SOLAR FLARES IN THE EXTREME ULTRAVIOLET

II. Comparisons with Other Observations

A. T. WOOD, JR.*
Harvard College Observatory, Cambridge, Mass., U.S.A.

and

R. W. NOYES
Smithsonian Astrophysical Observatory and Harvard College Observatory,
Cambridge, Mass., U.S.A.

(Received in final form 1 December, 1971)

Abstract. Extreme-ultraviolet (300–1350 Å) observations of nearly 500 solar flares from the satellites OSO 4 and OSO 6 have been compared with data in X-ray and radio wavelengths. It is found that EUV flares are closely associated with nonthermal X-ray and microwave bursts. The EUV maximum intensity generally precedes the maximum intensity in Hα or soft X-rays by up to several minutes. The EUV e-folding rise time and peak intensity both depend on the X-ray burst characteristics. Nonthermal X-ray flares tend to be accompanied by strong, rapidly rising EUV bursts, while thermal X-ray events are usually associated with weaker, more slowly rising EUV flares. These relations are consistent with a picture of the flare in which the EUV radiation is produced thermally in a region of high (chromospheric) density, which is being heated by collisional losses of the nonthermal electrons responsible for the impulsive X-ray and microwave burst.

1. Introduction

In a previous paper (Wood et al., 1972, hereafter referred to as Paper I), we have described and cataloged the ultraviolet observations of several hundred solar flares obtained by the Harvard College Observatory (HCO) experiments flown onboard OSO 4 in the fall of 1967 and OSO 6 in the fall of 1969. In the present paper, we will compare these extreme-ultraviolet (EUV) observations with simultaneous observations in the X-ray and radio spectral ranges, as well as in Hα.

In § 2, we discuss the observational data used in this study. In § 3, we present an analysis of these data, and in § 4, we describe in detail several selected events that illustrate the correlations found in § 3. In § 5, we summarize the results of this analysis and draw some conclusions.

2. The Data

In Paper I, we presented spatially and temporally resolved observations of solar flares in the extreme ultraviolet. These data have also been compared with simultaneous observations in other spectral regions, including X-ray, optical (Hα), and radio radiation.

* Present address: Physics Department, St. Bonaventure University, St. Bonaventure, New York.
TABLE I
Sources of X-ray observations

<table>
<thead>
<tr>
<th>Satellite</th>
<th>X-ray wavelength (or energy) ranges</th>
<th>Detector</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOLRAD 9</td>
<td>0.5–3 Å, 1–8 Å, 8–20 Å</td>
<td>Ionization chambers</td>
</tr>
<tr>
<td>VELA 5</td>
<td>4.5–8.2 keV, 8.2–14.9 keV, 14.9–22.2 keV, 22.2–44.5 keV</td>
<td>Scintillation detector + pulse-height analyzer</td>
</tr>
</tbody>
</table>

The X-ray data used in the study reported here were obtained from several satellite experiments, principally the Explorer 37-SOLRAD 9 experiment of the U.S. Naval Research Laboratory (NRL), the VELA 5 experiment of the Los Alamos Scientific Laboratory (LASL), and the OGO 5 experiment of the University of California at Berkeley (UCB). The wavelength or energy bands covered and the type of detector used by the various experiments are detailed in Table I.

The Hα data were taken principally from the Solar-Geophysical Data Bulletin (SGDB) published monthly by the Environmental Research Laboratories, Boulder, Colorado. Individual Hα flares are identified in the tables of Paper I by their SGDB number. Prints from Hα patrol films for a few selected events were obtained from the McMath-Hulbert (University of Michigan) and Big Bear (California Institute of Technology) Solar Observatories.

The radio data were also taken from SGDB, although many traces of intensity versus time were obtained from the radio observatories at Sagamore Hill (AFCRL), Mass., Toyokawa, Japan, and Ottawa, Canada. We have also obtained photographic records of meter-wave burst dynamic spectra from the Harvard station at Fort Davis, Texas. Observations of Sudden Frequency Deviations (SFD’s) made at radio frequencies – typically 5–10 MHz – but interpreted as the result of impulsive bursts of broadband EUV (10–1030 Å) radiation (Donnelly, 1969, 1970) were obtained from the University of Hawaii.

3. The Analysis

Time-resolved EUV observations, even with the relatively poor (30 s) resolution of the Harvard OSO 6 data, can help to elucidate the sequence of events that make up the flare process. With this goal in mind, we have compared the observed times of maximum intensity in the EUV, Hα, and X-ray ranges.

The EUV times were taken directly from the observed light curves described in Paper I. These times generally had an observational uncertainty of less than 30 s, the temporal resolution of the OSO 6 small-raster-mode data (for a description of the Harvard OSO 6 experiment, see Huber et al., 1971). Light curves typical of those observed by OSO 6 are shown in Figure 1 in Paper I. The times of maximum intensity in Hα were taken from SGDB in the following manner: If complete cinematographic (SGDB notation C) observations were used to arrive at the reported time of maximum,
the earliest such time was used; if no $C$ times were reported, the earliest visually determined (SGDB notation $V$) time was used. According to McIntosh (1970) the reported times of maximum refer to maximum intensity and are generally accurate to within ±1 min. This relationship has been empirically verified by Thomas (1970). The X-ray observations were taken from the observed light curves (see Paper I) and were also generally accurate to ±1 min, except those events observed by OGO 5, for which the accuracy was ±2 s. The time delays $\Delta t$ between EUV maximum and $H\alpha$ and X-ray maximum are listed for individual flares in the tables in Paper I.

Figures 1a and 1b show the distribution functions for the observed time delays between the EUV maximum and the $H\alpha$ and X-ray maxima, respectively. Positive $\Delta t$ means that the EUV maximum occurred earlier.
Figure 1a shows that the EUV emission tends to reach its peak earlier than the Hα emission. The average time delay for all the Hα flares observed is $+70 \pm 16$ s, where the quoted error is the standard deviation of the mean. The EUV peak is reached before Hα in 62 events, and after Hα in only 28; for this distribution the $\chi^2$ parameter is 12.84, leading to a probability, $P < 10^{-3}$, of chance occurrence, if the average time delay $\overline{\Delta t}$ were in fact zero.

In Figure 1b, the time delay between the EUV and X-ray maxima is slightly less: $\overline{\Delta t} = +40 \pm 7$ s. In this case, 60 events have an early EUV peak, and 32, a late EUV peak, leading to $\chi^2 = 8.52$ and $P < 0.01$.

If, however, we select only those flares that have a nonthermal component — as evidenced by the ‘impulsiveness’ or the spectrum of the X-ray burst (Kane and Anderson, 1970) — we find a somewhat different result. The 20 such events listed in Table II are among the strongest and fastest-rising of all the EUV bursts observed from OSO 6 (see Figure 2, Paper I). The time-delay distribution functions for these selected events are narrower and have a smaller average time delay than those plotted in Figures 1a and 1b. From column 3 of Table II, we find $\overline{\Delta t_{\text{Hα}}} = +49 \pm 13$ s, with 16 flares showing an early EUV peak, and 2 events, a late EUV peak, so that $\chi^2 = 10.88$

<table>
<thead>
<tr>
<th>Date (1969)</th>
<th>Time of EUV maximum (UT)</th>
<th>$\Delta t_{\text{Hα}}$ (s)</th>
<th>$\Delta t_{\text{X-ray}}$ (s)</th>
<th>e-folding rise time (s)</th>
<th>Ionic species</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>8/24</td>
<td>10:15</td>
<td>31</td>
<td>1</td>
<td>160</td>
<td>OVI</td>
<td></td>
</tr>
<tr>
<td>8/25</td>
<td>11:32</td>
<td>27</td>
<td>-27</td>
<td>15</td>
<td>CI</td>
<td>a</td>
</tr>
<tr>
<td>10/8</td>
<td>7:26</td>
<td>59</td>
<td>51</td>
<td>45</td>
<td>OVI</td>
<td>b</td>
</tr>
<tr>
<td>10/23</td>
<td>11:37</td>
<td>96</td>
<td>0</td>
<td>90</td>
<td>CI</td>
<td>c</td>
</tr>
<tr>
<td>10/24</td>
<td>21:14</td>
<td>-30</td>
<td>-50</td>
<td>15</td>
<td>CI</td>
<td>a</td>
</tr>
<tr>
<td>10/27</td>
<td>8:47</td>
<td>70</td>
<td>37</td>
<td>50</td>
<td>MgX</td>
<td>a</td>
</tr>
<tr>
<td>10/28</td>
<td>10:29</td>
<td>97</td>
<td>18</td>
<td>45</td>
<td>CI</td>
<td>a</td>
</tr>
<tr>
<td>11/18</td>
<td>0:45</td>
<td>85</td>
<td>-18</td>
<td>45</td>
<td>OVI</td>
<td>b</td>
</tr>
<tr>
<td>11/18</td>
<td>13:32</td>
<td>66</td>
<td>59</td>
<td>50</td>
<td>OVI</td>
<td>a</td>
</tr>
<tr>
<td>11/18</td>
<td>15:18</td>
<td>163</td>
<td>-2</td>
<td>120</td>
<td>OVI</td>
<td>a</td>
</tr>
<tr>
<td>11/18</td>
<td>16:48</td>
<td>*</td>
<td>135</td>
<td>45</td>
<td>OVI</td>
<td>b</td>
</tr>
<tr>
<td>11/18</td>
<td>21:23</td>
<td>112</td>
<td>112</td>
<td>20</td>
<td>OVI</td>
<td>a</td>
</tr>
<tr>
<td>11/19</td>
<td>1:46</td>
<td>17</td>
<td>47</td>
<td>30</td>
<td>OVI</td>
<td>a</td>
</tr>
<tr>
<td>11/19</td>
<td>5:01</td>
<td>13</td>
<td>13</td>
<td>75</td>
<td>OVI</td>
<td>a</td>
</tr>
<tr>
<td>11/19</td>
<td>8:18</td>
<td>87</td>
<td>27</td>
<td>15</td>
<td>OVI</td>
<td>d, a</td>
</tr>
<tr>
<td>11/20</td>
<td>4:38</td>
<td>*</td>
<td>87</td>
<td>75</td>
<td>OVI</td>
<td>c</td>
</tr>
<tr>
<td>11/20</td>
<td>8:12</td>
<td>-76</td>
<td>14</td>
<td>45</td>
<td>OVI</td>
<td>a</td>
</tr>
<tr>
<td>11/20</td>
<td>16:21</td>
<td>53</td>
<td>-15</td>
<td>30</td>
<td>OVI</td>
<td>a</td>
</tr>
<tr>
<td>11/20</td>
<td>20:46</td>
<td>0</td>
<td>60</td>
<td>30</td>
<td>OVI</td>
<td>a</td>
</tr>
<tr>
<td>11/22</td>
<td>23:22</td>
<td>13</td>
<td>73</td>
<td>40</td>
<td>MgX</td>
<td>a</td>
</tr>
</tbody>
</table>

* Hα maximum not observed for this event.

Notes to Table II:

a Radio Group I event (see text).
b Radio Group II event.
c No radio burst observed with this event.
d Largest EUV burst observed by OSO 6 ($E_{\text{max}} = 1.55 \times 10^{35}$ ergs/s at 1 AU).
and $P < 10^{-3}$; from column 4, $\Delta t_{X\text{-ray}} = +31 \pm 11$ s, with 15 early and 5 late events; thus $\chi^2 = 5.00$ and $P \approx 0.03$. The closer coincidence in times when only nonthermal events are considered suggests that impulsive EUV bursts are associated with the nonthermal component of X-ray bursts, in agreement with the recent observations of Kane and Donnelly (1971) and Parks and Winckler (1971). As we shall see below, in selected events that show nonthermal X-ray spectra, the EUV, Hα, X-ray, and radio bursts all reach maximum intensity simultaneously, to within the observational uncertainties. Indeed, for many flares the fine structure of the intensity variation in several of the spectral ranges shows detailed coincidence.

Another way of looking at the relative timing of the various flare processes is shown in Figure 2, where we have plotted $\Delta t_{X\text{-ray}}$ against $\Delta t_{\text{H} \alpha}$. In this figure, the nonthermal X-ray events are denoted by open circles, while the filled circles refer to those events with no discernible nonthermal component. The clustering of the nonthermal burst points around the origin is much more pronounced than for the thermal event points. While the latter do appear to cluster near the origin, they are also distributed into the upper-right and lower-left quadrants. Apparently, the observed correlation among the maximum emission of EUV, Hα, and X-ray bursts is not so strong for thermal as for nonthermal bursts, although the Hα and X-ray bursts do appear to be well-correlated for both classes of events. It is interesting that for thermal bursts with large positive or negative EUV time delays, the X-ray maximum tends to precede the Hα maximum by about 1 min. This disagrees with the results of Thomas and Teske (1971), which however refer to somewhat softer X-rays.

The good correlation among the times of EUV, Hα, and X-ray maxima for the

![Fig. 2. Plot of $\Delta t$ (EUV – X-ray) versus $\Delta t$ (EUV – Hα) (OSO 6 data). Open circles: events with nonthermal component. Filled circles: events with no nonthermal component.](image-url)
nonthermal bursts noted above suggests a close, causal relationship. One possible mechanism that accounts for this correlation is that the EUV radiation is produced as a result of heating of the chromospheric plasma by collisional losses of the same nonthermal electrons that are responsible for the impulsive X-ray (bremsstrahlung) and microwave (synchrotron) bursts, as suggested previously by Kane and Donnelly (1971).

For those events that show little or no nonthermal emission, the correlation among the EUV, Hz, and X-ray maxima is not so strong (Figure 2). In this case, the EUV may be generated indirectly in the atmosphere surrounding the source region, as the energy deposited at the source propagates outward. The propagation mechanism might be thermal conduction, radiation, shock waves, or a combination of these.

We note that thermal X-ray bursts show slower rises to maximum than do the nonthermal bursts (Kane, 1969; Kane and Anderson, 1970), and we would expect the EUV bursts associated with them to mimic this behavior. For the nonthermal events in Table II, the mean EUV rise time is $52 \pm 8$ s, while for the remaining (thermal) events associated with X-ray bursts, the mean rise time is $100 \pm 20$ s.

Thus it appears that EUV flares, like their X-ray counterparts, have both an impulsive and a slower component, probably arising from different mechanisms, as stated above. In each EUV flare, the proportions of the two components presumably depend on such conditions as the height of the instability, the local magnetic field, etc. Because the EUV bursts associated with nonthermal events tend to be more intense than those associated with thermal bursts (as noted in Paper I), and because the rise time for nonthermal events is less than for thermal events, we expect an inverse correlation between $I_{\text{max}}$ and rise time for EUV flares, as was already seen in Figure 2 of Paper I.

It is of interest to determine the relationship between the EUV and radio bursts associated with flares. From the radio observations tabulated in the Solar-Geophysical Data Bulletins covering the period of observation, we find that approximately 40% (82/211) of all the EUV bursts in our sample are associated with reported fixed-frequency radio bursts (the correlation was 70% for those EUV bursts associated with Hz flares). Also, approximately 18% (36/211) of all EUV bursts, and 24% of those associated with Hz flares, are accompanied by spectral type II or type III meter bursts or by both. The observed radio bursts can be divided into two groups, based on the shape of their spectra (Kundu, 1965; Smerd, 1969). Group I bursts have a maximum radio flux at 'high' frequencies ($\gtrsim 5000$ MHz) with a fall-off of flux at lower frequencies, no reported flux below $\sim 1000$ MHz, and no reported type II or type III meter bursts; Group II events have a flux maximum at high frequencies and a fall-off to lower frequencies, but then reach a minimum at $\sim 1000$ MHz, with the flux rapidly rising at frequencies $< 1000$ MHz, and are usually associated with type II and type III meter bursts.

Examples of the fixed-frequency spectra of typical bursts in each of these two groups, which were associated with EUV bursts, are shown in Figure 3. Several of the events shown in Figure 3 were also associated with observed nonthermal X-ray bursts, as noted in Table II.
Fig. 3. Fixed-frequency radio spectra of microwave bursts typical of Group I and Group II (see text).

One possible explanation that has been offered (Kundu, 1965) for the separation of the radio spectra into these two classes is that, in Group I events, the radiation is produced thermally, no electrons having been accelerated to the mildly relativistic energies necessary to produce the decimeter and meter bursts. However, this cannot be the case because, as we have mentioned, nonthermal X-ray bursts, indicating the presence of electrons with energies greater than 20–40 keV, are often observed at the
time of Group I radio bursts. A more attractive hypothesis is that Group I events are produced deeper in the chromosphere than are Group II events. In Group I events, all the energetic electrons are thermalized through collisions with the ambient plasma (see Frost, 1969), whereas in Group II events, while most of the nonthermal electrons are stopped in the chromosphere, a significant fraction propagates into the corona with enough energy to account for the observed type II and type III bursts at meter wavelengths. For both types of events, the decrease in the radio flux below about 5000 MHz is due to the increase of the optical depth of the overlying chromospheric plasma with decreasing frequency, or (if the density exceeds $10^{11}$/cm$^3$) to a cutoff of radiation below the local plasma frequency (Zirin et al., 1971).

The discovery of significant differences between EUV bursts associated with Group I or Group II radio bursts would help to clarify the above suggestion. We might expect, for instance, that chromospheric lines would be more greatly enhanced relative to coronal lines in Group I events. We have searched for such differences, but within the limitations of the present data, have found no differences in peak intensity, rise time, or time delay between the EUV and Hz or X-ray maxima.

From the tables of Hz flare data in SGDB, we have obtained the duration of each Hz flare in our samples. This was taken as the weighted average duration listed for each flare. For each observed EUV burst, a duration was also determined. The EUV duration was taken as the interval between the time when $I_f = I_0 + 0.10 I_m$ on the rising and falling portions of the flare light curve, where $I_f$ is the flare intensity, $I_0$ is the preflare intensity at the same point, and $I_m$ is the maximum intensity above the preflare level. The EUV durations for each flare are given in Paper I, Table II, and are plotted here in Figure 4, together with the corresponding Hz duration taken from

![Figure 4](image)
SGDB. (OSO 4 events were not used since the 5-min time resolution made any meaningful measurement of duration impossible.) In general, it is clear that the EUV burst is of much shorter duration than the Hα flare associated with it. We have also compared the EUV and soft X-ray durations for the flares in our sample and find that, in general, the EUV burst is of much shorter duration than the associated soft X-ray burst (especially at X-ray wavelengths longer than about 2 Å). This result is consistent with the observations of relative durations of soft X-ray and Hα flares recently reported by Thomas and Teske (1971), which showed that the soft X-ray burst typically has a duration that is up to several minutes longer than the Hα flare.

We have attempted to determine the relative EUV emission in different spectral lines, even though it was possible to observe each flare in only one line from OSO 4 and OSO 6. In order to obtain as homogeneous a sample of flares as possible, we selected for analysis only those EUV bursts associated with confirmed Hα subflares (importance classes −F, −N, and −B). From the average observed peak intensity for each spectral line, we computed the emission measure

$$\int N_e^2 dV,$$

where $V_i$ is the volume over which the particular ionization stage of interest is formed, and $N_e$ is the local electron density.

For most of the observed ionic species, the emission measure was calculated by dividing the observed flux by the emission rate for that particular ionic species, as read from the emission curves calculated by Cox (1969). For FeXXV and FeXXVI, which were not included in Cox's work, we have used the treatment described by Dupree (1968). The two methods of calculation for elements treated by both authors gave results that agreed to within 10%.

Figure 5 shows the variation with temperature of the average flare emission measure at flare maximum. Here we have used the temperature at which the number of ions in a particular ionization stage is the greatest (Allen and Dupree, 1967; Dupree, 1968; Wood and Dupree, 1968).

Implicit in Figure 5 is the assumption that the average of the maximum intensities observed in each spectral line fairly represents the maximum intensities for the 'average' Hα subflare. This assumption suffers not only from the small number of subflares observed in some spectral lines, but also because many lines were observed only with the OSO 4 instrument, with only 5-min time resolution. For these lines, the observed maximum intensity is probably an underestimate of the true maximum intensity. We cannot rule out the possibility of systematic effects, if the duration of near maximum intensity varies with temperature of formation. (An additional assumption, that all lines reach maximum simultaneously so that Figure 5 represents a unique instant in time during the flare, appears justified in light of the close agreement of individual light curves with SFD observations, as will be discussed below.)

In spite of the uncertainties that underlie Figure 5, one interesting characteristic of the curve is clear. The dependence of emission measure on temperature is very
similar to that seen in the quiet (Athay, 1966) or active (Noyes et al., 1970) Sun; in particular, lines formed at temperatures between $10^5$ and $5 \times 10^5$ K, characteristic of the chromosphere-corona transition zone in the quiet or active sun, all have relatively low emission measures. An equivalent statement of the similarity between Figure 6 and emission measure curves for quiet or active regions is that the enhancement $(I_{\text{flare}} - I_{\text{preflare}})/I_{\text{preflare}}$ is approximately the same for all EUV lines. Because of the low time resolution of the data, we suspect that the results shown in Figure 5 refer mainly to the nonimpulsive (thermal) component of the subflare emission, as discussed above. A possible interpretation of the data is that the temperature structure of the hot thermal plasma created by the flare instability is governed by thermal conduction, and therefore a steep transition zone rapidly develops, analogous to that observed in active regions (Noyes et al., 1970).

4. Detailed Description of Selected Events

In this section, we describe four specific events selected as examples of the types of observations on which the present report is based. They were chosen to show particularly well the detailed correlations described above, and are presented in chronological order.

25 August 1969, 11:33 UT

Figure 6 shows the observations for this flare (see also Figure 1 of Paper I). The Hα burst, reported as $-B$, reached maximum intensity at 11:33 UT. The HCO EUV

The spectrometer observed the flare in the C II resonance line at 1335 Å. X-ray observations were made by the UCB experiment onboard OGO 5, while the radio burst was observed at Sagamore Hill (4995 MHz, 8800 MHz), Berlin, West Germany (9400 MHz), and São Paolo, Brazil (7000 MHz). The fixed-frequency radio spectrum of this event is shown in inset (a) in Figure 6. Because of the lack of reported radio flux below ~2000 MHz, this burst can be classified as a Group I event, as described above.

In this flare, there is no doubt about the nonthermal nature of the X-ray burst, since the observed spectrum (inset (b)) clearly shows a power-law energy dependence (the 9.6–19 keV point is contaminated by radiation from the thermal component). As stated earlier, we believe that the absence of low-frequency radio emission from an event in which high-energy electrons were certainly produced indicates that the flare originated deep in the chromosphere.
Figure 6 also shows the detailed agreement between the starting times of the EUV and X-ray bursts, as well as the times of maximum. This is typical of the agreement found in the 19 other events listed in Table II, although the nonthermal nature of the X-ray burst is clearer here than in many of the other events observed.

We note that after flare maximum the EUV intensity decays gradually, more like the soft (9–19 keV) X-ray component than the hard (48–80 keV) component. The rise time of the EUV intensity is faster than that of the soft X-ray component; whether it is as fast as the hard component cannot be determined, owing to the 30-s time resolution of the data. It seems likely, however, that the EUV rise is related to the hard (nonthermal) component, and EUV decay to the soft (thermal) component.

27 August 1969, 14:07 UT

This event occurred in the same active region where the 25 August flare appeared; in Hz, the flare was classified as — N. Maximum intensity in Hz was reported at 14:07 UT by three of the seven observatories reporting the event.

The Harvard instrument observed the flare at 897 Å, near the head of the Lyman continuum. The observed EUV intensity curve, together with the radio intensity curves from Sagamore Hill are shown in Figure 7; the radio burst falls into Group II as described above (8/27 event in Figure 3).

The EUV burst shows two maxima, separated by about 100 s. The primary maximum in the EUV corresponds to the radio burst maximum to within the observational errors. The secondary EUV maximum agrees quite closely with a small post-burst increase (Kundu, 1965) observed at 8800 and 15 400 MHz in the radio-flux observations. According to Kundu, postburst increases are generally believed to be radiation from a thermal source with a temperature between $10^5$ and $10^7$ K.

None of the three X-ray experiments from which we have obtained data was in sunlight at the time of this burst, so that we cannot conclude anything about the X-ray burst that presumably occurred at the same time. However, the radio burst profile shows that, in the microwave region, this burst was impulsive. This is usually a sign of the occurrence of a nonthermal event (Kundu, 1965), so that it seems reasonably safe to conclude that the X-ray burst associated with the event was probably nonthermal. If this were in fact the case, then the first Lyman continuum peak was probably associated with the nonthermal burst and the second with the thermal component that followed. The primary EUV burst, associated with the nonthermal event, shows a much faster rise to maximum intensity than does the secondary burst (rise time for the primary burst was 70 s, and for the secondary burst, about 200 s). The delay of the more gradual secondary burst relative to the more impulsive primary burst is in accord with the findings of Kane and Anderson (1970) and with the picture of the EUV flare discussed above.

24 October 1969, 21:14 UT

This flare has already been discussed in some detail (Zirin et al., 1971), but no mention was made of the EUV emission during the flare. The flare was classified as 2B in Hz.
Fig. 7. Observations of flare of 27 August 1969 at 14:07 UT. Upper trace: H I Lyman continuum 897 Å EUV flux (OSO 6). Lower traces: microwave radio fluxes (labeled with frequencies) (AFCRL; courtesy J. Castelli).

by McMath-Hulbert; the observations are shown in Figure 8. Rather than point out the features already discussed by Zirin et al., we merely note the similarity of the light curves of the 10–1030 Å flux as denoted by the SFD trace, the 1098 Å C I continuum flux from OSO 6, the 8800-MHz radio flux from Sagamore Hill, and the 48–80 keV hard X-ray flux from OGO 5. This event is particularly indicative of the detailed coincident time structure in both the EUV and the hard X-ray fluxes, which we and others (Kane and Donnelly, 1971; Parks and Winckler, 1971) have found. Although much of the fine structure evident in the SFD trace is not present in the EUV light curve, this no doubt results from the coarse time resolution of the OSO 6 EUV data relative to the SFD observations (30 sec versus 1–2 sec).
Fig. 8. Observations of flare of 24 October 1969 at 21:14 UT. (a) 48–80 keV X-ray flux (OGO 5; courtesy S. R. Kane). (b) 8800 MHz radio flux (AFCRL; courtesy J. Castelli). (c) 10 MHz Sudden Frequency Deviation (University of Hawaii; courtesy R. F. Donnelly and S. Young). (d) C1 continuum 1098 Å EUV flux (OSO 6).

Fig. 9. Observations of flare of 18 November 1969 at 16:47 UT. Upper portion: reproduction of meter-wave dynamic spectrum (Harvard College Observatory; courtesy A. Maxwell). Lower trace: OVI 1032 Å count rate (OSO 6). (Arrows are explained in text.)
18 November 1969, 16:47 UT

The EUV and radio bursts shown in Figure 9 occurred shortly before the reported time of Hα maximum of this 2B flare. The Hα event began at about 16:36 UT and reached maximum intensity at 16:45 UT. The fixed-frequency spectrum of the radio burst is shown in Figure 3, as the 11/18 event in Group II. The meter-wave bursts all occurred earlier than 16:51 UT, the time of the centimeter-wave maximum. At least 5 type II (slow drift) and type III (fast drift) bursts can be seen in the reproduction (Figure 9) of the photographic record of the dynamic spectrum of this burst from the Harvard station at Fort Davis, Texas. The most striking feature of Figure 9 is the coincidence in time of the largest maximum in the EUV (OVI, 1032 Å) light curve and the start of a large type II radio burst. In addition, each secondary maximum in the EUV light curve coincides with a type II or type III burst, as denoted by the arrows in Figure 9. Although precise timing is hampered by the 30-s time resolution of the EUV data, the coincidences support the connections between the acceleration of mildly relativistic electrons and the generation of EUV bursts.

5. Summary and Conclusions

In this paper and Paper I, we have presented the first spatially and temporally resolved EUV observations of solar flares. From comparisons of our data with Hα, X-ray, and radio data for the same flares, we find that the EUV emission generally occurs simultaneously with the impulsive (nonthermal) X-ray and microwave burst, and its maximum generally precedes the maximum intensity of the Hα and soft (thermal) X-ray burst by up to several minutes. The EUV emission rises very rapidly to maximum intensity and decays somewhat more slowly to the preflare level. In general, the EUV burst lifetime is much shorter than the Hα or soft X-ray burst, although it is generally longer than the lifetime of the accompanying nonthermal X-ray or microwave burst.

In general, our data do not allow us to distinguish between EUV bursts associated with Group I and Group II radio bursts. However, EUV burst parameters (rise time, peak intensity) do depend on the X-ray burst characteristics. Nonthermal X-ray bursts are accompanied by strong, rapidly rising EUV events, while X-ray events with a weak, or completely missing, nonthermal component tend to be associated with weaker, more slowly rising EUV flares.

Comparison of the EUV light curves with light curves in other spectral ranges very often shows detailed coincident time structure. This is especially noticeable in the events of 27 August 1969 (Figure 7) and 18 November 1969 (Figure 9).

The observations presented in this paper suggest a picture in which the EUV emission is a mixture of two components, analogous to the X-ray emission from flares. Each of these two components is excited by different, though related, mechanisms. The EUV radiation associated with impulsive, nonthermal X-ray bursts is produced thermally as a result of direct heating by the injection into the chromo-
sphere of energetic, nonthermal electrons, accelerated in the flare instability. The second EUV component is generally associated with thermal X-ray bursts and may represent the indirect heating of nearby chromospheric plasma by conduction, shock waves, or radiation from the very hot plasma in the source region.

The observed dependence of the maximum emission measure on temperature for flares (Figure 5) suggests that the flare region may have a temperature structure similar to that of an active region, in which a narrow transition zone separates a region of very high temperature from the cooler ambient chromospheric plasma. This interpretation further suggests that thermal conductivity can be a significant factor in determining the structure even on time scales as fast as the flare rise.

This picture is uncertain because to date any given flare has been observed only in a single spectral line. The crucial tests of the picture can be made only with observations at high spatial (∼5 arc sec) and temporal (∼5 s) resolution made simultaneously in several spectral lines formed over a wide range of temperature. Such observations are needed to determine whether all the EUV lines brighten simultaneously, or whether, for example, lines formed at lower temperature reach maximum before those formed at high temperature. Such observations would also show the detailed spatial structure of the EUV emission and its relation to the X-ray and Hα-emitting regions. Plans are under way to obtain such observations from the Apollo Telescope Mount (ATM) to be flown as part of the forthcoming Skylab program of the National Aeronautics and Space Administration.

Acknowledgements

We would like to thank G. Withbroe, W. Tucker, G. Blumenthal, A. Dupree, E. Reeves, and W. Parkinson for much helpful discussion. We are grateful to many investigators who have supplied us with often unpublished observations: S. R. Kane (University of California, Berkeley), R. W. Milkey (Los Alamos Scientific Laboratory), D. M. Horan (Naval Research Laboratory), H. D. Prince (McMath-Hulbert Solar Observatory), J. M. Pasachoff (Big Bear Solar Observatory), J. P. Castelli (Air Force Cambridge Research Laboratory), H. Tanaka (Toyokawa, Japan), M. Ishitsuka (Huancayo, Peru), A. E. Covington (Ottawa, Canada), and R. F. Donnelly and S. Young (University of Hawaii). The research described here has been supported, in part, by the National Aeronautics and Space Administration through contracts NAS 5-9274 and NAS w-184.

References


