broadening. For both the instrumental and source-size broadening, the angular broadening \( \delta \theta \) results in a corresponding broadening in wavelength \( \delta \lambda \) given by

\[
\delta \lambda = 2d \cos \theta \delta \theta, \tag{3}
\]

because of the Bragg relation, \( \lambda = 2d \sin \theta \). If \( \delta \theta \) is defined as either the FWHM of the instrument rocking curve \( \delta \theta_t \) or the FWHM of the source \( \delta \theta_s \), then

\[
\Delta \lambda_t = 2d \cos \theta \delta \theta_t, \quad \Delta \lambda_s = 2d \cos \theta \delta \theta_s. \tag{4}
\]

The angle \( \delta \theta_t \) is 14" for the iron-line spectrometer and 35" for the calcium-line instrument. Combining equations (1) through (4) gives

\[
\text{FWHM} = \left[ (2d)^2 \cos^2 \theta (\delta \theta_t^2 + \delta \theta_s^2) + 4 \ln 2 \left( \frac{\lambda}{c} \right)^2 \left( \frac{2kT}{M} + \xi^2 \right) \right]^{1/2}. \tag{5}
\]

The size of the source and the Doppler broadening can be unfolded by comparing the Fe xxx resonance-line width at 1.85 \( \AA \) to the Ca xix resonance-line width at 3.177 \( \AA \). If Doppler broadening dominates all other broadening mechanisms, then the ratio FWHM(Ca)/FWHM(Fe) \( \approx 1.72 \), the ratio of wavelengths. However, if source size broadening dominates, then FWHM(Ca)/FWHM(Fe) \( \approx 0.69 \), which is the ratio of \( \cos \theta \) for both lines. Thus the ratio of FWHM can vary by a factor of 2.5, depending on the relative contributions of Doppler broadening and source-size broadening.

The FWHM of the iron and calcium resonance lines are shown in Figure 6 for part of the rise phase of the event. The first calcium data point near 0702 is probably spuriously high.

\[\text{Figure 6.—The FWHM for the resonance lines of Ca xix and Fe xxi. The Fe xxi width measurements are not corrected for the effect of blended Fe xxi satellite lines, but they produce only a small increase in line width and do not significantly alter conclusions concerning source size based on the ratio of Fe xxi to Ca xix line widths.}\]
because of blending with the 0650 flare in region 255. After about 0813, the FWHM of the calcium line is about constant at 2.3 mA and the FWHM of the iron line is similarly constant at about 2.1 mA. The statistics for the calcium data are better than for the iron-line data, and hence there is less scatter for the calcium line. From Figure 6 and later data, it is clear that FWHM(Fe) ≈ FWHM(Ca) over the time intervals of interest, ignoring the single calcium-line data point at 0702. From Figure 5, the temperature for both iron and calcium over most of the flare is about constant at ~ 10^7 K. Using this value in equation (5) and setting FWHM(Fe) = FWHM(Ca) leads to a relationship between ξ and δ0, if ξ is also assumed to be the same for iron and calcium. This relationship is shown in Figure 7. The smallest value of δ0, that satisfies an equality in FWHM between calcium and iron lines is 83".

The effect of a blend with region 255 flares is to broaden the calcium line but not the iron line. The effect of this on the analysis is that derived source sizes would be smaller than actual source sizes and derived turbulent velocities would be larger than actual turbulent velocities.

Using actual values of the FWHM from Figure 6 and for later times in equation (5), and using Figure 7, results in the values of ξ and δ0 as a function of time shown in Table 1. We have expressed the results for the rise time as upper and lower limits, because of a possible blend with region 255 flares. However, it can be seen that for the times 0717 and 0723 the values do not differ significantly from later values where blending is considered insignificant. Thus, if a blend is important, it is most significant for times before about 0715.

The effect of a blend on the results in Table 1 can be quantitatively estimated. For example, if the calcium-line FWHM were broadened by 20% (about as large as expected), then after correcting for the blend FWHM(Ca) = 0.8 × FWHM(Fe) and a different curve is obtained from that shown in Figure 7. Using this different curve, and the “corrected” value of the measured FWHM for the calcium line, the values of δ0 and ξ for the first entry in Table 1 become 230" and 76 km s^{-1}. Thus the source size is not appreciably affected but the turbulent velocity is reduced considerably.

At times near the onset of the event (~0703), the “size” of the event, or the distance along the plane of dispersion of the spectrometer over which X-ray emission occurs, is close to 200". At this time the turbulent motions are ~ 170 km s^{-1}, and may be much less. As the event develops, the “size” of the emitting region decreases to about 110" (near 0900), and the mass-motion velocities appear to decrease to about 70–80 km s^{-1}, although the decrease of mass-motion velocity is uncertain because of blending. The “size” of the X-ray event is quite large and is consistent with the hypothesis that the November 14 event is an LDE such as is described in § I.

Figure 7 also shows that the derived sizes and turbulent motions are not sensitive to the assumptions that T_{Fe} = T_{Ca} and ξ(Fe) = ξ(Ca). In many flares T_{Fe} is slightly higher than T_{Ca}. If we assume as an example that T_{Fe} = 1.3 T_{Ca} and ξ(Fe) = 1.3 ξ(Ca), a relation is obtained similar to that just described, and is shown in Figure 7. Values of δ0 and ξ obtained with this curve do not differ significantly from the values obtained from the curve calculated under the assumptions of equal temperatures and turbulent velocities for the iron and calcium lines.

In addition to the large width of the profiles, the shapes of the profiles indicate large anisotropic bulk motions for part of the X-ray emission. At times near 0700, the profiles exhibit a broadening on the red wing of the line. This broadening may be a combination of Doppler and spatial influence on the total line profile. Only the broadening of the calcium line could be affected by blending with region 255 events. Since the red-wing broadening is also seen on the iron line, at least some of it is intrinsic to the limb event. The red-wing broadening we refer to is too large to be attributed to satellite line emission. One result of this is that the analysis just presented on the source size and nonthermal random motions should be regarded as an approximate treatment, since symmetric Gaussian profiles were assumed for all broadening mechanisms. Nevertheless, the
values of $\delta \theta_x$ and $\xi$ obtained, and their behavior with time, should be correct to within 50%. We also note that these values are not sensitive to the precise values of temperature used for the calcium and iron lines.

At other times during the rise phase both blue- and red-shifted wings are apparent. In Figure 8 we show the Ca xix line profiles at different times. The profiles at 0711:26 and 0711:44 do not show significant Doppler shifted emission and are included for comparison with the other profiles. In the 0706:59 spectrum, a weak blue wing is apparent on the Ca xix resonance line, while in the 0713:35 and 0714:20 spectra a relatively strong red wing is seen on the profile of the blended forbidden line of Ca xix. The dashed lines in the figure qualitatively indicate a possible deconvolution of the Doppler-shifted and unshifted components, assuming that only two components are present. (The solid lines indicate the continuum level.) If the red wing is attributed to radial outflow, the outflow velocity is between 550 and 800 km s$^{-1}$, again depending on where the event occurred in active region 244 and assuming that the plasma moved outward along a solar radius. These velocities are smaller than determined from the CME. The Doppler line-of-sight velocity actually measured is about 260 km s$^{-1}$, and a similar velocity is obtained for the blue-wing components seen on some of the profiles. However, an alternative explanation for the red wing is that it is due to a flare in region 255 that began on or before 0715. The calcium line W is slightly widened when the red wing is seen (see Fig. 6). It is not certain that we are seeing radial outflow in this case. It is equally likely that the red wing is in fact due to a flare in region 255. Blue- and red-wing components to X-ray line profiles of limb flares were first reported by Bentley et al. (1984) from the analysis of SMM X-ray spectra.

In addition to providing information on possible high-velocity motions for part of the X-ray emitting region, the calcium-line profiles also show that the bulk of the plasma is moving away from the Sun, at speeds much less than 550–800 km s$^{-1}$. The technique used to obtain this result is described in Seely and Feldman (1984). Briefly, the measured angle at which a spectral line falls depends on the angle of incidence of the radiation on the crystal. If a source outside the solar limb is moving away from the Sun, the angle of incidence of the radiation on the crystal changes and therefore the measured angle at which the Bragg relationship for diffraction is satisfied changes. If the angle changes slowly and in a systematic manner, an interpretation of this effect in terms of a moving source is most likely correct. Also, the absolute value of the measured angle, coupled with information on the spacecraft pointing, gives information on the location of the flare. For the November 14 flare, the absolute value of the angle has provided us with further confirmation that the bulk of the calcium and iron emission arises from the limb event.

Measurements of the angles at which the centroid of the calcium emission is found reveal that the source increased in altitude as the event progressed. An absolute altitude increase cannot be determined, but a relative increase can be measured. If the altitude increase is assumed to be along the direction of the transient, and if the altitude of the source at times near 0700 is defined as zero, then the relationship shown in Figure 9
is obtained. For a brief time after 0700, the source appears to be rising at a speed of about 200 km s\(^{-1}\). However, this value depends on the first data point at 0700, when the calcium profile is very likely contaminated with the event in region 255 that peaked at 0650. If this point is therefore disregarded, the speeds are around 30 km s\(^{-1}\) near 0700. These speeds are upper limits, since some additional contamination may be present at these times. After about 0813, contamination should be negligible. At times later than 0800, the speeds decrease to very small values of about 1.7 km s\(^{-1}\). High spatial resolution images are necessary to fully understand these results.

Finally, we are able to derive volume emission measures for the event using the resonance-line fluxes and measured temperatures. These are shown in Figure 1 as a function of time for the calcium line only. The emission measures derived from the iron resonance line are about a factor of 4 larger than those based on the calcium line. We feel this reflects atomic-physics inaccuracies in the part of the contribution function of Fe xxv that is far from the temperature of maximum ion abundance and maximum emitting efficiency of the Fe xxv line. The calcium-emission measures should be more accurate and show that the emission measure varied from about \(10^{48}\) to \(10^{49}\) cm\(^{-3}\). These values are typical for the X-ray LDEs described by Pallavicini, Serio, and Vaiana (1977). Blending with region 255 flares will not seriously affect the values of the emission measures.

It is not possible for us to obtain accurate electron densities, since density-sensitive line ratios are not available, and we do not have the spatial resolution needed to estimate volumes \(V\) and hence derive densities from the emission measures \(N_e V\). If we simply cube the sizes corresponding to \(\delta \theta_s\) (an overestimate), the densities we obtain range from 1 to \(5 \times 10^9\) cm\(^{-3}\). If the densities were this low, transient ionization effects would be so low that transient ionization effects would appear in the iron spectra. Since such effects are not seen, it appears that the actual emission occurs in smaller, higher density volumes that extend over a volume of 2-3', i.e., the filling factor is less than unity. This overall extent of space in which the X-ray emission occurred decreased during the event. The value of \(\delta \theta_s\) decreased by at least a factor of 2 between 0700 and 0850. Since no observations with adequate spatial resolution are available, it is difficult to interpret this result in terms of the spatial structure of loops. A similar result was not found by Kahler (1977) or Pallavicini, Serio, and Vaiana (1977), but this is not significant because it could well be that in our case the actual size of the structures remained the same, or even increased, while some of the hotter regions cooled, leaving other similarly hot components that were spatially closer to one another.

Nonthermal velocities on the order of 100 km s\(^{-1}\) are also derived from the line widths. The velocities are uncertain during the rise phase because of possible blending with region 255 flares.

The mass ejection is one of the larger events observed by the Solwind coronagraph on P78-1. The X-ray spectra associated with the mass ejection reveal the following:

1. The emission region is at least 1'-1-2' above the solar surface.

2. Analysis of the line widths shows that the event covered a considerable distance on the plane of the sky above the solar limb, as much as 3' at times near 0700 UT. The combination of emission-measure and source-size results suggests that the X-ray emission does not uniformly fill a volume deduced by simply cubing the "size," \(\delta \theta_s\). In this case the deduced electron density would be so low that transient ionization effects would appear in the iron spectra. Since such effects are not seen, it appears that the actual emission occurs in smaller, higher density volumes that extend over a volume of 2'-3', i.e., the filling factor is less than unity. This overall extent of space in which the X-ray emission occurred decreased during the event. The value of \(\delta \theta_s\) decreased by at least a factor of 2 between 0700 and 0850. Since no observations with adequate spatial resolution are available, it is difficult to interpret this result in terms of the spatial structure of loops. A similar result was not found by Kahler (1977) or Pallavicini, Serio, and Vaiana (1977), but this is not significant because it could well be that in our case the actual size of the structures remained the same, or even increased, while some of the hotter regions cooled, leaving other similarly hot components that were spatially closer to one another.

3. The line profiles show blue- and redshifted emission that occurs sporadically during the rise phase. Measured Doppler velocities are about 260 km s\(^{-1}\), but velocities up to 800 km s\(^{-1}\) are inferred for the redshifted component if the true motion is along the direction of the CME. However, in the case of the redshifted emission, it is equally likely that the emission is due to a flare in region 255.

4. The event appeared to increase in height above the limb as the flare progressed.

5. The peak temperatures of the November 14 event deduced from the iron lines are about \(15 \times 10^6\) K. We note that the temperatures deduced for all classes of flares by Pallavici, Serio, and Vaiana (1977).
vicini, Serio, and Vaiana (1977) are significantly lower than our temperatures, in part due to the different techniques used to calculate temperatures. Nevertheless, most of the LDEs reported previously were probably cooler than our event. The November 14 event represents one of the brighter and hotter members of the class of long-duration events.

The November 14 X-ray emission might be emission from the debris of the original structure or structures that erupted and produced the CME. Our results do not contradict the suggestion of Pallavicini, Serio, and Vaiana (1977) that LDEs are produced by heating of cool plasma that is part of the eruptive prominence. High-resolution images, combined with crystal spectroscopy, are needed to fully understand the physical processes occurring in the X-ray emitting regions.

There are other events similar to the November 14 event in the P78-1 data base. One such event is the 1979 June 5 flare discussed by Doschek et al. (1980). This event produced a CME that was observed by the Solwind coronagraph (Poland et al. 1981). The CME was diffuse and complex and expanded outward at about 830 km s$^{-1}$. Also, because the event occurred at N20, E16, the height of the X-ray emission could not be measured, although its spatial dimension along the direction of dispersion was about 1'. We are compiling a list of additional long-duration X-ray events for which CMEs have been observed by the Solwind coronagraph.

This work was partly supported by a NASA grant from the Office of Solar and Heliospheric Physics. The authors would like to thank Drs. H. Gursky and J. Karpen for critical readings of the manuscript, and would also like to thank Dr. Gursky for suggesting the application to the November 14 event of the Seely and Feldman (1984) technique for measuring the outward motion of flares above the limb. The authors would like to thank an anonymous referee for many helpful suggestions that resulted in a substantial improvement of the text.

REFERENCES


G. A. DOSCHEK: Code 4170, Naval Research Laboratory, Washington, DC 20375-5000
U. FELDMAN: Code 4174, Naval Research Laboratory, Washington, DC 20375-5000
R. W. KREPLIN: Code 4175, Naval Research Laboratory, Washington, DC 20375-5000
J. F. SEELY: Code 4174S, Naval Research Laboratory, Washington, DC 20375-5000
N. R. SHEELEY, JR.: Code 4172, Naval Research Laboratory, Washington, DC 20375-5000