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CHARACTERISTICS OF THE WHITE-LIGHT SOURCE IN THE 1981 APRIL 24 SOLAR FLARE

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ABSTRACT

The "white-light" flare on 1981 April 24 (~ 1358 UT) was very well observed in the continuum emissions at the optical, hard X-ray, and radio wavelengths. The time-intensity profiles of the three emissions are basically similar to each other. *Impulsive* and *gradual* components can be clearly identified in all the three types of emission. At the times of the impulsive and gradual maxima the observed white-light power was $\sim 1.4 \times 10^{27}$ and $\sim 7 \times 10^{27}$ ergs s^{-1}, respectively. The corresponding power in electrons ≥ 25 keV deduced from the observed hard X-ray spectra was $\sim 7 \times 10^{28}$ and $\sim 1 \times 10^{29}$ ergs s^{-1}, respectively. A good temporal relationship is observed between the *impulsive* hard X-ray and white-light emissions. The relationship between the *gradual* hard X-ray and white-light emissions, however, is relatively poor. A model in which the white-light emission is produced nonthermally in the upper chromosphere through the energy provided by energetic (≥ 25 keV) electrons is consistent with the observations, provided the white-light source during the impulsive phase consists of an overdense region located somewhat higher in the chromosphere than the levels where hydrogen densities of $\sim 10^{14}$ cm^{-3} normally occur. At the maximum of the *gradual* phase, the white-light emission might, within the limits of the observational uncertainties, be produced by higher energy ($\gtrsim 100$ keV) electrons in a normal chromospheric structure.

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

I. INTRODUCTION

Among the many types of solar flare observations, the observations of white-light flares are relatively rare. This is partly because of the small magnitude of the white-light (continuum) enhancement above the quiescent background. Hence the enhanced optical continuum is detectable only in very large flares, although some enhancement of the continuum emission probably occurs even in smaller flares (McIntosh and Donnelly 1972). Past observations of white-light flares have been discussed by Svestka (1976), Zirin and Neidig (1981), Neidig (1983), Ryan *et al.* (1983), Neidig and Wiborg (1984), and others. In most cases useful observations during the critical time intervals, such as the impulsive phase and flare maximum, were not available, because of either poor seeing or inadequate time resolution and spectral coverage. In addition, important information, such as energy deposition by the energetic particles as deduced from the hard X-ray and γ-ray measurements, was also not available for some flares. Consequently, the energetics of white-light emission and its role in the solar flare process are not well understood.

The large white-light flare on 1981 April 24 (~ 1358 UT) was very well observed at the hard X-ray, optical, and radio wavelengths. Energetic particles escaping from the Sun were detected in the interplanetary space and in the vicinity of Earth. The flare had distinct *impulsive* and *gradual* phases and provided the best available measurements of the optical continuum in a solar flare. In this *Letter* we present these observations and discuss their interpretation in terms of the energetics of the flare and the role of energetic electrons in the production of optical continuum emission.

II. OBSERVATIONS

The hard X-ray observations were made with the X-ray Spectrometer aboard the *ISEE 3* (*International Sun-Earth Explorer 3*) spacecraft (Anderson *et al.* 1978; Kane *et al.* 1982). Here we will be primarily concerned with the hard X-ray measurements which cover the 12–1500 keV energy range in 12 energy channels. The basic time resolution is 0.5 s for 12–180 keV X-rays and 1–4 s for higher energies.

The optical data were obtained from photographic images taken with the Multiband Polarimeter (MBP) (Neidig and Beckers 1983) at Sacramento Peak Observatory, in six bands at wavelengths chosen to exclude strong chromospheric lines. The time between successive exposures was 5 s, yielding 30 s resolution at a given wavelength. White-light flare spectra are known to be relatively flat for $\lambda \gtrsim 4000$ Å but rise steeply at $\lambda \lesssim 4000$ Å (Zirin and Neidig 1981; Neidig 1983). The ob-

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servations of the April 24 flare, which include measurements both longward and shortward of 4000 Å, are consistent with this spectral shape at all times during the flare. We have computed the total radiated power as the sum of the power in two assumed $\Delta\lambda$ intervals, 2500–4000 Å and 4000–10,000 Å, using the intensity measurements in bands centered at 3610 and 4957 Å, respectively, as representative intensities for these intervals. The indicated time of white-light measurements presented herein relates to the time of the 2500–4000 Å interval measurement, which contains approximately half of the continuum energy.

The principal characteristics of the 1981 April 24 (~ 1358 UT) flare may be summarized as follows. The Hα flare was of importance 2B and was located at N19, W50 in the Boulder region 3049. The associated soft X-ray burst (X5.9) and microwave burst (14,300 sfu at 35 GHz) were very intense. The peak frequency f_{max} for the microwave emission spectrum was $\gtrsim$ 35 GHz. Intense type II, III, and IV radio bursts in the metric-decimetric range have also been reported. Following the optical flare, energetic protons were observed in the interplanetary space (McGuire 1983), and a polar cap absorption (PCA) event was also recorded. Thus the event was a major solar flare which produced many energetic emissions. Gamma-ray observations were not available for this flare (the *SMM* satellite was in Earth's shadow).

The structure of the white-light flare was very complex. A total of 10 individual centers of activity ("kernels") could be identified. Most of the emission, however, originated in one center, which produced ~ 100% and ~ 96% of the total continuum emission at the peak of the impulsive and gradual phases, respectively. In the following discussion we will consider only the sum of the instantaneous emissions from all 10 centers of activity.

The *impulsive* and *gradual* phases of the flare can be clearly identified in all the three emissions shown in Figure 1. For X-rays $\gtrsim$ 70 keV, the *impulsive* enhancement started at ~ 1345:30 UT, reached its principal maximum at ~ 1347:25 UT, and then decreased rapidly during the next 35 s. The total duration of the impulsive burst was ~ 2.5 minutes. The *gradual* enhancement started at 1348:10 UT and had a duration of ~ 20 minutes. Relatively large fluctuations were superposed on the gradual emission, giving rise to seven individual peaks and valleys. The time between the peaks varied from 64 s to 134 s, the average time being ~ 110 s. Similar features can also be identified in the profiles of the 35 GHz emission and X-rays < 70 keV. However, the relative amplitude of the fluctuations is much smaller in the low-energy X-rays.

The variations in the white-light emission are, in general, similar to those in the X-ray emission. There are several features of this relationship which need to be noted:

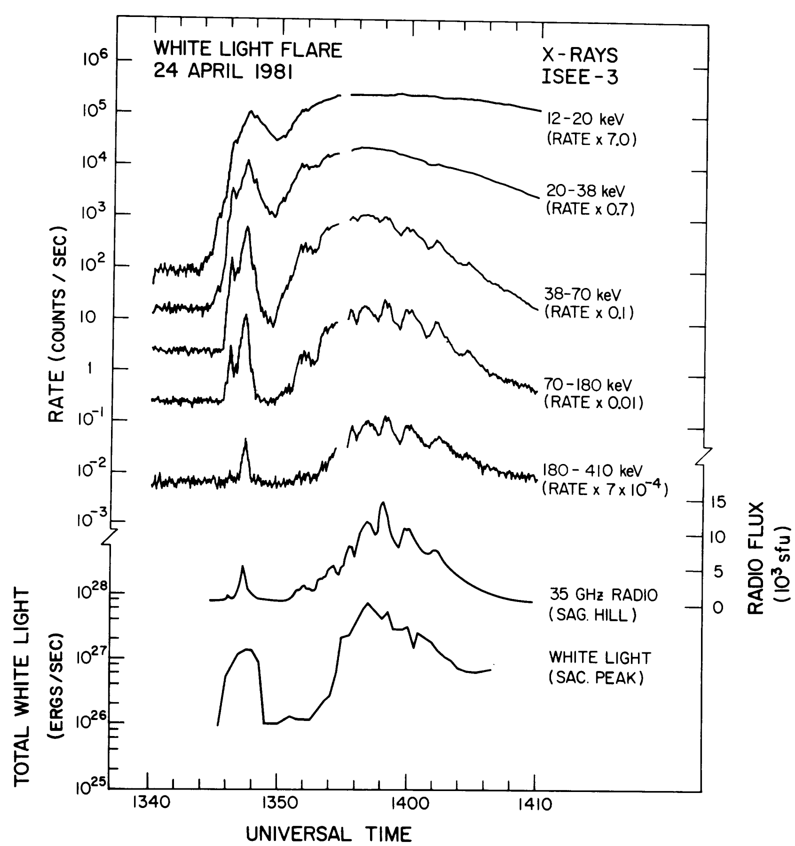

FIG. 1.—Time-intensity profiles of the hard X-ray, microwave, and white-light emissions during the 1981 April 24 flare. No X-ray data are available from 1354:10 to 1355:10 UT because of a gap in the spacecraft telemetry. The X-ray data are averaged over 4 s. The time resolution for 35 GHz radio and white-light measurements is ~ 1 s and 30 s, respectively. Errors in the white-light power are estimated to be $\lesssim$ 50% in a relative sense. The *impulsive* (before 1350 UT) and *gradual* (after 1350 UT) phases can be clearly identified in this flare. Note the fluctuations in the X-ray and microwave emissions during the gradual phase. The apparent fluctuations in the gradual white-light emission are within the uncertainties of the measurements and hence may not be significant.

1. The impulsive phase white-light emission shows only one broad maximum instead of the two distinct peaks visible in the $E \gtrsim 20$ keV X-rays. Also, the white-light emission in the later impulsive phase (~ 1348 UT) remains strong while the $\gtrsim 70$ keV X-rays return to background level. At ~ 1349:30 UT the white-light emission returned to the background level. At that time $\lesssim 70$ keV X-rays also reached a minimum, although they did not return to their background level. Thus the temporal variations of the impulsive phase white-light emission bear greater similarity to the lower energy X-rays.

2. At the end of the impulsive phase, the white-light emission nearly returns to the background level and remains at that level for ~ 2 minutes before the start of the gradual phase increase. On the other hand, the low-energy (20–38 keV) X-ray flux does not return to the background level, between the impulsive and gradual maxima. The onset of the gradual phase increase in the white-light emission coincides much better with the onset of the gradual 180–410 keV X-rays.

The measured X-ray fluxes were found to be consistent with the double power-law spectrum

$$\frac{dJ}{dE} = \begin{cases} k_1 E^{-\gamma_1} & \text{for} \quad E \le E_B \\ k_2 E^{-\gamma_2} & \text{for} \quad E \ge E_B \end{cases} \qquad (1)$$

$$\text{photons cm}^{-2}\ \text{s}^{-1}\ \text{keV}^{-1},$$

where E is the photon energy (keV) and $k_1, k_2, \gamma_1, \gamma_2$, and E_B are spectral parameters. Observations of the spatial structure of the hard X-ray source in other flares indicate that most of the hard X-ray emission is produced very low in the solar atmosphere (Kane *et al.* 1982; Kane 1983). Hence, using a thick target bremsstrahlung formula (cf. Evans 1955), the spectrum of the injected/accelerated electrons and their energy content can be deduced. The procedure for fitting the X-ray spectra and obtaining the electron spectra has been described elsewhere (cf. Kane *et al.* 1983).

A total of 42 "white-light" measurements were made during this flare, each measurement separated by 30 s. Of these 42 measurements, eight occurred during the impulsive phase, and 34 occurred during the gradual phase. The simultaneous measurements of X-ray fluxes were used to deduce the electron spectra at the times of the white-light measurements. The observed white-light power and the parameters of the hard X-ray spectrum as well as the deduced electron power at the time of the impulsive and gradual peaks are presented in Table 1. It can be seen that the hardness of the X-ray spectrum is very modest, especially above 70 keV ($\gamma \approx 4$).

In order to obtain a quantitative estimate of the correlation between the energetic electrons and white light, correlation coefficients between P_e and P_w were computed separately for the impulsive and gradual phases. Throughout the flare, P_e ($\gtrsim E_{e0}$) is greater than P_w as long as the electron energy $E_{e0} \lesssim 40$ keV. For P_e ($\gtrsim 25$ keV) and P_w, the correlation coefficients were found to be 0.92 and 0.74 for the impulsive and gradual phases, respectively. For P_e ($\gtrsim 150$ keV) and P_w, the corresponding correlation coefficients were 0.53 and 0.82, respectively. Thus electrons $\gtrsim 25$ keV are much better correlated with white light during the impulsive phase. During the gradual phase, the electrons $\gtrsim 150$ keV have slightly better correlation; however, P_e ($\gtrsim 150$ keV) is less than P_w.

TABLE 1

ENERGY DISTRIBUTION IN 1981 APRIL 24 FLARE

PARAMETER	PHASE: Impulsive	PHASE: Gradual
Time of maximum (UT)	1347:25	1358:04
White light:		
Power at Sun (ergs s^{-1})	$\sim 1.4 \times 10^{27}$	$\sim 7 \times 10^{27}$
Hard X-rays:		
Flux (photons cm^{-2} s^{-1} keV^{-1}):		
25 keV	107	202
100 keV	0.8	1.6
Spectrum (10–1500 keV):		
γ_1	3.3	3.4
γ_2	4.2	3.6
E_B (keV)	71	50
Electrons at Sun (deduced):		
Rate (particles s^{-1}):		
$\gtrsim 25$ keV	1.3×10^{36}	2.4×10^{36}
$\gtrsim 100$ keV	1.1×10^{34}	2.1×10^{34}
Power (ergs s^{-1}):		
$\gtrsim 25$ keV	7.1×10^{28}	1.4×10^{29}
$\gtrsim 100$ keV	2.4×10^{27}	4.6×10^{27}

III. DISCUSSION

Following the suggestion by Kane and Donnelly (1971) that impulsive EUV emission is produced nonthermally in the upper chromosphere by energetic electrons precipitating downward from the corona, Hudson (1972) proposed that energy deposition in the chromosphere (density $n = 10^{12}$–10^{13} cm^{-3}) by electrons $\gtrsim 10$ keV and subsequent ionization and free-free and free-bound transitions give rise to the white-light continuum, too. Quantitative modeling of such a white-light source is currently in progress (Canfield, Fisher, and McClymont 1983). On the other hand, Svestka (1970) and Najita and Orrall (1970) have argued that the white-light emission originates in the photosphere, which is heated as a result of the energy deposition by $\gtrsim 20$ MeV protons. Both points of view have been discussed extensively in the literature (cf. Brown and Smith 1980).

The present hard X-ray observations show that there is sufficient power in electrons $\gtrsim 40$ keV to supply the white-light emission at *all* times during the April 24 flare. The temporal correlations in the *impulsive* phase suggest an association with $\gtrsim 25$ keV electrons. During the *gradual* phase, whereas the temporal correlation is optimum for $\gtrsim 150$ keV electrons, the highest energy electrons with sufficient power are those with energy $\gtrsim 75$ keV. The better temporal correlation at higher electron energies in the gradual phase is due mainly to the fact that the onset of the gradual phase white-light emission is delayed by several minutes, relative to the onset of the gradual phase X-ray emission at lower energies. This delay could be expected if, for example, during 1349–1353 UT the electrons were depositing their energy over a larger area than the observed white-light source, so that the electron-produced white-light emission at that time would be too faint for detection (the possibility of a much larger target area during the gradual phase of the April 24 flare may, in fact, be indicated by the extent of the Hα emission, which is far more widespread than the white-light emission [Neidig and Beckers 1983]).

Thus, on the basis of both energetics and timing we conclude that the impulsive phase white-light source is associated with electrons of relatively low energy $E_e \approx 25$–40 keV. These energies are somewhat lower than those inferred by Rust and Hegwer (1975) who found a temporal correlation between white-light *intensity* and 60–100 keV X-rays in the 1972 August 7 flare.

The range of a 25 keV electron is limited to a column density $\sim 5 \times 10^{19}$ cm^{-2} (cf. Bai 1982), which means that the bulk of the $\gtrsim 25$ keV electron power can be deposited in the chromosphere. This is consistent with the model proposed by Hudson (1972) where the white-light emission is produced by electrons $\gtrsim 10$ keV through collisional ionization and subsequent free-free and free-bound transitions. Although Hiei (1982) and Neidig (1983) suggested that a substantial fraction of the flare optical continuum was due to H^- emission originating below the chromosphere, more recent analysis of the spectrum of the April 24 flare indicates that the dominant emission mechanism is free-bound transitions originating in the chromosphere (Neidig and Wiborg 1984). The latter analysis used spectral data at the peak of the gradual phase, although the MBP data used herein show evidence for a strong Balmer jump, characteristic of free-bound transitions, at all times during the flare. Thus, the optical data are consistent with a chromospheric origin in both the impulsive and gradual phases.

We are able to show that there is both sufficient power and range in the energetic electrons to produce the white-light emission in the *approximate* atmospheric regime indicated by spectral analysis. Nevertheless, we cannot conclude that the energy is transported *directly* to *all* parts of the white-light source by electrons, because spectral data are not available with which to derive the actual column densities at all times and locations within the white-light source.

In the case of direct energy transport by electrons the upper limit on the allowable column density within the white-light source is set by the range of the energetic electrons. If we assume that the white-light emission is due to free-bound transitions of hydrogen under optimum conditions (10^4 K and optically thin: see, for example, Brown and Mathews 1970) then the observed intensities at 5000 Å at the peak of the impulsive and gradual phases (2×10^5 and 8.4×10^5 ergs cm^{-2} s^{-1} sr^{-1} Å^{-1}, respectively), could be produced within the column density limits if the electron densities in the white-light source were 2×10^{14} and 7×10^{13} cm^{-3}, respectively. A density of 2×10^{14} cm^{-3}, however, would be encountered in the normal solar atmosphere, even if totally ionized, at column depths exceeding 3×10^{21} cm^{-2} (Vernazza, Avrett, and Loeser 1981), which is almost two orders of magnitude larger than the range ($\sim 5 \times 10^{19}$ cm^{-2}) of a ~ 25 keV electron. Therefore we can conclude only that *if* the energy is transported directly by $E \gtrsim 25$ keV electrons, then the white-light source in the impulsive phase must consist of an overdense region located somewhat higher in the chromosphere than the levels where hydrogen densities of 10^{14} cm^{-3} normally occur. Such an overdense region would be consistent with the inhomogeneities in the vertical structure of the hard X-ray source deduced by Kane (1983) through the stereoscopic observations.

In the case of the *gradual* white-light emission, which seems to be somewhat better correlated with higher energy electrons, the electron density and column density constraints might be accommodated by the normal solar atmospheric structure. For example, ~ 100 keV electrons can penetrate to levels where the density is $\sim 10^{14}$ cm^{-3}. The energy carried by these electrons at the time of the gradual phase maximum is $\sim 5 \times 10^{27}$ ergs s^{-1} (see Table 1) which is comparable to the peak white-light power within the uncertainty (a factor of 2 in the absolute sense) of the white-light measurements. However, we would like to emphasize that the *detailed* temporal correlation between the white-light and $\gtrsim 100$ keV electrons is very poor during the rising part of the gradual phase.

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