THE ENERGY SPECTRA OF SOLAR FLARE ELECTRONS*

Paul Evenson[+], Dietrich Hovestadt[‡], Peter Meyer[x], and Dan Moses[x]

[+]Bartol Research Foundation, University of Delaware
Newark, DE 19716 USA

[‡]Max-Planck Institute for Extraterrestrial Physics
8046 Garching, West Germany

[x]Enrico Fermi Institute and Department of Physics
University of Chicago, Chicago, IL 60637 USA

ABSTRACT. A survey of 50 electron energy spectra from .1 to 100 MeV originating from solar flares has been made by the combination of data from two spectrometers onboard the ISEE-3 (ICE) spacecraft. The observed spectral shapes of flare events can be divided into two classes through the criteria of fit to an acceleration model. This "standard" two step acceleration model, which fits the spectral shape of the first class of flares, involves an impulsive step that accelerates particles up to 100 keV and a second step that further accelerates these particles up to 100 MeV by a single shock. This fit fails for the second class of flares that can be characterized as having excessively hard spectra above 1 MeV relative to the predictions of the model. Correlations with soft x-ray and meter radio observations imply that the acceleration of the high energy particles in the second class of flares is dominated by the impulsive phase of the flares.

I. INTRODUCTION.

Previous surveys of electron flare spectra with energies extending up to 10 MeV have been conducted by Datlowe (1971), Simnett (1974), Lin et al. (1982), and Evenson et al. (1984). The study presented in this paper has the advantage of nearly continuous coverage over a four year period of high solar activity in the absence of magnetospheric effects due to the orbit of the spacecraft. Two independently well calibrated instruments on the same spacecraft are used to cover two adjacent energy ranges. The total energy range and the resolution are well suited to explore the spectral regime characteristic of the second step of acceleration. The combination of improvements in this study yield results not identified in previous surveys.

2. METHOD.

Measurements of solar flare electrons in the energy range of .075 to 1.30 MeV were obtained from the ULEWAT spectrometer (Hovestadt et. al. 1978) and electron spectra in the range of 5 to 100 MeV were measured with the MEH spectrometer (Meyer and Evenson, 1978). No attempt was made at normalization of the two sources of data as each instrument was judged to be adequately calibrated by independent methods. The time interval of the survey extends from launch of ISEE-3 in August 1978 through December 1982.

*Supported, in part, by NASA contract NAS5-26680 and NASA grant NGL-14-001-005.

Two requirements for inclusion of a flare in the survey were applied: first, all energy bins in the ULEWAT data must have an impulsive (~ 1 day rise time) enhancement over background and, second, all energy bins in the MEH data through the 10 MeV bin must also have an impulsive enhancement over background. The majority of events observed with ULEWAT has no measurable counterpart in MEH. To relate the interplanetary particle spectrum to the source spectrum, the assumptions were made that the spectrum of particles escaping from a flare is identical to the spectrum of particles accelerated in that flare and that the propagation of particles from the flare is a simple diffusion process which does not change the energy of the particles. With these assumptions the spectrum at the source is obtained by subtracting the pre-flare background flux from the flare maximum flux in each energy bin (Lin et al. 1982).

The classification of spectral shape by comparison with the prediction of a single shock acceleration is equivalent to comparison with a spectral shape which is a power law in momentum (Blandford and Ostriker, 1978). Following Ellison and Ramaty (1985), the loss of efficiency in acceleration of the highest energy particles due to effects such as the diffusion length of the particle being greater than the size of the shock is modeled by an exponential roll-off in energy above a characteristic energy, E_o. A good power law in momentum fit to an energy spectrum is shown in the example of Figure 1, and replotted as a function of rigidity in Figure 2. The case of a spectrum that deviates from a power law in momentum (rigidity) predicted by the single shock model is obvious on a rigidity plot (Figure 3).

3. RESULTS. A detailed list of the properties of the individual flares in this study will be presented in a full paper now in preparation. Of the 50 events included in the survey, 31 can be modeled by the single shock mechanism and these will be referred to as class II events. The events which deviate from a power law in momentum will be referred to as class I events. Sixteen of the class I spectra are consistent with a power law shape in kinetic energy while 3 spectra are flatter at high energies. Events with an identified source position on the sun show a selection effect in favor of well connected flares which is more pronounced in the class I events. The average 25-45 MeV proton flux from the class II events is higher than that of the class I events while the average electron to proton ratio at 25-45 MeV of the class II events is lower than that of the class I events.

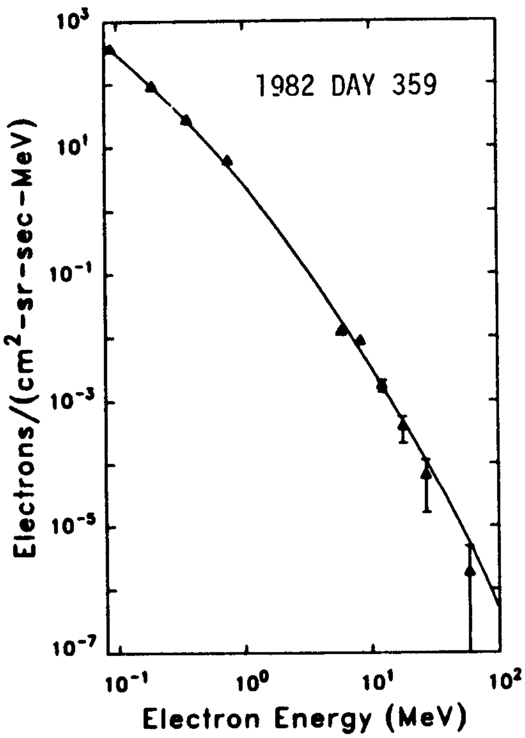

Fig. 1: Flare energy spectrum fit by single shock model with compression ratio, r=2.3, and e-folding energy, E_o=60 MeV.

4. DISCUSSION. While the spectra of class II electron flare events are well

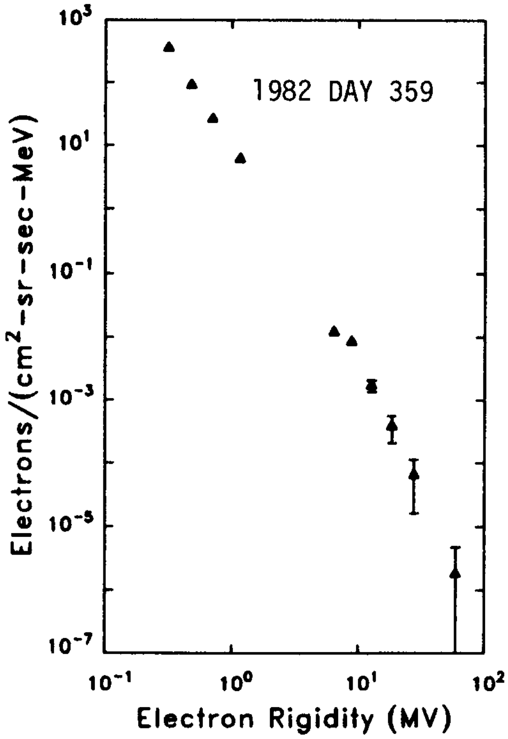

Fig. 2: Flare rigidity spectrum of a typical class II event.

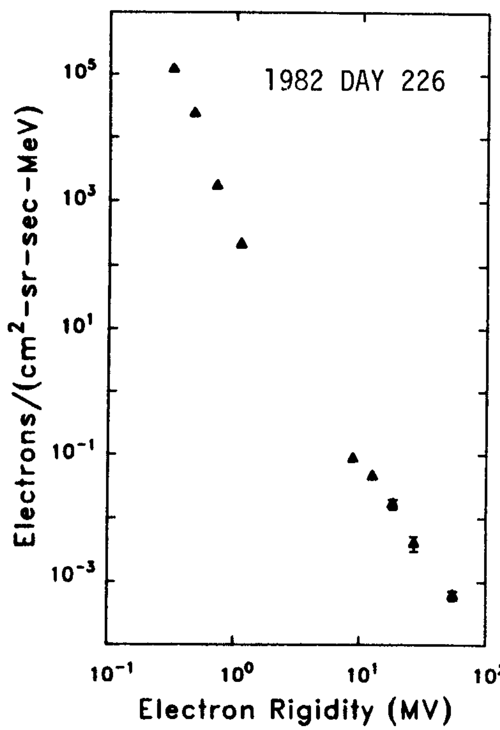

Fig. 3: Flare rigidity spectrum of a typical class I event.

modeled by single shock acceleration, the spectra of class I events require more complicated models. Obvious candidates include more than one acceleration site, a single shock with a compression ratio which varies in either space or time, an energy dependent escape mechanism, and an injection spectrum at high energies which is flatter than the spectrum produced by the shock. The electron spectra alone cannot distinguish between these options.

The duration of the soft x-ray thermal emission (1-8 Å) of flares provides a powerful tool in classifying flares associated with energetic interplanetary electrons as was first recognized by Cane et al. (1985). For all interplanetary particle events associated with soft x-ray events listed in Solar Geophysical Data, the class I events are associated with the impulsive (< 1 hour duration) soft x-ray events while the class II events are associated with the long duration (> 1 hour duration) soft x-ray events. Pallovicini et al. (1977) have demonstrated that the duration of the soft x-ray emission is further associated with the volume and coronal height of a flare: the impulsive flares (class I) are compact and low in the corona while the long duration flres (class II) are diffuse and higher in the corona.

The association of class II events with diffuse events high in the corona is consistant with the single shock acceleration model used to fit the electron spectra. Also, in support of the single shock acceleration model for class II events is the correlation by Cane et al. (1985) of the long duration x-ray events with interplanetary shocks and coronal mass ejections. The duration of gamma-ray emission bursts (Chupp, 1984) in the class II events is also consistent with a shock of velocity 10^3km/s traversing the 10^{13}-10^{14}km^3 volume associated with the long duration soft x-ray events. The relative height in the corona of class II flares results in less coronal diffusion than of class I flares and predicts less sensitivity to the degree of connection with the flare site.

The association of class I events with impulsive, compact events low in the corona is inconsistant with a single shock model with a compression ratio which varies in time or space. Multiple acceleration sites would be expected to produce multiple soft x-ray impulses which are not seen. The spectral shape of the gamma-ray continuum for the impulsive 1972 August 4 flare suggests that the electron spectrum at the acceleration site has a class I spectral shape (Ramaty et al. 1975) and thus the escape mechanism is not energy dependent.

A model of class I flare acceleration dominated by the impulsive (magnetic reconnection) phase of the event is consistant with both the observed electron spectral shape and the soft x-ray emission by a compact and impulsively heated volume of plasma. One might expect evidence of beaming along the direction of the electric field resulting from magnetic reconnection and Cane et al. (1985) have found a correlation of the impulsive soft x-ray events with strong type III radio bursts which accompany streaming electrons. Tentative association of the directivity of gamma-rays described by Vestrand et al. (1984) with class I events provides further evidence for electron beaming. The component of shock accelerated particles appears to be restricted to the lower energies by the size and density of the heated plasma region and the shape of the electron spectrum is consistant with such a component.

5. ACKNOWLEDGEMENTS. We would like to thank Mr. Leo Krawczyk and Ms. Judith Fontana-Kroeger for assistance in preparing this paper. We would also like to thank Mr. Richard Kroeger for helpful discussions.

REFERENCES

Blandford, R. and Ostriker, J. 1978, Ap.J. 221, L29.
Cane, H., McGuire, R. and von Rosenvinge, T. 1985, submitted to AP.J.
Chupp, E. 1984, Ann. Rev. Astron. Astrophy., 22, 359.
Datlowe, D. 1971, Solar Phys. 17, 436.
Ellison, D. and Ramaty, R. 1985, accepted in Ap.J.
Evenson, P., Meyer, P., Yanagita, S. Forrest, D. 1984, Ap.J. 283, 439.
Hovestadt, D., Gloeckler, G., Fan, C., Fisk, L., Ipavich, F., Klecker,B., O'Gallagher, J., Scholer, M., Arbinger, H., Cane, J., Hofner, H. Kunneth, E., Laeveranz, P. and Tums, F. 1978, IEEE Trans. GE16, 166.
Lin, R., Mewaldt, R. and Van Hollebeke, M. 1982, Ap.J. 253, 949.
Meyer, P., Evenson, P. 1978, IEEE Trans. GE16, 180.
Pallavicini, R., Serio, S. and Vaiana, G. 1977, Ap.J. 216, 108.
Ramaty, R., Kozlovsky, B. and Lingenfelter, R. 1975, Space Sci. Rev. 18, 341.
Simnet, G.M. 1974, Space Sci. Rev. 16, 257.
Vestrand, W., Forrest, D., Chupp, E., Rieger, E. and Share, G. 1984, Bull.of AAS. 16, 475.