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GAMMA-RAY AND OPTICAL OBSERVATIONS OF THE 1979 NOVEMBER 8 SOLAR FLARE

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ABSTRACT

The solar flare on 1979 November 8 $11^{h}21^{m}28^{s}$ UT was observed by the Tel Aviv telescope of the Big Bear Solar Observatory and the High Resolution Gamma-Ray Spectrometer (designated C-1) on the High Energy Astronomy Observatory *HEAO 3*. Photographs in Hα show the development of the flare and a subsequent Moreton wave. Although the flare was not detected with the high spectral resolution germanium detectors, the *HEAO* C-1 CsI shield detected a statistically significant signal above 80 keV, from 420 to 585 keV, and above 3.8 MeV. The temporal structure of microwave, optical, X-ray, and gamma-ray emission is consistent to within ~ 1 s with a simultaneous flare response at all energies. There is no evidence for either second-stage acceleration of charged particles (Bai and Ramaty) or a delay between gamma-ray and X-ray continuum emission due to energy-dependent electron energy loss times (Bai and Ramaty).

Subject headings: gamma rays: general — Sun: flares

I. INTRODUCTION

Gamma-rays ($E > 200$ keV) have been observed only from a small number of solar flares. For the flares of 1969 March and November (Langer, Petrosian, and Frost 1980), 1972 August 4 and 7 (Chupp *et al.* 1973; Bai and Ramaty 1976, 1979; Suri *et al.* 1975; van Beek, Hoyng, and Stevens 1973), and 1978 July 11 (Hudson *et al.* 1980), second-stage acceleration of energetic particles was invoked to explain the time delay between the onset of impulsive hard X-ray emission and the rise of gamma-ray emission. Energetic protons and neutrons were also postulated to explain the observed gamma-ray lines at 2.2 and 4.4 MeV and their delay compared to the gamma-ray continuum. These time delays ranged from ~ 20 s to more than 100 s.

In the X-ray range, thick-target bremsstrahlung is generally accepted as the mechanism for the generation of photons at energies from 10 to 200 keV by a non-thermal distribution of electrons (Kane *et al.* 1979). At lower energies, a flare kernel with a temperature of $\sim 10^{7}$–10^{8} K is invoked to explain X-ray flares (Petrasso, Gerassimenko, and Nolte 1979).

In contrast to the flares mentioned above, the 1979 November 8 flare discussed here does not show a time delay between hard X-ray and gamma-ray observations. The instruments used for the present observations and the resulting data are described in §§ II and III. An interpretation of these results and comparison with other flares are presented in § IV.

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II. GAMMA-RAY OBSERVATIONS

The *HEAO* C-1 Gamma-Ray Spectrometer is designed for high resolution gamma-ray observations of cosmic sources. A detailed description of the instrument is given by Mahoney *et al.* (1980). The central cluster of four cooled high purity germanium crystals is surrounded by a CsI anticoincidence shield. In its nominal orientation, the viewing direction of the high resolution germanium crystals is perpendicular to the instantaneous Earth-Sun line. Since the solar gamma-ray flux undergoes significant, energy-dependent attenuation in material outside the experiment, the anticoincidence shield, and the cryostat walls before reaching the germanium detectors inside the cryostat, a statistically significant signal in these detectors is expected only for intense, long duration flares. No signal was detected within the germanium crystals from the 1979 November 8 flare, in agreement with calculations based on the observed shield response. For an exposure time of 40 s, the minimum detectable flux (photons cm^{-2} s^{-1}) at the 3 σ level of significance for a narrow line is 0.22 at 511 MeV, 0.07 at 2.22 MeV, 0.13 at 4.4 MeV, and 0.20 at 6.1 MeV.

The CsI(Na) shield resembles a hollow cylinder with rounded corners and collimation holes along the viewing direction of each of the germanium detectors. In the nominal viewing geometry, the collimator and two of four shield quadrants are exposed to the Sun. The collimator is a cylindrical slab of 33.1 cm diameter and 6.6 cm height, viewed edge-on. The two exposed shield quadrants have a combined projected area of 20.8 cm height and 33.1 cm width. Each of these shield pieces is viewed by photomultiplier tubes and read out to the telemetry stream separately. Their total geometric area for exposure to the Sun is 907 cm^{2}.

For each CsI shield piece three counting rates are recorded: the LLD (lower level discriminator) rate contains all events of energy $E > 80$ keV and is read out every 1.28 s. The (511 keV) window rate contains all events within the energy band from 420 to 585 keV and is read out every 10.24 s. The ULD (upper level discriminator) rate records all events $E > 3.8$ MeV and is also read out every 10.24 s.

A roving pulse height analyzer samples the pulse height spectrum of any of the shield pieces with a duty cycle of 50%, alternating 40.96 s of spectrum accumulation with 40.96 s of readout to telemetry. Unfortunately, the roving pulse height analyzer was in the readout mode at the time of the flare, so that there is no direct gamma-ray spectrum information from the *HEAO* C-1 experiment except for the three integral rates mentioned above.

The *HEAO 3* spacecraft was launched on 1979 September 20 into a circular orbit of 500 km altitude and 43°.6 inclination. At the time of the peak of the 1979 November 8 flare, the *HEAO 3* spacecraft was above the geographical location 110°.8 E, 11°.2 N, moving in a north-easterly direction from the sunlit portion of the orbit toward the terminator. To account for absorption by the intervening atmosphere along the line of sight to the Sun, the moment of entry into the "night" side of the orbit precedes the moment of optical occultation which is calculated for the solid Earth horizon. With a 10% attenuation criterion for gamma-rays of 100 keV energy, we use an instantaneous tangent height of the line of sight to the Sun of 90 km to determine the moment of entry into the "night" portion of the orbit at $11^h22^m20^s$.

The solar flare was detected in the three exposed shield pieces (collimator, shield quadrants 1 and 2), but was not observed by the two remaining quadrants. The sums of counting rates in the three exposed shield pieces during two 99 s intervals before and after the solar flare were used to determine best-fit parabola models for the background counting rate variation as a function of time. After subtraction of the interpolated background model values, we obtain the net signal counting rates shown in the LLD, window, and ULD bands in Figure 1.

The net signal for LLD events rises from the 10% value to the peak at $11^h21^m28^s$ within 10 s and drops to the 10% value within another 27 s. The average rates (counts s^{-1}) during the 10.24 s interval beginning at $11^h21^m20^s$ are $I(\text{LLD}) = 27{,}649 \pm 58$, $I(\text{window}) = 603 \pm 10.8$, and $I(\text{ILD}) = 92.7 \pm 7.9$.

III. OTHER OBSERVATIONS

The sunspot group MtW 21030 = AR 2099 was active from 1979 November 5–16. Soft X-ray emission was recorded from 35 of 62 flares which had been observed optically during this period. Gamma-ray emission above 100 keV from seven of these flares was detected by the *HEAO 3* Gamma-Ray Spectrometer: the flare discussed here is one of three events with peak gamma-ray flux levels comparable to or larger than those of the 1972 August flares at all energies from 100 keV to several MeV.

Optical information for the 1979 November 8 flare is derived from the Tel Aviv telescope of the Caltech Big

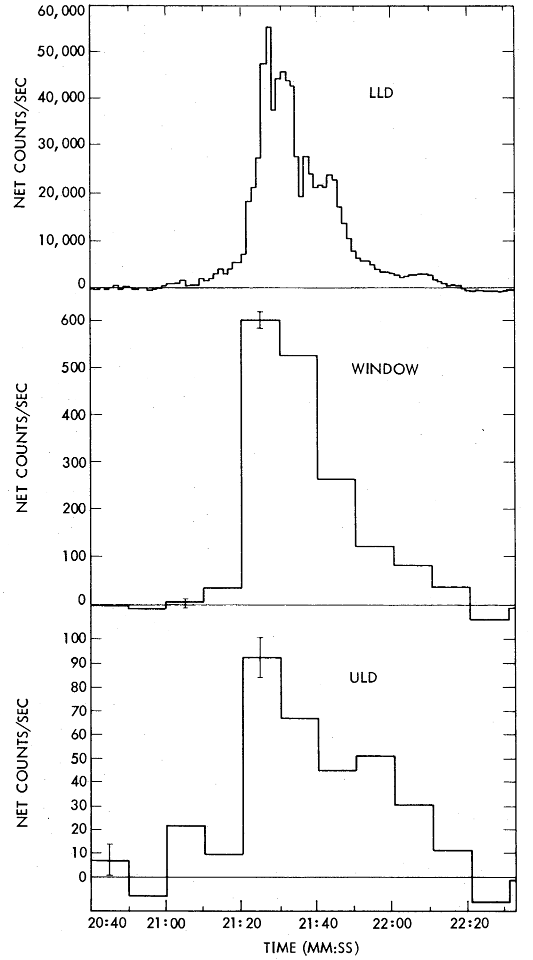

FIG. 1.—Net response to the 1979 November 8 solar flare in the collimator, shield 1 and 2. The net LLD ($E > 80$ keV), window (420 to 585 keV), and ULD ($E > 3.8$ MeV) rates were obtained after subtraction of a parabolic background approximation. The values of the typical 1 σ rate are indicated; for the LLD rates 1 $\sigma \approx 200$. To obtain universal time, add 11^h to the values shown here.

Bear Solar Observatory. The camera, which operated in Hα light, took one 0.5 s exposure every 19 s. A question mark–shaped area brightened and faded during November 8; at 11^h it had faded but began to brighten steadily to reach the preflare state visible in the first Hα frame in Figure 2 (Plate 11) at $11^h20^m43^s$.

In the second frame of Figure 2 at $11^h21^m20^s$, the flare had just begun, and the distant point *a* had brightened. Note that point *a* was connected to the flare area by curved dark fibril structure in the chromosphere which delineates the lines of force from preceding to following magnetic polarity. Measured along this arc, the distance from the flare to point *a* was 186,000 km. If we assume that the flare began midway between the frames at $11^h21^m01^s$ and $11^h21^m20^s$, then the resulting velocity of 18,600 km s^{-1} suggests that energetic electrons or protons produced the emission at *a*. A series of type II bursts was observed at this time at the Weissenau Observatory (Urbarz 1980).

The third frame of Figure 2 at $11^h21^m39^s$ shows a large increase in Hα brightness at the flare spot and a further brightening of point *a*, consistent with the assumption from *HEAO* C-1 gamma-ray data that the flare peaked at $11^h21^m28^s$. The fourth frame at $11^h21^m57^s$, taken near the end of the gamma-ray flare, shows that the flare region had expanded and decreased in brightness while emission at point *a* had increased.

A Moreton magnetohydrodynamic wave (Uchida 1973) moved out from the flare region, first appearing at $11^h22^m35^s$ (not shown) some distance from the flare. It can be seen as a diffuse brightening marked *w* in frames 5 and 6 of Figure 2. Two consecutive type II bursts, beginning at $11^h22^m00^s$ and $11^h23^m30^s$, were observed by Urbarz (1980). Microwave data from Berne University observations show that the first main peaks at 10.4 and 35 GHz, respectively, occurred at $11^h21^m28^s$ (Wiehl 1980). The fact that the 35 GHz flux was more intense than the 10.4 GHz flux suggests that either synchrotron self-absorption occurred or that the higher frequency emission originated lower in the photosphere.

Observations with the X-ray instrument on the *ISEE 3* spacecraft (Kane 1980), not shown here, also indicate that emission in several energy bands between 12 and 168 keV peaked at 1979 November 8 $11^h21^m28^s$.

The gamma-ray spectrometer on the spinning *P78-1* spacecraft (Imhof 1980) was exposed to the Sun every 5 s at $11^h21^m25^s$, 30^s, etc. A comparison of counting rates at each exposure indicates that the signal in the *P78-1* germanium detectors is also consistent with peak emission at $11^h21^m28^s$.

Although pulse height analysis data are not available from *HEAO* C-1, rough spectral features can be derived from the broad-band gamma-ray observations. The LLD and window data combined can be used to define the slope and amplitude of a power-law spectrum shape which satisfies the $E > 80$ keV and $420 < E < 585$ keV criteria after energy-dependent efficiency correction and normalization. For the 10.24 s interval which includes the peak of the flare, the resulting differential photon flux spectrum, $J(\text{photons cm}^{-2}\ \text{s}^{-1}\ \text{keV}^{-1}) = 0.6\ (E/100)^{-2.8}$, is shown in Figure 3 as the heavy solid line. Similarly, the window and ULD data together define another power law, $J = 0.22\ (E/100)^{-2.2}$, shown as the heavy broken line in Figure 3. Note that a single power law from 100 keV to several MeV is ruled out since it would imply a window event rate significantly higher than the observed rate.

Because of uncertainties in the shield efficiency, a systematic error of $\pm 20\%$ (large compared to the statistical errors) is estimated for the absolute intensities of the inferred spectra and $\pm 10\%$ for the power-law indices. The systematic uncertainties for data from other experiments are not known; if they are comparable to those of *HEAO* C-1, then agreement between the experiments to within a factor of 2 in intensity in overlapping energy ranges is apparent.

The best power-law fit for germanium detector data in the 60–260 keV range from the Lockheed experiment aboard *P78-1* (Imhof 1980) is shown in Figure 3 as a dash-dotted line. X-ray data between 12 and 170 keV from the *ISEE 3* hard X-ray experiment (Kane 1980) are consistent in intensity and shape with the *P78-1* and *HEAO* C-1 spectral data for this solar flare.

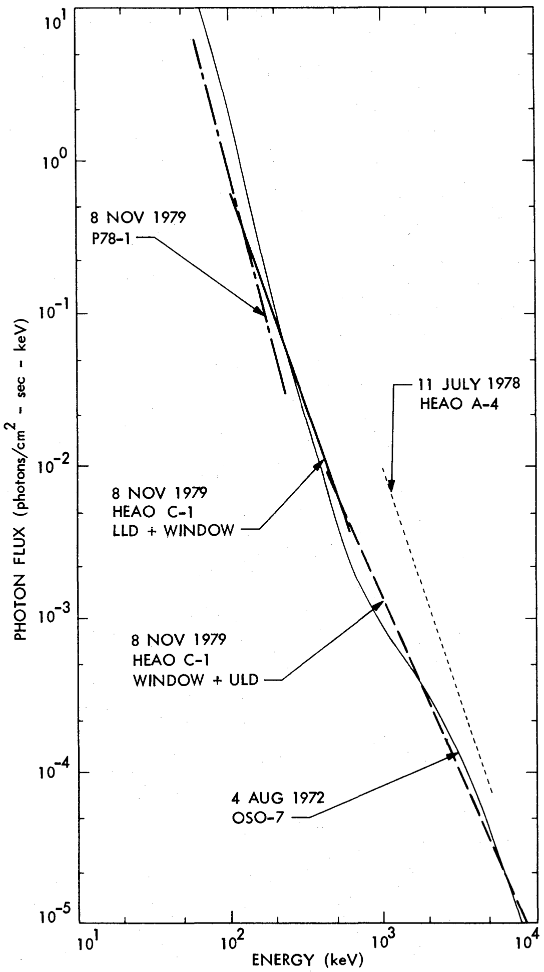

FIG. 3.—Continuum gamma-ray spectra of three prominent solar flares. Data for the peak of the 1979 November 8 flare are shown as heavy lines and are explained in the text. The *P78-1* spectrum was recorded by Imhof (1980). The continuum spectrum of the 1972 August 4 flare (Suri *et al.* 1975; van Beek *et al.* 1973; Bai and Ramaty 1973) is shown as a thin solid line, marked "*OSO 7*". The continuum spectrum of the 1978 July 11 flare (Hudson *et al.* 1980) is drawn as a dotted line.

There is no available information on interplanetary energetic particle measurements relating to the 1979 November 8 flare. Observations from *ISEE 3* (Klecker *et al.* 1980) showed that there is no correlation between the solar flare 2.2 MeV deuterium formation gamma-ray line intensity and the interplanetary particle flux; this suggests that particles observed in interplanetary space are not representative of the energetic particle distribution in the flare region.

IV. DISCUSSION

The data presented above show that the flare peak occurred simultaneously at all energies to within the readout rate of the observations which varied from 1 to 19 s. In particular, microwave observations, X-ray measurements, and the *HEAO* C-1 LLD measurements determine a flare rise and peak coincident to within 1 s. The gamma-ray broad-band data in Figure 1 demonstrate that the impulsive increase in the flare emission is simultaneous to within 10 s at energies from 100 keV to above 4 MeV.

We draw the following conclusions from the available temporal and spectral information:

1. The 1979 November 8 solar flare is of the short duration impulsive type with a peak at $11^{h}21^{m}28^{s}$. The duration of the gamma-ray flare, indicated by the time between 10% signal levels, is 37 s. This is significantly shorter than the 1000 and 300 s equivalent durations of the 1972 August 4 and 1978 July 11 flares, respectively (see Table 1). In fact, a survey of 20 other solar flares observed with *HEAO* C-1 shows that most of them have durations of less than 1 minute. We conclude that the 1972 and 1978 flares were unusual at least with respect to their duration.

2. Emission at all energies from the microwave band through the gamma-ray region above 100 keV peaked simultaneously within ~ 1 s (near 0.5 MeV and above 4 MeV simultaneously to within 10 s).

3. The peak-flux gamma-ray continuum spectrum of the 1979 November 8 flare is similar in shape to that of the 1972 August 4 flare. The photon flux levels of the two flares are within a factor of 2 of each other at all energies (Fig. 3). However, the microwave flux level for the 1972 flare was higher than that of the 1979 flare by a factor of 4 (Table 1). It appears that different parts of the electromagnetic spectrum do not scale from flare to flare. A comparison of *HEAO* C-1 gamma-ray data for 20 other solar flares with X-ray, optical, and microwave data also shows no apparent correlation. This suggests that neither relations between microwave and low-energy gamma-ray emission, based on radiation from relativistic electrons (see Ramaty 1973, and references therein) nor empirical relations (Hudson, Canfield, and Kane 1978) seem to apply for the 1979/1980 group of impulsive gamma-ray emitting flares.

4. There is no evidence for line emission in either the CsI shield or the germanium detector data. The 3 σ upper limit for detection of the 2.2 MeV line during a 40 s interval in the two germanium detectors nearest to the Sun is <0.07 photons cm^{-2} s^{-1} (see Table 1), compared with a positive signal of 0.28 photons cm^{-2} s^{-1} detected by Chupp *et al.* (1973) for the 1972 August 4 flare. This suggests that the relative number of energetic neutrons was lower during the 1979 flare than during the 1972 flare by at least a factor of 4. We point out that the very intense flare on 1979 November 9, with an integral continuum flux $I(>1 \text{ MeV}) = 10$ photons cm^{-2} s^{-1}, also had a relatively low deuterium line flux of $I(2.2 \text{ MeV}) = 0.3$ photons cm^{-2} s^{-1}.

5. The observed X-ray and gamma-ray spectrum hardens between 0.1 and 1 MeV. A simple two power-law model results in slopes of index 2.8 below $\approx$0.5 MeV and index 2.2 above $\approx$0.5 MeV. This spectral shape can be interpreted (Bai and Ramaty 1976) as due to bremsstrahlung by electrons with a single power-law spectrum at all energies up to ~ 10 MeV. The spectrum hardening would be due to the fact that the spectrum index of the bremsstrahlung cross section changes by ≈ 1.0 between the nonrelativistic and relativistic domain (Bai 1977).

6. There is no evidence for any significantly delayed "second-phase" acceleration of the type proposed by Bai and Ramaty (1976). However, emission more than 52 s

TABLE 1

PROPERTIES OF PROMINENT GAMMA-RAY FLARES

Flare date	1972 August 4	1978 July 11	1979 November 8
Microwave flux at 35 GHz			
(SFU = 10^{-22} W m^{-2} Hz^{-1})	8,000	12,000	2,000
Soft X-ray flux (ergs cm^{-2} s^{-1})	?	3	0.1
Low-energy gamma-ray flux			
($E > 100$ keV) (photons cm^{-2} s^{-1})	67[a, b]	500[c]	32
High-energy gamma-ray flux			
($E > 1$ MeV) (photons cm^{-2} s^{-1})..........	1[d]	5[c]	1.0
Rise time (s)	102[a, b, d]	62[c]	10
Decay time (s)	600[a, b, d]	150[c]	27
Line flux (photons cm^{-2} s^{-1})			
or 3 σ upper limit[c]			
0511 MeV	0.063	...	<0.22
2.223 MeV	0.28	1.0	<0.07
4.434 MeV	0.03	0.18	<0.13
6.13 MeV	0.03	...	<0.20

[a] Adapted from van Beek *et al.* 1973.

[b] Bai and Ramaty 1976.

[c] Adapted from Suri *et al.* 1975 for the 1972 August flare, from Hudson *et al.* 1980 for the 1978 July flare, and computed for 40 s integration time for the present data.

[d] Rise time is determined from 10% to 100% of first burst or main peak flux. Decay time is determined from 100% to 10% of main peak or last burst flux. Gamma-ray characteristic times were derived from LLD data.

after the 1979 November 8 flare would not have been observable because of Earth occultation.

7. There is also no evidence for the time delay (of up to 20 s) between gamma-ray and X-ray continuum emission which might be due to an increase of electron energy loss time with electron energy as proposed by Bai and Ramaty (1979) for the 1972 August 4 flare.

8. The 1979 November 8 flare had an open magnetic configuration and was impulsive (like the rest of the gamma-ray emitting flares from the same active region). The 1972 August 4 flare, on the other hand, occurred inside a larger, but tightly confined region bounded by sunspots and twisted fields (Tanaka and Zirin 1973), where energy could be stored for a longer period of time. The flare area and total Hα emission were $\sim$10 times larger for the 1972 than the 1979 flares.

Many persons have contributed to the development and successful operation of the *HEAO* C-1 Gamma-Ray Spectrometer. We wish to acknowledge in particular the efforts toward a smooth data flow by the teams working with W. Bradley (MSFC), J. Seebach (TRW), G. Vincent (GSFC), and H. Cox (JPL). The computer programs for this analysis have very ably been produced by J. Bradley, A. Dunklee, and B. Gokhman. The scientific advice of Drs. R. Ramaty and H. Hudson is greatly appreciated.

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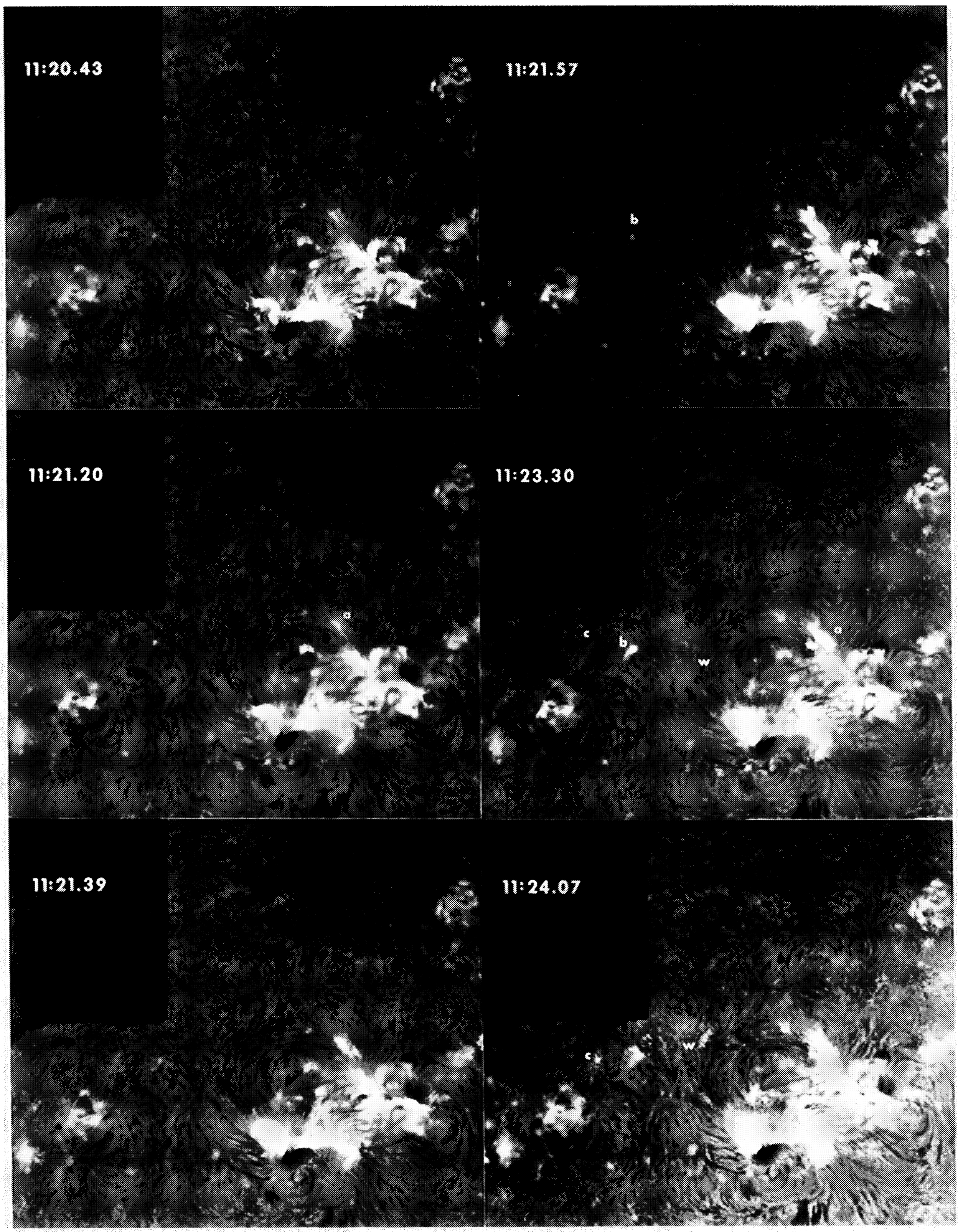

FIG. 2.—Hα photographs of the 1979 November 8 solar flare. Six frames at $11^h20^m43^s$, 21^m20^s, 21^m39^s, 21^m57^s, 23^m30^s, and 24^m07^s show the development of the flare, distant bright points *a* and *b*, and the Moreton wave *w*. North is on top, east is to the right.

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