N87-21797

FAST FLUCTUATIONS OF SOFT X-RAYS FROM ACTIVE REGIONS

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A selection of short lived ($\lesssim 10^2$s) small soft X-ray bursts is studied using data from HXIS, and the results are compared with data from HXRBS with a view to understanding conditions at the onset of flares. Short-lived events provide an opportunity to study the radiation from the primary energy transfer process without confusion from the slowly-varying thermal X-ray emission which characterizes the decay of a large flare. The fast decay of the soft X-rays, only a few tens of seconds, suggests that they occur in the dense chromosphere, rather than in the corona, but this is of course a selection effect. The results indicate that the short events may be signatures of several different phenomena, depending on their characteristics. Some events occur in association with reverse-drift type III bursts and simultaneous flaring elsewhere on the Sun, thus suggesting dumping of particles accelerated at a remote site. Some events have hard X-ray bursts and normal type III bursts associated with them, while others have neither. The latter events place strong constraints on the non-thermal electron population present.

Introduction

There have recently been a number of analyses of solar flare phenomena which are characterized by a short, hard X-ray spike lasting $\lesssim 10^2$s. (Crannell et al, 1978, Wiehl and Desai, 1983, Batchelor et al, 1984). Part of the motivation for such studies is to understand (a) where in the solar atmosphere the X-rays are produced, (b) the X-ray production mechanism -thermal or non-thermal bremsstrahlung, and (c) the origin of the charged particles which carry the energy to power the flare. It has long been assumed that these particles are electrons. However, Simnett (1985) has argued that an energetically-dominant non-thermal ion population might be better able to explain a wider variety of flare phenomena than an energetically-dominant electron population.

With the advent of comprehensive data from recent spacecraft we believe progress can be made in understanding the above topics. Simple events should be easier to interpret than large, complex events, despite the relativity weak signals from some of the former. The large events are almost certainly a combination of two effects, the impulsive deposition of energy to give the short hard X-ray burst followed by ablation of heated chromospheric plasma into the corona. X-ray emission from this material in a typical large flare confuses any attempt to isolate the radiation from the primary energy transfer process. In this paper we study a selection of short-lived soft X-ray events seen in 1980 by the Hard X-ray Imaging Spectrometer (HXIS) (van Beek et al (1980)) on the Solar Maximum Mission (SMM). We discuss them in the context of the >27 keV X-ray burst seen by the Hard X-ray Burst Spectrometer (HXRBS) (Orwig et al. 1980), also on SMM, and take into account simultaneous ground-based H_α and radio observations.

The X-ray emission is either thermal or non-thermal bremsstrahlung, or a combination of both. Non-thermal bremsstrahlung would naturally come from non-thermal electrons and rapid fluctuations of hard X-rays (>28 keV) are readily explained by modulation of the electron source. The spectrum radiated by such electrons will extend to the soft X-ray region ($\approx$3.5 keV). However, the majority of the soft X-rays have generally been assumed to reflect a thermal origin in plasma heated by the primary energy carriers, be they electrons or ions. If the radiation is thermal, then the very rapid decays ($\ll$1s above 28 keV) are more difficult to understand, although the soft X-ray variations such as those reported here may be reasonable if the radiating region is in the chromosphere. The main problem with a rapidly declining thermal source is the cooling mechanism and for this reason it is unlikely that the X-ray source can be in the corona, where cooling times are longer than the time scales discussed here. Analysis of the events presented in this paper should have a direct bearing on these points.

The Observations

We have earlier presented observations of rapid soft X-ray flares (Simnett and Dennis, 1985). Figure 1 shows an example of the most rapid soft X-ray spike HXIS observed, on 1980, July 10 at 01:50 UT, which lasted <30s. The lower panel of Figure 1 shows an expansion of 40s of data from HXRBS where the accumulation periods for the two HXIS data points above background are shown in black. It is probable that the soft X-ray onset was no earlier than 01:50:18UT and that the intensity returned to background by 01:50:37 UT. From comparison of other fast events, the soft X-ray maximum may be reached just before the hard X-ray maximum. Under these assumptions the soft X-ray amplitude would be 50%-100% higher than plotted and the total width would be $\approx$19s. The event was compact, imaged below the 8" x 8" resolution of HXIS, but on the limb. It was accompanied by a type III radio burst.

Figure 2 shows an example of an event with no hard X-ray, microwave, decimetric or metric emission. The clean fast decay event occurred at 07:07:46 UT on 1980, July 7 and the intensity-time history of 3.5-8.0 keV X-rays from four 8" x 8" HXIS pixels is shown in the upper right panel. The 3.5-5.5keV X-ray image of this event is shown in the lower panel. The left panels in Figure 2 show a similar, but more complex event, which occurred a few minutes earlier from a point approximately 14"E and 2"N of the former event. The active region being studied was then at N28 W48, but there was no reported H_α emission. (Unless otherwise acknowledged, ground based observations are from "Solar Geophysical Data", U.S. Dept. of Commerce, Boulder, CO.). At this position on the Sun, the observed separation of the two events corresponds to $\approx 1.5 \times 10^4$km. Ten minutes later at 07:18 UT another small event occurred

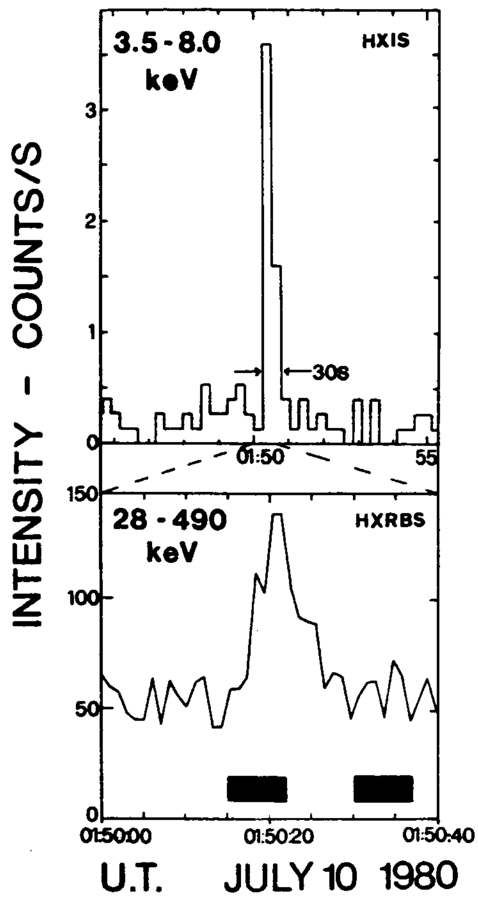

Fig. 1 The short soft X-ray spike on 1980 July 10. The hard X-ray intensity is shown expanded in the lower panel.

where the emission was in a band joining the bright points shown in Figure 2. One interpretation is that there is a magnetic loop linking these points and that the events in Figure 2 occur at opposite ends. There may even be small unresolved loops at these points which contain the bulk of the X-ray emitting plasma; the overlying loop would then be energized by the event at 07:18 UT. We stress then none of these events produced any detected hard X-ray or radio emission.

Some fast spikes occur when there is activity from a remote region. Figure 3 shows the intensity-time history of 16-30 keV (upper panel) and 3.5-5.5 keV (lower panel) X-rays from HXIS for the period 10:09 UT-10:20 UT on 1980, July 7. The feature of interest is the soft X-ray spike superimposed on the decay of the first event, which also had a hard X-ray burst reaching 280 c/s and extending to over 100 keV (shown hatched). The emission from HXRBS corresponding to the earlier, 10:14 UT event is not shown. If we assume the soft X-ray emission associated with the spike to be that above the heavy solid line drawn on the decay of the 3.5-5.5 keV X-rays, then the duration of the spike is 85s. Although there was microwave emission reported throughout the period covered by Figure 3, the maximum intensity at 9.1 GHz was at 10:17:48 UT, coincident with the spike. The spectrum of the burst is hard, as it is remarkable that such a weak event in soft X-rays would be detectable by HXIS above background in the 16-30 keV energy band. There was a 1N H_α flare reported from Hale region 16955, then at N29 W50, from 10:05 UT to10.23UT, with a maximum at 10:15 UT. This was the region studied by HXIS. However, there was another 1N H_α flare from 10:10 UT to 10:33 UT, with a maximum at 10:18 UT, from a region at N21 E44. There was also a reverse drift metric type III burst (A.O. Benz, private communication) at 10.17 UT which did not extend in frequency above 400 MHz. This would correspond to an electron density of 2 x $10^9 cm^{-3}$ if the emission is at the plasma frequency. In the quiet Sun such densities are typically found at the top of the chromosphere or the base of the corona. (Vernazza et al, 1981) although during activity the altitude may be somewhat higher. The short spike was imaged a few arc-seconds to the southwest of the brightest point of the earlier, decaying flare. The data are consistent with an electron beam escaping from the easterly region and impacting the (presumably) density enhanced corona above region 16955. A similar event on 1980, June 24, was

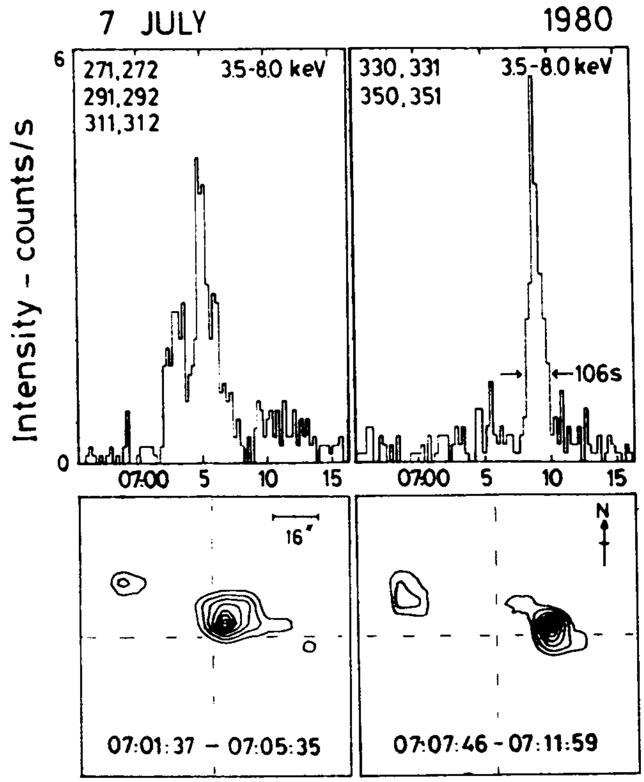

Fig. 2 The fast events with no hard X-ray emission from well-separated points.

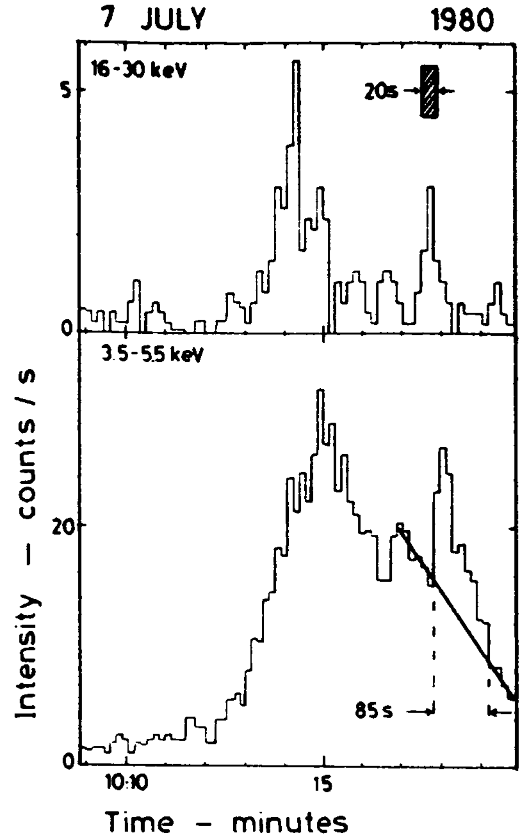

Fig. 3 The X-ray spike superimposed on the decay of an earlier event

reported by Simnett et al (1984) although in this instance both active regions were visible to HXIS.

We have assumed the spike is superimposed on an undisturbed, decaying background from the earlier flare. If this is correct, then the site of the spike and the site of the decaying flare must be physically separate, and not in good thermal contact. This either points to a vertical separation in the solar atmosphere, or to the existence of structures well below the 8" x 8" resolution of HXIS. If the spike is non-thermal bremsstrahlung from precipitating electrons which do not penetrate the 400 MHz plasma level (or the 200 MHz plasma level if the emission is at the second harmonic) then the former explanation would be consistent with the data.

Figure 4a, b, shows the 3.5-8.0 keV X-ray intensity-time history for two isolated events. The FW $^{1}/_{10}$M are 106s and 152s respectively, but they both have weak, long decays. Both are associated with hard X-ray bursts extending above 100 keV seen by HXRBS. That on 1980 September 26 started at 10:37:40 UT, reached a peak intensity of 349 c/s at 10:37:50 UT, and lasted 50s. That on 1980, July 10 reached a peak intensity of 535 c/s

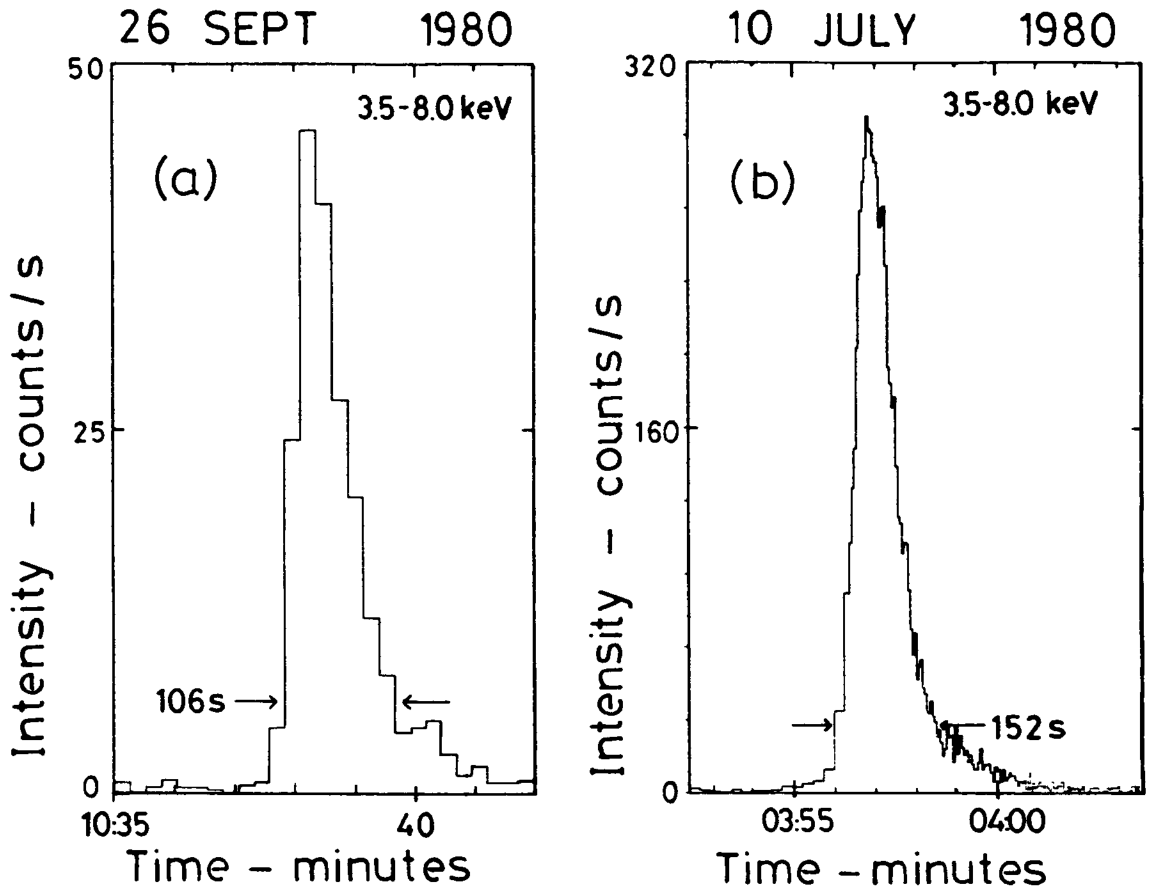

Fig. 4 (a) The fast event on 1980 September 26 (b) The fast event of 1980 July 10

at 03:56:55UT, slightly <u>after</u> the peak in soft X-rays.

The September 26 event was accompanied by a microwave burst which started at 10:37:30 UT and reached a maximum of 34 x $10^4 Jy$, at 19.6 GHz, at 10:37:48 UT. At this time HXIS was studying Hale region 17145, then at N17 W56. There was no optical flare reported from this region, but there was a -F H_α flare from region 17167, then at S19 E44, which reached maximum brightness at 10:37 UT. There was metric radio emission between 10:37:42 uT and 10:38:18 UT, including a reverse drift burst. The latter is indicative of downward moving electrons. If we apply the same reasoning to this event as we did to the event shown in Figure 3, then we might be witnessing X-ray emission from particles accelerated at one site and transferred to a remote site via the large scale coronal magnetic field. There was no evidence of any X-rays >16 keV from HXIS in this event. Considering the relative strengths of the events at 3.5-8.0 keV, and >28 keV for the event and that shown in Figure 3, this is surprising if all X-rays are coming from the area imaged by HXIS. It would be more reasonable if some of the hard X-ray burst seen by HXRBS was from a different region.

Figure 4b shows a much stronger event on 1980, July 10. There was a significant hard X-ray burst seen by HXIS, above 16 keV, capable of producing a weak image, yet the peak intensity seen by HXRBS was only 535 c/s. Therefore, a comparison with the September 26 event shows either that the X-ray spectra between the two events were very different or that the above conclusion that some, or most, of the hard X-rays from the September 26 event were from the east hemisphere flare is correct. There is an additional unusual feature about this event in that the soft X-ray intensity is already declining before the hard X-ray burst reaches maximum. The latter is very structured, with three prominant peaks, the last being the most intense. This event might be more consistent with other events, from spectral and temporal considerations, if the last and longest hard X-ray spike were from a region not imaged by HXIS. There was decimetric, metric and dekametric activity from 03:56-03:57 UT but no reported H_α flare.

The final event on 1980, July 11 at 05:31:30 UT is shown in Figure 5. The soft X-ray enhancement coincident with the hard X-ray burst fell virtually to background level before rising again for the small event at 05:33 UT. The 40s duration of the hard X-ray burst, which reached an intensity of 103 c/s and extended to beyond 100 keV, is indicated by the cross-hatched box in Figure 5. The 5.2 GHz microwave burst reached 8 x $10^4 J_Y$ at 05:31:30 UT, essentially coincident with the hard X-ray burst maximum at 05:31:35 UT. There was metric and decimetric type III activity from 05:31:30 UT-05:33 UT (A. O. Benz, private communication).

This small event was from N20 E55, associated with a -N H_α flare which started at 05:32 UT and had a maximum at 05:34 UT. The initial soft X-ray burst appears to be quite definitely associated with the hard X-ray burst, but yet the following stronger soft X-ray emission has no corresponding hard X-rays. The second burst is delayed long enough that any thermal effects of energy deposition at the time of the hard X-ray burst must have dissipated.

We note that there was a 1F H_α flare in progress at this time from S11 E83, with a maximum at 05:39: UT. In view of the associations discussed above in relation to other events it is plausible that this event is also associated with activity from a remote region. One might speculate that the first spike in Figure 5 is non-thermal bremsstrahlung from electrons, while the later emission is thermal X-rays from plasma heated by ions. If the distance travelled by the particles is 8 x 10^{-10}cm, consistent with the separation of the two flaring regions, cf e observed delay of ≈80s between the first spike and the subsequent soft X-ray emission may be accounted for by electrons of ≈30 keV and protons of ≈400 keV.

Conclusions

The events discussed above provide a unique insight into the correspondence between hard and soft X-ray emission in solar events which are not confused by large scale chromospheric ablation and its associated thermal X-ray signature. We have focused on the features of the events which we think provide good boundary conditions for a sound interpretation. The interpretations we have made appear reasonable, but they are not meant to exclude other explanations which match the boundary conditions. The soft X-ray spikes are compact events, typically, but not always, below the 8" x 8" resolution

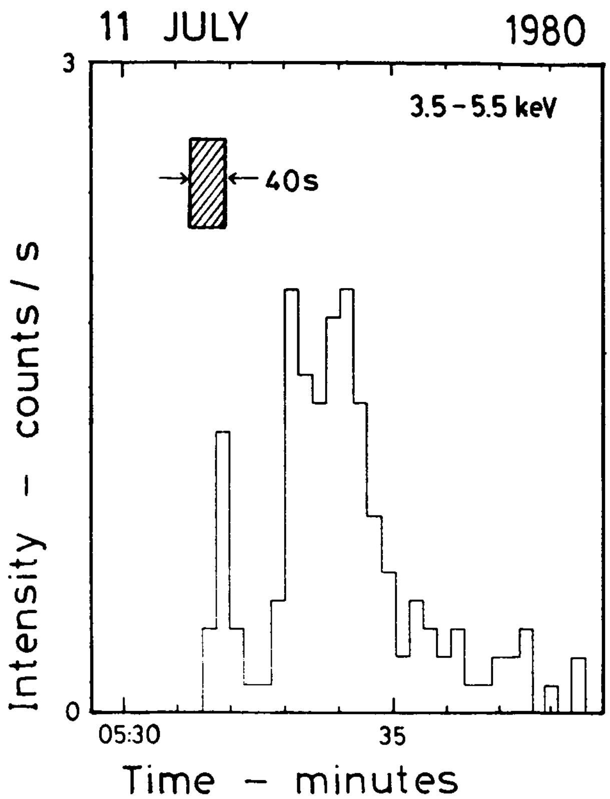

Fig. 5 A soft X-ray spike coincident with the hard X-ray burst (shown hatched) but separated from the main event.

HXIS. Some events, such as that on July 7 and on 1980, June 27 at 19.50 UT (Simnett and Dennis, 1985) had no reported radio activity at any wavelength. This would argue against non-thermal electrons as the dominant energy carrier in these events, especially as the hard X-ray intensity is also below the HXRBS threshold. The rapid decay of the soft X-ray events is unlikely to be a signature of hot plasma in the corona. Therefore we believe these events either take place at the top of the chromosphere, or are non-thermal electron bremsstrahlung. The very short spikes which occur in coincidence with hard X-rays, such as those shown in Figure 1 and 5, are most likely examples of the latter. Finally, we believe the events where (a) there is a reverse drift radio burst and (b) simultaneous flaring from widely separated regions argues strongly for a particle beam interpretaion, coupled with extensive magnetic coronal loops linking the flaring regions; where in the large loop the energy release and particle acceleration occur are open questions.

Acknowledgements

We are grateful to Dr. A. O. Benz for useful discussion and for making unpublished data available to us.

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