EXTREME ULTRAVIOLET OBSERVATIONS OF SOLAR FLARES

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Abstract

Extreme ultraviolet observations of solar flares made by the Harvard College Observatory experiments onboard OSO 4 and OSO 6 have been analyzed. The data were obtained with spatial resolution as good as 35 arc sec and temporal resolution as good as 30 sec. The principal results of the analysis are 1) euv bursts generally reach maximum intensity before either the Hα or x-ray burst associated with the flare, except that, for those flares that have nonthermal x-ray bursts, the euv, Hα, and x-ray maxima all appear to be simultaneous; 2) euv peak intensity is correlated with burst e-folding rise time. A picture is suggested to explain the observations, in which the euv emission is produced in chromospheric gas that is being heated by the collisional losses of nonthermal electrons.

I. Introduction

For the past several years, Harvard College Observatory has been carrying out a program of solar observations in the extreme ultraviolet (λλ 300 - 1350Å), designed to observe solar features with good spatial, spectral, and temporal


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resolution. This program has provided a unique set of observations of solar flares at and near the most recent peak in the 11-yr cycle of solar activity. The investigations reported here treat observations of solar flares with spectral resolution of 3.2Å (sufficient to isolate individual emission lines), spatial resolution as good as 35 arc sec (about 20,000 km near the center of the solar disk), and temporal resolution as good as 30 sec. These data provide important clues toward the understanding of the flare process.

II. Observations

The euv data used in this study were obtained by the Harvard College Observatory experiments onboard the satellites Orbiting Solar Observatory (OSO) 4 and OSO 6. OSO 4 was launched on Oct. 23, 1967, and returned data until Nov. 29, 1967. OSO 6 was launched on Aug. 9, 1969, and the Harvard instrument is still operable, although flare observations did not extend beyond the end of 1969. This report includes data from the five-week lifetime (Oct. 25-Nov. 29, 1967) of the OSO 4 experiment and from the first 3 1/2 months (Aug. 14-Nov. 25, 1969) of the OSO 6 experiment.

During these two periods, more than 450 rapid brightenings were observed in euv emission lines and continua; most of these were associated with Hα subflares observed from the ground. Some of the euv bursts were associated with larger Hα flares of importance classes 1, 2, and 3.

The OSO 4 and OSO 6 data used here were spectroheliograms, either of the entire visible hemisphere (OSO 4) or of selected areas 6.8 x 7.9 arc min (OSO 6) obtained at a fixed and predetermined wavelength. The spectral resolution of both spectrometers was 3.2Å, so that all of the energy in the selected emission line could be recorded, even if large Doppler shifts occurred. The spatial resolution of the OSO 4 instrument was 1 arc min, and the temporal resolution was 307.2 sec. For the OSO 6 instrument, the spatial and temporal resolutions were 35 arc sec and 30.72 sec, respectively. For further details on the experiments, see Reeves and Parkinson (1970) and Huber et al. (1972).

From the observed sequences of spectroheliograms, we have plotted light curves showing the time history of the emitted intensity for selected raster elements. The light curves were generally constructed for those points in the instrumental field of view where a solar flare was observed from the ground at a time when the spacecraft was in daylight.
In the OSO 4 observations, we have identified 269 flares, in 36 spectral lines of 24 ionic species ranging from neutral hydrogen to Fe XV and Fe XVI. In the data from OSO 6, we have identified 211 flares in 10 spectral lines of 10 ionic species. Together, these observations cover a temperature range from $10^4$ to $3.5 \times 10^6$ °K. Flare brightenings have been observed in the EUV lines of the following ions: H I, He I, He II, C I, C II, C III, N II, N III, N IV, N V, O I, O II, O III, O IV, O V, O VI, Ne VII, Ne VIII, Mg IX, Mg X, Si IV, Si XII, Fe XV, and Fe XVI.

III. Observational Results

A detailed discussion of all the results of our analysis is beyond the scope of this paper and is presented elsewhere (Wood et al., 1972; Wood and Noyes, 1972). However, we shall discuss some of the more important results here.

Figure 1 shows two typical EUV light curves and displays the general characteristics of all of the observed light curves. The EUV emission generally shows a rapid, apparently exponential rise to maximum intensity (e-folding rise times as short as 15 sec have been observed), followed by a somewhat slower decay to the preflare level. In some but not all cases, the decay shows one or more secondary maxima, which often correlate well with similar peaks in the x-ray or radio flux.

Figure 2 shows the observed correlation between the peak observed EUV intensity and the e-folding rise time measured from the light curves, and exhibits an interesting tendency for the stronger EUV bursts to have the shortest rise time. It has been recently pointed out (Kane and Anderson, 1970) that there often appear to be two x-ray burst components, one impulsive and one slow. It is apparent from Fig. 2 that the EUV light curves also show this dichotomy. As we and others have noted elsewhere (Kane and Donnelly, 1971; Wood and Noyes, 1972), the intensity profile of EUV bursts associated with impulsive x-ray events appears to have the same detailed time structure as that of the nonthermal x-ray component. We find (Wood and Noyes, 1972) that the EUV bursts associated with nonthermal, i.e., impulsive, x-ray bursts are among the events having the fastest rise times, whereas those events associated with x-ray bursts having no discernible nonthermal component have much slower premaximum rises. For 20 EUV events clearly associated with nonthermal x-ray bursts (see Wood and Noyes, 1972), the average rise time was $52 \pm 8$ sec, whereas, for all other EUV bursts accompanied by an x-ray burst, the average rise time was $100 \pm 20$ sec.
Fig. 1 Euv light curves typical of those observed by OSO 6.

These results suggest a picture that might explain the correlation between peak euv intensity and burst rise time, as well as the correlation between the euv and nonthermal x-ray bursts. In this picture, the euv radiation is produced thermally as chromospheric plasma is heated by the collisional losses of the nonthermal electrons that are responsible for the impulsive nonthermal x-ray burst. The ratio of total number of thermal to nonthermal electrons may vary from flare to flare, and one would expect to see a corresponding variation in the observed euv rise rate, since, as stated previously, the euv bursts associated with nonthermal x-ray bursts have much shorter rise times than do the euv flares associated with thermal x-ray bursts. A plot of x-ray burst intensity against rise time would probably appear very similar to Fig. 2.

An important question that the euv flare observations can help to answer is; What is the relative timing of the euv, Hα, and x-ray bursts from a typical flare? Figure 3 shows a two-dimensional plot of Δt(euv - Hα) against Δt(euv - x-ray),
Fig. 2 Observed correlation between euv peak intensity and burst rise time (OSO 6 data).

where the Δt's are the observed time lags between the euv maximum intensity and the maximum intensity in Hα or x-rays, respectively. The Δt's were defined such that positive Δt means that the euv maximum occurred first. In Fig. 3, the filled points denote those events having no discernible nonthermal burst component, whereas the open circles denote nonthermal x-ray events. The difference in the distributions of the filled and open circles is quite striking. To within the observational uncertainties (Hα: ±1 min; x-ray: ±1 min; euv: ±30 sec), the Hα, x-ray, and euv bursts associated with nonthermal events all reached maximum intensity simultaneously. On the other hand, for bursts that are predominantly slow (thermal), the x-ray and Hα bursts seem to be unrelated to the euv, although closely related (at least in the time of maximum intensity) to each other.
Fig. 3 Plot of $\Delta t(\text{euv} - \text{Ha})$ against $\Delta t(\text{euv} - \text{x-ray})$ (OSO 6). Open circles = events with nonthermal component; filled circles = events with no nonthermal component.

Figures 4 and 5 show, by means of examples, the close agreement between the euv light curves derived from the OSO 6 flare data and time-intensity curves in other spectral ranges. Figure 4 shows the radio and euv observations of a class 1N flare that occurred at 14:08 UT on Aug. 27, 1969. The radio data were obtained from the Air Force Cambridge Laboratory (AFCRL) station at Sagamore Hill, Mass. The euv data from OSO 6 were observed in the Lyman continuum of neutral hydrogen at 897Å. This burst shows quite well the occurrence of the two components mentioned previously. The time of the primary euv peak agrees quite closely with the occurrence of an impulsive microwave burst. Unfortunately, there are no x-ray observations available for this event, so we cannot state categorically that a nonthermal burst did occur. The time of occurrence of the secondary maximum in the euv emission also agrees quite closely with the time of occurrence of a small post-burst increase in the radio flux at frequencies greater than 8800 MHz. Kundu (1965) states that post-burst increases are probably of thermal
Fig. 4 Observations of 8/27/69 event at 14:08 UT. Upper trace = Lyman continuum at 897 Å (OSO 6); lower traces = radio burst observations (Sagamore Hill; courtesy of J. Castelli).

origin. Figure 4 shows that the secondary maximum in the euv, associated with the thermal source, has a much longer rise time (∼ 200 sec for the secondary burst vs 70 sec for the primary peak), which is consistent with the picture we suggested previously.

Figure 5 shows the euv, Sudden Frequency Deviation (SFD) (Donnelly, 1969, 1970), x-ray, and radio observations of a
class 2B flare that occurred on Oct. 24, 1969. This event has been analyzed previously in detail (Zirin et al., 1971) but with no comment on the ultraviolet observations. The euv data for this event are derived from two sources: 1) SFD observations for this event were obtained from the University of Hawaii. SFD observations are interpreted as the result of rapid ionization in the ionospheric F-layer by an impulsive increase in the 10 - 1030Å euv flux; and 2) the OSO 6 observations of the C I continuum at 1098Å. The x-ray data were obtained from the University of California, Berkeley experiment onboard OGO 5, and the radio observations were made at Sagamore Hill (AFCRL).

The significant feature of Fig. 5 is the marked similarity between the x-ray, radio and SFD light curves. The detailed time structure evident in these three traces is not present in the euv data from OSO 6, probably because of the rather poor time resolution of the OSO 6 data when compared to the x-ray, radio and SFD observations (30 vs 1-2 sec). However,
the major time structure of the OSO 6 data does agree closely with the other observations. This further supports our conclusion that there is an intimate physical relation between the euv and nonthermal x-ray bursts, and thus between the euv and nonthermal electrons in the solar atmosphere.

References


