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RAPID ACCELERATION OF ENERGETIC PARTICLES IN THE 1982 FEBRUARY 8 SOLAR FLARE

S. R. KANE[1]
Space Sciences Laboratory, University of California, Berkeley
E. L. CHUPP AND D. J. FORREST
University of New Hampshire, Department of Physics
G. H. SHARE
E. O. Hulburt Center for Space Research, Naval Research Laboratory
AND
E. RIEGER
Max-Planck-Institut für Physik und Astrophysik, Institut für extraterrestriche Physik
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ABSTRACT

Hard X-ray and gamma-ray measurements of the 1982 February 8 (~ 1250 UT) solar flare made with spectrometers aboard the *ISEE 3* and *SMM* spacecraft show that bursts of photons from ~ 40 keV to ~ 40 MeV are coincident to within ±1 s. This indicates that the acceleration of particles to relativistic velocities can occur promptly (within ~ 1 s). As far as the energetic particles interacting at the Sun are concerned, the "two-phase" process, which requires several minutes for particle acceleration to relativistic velocities, cannot account for the present gamma-ray observations. Even the "two-step" acceleration process, which is assumed to occur in a small magnetic loop, is severely constrained by the present observations.

Subject headings: particle acceleration — Sun: flares

I. INTRODUCTION

Solar flares are known to produce high-energy electrons and ions, some of which escape from the Sun and are detected in interplanetary space. Measurements of the electrons at the Sun are obtained by observations of the X-rays produced by bremsstrahlung and the radio emission generated through the synchrotron and plasma processes. Measurements of the ions at the Sun are obtained by observations of the gamma rays and neutrons produced by nuclear interactions with the ambient solar gas. In large flares the energy spectrum is estimated to extend from ~ 10 keV to $\gtrsim$ 25 MeV for electrons and ~ 10 MeV per nucleon to $\gtrsim$ 1 GeV per nucleon for the ions (Chupp 1983).

Because of the wide range of particle energies involved, it has been suggested that the acceleration of these particles occurs in two phases (cf. Wild, Smerd, and Weiss 1963; de Jager 1969; Sturrock 1974; Ramaty *et al.* 1980) and/or in two steps (Bai 1982), the first phase/step providing an injection of medium energy particles to the second phase/step for further acceleration to high energies. In this way, even a relatively slow and inefficient acceleration process can have adequate time to energize low-energy particles to very high energies. The occurrence of gradual (extended) hard X-ray emission following an impulsive X-ray burst, and in association with a type II radio burst, has been considered as evidence for a two-phase acceleration process (Frost and Dennis 1971). Similarly, some observations of time delays in peaks of the high-energy X-rays and gamma-ray line emission with respect to the corresponding peaks at lower energies have been cited as evidence of the two-step acceleration process (Bai 1982; Bai and Dennis 1985).

The hard X-ray and gamma-ray bursts in the 1980 June 7 and 21 solar flares have been studied extensively to deduce the properties of the acceleration process. The simultaneous occurrence (within 1 s) of the hard X-ray maxima over a wide range of energies indicates a single fast acceleration process, at least for electrons (Kane *et al.* 1983). Forrest and Chupp (1983) have examined the starting times of the hard X-ray and gamma-ray line emission through statistical tests. They found that the onset of the two emissions is essentially simultaneous (within ±0.8 s for the 1980 June 21 flare and ±2.2 s for the 1980 June 7 flare). When the interaction times for the energetic ions and electrons were taken into account, it was found that the observations are consistent with simultaneous acceleration and/or injection of electrons and ions. On the other hand, Bai (1982) has examined the same two flares with emphasis on the time delay between the occurrence of the hard X-ray and gamma-ray maxima. He claims that the observations support a two-step acceleration process. Two kinds of acceleration processes operating successively within a few seconds have also been proposed by Nakajima *et al.* (1983).

We present below more definitive observations relevant to this question. The photon measurements presented here extend from 15 keV to $\gtrsim$ 25 MeV and support the existence of a single acceleration process capable of accelerating particles to relativistic velocities on a time scale of $\lesssim$ 1 s.

[1]Visiting Scientist at the Department of Physics, University of New Hampshire, Durham, New Hampshire.

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II. OBSERVATIONS

The observations reported here were made with the gamma-ray spectrometer (GRS) experiment aboard the *Solar Maximum Mission* (*SMM*) satellite and the X-ray spectrometer aboard the *International Sun Earth Explorer 3* (*ISEE 3*) spacecraft. The *SMM* and *ISEE 3* instruments have been described earlier by Forrest *et al.* (1980) and Kane *et al.* (1982), respectively. The *SMM* instrument measures both continuum and line spectra of photons from 10 keV to 100 MeV in several energy bands with time resolution ranging from 0.128 to 2.05 s. Accumulation of a complete energy loss (0.3–9 MeV) spectrum requires 16.384 s. The *ISEE 3* instrument is designed for X-ray continuum measurements in 12 energy channels. At the time of the present observations, the *ISEE 3* instrument measured 15 keV–1.9 MeV photons with a time resolution of 0.5–4 s. (At ~ 1 MeV, the *SMM* instrument is ~ 20 times more sensitive than the *ISEE 3* detector).

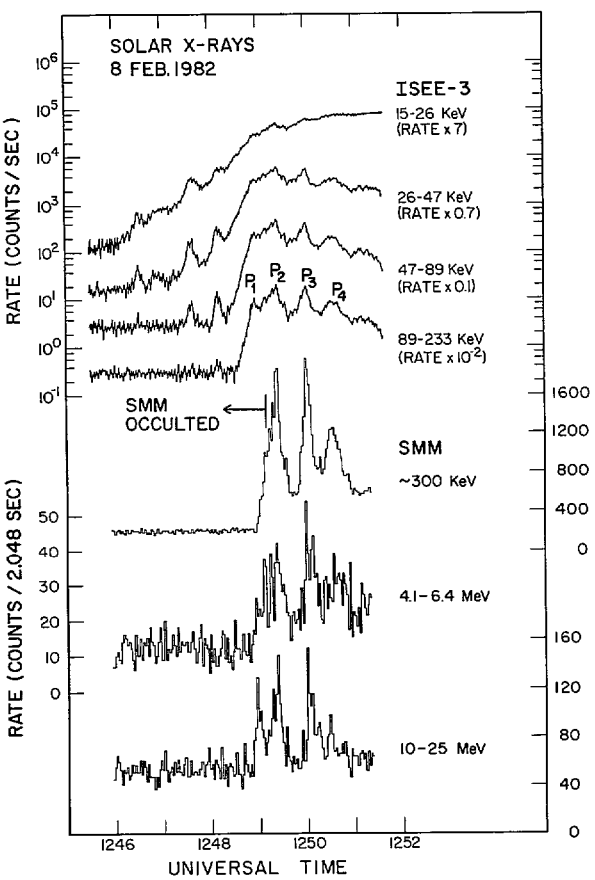

FIG. 1.—The time-intensity profiles of the X-ray and gamma-ray emission associated with the 1982 February 8 (~ 1250 UT) solar flare. Only data from the 15–233 keV X-ray channels (1 s averages) in *ISEE 3* and ≳ 300 keV X-ray and gamma-ray channels (2 s averages) in *SMM* are shown. In order to cover the large dynamic range, the *ISEE 3* and *SMM* data are plotted on log and linear scales, respectively. There are four relatively sharp peaks, P_1, P_2, P_3, and P_4, in the *ISEE 3* data. During the early part of the event, *SMM* was just coming out of Earth's shadow and hence only the peaks P_2, P_3, and P_4 were recorded by the *SMM* instrument. Note the good agreement between different photon energies for the times of occurrence of the peaks.

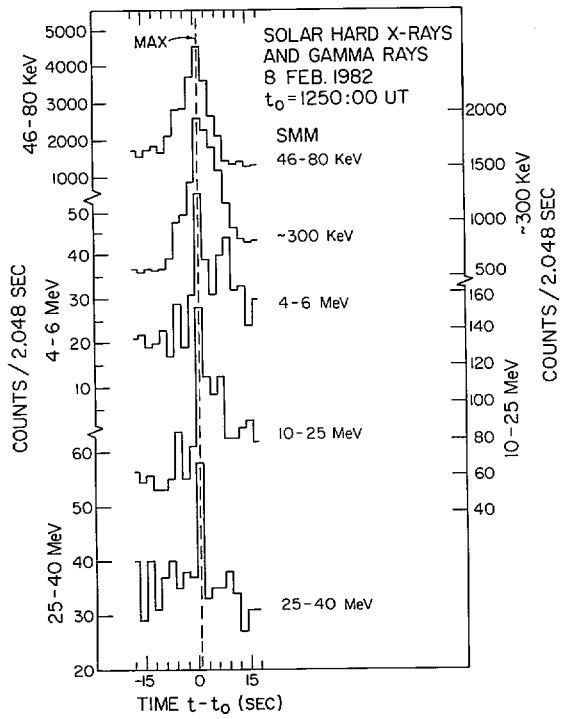

FIG. 2.—An expanded plot of the 46–80 keV, ~ 300 keV, 4–6 MeV, 10–25 MeV, and 25–40 MeV photon rates at the time of the peak P_3. All rates are averaged over 2.048 s. Note that the maximum, marked by a dashed line, occurs simultaneously at all energies.

The solar flare gamma-ray burst occurred at ~ 1250 UT on 1982 February 8. The Hα flare was 1B in importance and was located at S13, W88 in the Hale region 18176. The flare produced large soft X-ray (X 1.4) and microwave bursts. The peak radio emission in the 3–35 GHz range increased with frequency; the peak flux at 35 GHz was 7628 sfu. Thus the 3–35 GHz microwave spectrum had a positive slope, with the maximum located at a frequency $\upsilon_{max} \gtrsim 35$ GHz. In the decimetric/metric region, intense bursts of type II, III, IV, and V were recorded in association with the flare. Energetic particles were detected in interplanetary space by the anti-coincidence plastic shield in the *ISEE 3* X-ray spectrometer and by other particle detectors soon after the hard X-ray burst (*Solar Geophysical Data*).

The X-ray and gamma-ray emission profiles observed with the *ISEE 3* and *SMM* instruments are shown in Figure 1. Only the 15–233 keV X-ray channels in *ISEE 3* and ≳ 300 keV X-ray and gamma-ray channels in *SMM* are presented. The *ISEE 3* measurements show that the X-ray emission started at ~ 1245:30 UT and had as many as nine individual peaks during the following 6 minutes. In the 90 keV–1 MeV range, there were four relatively sharp peaks, P_1, P_2, P_3, and P_4, at 1248:57 UT, 1249:24 UT, 1250:01 UT, and 1250:30 UT, respectively. An expanded plot of the largest peak, P_3, is shown in Figure 2. During the early part of the event, the *SMM* was just coming out of Earth's shadow. Therefore, prior to about 1249:20 UT, the ≲ 300 keV X-ray fluxes incident on *SMM* were heavily attenuated by Earth's atmosphere, and hence the peak P_1 could not be detected at those energies.

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Some attenuation appears to have occurred even in the 4.1–6.4 MeV photons. However, the four peaks, P_1, P_2, P_3, P_4, can be clearly identified in the 10–25 MeV range, their times of occurrence agreeing within ~ 2 s (data accumulation time) with the lower energy photons observed with the *ISEE 3* and *SMM* instruments. The largest peak shown in Figure 2, P_3, can also be seen in the 25–40 MeV channel and is coincident with the 10–25 MeV peak.

In order to check for possible energy-dependent delays in the time of occurrence of the photon flux maximum P_3, a cross-correlation analysis of the 40–80 keV, ~ 300 keV, 4.1–6.4 MeV, 10–25 MeV and $\gtrsim 25$ MeV channel count rates was performed. Because of the differing time resolution for different energy bands, the energy channels below 300 keV were averaged over 2 s. A total of 21 data points, 10 before and 10 after the peak P_3, were used for each channel. The correlation coefficient $r(\Delta t)$ was then computed between the time-series of ~ 300 keV count rates and other channels for different lag times $\Delta t = t - t_{300}$ with respect to the 300 keV data. A total of 11 lags (± 5 and 0) equivalent to ± 10 s were used. For 40–80 keV, 4.1–6.4 MeV, 10–25 MeV and $\gtrsim 25$ MeV photons, the maximum correlation coefficients were found to be 0.89, 0.75, 0.89, and 0.49, occurring at lag times $-1, 0, 0, -1$, respectively. Hence there is no systematic energy dependent delay in the time of the counting rate maximum.

III. DISCUSSION

The 1982 Februrary 8 flare produced photons from ~ 15 keV to $\gtrsim 25$ MeV essentially simultaneously within ± 1 sec. The continuum spectrum in the 15 keV to 10 MeV range indicates the presence of electrons with kinetic energy at least up to ~ 10 MeV. The excess emission above the bremsstrahlung continuum in the 4–8 MeV range observed in this event requires the presence of ions with kinetic energy $\gtrsim 10$ MeV per nucleon (cf. Ramaty 1985).

In earlier studies, the peak times of 4–7 MeV gamma-rays were found to be delayed with respect to peak times of $\gtrsim 300$ keV X-ray continuum by 2 to 45 sec (Gardner *et al.* 1981; Chupp 1983). However, these delays may be caused by a temporary storage of accelerated particles and hence may not be a characteristic of the acceleration itself. The importance of the present work stems from the fact that essentially no delay implies a very short characteristic time for the acceleration process.

The origin of the $\gtrsim 10$ MeV photon emission can be primary electron bremsstrahlung and/or meson production decay. If these photons represent a continuation of the 15 keV–10 MeV bremsstrahlung to higher energies, as considered, for example, by Ramaty *et al.* (1983) and Rieger *et al.* (1983) for the 1980 June 21 flare, then electrons with energies up to at least ~ 30 MeV are required. On the other hand, the $\gtrsim 10$ MeV photons could be the result of π° meson decay, and electron bremsstrahlung from $\pi^\pm$ meson decays which requires ions with energies probably greater than 300 MeV. Regardless of the source of the radiation, the observations of $\gtrsim 10$ MeV photons imply the simultaneous acceleration of energetic electrons or ions ($\gtrsim 10$ MeV) at the highest energies with those at the lower energies (~ 100 keV).

The present observations of energetic particles interacting at the Sun thus require a quasi-continuous injection of particles accelerated to $\gtrsim 10$ MeV energy on a time scale of $\lesssim 1$ s to explain the major emission peak in Figure 2. In the 1982 February 8 flare, the rapid time scale is observed for a large part of the nonthermal energy produced by the flare and for particles extending to high energies ($\gtrsim 10$ MeV). In contrast, the rapid time scales reported by Hurley *et al.* (1983) and Kiplinger *et al.* (1983) were for weak isolated peaks at much lower energies ($\lesssim 100$ keV).

Processes for rapid acceleration of ions have been discussed in the literature (i.e., Decker and Vlahos 1985 and Vlahos *et al.* 1985). We consider below two models in which both electrons and ions are accelerated to high energies through shocks.

The present observations are not consistent with a two-phase acceleration process (Sturrock 1974; Ramaty *et al.* 1980), which requires several minutes to accelerate particles to high energies. We examine below the two-step process (Bai 1982; Bai *et al.* 1983), which presumably can operate on a time scale of a few seconds. In this process the second step is assumed to be the first-order Fermi acceleration occurring inside a magnetic loop of half-length d. Energetic particles (e.g., electrons with kinetic energy up to ~ 100 keV and protons with energy up to ~ 1 MeV) produced during the first step are reflected by colliding with two shock fronts moving upward from both footpoints of the loop. The size of the loop determines the delay Δt of the high-energy ($\gtrsim 150$ keV) X-rays or nuclear gamma rays with respect to the low-energy hard X-rays, i.e., $\Delta t \approx d/V_s$ where V_s is the parallel component of the shock velocity. The larger the flare area (Hα-importance), the larger is the loop size, and hence larger is the expected delay Δt. From Table 1 of Bai *et al.* (1983) we find that for a flare of Hα-importance 1B, the expected delay is $d/V_s \approx 10$ s. However, in the present 1982 February 8 flare of Hα-importance 1B, no delay has been observed, indicating that the delay, if present, is $\lesssim 1$ s. Hence, in this respect, the two-step model is not consistent with the present observations.

Next we consider the acceleration time in the two-step model. The rate of energy gain for electrons is given by equation (10) of Bai *et al.* (1983):

$$\frac{dw}{dt} = 2\langle \mu^2 \rangle \beta_p^2 (d/V_s)^{-1}, \tag{1}$$

where w is the total energy of an electron, β_p is the ratio of the electron velocity to the speed of light c, and μ is the cosine of pitch angle of the electron. The initial value w_0 of w at time $t = 0$ is assumed to be greater than the "injection energy." Substituting $\beta_p^2 = [1 - (m^2c^4/w^2)]$ in equation (1) and integrating we get the time t required for accelerating an electron of total energy w_0 to energy $w(t)$

$$t = \frac{1}{4\langle \mu^2 \rangle} \frac{d}{V_s} \ln \frac{w^2 - m^2c^4}{w_0^2 - m^2c^4} \text{ s}, \tag{2}$$

where $mc^2 = 0.511$ MeV is the rest energy of electron. Following Bai *et al.* (1983) we take $\langle \mu^2 \rangle = 0.5$ and $d/V_s = 10$ (Table 1 of Bai *et al.* 1983). Then for an electron of initial

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kinetic energy ~ 100 keV ($w_0 \approx 0.611$ MeV) to obtain an energy of ~ 10 MeV ($w \approx 10.511$ MeV) the time required is $t \sim 35$ s, which is much larger than the observed time. (If the impulsive [first-step] acceleration process is *highly* efficient so that the injection energy of electrons for the second step is $\gg 100$ keV, this time t will be shorter. Then, of course, the second step may not be necessary.) If we assume that the relevant magnetic loop in the 1982 February 8 flare was much smaller than that expected from the Hα-flare importance and set $d/V_A \approx 1$ s, we find the acceleration time to be $t \approx 3.5$ s, which is still larger than the observed time of $\lesssim 1$ s. It may be possible to reconcile the two-step acceleration process with the present observations by assuming a small loop confined to the photosphere and lower chromosphere. That is, however, expected to reduce the efficiency of the acceleration process because of the larger rate of particle energy loss in the higher density of the ambient plasma. Moreover, it would be difficult for the energetic electrons to escape into the corona and produce type III radio bursts and/or escape into the interplanetary space. If the magnetic loop is small so that $d/V_s \approx 1$ s, the shock fronts will reach the top of the loop in ~ 1 s. In order to continue the acceleration process for the duration of the hard X-ray burst, a new pair of shocks must be generated every ~ 1 s in the same loop. This may not be possible, however, because the shock formation time appears to be $\gtrsim 2$ s (Smith and Brecht 1985). Another possibility, of course, is the successive production of shock pairs in different but similar loops. In either case the present observations put severe constraints on the two-step acceleration process. It is important to note that our measurements do not place constraints on the escape of energetic particles from the Sun into interplanetary space. A two-step or two-phase acceleration for these interplanetary solar particles is not excluded by our measurements.

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REFERENCES

Bai, T. 1982, in Gamma Ray Transients and Related Astrophysical Phenomena, ed. R. E. Lingenfelter *et al.* (New York: AIP), p. 409.
Bai, T., and Dennis, B. R. 1985 *Ap. J.*, **292**, 669.
Bai, T., Hudson, H. S., Pelling, R. H., Lin, R. P., Schwartz, R. A., and von Rosenvinge, T. T. 1983, *Ap. J.*, **267**, 433.
Chupp, E. L. 1983, in *Recent Advances in the Understanding of Solar Flares*, ed. S. R. Kane, Y. Uchida, K. Tanaka, and H. S. Hudson (Dordrecht: Reidel), p. 383.
Decker, R. B., and Vlahos, L. 1985, *J. Geophys. Res.*, **90**, 47.
de Jager, C. 1969, in *Solar Flares and Space Research*, ed. C. de Jager and Z. Švestka (Amsterdam: North-Holland), p. 1.
Forrest, D. J., *et al.* 1980, *Solar Phys.*, **65**, 15.
Forrest, D. J., and Chupp, E. L. 1983, *Nature*, **305**, 291.
Frost, K. J., and Dennis, B. R. 1971, *Ap. J.*, **165**, 655.
Gardner, B., *et al.* 1981, *Bull. AAS*, **13**, 903.
Hurley, K., Niel, M., Talon, R., Estulin, I. V., and Dolidze, V. Ch. 1983, *Ap. J.*, **265**, 1076.
Kane, S. R., Fenimore, E. E., Klebesadel, R. W., and Laros, J. G. 1982, *Ap. J.* (*Letters*), **254**, L53.
Kane, S. R., Kai, K., Kosugai, T., Enome, S., Landecker, P. B., and McKenzie, D. L. 1983, *Ap. J.*, **271**, 376.
Kiplinger, A. L., Dennis, B. R., Emslie, A. G., Frost, K. J., and Orwig, L. E. 1983, *Ap. J.* (*Letters*), **265**, L99.
Nakajima, H., Kosugai, T., Kai, K., and Enome, S. 1983, *Nature*, **305**, 292.
Ramaty, R. 1985, in *The Physics of the Sun*, ed. P. A. Sturrock, in press.
Ramaty, R., *et al.* 1980, in *Solar Flares*, ed. P. A. Sturrock (Boulder: Colorado Associated University Press), p. 117.
Ramaty, R., Murphy, R. J., Kozlovsky, B., and Lingenfelter, R. E. 1983, *Ap. J.* (*Letters*), **273**, L41.
Reiger, E., Reppin, C., Kanbach, G., Forrest, D. J., and Chupp, E. L., and Share, G. H. 1983, in *18th Int. Cosmic Ray Conf.*, Bangalore, **10**, 338.
Smith, D. F., and Brecht, S. H. 1985, *J. Geophys. Res.*, **90**, 205.
Sturrock, P. A. 1974, in *IAU Symposium 57, Coronal Disturbances*, ed. G. Newkirk (Dordrecht: Reidel), p. 437.
Vlahos, L., *et al.* 1985, in *Energetic Phenomena on the Sun* (Proc. *Solar Maximum Mission* Workshop, Goddard Space Flight Center), chap. 2.
Wild, J. P., Smerd, S. F., and Weiss, A. A. 1963, *Ann. Rev. Astr. Ap.*, **1**, 291.

E. L. Chupp and D. J. Forrest: Department of Physics, University of New Hampshire, Durham, NH 03824

S. R. Kane: Space Sciences Laboratory, University of California, Berkeley, CA 94720

E. Rieger: Max-Planck-Institut für Physik und Astrophysik, Institut für extraterrestriche Physik, 8046 Garching, West Germany

G. H. Share: Naval Research Laboratory, Code 4152, Washington, DC 20375

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