A STATISTICAL ANALYSIS OF HARD X-RAY SOLAR FLARES

G. PEARCE
Department of Astrophysics, Oxford University, Nuclear Physics Laboratory, Oxford;
St Hilda's College, Oxford;
Astrophysics Division, Rutherford Appleton Laboratory, Chilton, Oxfordshire;
St. John's College, Oxford;
and *Wolverhampton University, U.K.*

A.K. ROWE
St. John's College, Oxford, U.K.

and

J. YEUNG
Astrophysics Division, Rutherford Appleton Laboratory, Chilton, Didcot, Oxfordshire, U.K.

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Abstract. In this study we perform a statistical study on, 8319 X-Ray solar flares observed with the Hard X-Ray Burst Spectrometer (HXRBS) on the Solar Maximum Mission satellite (SMM). The events are examined in terms of the durations, maximum intensities, and intensity profiles. It is concluded that there is no evidence for a correlation between flare intensity, flare duration, and flare asymmetry. However, we do find evidence for a rapid fall-of in the number of short-duration events.

1. Introduction

In the past, many statistical studies of solar flares have been conducted in an attempt to identify what might be thought of as the 'average' flare or to identify distinct flare classes. These have been performed on data at various wavelengths including X-ray and Hα.

Attempts have been made to classify solar flares into various flare types. For example in a recent review by Bai and Sturrock (1989) flares are classified into

(1) Thermal Hard X-Ray Flares;
(2) Non-Thermal Hard X-Ray Flares;
(3) Impulsive GR/P Flares (Gamma-ray/proton flares);
(4) Gradual GR/P Flares; and
(5) Quiescent Filament-Eruption Flares.

In the case of Thermal Hard X-Ray Flares, the hard X-ray emission below 40 keV is dominated by thermal bremsstrahlung. The impulsive component is embedded in the gradual thermal component, and there is no clear-cut separation between the two. The hard X-ray spectrum above 40 keV is very steep with spectral indices in excess of 7. Non-Thermal Hard X-Ray Flares account for most HXRBS flares with count rates above 1000 counts s^{-1}. Flares belonging to this class show impulsive variations with time scales ranging from 0.1 to 30 seconds. Spectral indices range from about 2 to greater than 7. Impulsive GR/P Flares are believed to be similar to Non-Thermal Hard X-Ray Flares. However, an additional process takes

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place during the first phase of such flares. This process involves the acceleration of electrons to relativistic energies and protons to gamma-ray producing energies. Gradual GR/P flares appear to show great variations from other flare classes. In previous studies many flare types, for example two-ribbon flares, proton flares, extended flares, and long decay events, have been included in this category. Quiescent Filament-Eruption Flares are frequently associated with the development of pairs of faint Hα ribbons, interplanetary shocks, interplanetary protons and heavy ions. Quiescent Filament-Eruptions on the other hand do not lead to impulsive flare activity (Bai and Sturrock, 1989).

Attempts have also been made to classify events on the basis of size, duration, and flare profiles. For example, large events have been described by Zirin and Tanaka (1973); Fritzová-Svestková and Svestka (1973); de Jager *et al.* (1985); Mein and Mein (1982); Svestka *et al.* (1982); Hoyng *et al.* (1983); Wu *et al.* (1983); Doyle *et al.* (1985); and Harrison (1986). Long duration events have been described by Kahler (1977); Pallavicini *et al.* (1977); Kreplin *et al.* (1983). Further classification schemes have referred to impulsive flares (Crannell *et al.*, 1978; Matzler *et al.*, 1978; Doyle *et al.*, (1985) and subflares and microbursts have been characterised by Schadee *et al.* (1983) and Lin *et al.* (1984).

The distribution of parameters such as the maximum emission measures, maximum temperatures and the rise and decay profiles of flares has been undertaken by, for example, Culhane and Phillips (1970) and Phillips (1972). These authors examined 150 X-ray events from OSO-4 (3–4.5 keV). Similarly, Datlowe *et al.* (1974a, b) examined flare events from OSO-7 data (5–100 keV). Earlier studies by Drake (1971) examined several thousand X-ray bursts observed by Explorers 33 and 35 (1–6 keV). These studies found no evidence for pseudo-classifications or subgroups of flares. The instruments involved in such studies were full-sun observing devices. A more recent study by Pearce and Harrison (1988) using spatially resolved events from the Hard X-ray Imaging Spectrometer (HXIS) (3–30 keV) on board the Solar Maximum Mission (SMM) satellite also concluded that there was no evidence for more than one class of event.

The previous analyses by Pearce and Harrison (1988) in the X-ray and Yeung and Pearce (1989) in Hα have revealed that there is a rapid decrease in the number of events at relatively low values of flare duration. This could be a threshold effect due to the instrumentation. We feel, however, that this is unlikely to be the case since this effect is present in both of these studies which have involved independent instruments of different sensitivities. With these unresolved problems in mind, we have analysed HXRBS events in order to discover whether this effect is also present in this data set. Dennis (1985) (Figure 3 therein) presented an analysis involving over 6000 flares recorded by HXRBS, for events above $\sim$ 30 keV. Our study involves using over 8000 solar flares from the HXRBS data set. We plot various distributions of parameters to address several areas of solar flare physics. Distributions in duration and intensity are used to confirm or refute often- used flare classifications, for example, the so-called long duration events, microflares etc. An examination of the distribution of intervals between flares provides a method for studying the potential rate of sympathetic flaring — i.e. the triggering of flare activity by another flare activity — the existence of which has been in dispute for many years. Several plots are used to examine the form of the hard X-ray burst and, therefore, the nature of the accelerated electron population in the impulsive phase of the flare. These include plots of burst asymmetry, duration and intensity. These studies benefit from the analysis of a very large data-set.

2. Data Analysis

For the purpose of this study we use data obtained by the Hard X-Ray Burst Spectrometer (HXRBS) on board the Solar Maximum Mission (SMM) satellite. The HXRBS is a full-sun instrument which observes the Sun in the energy range that varied from 25 to 450 keV at launch in 1980 to about 60 keV to over 500 keV at the end of the mission in 1989. This analysis in some instances is limited to the period 1980–1985 because of detector variability after this date.

The study was divided into the following areas:

A) An investigation of all HXRBS events during the period 1980-1985 in respect of

A1) The distribution of their maximum intensities.

A2) The distribution of their durations.

A3) The distribution of the intervals between consecutive flares.

Our objective in the first two parts of the analysis is to determine whether any distinct flare types exist. An average background count rate of 40 counts sec^{-1} was subtracted from all the maximum intensity readings.

In the third part of this investigation we attempt to discover whether there is any evidence for sympathetic flaring (i.e. one flare event triggering off another flare event at a site nearby). A problem arises in respect of this part of the analysis because of the lack of spatial resolution of the HXRBS instrument. Thus it is not possible to draw a direct connection between events by examination of their location of interaction, and so statistics alone must be used.

Of the 8319 events observed, 1189 events, for which the following flags were indicated, were rejected: SN (event began in spacecraft night), IN (event interrupted by spacecraft night), EN (event ended in spacecraft night), SA (event ended in the South Atlantic Anomaly), SG (event began in a data gap), DG (data gaps occurred during the event), ND (event occurred during a period of noisy data), EG (event ended in a data gap), AX (event was due to the motion of the instrument through trapped particles), NS (event was non-solar in origin), GB (Event verified as non-solar γ-ray burst) and EW (status file contains incorrect on-time information). A full discussion of these flags is given in Dennis *et al.* (1987).

B) An investigation of HXRBS events during the period 1980–1985 in respect of

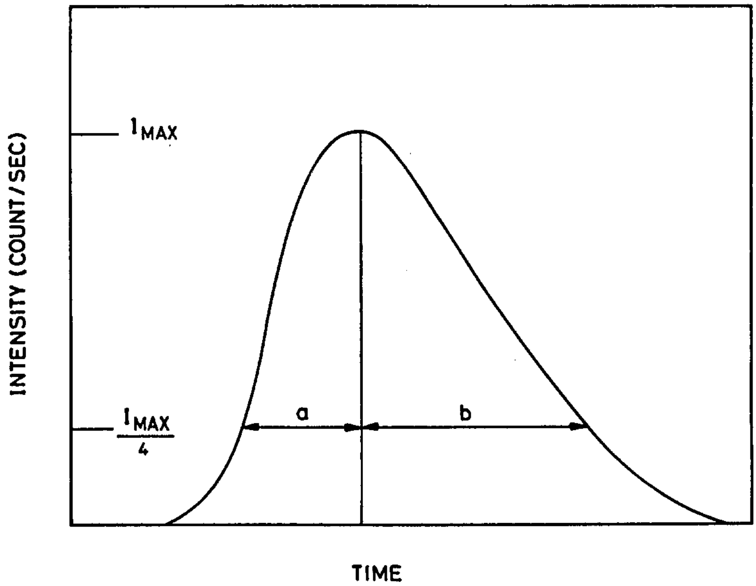

Fig. 1. An idealised flare profile. a and b are the rise and decay times respectively, measured at quarter maximum intensity.

B1) The distribution of the event asymmetry.

B2) The variation of the peak intensity with the burst duration.

B3) The variation of the peak intensity with the degree of event asymmetry.

B4) The variation of event asymmetry with the burst duration.

These parameters were chosen to be consistent with and to allow direct comparison with previous studies undertaken (e.g. Pearce and Harrison, 1988) using X-ray data.

Again we looked for any indication of the existence of distinct flare types. To this end the simple parameters of rise time, a (where a = peak time – start time); decay time, b (where b = duration $-a$); duration, $a + b$; and asymmetry, $(b - a)/(b + a)$, were calculated from the HXRBS event listing. A typical idealised flare profile is shown in Figure 1. The value for the maximum intensity was also taken from the HXRBS Event Listing 1980–1989, and again an average background rate of 40 counts $\sec^{-1}$ was subtracted from the value listed.

Again of the 8319 events observed during this period, 1189 were rejected for the same reason as in part A. The criteria for acceptance of an event into this part of the study were that ambiguities due to a complicated time-intensity structure and the uncertainties arising in the background were eliminated.

3. Results

A.1. Intensity Distributions

In each of the years, 1980 to 1985, we find a distribution which consists of one distinct peak, a long tail-off at higher intensities and a sharp fall-off at lower intensities. We find that the peak occurs at the same intensity, 30 ± 4 counts s^{-1}, for all years.

We fit the data with a linear rise to maximum and then a tail-off of the form

$$\text{Number of events} \propto I^{\alpha}$$

where I is the maximum intensity of the event in counts per second.

We find that the best fit is obtained for $\alpha = -1.8 \pm 0.1$. A fit to the data for the years 1980–1985 is shown in Figure 2a, and Figure 2b (Figures 2–9 can be found at the end of this article) shows the equivalent log–log plot. This result is in agreement with the value found by Dennis (1985).

A.2. Duration Distributions

In Figure 3 we show the distribution of flare durations for the years 1980–1985 collectively. In each of the years 1980 to 1989, we observe a distribution with a distinct main peak, a long tail-off at longer duration, a sharp fall-off at shorter durations and also a secondary peak. We find that the main peak occurs at a duration of 45 ± 10 s for all years. The secondary peak occurs at $\sim$ 190 s for all years. The secondary peak at $\sim$ 190 s is an artefact of the data acquisition procedure (Dennis, private communication), and so events with durations of 150–200 s (between the two dashed lines in Figure 3) were not considered in our analysis.

Unlike the intensity distributions, we were unable to find a fit to the duration distributions which was valid for all years. This may be because the data cannot be fitted by a single distribution, or it may be due to the same data distortion that causes the 190 s secondary maximum. The absence of short-duration events may be due to threshold effects arising from the instrument. However, HXRBS has a temporal resolution of 0.125 s, and so a drop off in the number of events of duration 50 s and less would appear to be real. However, low intensity events are hard to detect. It should be noted that we are unable to record events occurring during spacecraft (SMM) night, which affects the counting of long duration events more than short duration events. A correction was made to the number of events recorded in each time duration by assuming a spacecraft day of 60 min and a spacecraft night of 30 min.

A.3. Distribution in Time

It is of interest to discover whether cascades of flares exist, that is, events where one flare, by some mechanism, initiates another. Consequently, the distribution of the time intervals between consecutive HXRBS events was examined. The time between initiation of consecutive events was limited to 60 minutes in this instance,

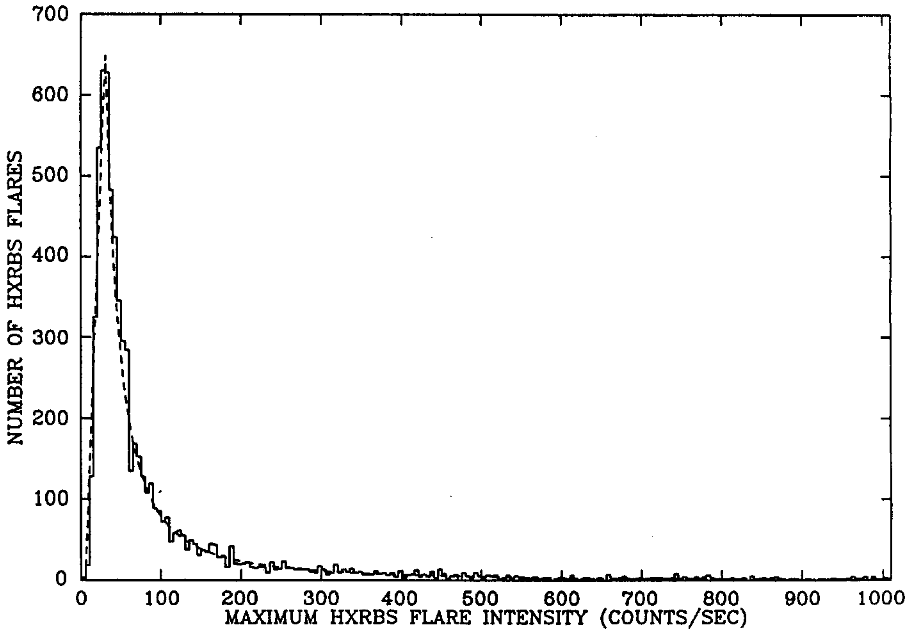

Fig. 2a. The distribution of the maximum flare intensity for all flares seen in the period 1980–1989.

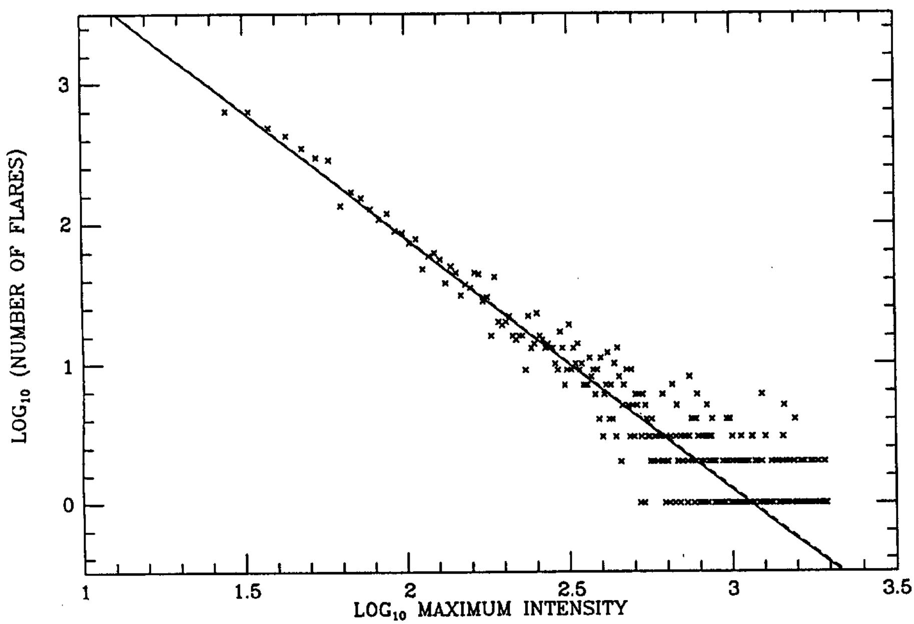

Fig. 2b. $\log_{10}$ (number of flares) against $\log_{10}$ (maximum intensity).

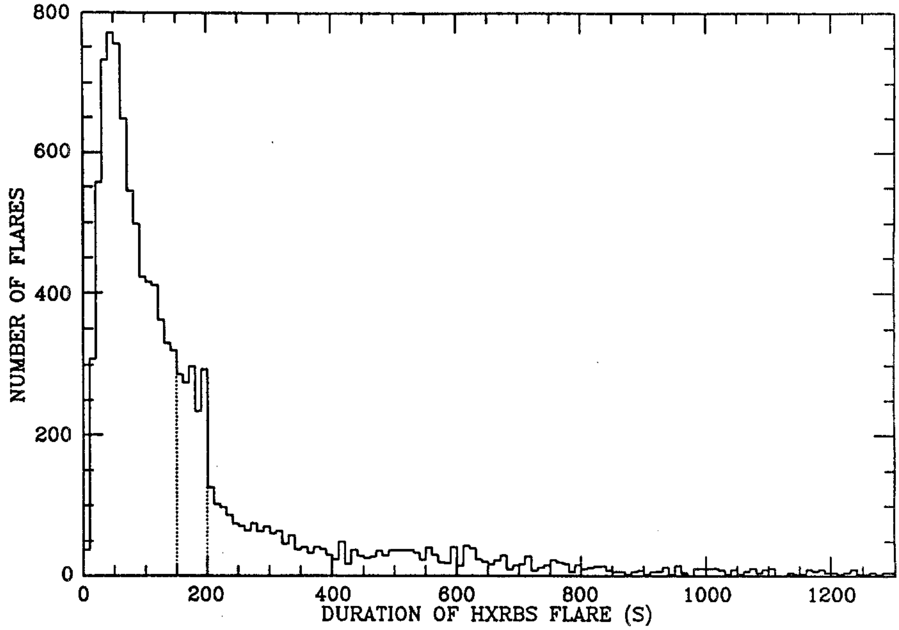

Fig. 3. The distribution of flare duration for all flares seen in the period 1980–1985.

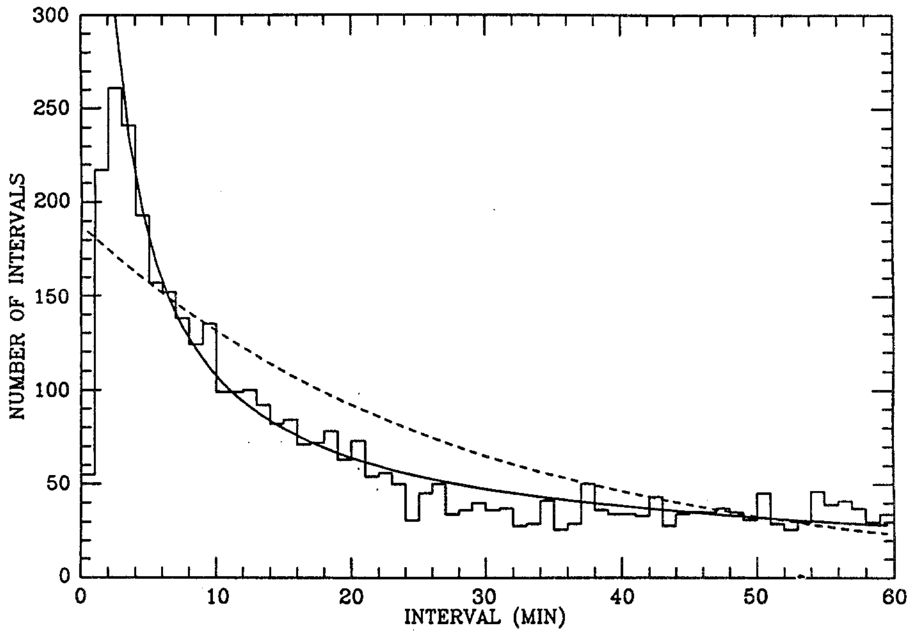

Fig. 4. The distribution of intervals between flares. The dotted line shows the distribution expected if flares occur at random, and the solid line shows the fitted distribution.

as it seems unlikely that events of this type which were further apart in time could be strongly related (Pearce and Harrison, 1990). The distribution obtained (Figure 4) exhibits a peak, a long tail, and a decline at shorter intervals. The peak occurs in the region of 3 minutes.

If the flares occurred purely randomly in time, we would expect the distribution of the intervals between consecutive flares to be of the form,

$$\text{number of intervals} \propto \mathrm{e}^{-t/\tau}$$

where t is the interval between flares and τ is the mean flare interval. In order to take account of the solar cycle each year was fitted individually, and so for the total distribution a fit of the form,

$$\text{number of intervals} = \sum_i \frac{N_i}{\tau_i} \mathrm{e}^{-t/\tau_i}$$

for $i = 1980$ to 1989, was attempted. This fit is shown as the dashed line in Figure 4. It was found that this distribution did not fit the data, and, instead, the best fit (solid line in Figure 4) was found to be of the form

$$\text{number of intervals} \propto t^{\beta}$$

with $\beta = -0.75 \pm 0.1$, as verified by the log–log plot of Figure 5.

Clearly since the data does not fit an exponential distribution, the flares do not appear to be randomly distributed in time. However, it is not possible in this analysis to say whether there is any evidence for sympathetic flaring. The sharp fall-off at short intervals is most likely due to two events with such a short time interval between them being counted as a single event. The argument against sympathetic flaring would suggest that there is a "relaxation period" during which the region would not flare again due to the magnetic status of the region.

B.1. Asymmetry Distribution

Figure 6 shows the distribution of event asymmetry. The event asymmetry is defined as $(b - a)/(b + a)$. The histogram shows that most events are fairly symmetrical in time, although there is some evidence of a bias towards events where the decay time, b, is longer than the rise time, a.

B.2. Variation of Maximum Intensity With Event Duration

Figure 7 shows a scatter plot of the maximum flare intensity versus the flare duration, $(a + b)$. Clearly there is a wide scatter of points, and so there appears to be no evidence of a correlation between flare duration and maximum intensity. The product-moment correlation coefficient for the data is 0.27, which suggests that there may actually be a slight trend, with events which have a higher maximum intensity also having longer durations. This, of course, is not unexpected, but from Figure 7 we see that the large scatter of the points obscures any such trend.

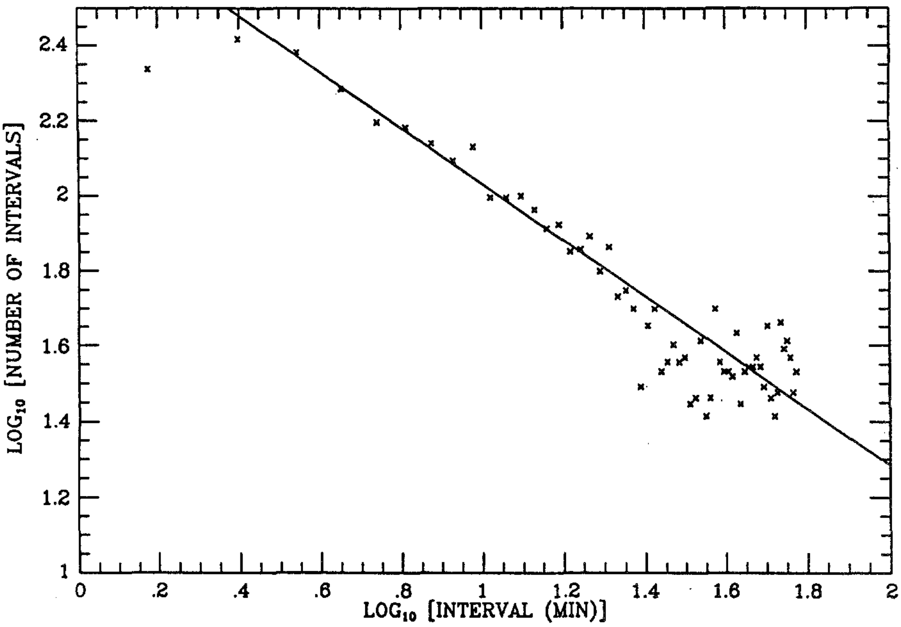

Fig. 5. $\log_{10}$ (number of intervals) against $\log_{10}$ (interval in minutes).

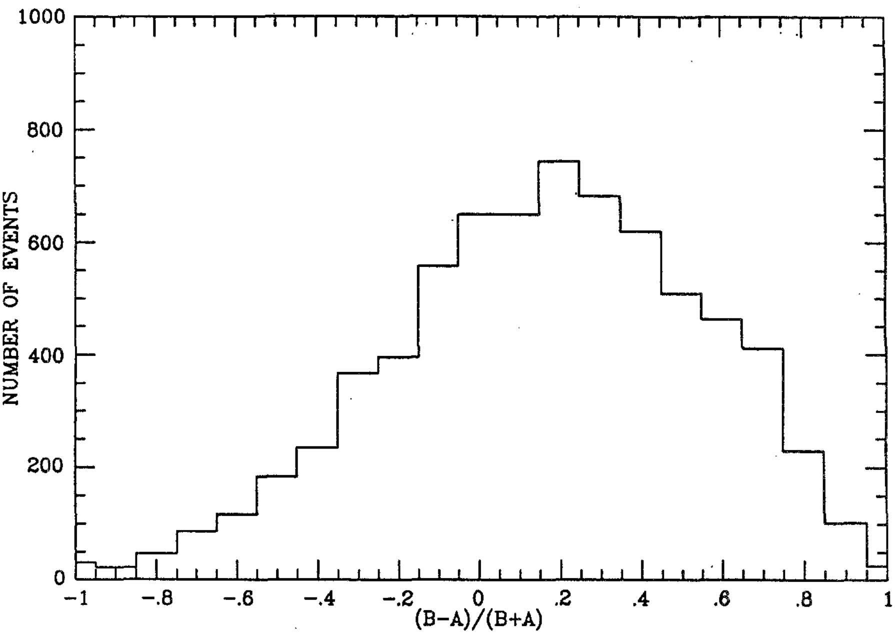

Fig. 6. The distribution of flare asymmetry, $(b-a)/(b+a)$.

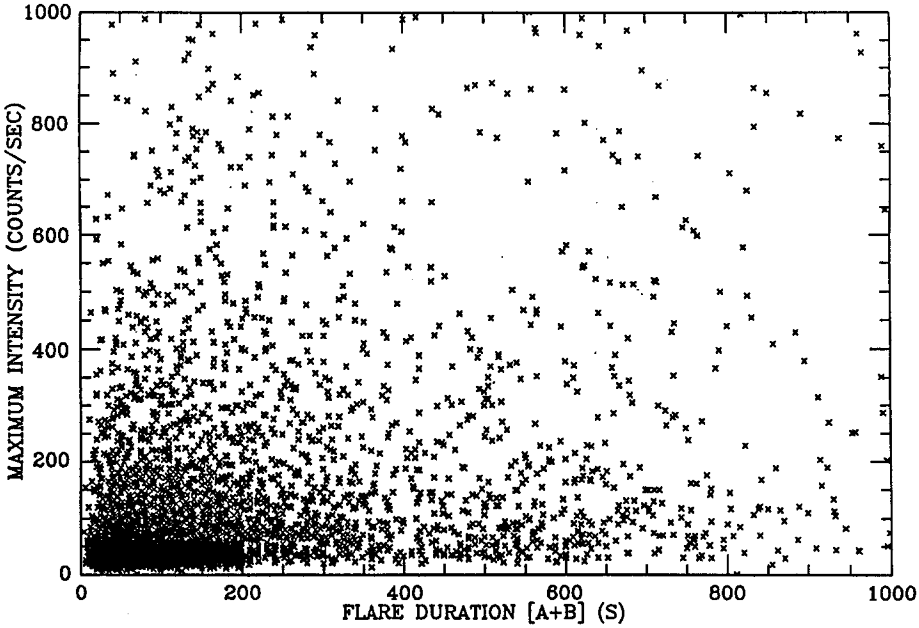

Fig. 7. The variation of maximum intensity with flare duration, $(a + b)$.

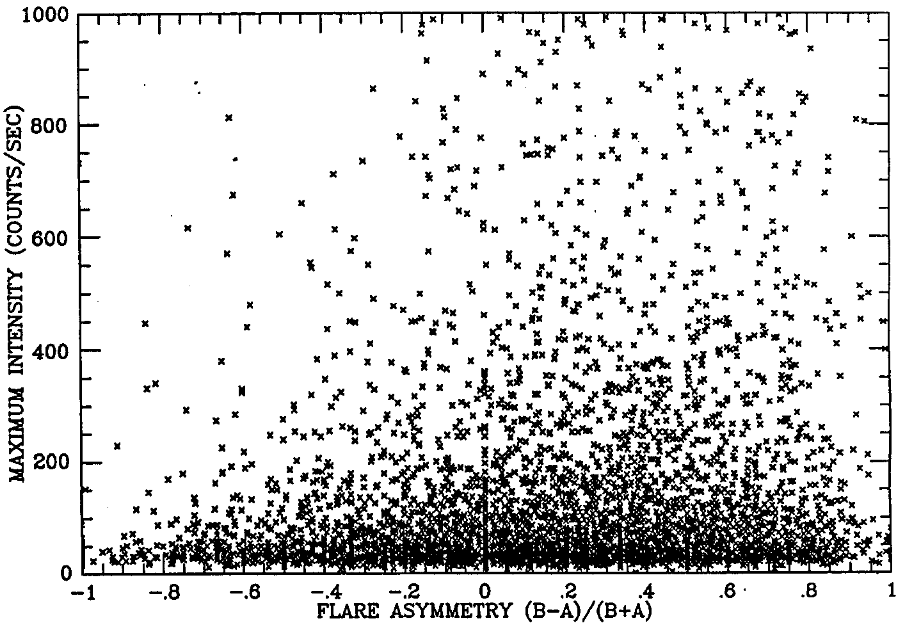

Fig. 8. The variation of maximum intensity with flare asymmetry, $(b - a)/(b + a)$.

B.3. VARIATION OF MAXIMUM INTENSITY WITH EVENT ASYMMETRY

In Figure 8, we show a scatter plot of the maximum flare intensity versus the flare asymmetry. There is no evidence of correlation, and the product moment correlation coefficient of 0.08 confirms this result.

B.4. EVENT ASYMMETRY AND DURATION

Figure 9 illustrates a scatter plot of the event duration, $(a + b)$, versus asymmetry, $(b - a)/(b + a)$. There is no evidence of correlation, and the product moment correlation coefficient of 0.16 confirms this.

4. Conclusions

From the investigation of the intensity distribution of flares, we conclude that in each of the years 1980 to 1989, there is a single-event type distribution which consists of one distinct peak (which occurs at 30 ± 4 counts s^{-1} for each of the years considered), a radical fall-off in flare numbers at lower intensities, and a long tail-off at higher intensities which can be fitted by a power law fall- off of the form I^{α}, where $\alpha = -1.8 \pm 0.1$ in agreement with Dennis (1985).

The investigation of the duration distribution for HXRBS events revealed a distribution with a peak, a long tail and a drop-off at shorter durations. We conclude that this drop-off at shorter durations appears to be a real effect rather than an instrumental effect, since similar trends have been found in the analysis of other data sets in soft X-ray (Pearce and Harrison, 1989) and Hα (Yeung and Pearce, 1989). It should be noted however that low intensity events are more difficult to detect. The main peak in the distribution occurs in the same place, 45 ± 10 seconds, over the entire solar cycle.

These distributions indicate that, at these energies, there is only one event type, or spectrum of events. We do not see evidence to suggest that classifications based on different physical conditions can be applied to flares. For example, the 2-ribbon and single-loop flare models which are based on Hα observations, and often discussed as if they result from different processes are not supported by our results. Furthermore, if coronal heating and solar wind acceleration are the result of microflares, we may expect to see the distributions continue to rise as we progress to lower intensities/durations. Since we believe that the fall-offs are real, we do not see evidence for such activity at these energies.

The distribution of the intervals between flares revealed a distribution which could not be fitted by the expected exponential distribution, i.e. the distribution expected if flares occurred at random, but instead was fitted by a power law fall-off of the form t^{β}, with $\beta = -0.75 \pm 0.1$. From this result we conclude that the events are not randomly distributed in time. Indeed it appears to negate sympathetic flaring and suggests a need for a relaxation period.

From the histogram shown in Figure 6, we conclude that the events analysed show a high degree of flare symmetry. The slight asymmetry in the histogram

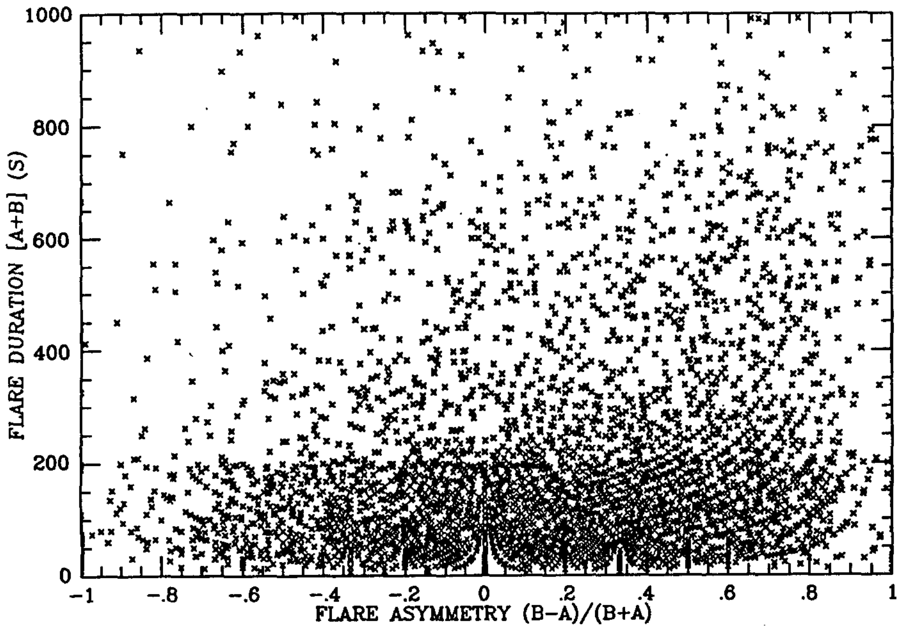

Fig. 9. The variation of flare duration $(a + b)$, with flare asymmetry, $(b - a)/(b + a)$.

suggests that events where the decay time is longer than the rise time are slightly more likely than events where the reverse is true. We also show that there is no relationship between the maximum flare intensity and flare asymmetry. Brighter flares are therefore not necessarily more symmetric than weaker flares and vice versa. There also appears to be no simple relationship between HXRBS event duration and event asymmetry. Longer lived flares are not necessarily more symmetrical than short lived events and vice versa. There does, however, appear to be some relationship between maximum flare intensity and duration, with the more intense flares having longer durations. However any such trend is swamped by the large scatter of events.

Models of flare acceleration processes must produce electron beam populations consistent with these findings. For example, the asymmetry must reveal something about the arrival time of different components of the population at the target.

Finally, we conclude that this analysis has confirmed that the fall-off towards flares of shorter durations and intensities does appear to be a real effect, since this has been observed in two recent previous studies involving two other independent solar data sets. There also appears to be strong continuous distribution of flare types, which has also beenobserved in analyses involving two other solar data sets.

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