SPATIAL STRUCTURE OF HIGH ENERGY PHOTON SOURCES IN SOLAR FLARES

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ABSTRACT

Stereoscopic observations of high energy ($\gtrsim$ 100 keV) photon emission from five solar flares have been made with the X-ray spectrometers aboard the ISEE-3 (International Sun Earth Explorer-3) and PVO (Pioneer Venus Orbiter) spacecraft. The observed altitude structure of the photon source and its dependence on the photon energy and time during a flare are compared with the predictions of thermal and non-thermal models of the hard X-ray source. In the case of the *impulsive* source, it is found that (1) the thermal model with adiabatic compression and expansion of a magnetically-confined plasma and the thin target (non-thermal) model are *not* consistent with the observations; (2) the thick target (non-thermal) model and the dissipative thermal model are *partially* in agreement with the observations; (3) the emission probably originates in many individual non-thermal sources distributed in altitude, the lower altitude sources being brighter than those at higher altitude. In the case of the *gradual* source, it is found that (1) models with purely coronal sources are not consistent with the observations; (2) a partial precipitation model with trapped as well as precipitating electrons is consistent with the observations.

1. INTRODUCTION

One of the critical tests for models of solar flares is their prediction regarding the location and altitude dependence of the high energy photon sources during the impulsive and gradual phases. During the impulsive phase, some thermal models, for example, require that the hard X-ray source be located in a low density region at coronal altitudes (cf. Crannell *et al.*, 1978). Non-thermal models may require a high altitude "thin target" source associated with an electron trap (Datlowe and Lin, 1973; Ramaty, 1973; Takakura, 1974), a low altitude "thick target" source due to an electron beam (Brown, 1971; Hudson, 1972) or an extended source due to partial precipitation of electrons from a "leaky" electron trap (Kane, 1974; Melrose and Brown, 1976). The gradual (extended) hard X-ray source, often associated with the second stage of the particle acceleration process, has been assumed to be confined primarily to coronal altitudes (Brown and Hoyng, 1975; Hudson, 1978).

In order to verify the validity of these models, it is important to determine observationally the altitude structure of the impulsive and gradual (extended) hard X-ray sources in solar flares. The X-ray emission to be observed must be >30 keV, and preferably $\gtrsim$100 keV, so that possible ambiguities due to the contamination from the relatively slowly-varying thermal sources can be reduced to a minimum. Moreover, the dependence of the altitude structure on X-ray energy and its variation with time during a flare also need to be measured. No such imaging observations are presently available. An alternative technique consists of viewing the

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flare from two different directions with the help of hard X-ray spectrometers aboard two or more spacecraft separated in heliographic longitude (Kane, 1981). If the X-ray source is partially occulted by the photosphere from the line of sight of one of the spectrometers, a measure of the altitude dependence of the X-ray source brightness can be obtained. We summarize below such stereoscopic measurements of solar flare X-rays $\gtrsim$100 keV and examine their implications with respect to the models of solar flares.

2. OBSERVATIONS

The stereoscopic observations reported here were made with X-ray spectrometers aboard the ISEE-3 (International Sun Earth Explorer-3) and PVO (Pioneer Venus Orbiter) spacecraft. These instruments have been described elsewhere (Kane *et al.*, 1982). The ISEE-3 hard X-ray spectrometer covers 26 - 3170 keV X-rays in 12 energy channels. The X-ray energy range covered by the PVO instrument is 100 - 2000 keV in 4 energy channels. The time resolution of the two sets of observations is 0.5 - 8 s. The ISEE-3 and PVO spacecraft are located at different distances from the sun. For comparison, the fluxes and arrival times of solar flare photons at the two spacecraft have been converted to equivalent values at the earth's distance from the sun.

Measurements of four well-observed flares, viz., one on 5 October 1978 and three on 5 November 1979, have been partially analyzed earlier (Kane *et al.*, 1979, 1982). Now preliminary measurements for the 14 September 1979 flare are also available. Table I presents the principal characteristics of the five flares. Flares 1 and 2 occurred behind the east limb of the sun. They were in full view of the PVO instrument, but were partially occulted from the ISEE-3 line of sight. On the other hand, flares 3, 4, and 5 were well observed from the earth, their Hα importance being $\gtrsim$1B. All the three flares were in full view of the ISEE-3 instrument, but were partially occulted from the PVO line of sight. For all the five flares, the estimated minimum altitude h_{min} above the photosphere which could be viewed from the occulted spacecraft is also given in Table I.

The time-rate profiles of the hard X-ray bursts associated with flares 1, 3, 4, and 5 have been presented elsewhere (Kane *et al.*, 1979, 1982). Each of the four bursts was primarily impulsive. In the last flare, the impulsive burst was followed by a small gradual burst, which lasted for ~5 min. The X-ray time-rate profile for flare 2 (14 September 1979) is shown in Figure 1. The event started at ~0653 UT. It consists primarily of a gradual hard X-ray burst, on which small fuctuations are superimposed. The observed duration of the burst is $\gtrsim$13 min. and ~5 min. for ~30 keV and ~100 keV X-rays, respectively. The overall time-rate profiles recorded by ISEE-3 and PVO are similar, including the first major maximum at ~0657 UT. It is interesting to note that the small impulsive burst at ~0653:40 UT. and the large impulsive burst at ~0703 UT, which were clearly recorded by the PVO instrument, are not present in the ISEE-3 data. The sources of these impulsive X-ray bursts were almost completely occulted from the ISEE-3 line of sight.

In order to compare the X-ray fluxes from the occulted and unocculted parts of the X-ray source, the following procedure is adopted. Since the ISEE-3 instrument measures 26 - 3170 keV X-rays in 12 energy channels, compared to the four rleatively wide energy channels of the PVO instrument, covering 100 - 2000 keV X-rays, power law X-ray spectra are fit only to the ISEE-3 observations. Fluxes of 150, 350, 750, and 1500 keV X-rays are computed from the observed PVO counting rates, assuming that the shape of the X-ray spectrum incident at PVO is similar to that incident at ISEE-3. If necessary, the observed spectrum at ISEE-3 is extrapolated to cover the PVO energy range. Since the deduced X-ray fluxes for PVO are relatively insensitive to small variations in the assumed incident X-ray spectrum, the results presented in this paper are not expected to be critically dependent on the above assumption.

TABLE I.
Characteristics of the Occulted and Unocculted Hard X-Ray Flares

Flare No.	1	2	3	4		5	
Date	5 Oct. 1978	14 Sept. 1979	5 Nov. 1979	5 Nov. 1979		5 Nov. 1979	
Hα Flare:							
Importance	–	–	1B	2B		1B	
Location	Behind Limb	Behind Limb	S13.4°, E49.0°	S14.2°, E44.6°		S15.4°, E44.0°	
X-ray Burst							
Type	Impulsive	Gradual	Impulsive	Impulsive	Impulsive	Gradual	Total
t_{max} (UT)	0631:41	~0657:11	1741:20	2149:01	2347:22	2347:46	2347:30
Occult. Sp.	ISEE-3	ISEE-3	PVO	PVO	PVO	PVO	PVO
h_{min} (km)	~25000	~30000	0±100	2000±1000	2500±1000	2500±1000	2500±1000
Δt (s)	4	16	8	16	8	8	40
50 keV X-rays (ISEE-3):							
Flux	0.1	2.9	1.3	2.2	16.6	2.2	~8.0
γ	3.4	4.1	3.0	3.3	2.1	3.2	~2.4
150 keV X-rays (ISEE-3):							
Flux	2.45×10^{-3}	1.48×10^{-2}	4.8×10^{-2}	5.9×10^{-2}	1.3	6.4×10^{-2}	0.42
γ	~3.4	5.5	3.0	3.3	~3.0	3.2	3.2
(PVO):							
Flux	0.27±0.01	$(1.11 \pm 0.01) \times 10^{-1}$	$(4.4 \pm 0.3) \times 10^{-2}$	$(2.5 \pm 0.3) \times 10^{-2}$	$(5.7 \pm 0.3) \times 10^{-2}$	$(1.8 \pm 0.2) \times 10^{-2}$	$(3.5 \pm 0.2) \times 10^{-2}$
350 keV X-rays (ISEE-3):							
Flux	$\sim 1.39 \times 10^{-4}$	1.41×10^{-4}	3.6×10^{-3}	4.0×10^{-3}	6.4×10^{-2}	3.0×10^{-3}	3.0×10^{-2}
γ	~3.4	5.5	3.0	3.3	3.6.	4.7	3.2
(PVO):							
Flux	$(4.1 \pm 0.1) \times 10^{-2}$	$(1.99 \pm 0.09) \times 10^{-3}$	$(3.1 \pm 0.2) \times 10^{-3}$	$(1.7 \pm 0.1) \times 10^{-3}$	$(5.1 \pm 0.2) \times 10^{-3}$	$(6.3 \pm 1.1) \times 10^{-4}$	$(2.7 \pm 0.1) \times 10^{-3}$
Flux ratio:							
150 keV	$(9.1 \pm 0.3) \times 10^{-3}$	0.13±0.002	0.92±0.06	0.43±0.04	$(4.4 \pm 0.3) \times 10^{-2}$	0.28±0.04	$(8.3 \pm 0.4) \times 10^{-2}$
350 keV	$(3.4 \pm 0.1) \times 10^{-3}$	$(7.1 \pm 0.3) \times 10^{-2}$	0.86±0.06	0.42±0.03	$(8.0 \pm 0.4) \times 10^{-2}$	0.21±0.04	$(9.0 \pm 0.3) \times 10^{-2}$

Occult. Sp. = Occulted Spacecraft
h_{min} = Occultation height
Δt = Averaging time for spectra
Flux: Photons cm^{-2} sec^{-1} keV^{-1}
Flux ratio: occulted flux / unocculted flux

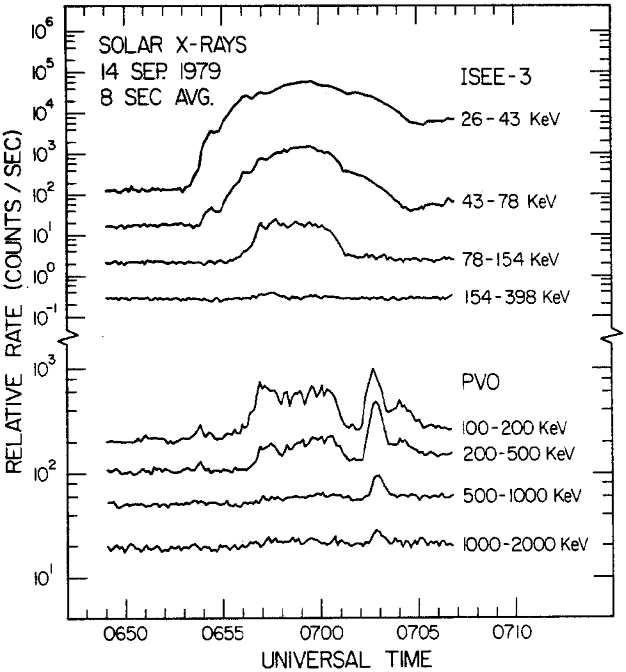

Figure 1. The time-rate profiles of the hard X-ray emission recorded by the ISEE-3 and PVO spacecraft during the 14 September 1979 solar flare. The flare, which apparently occurred behind the East limb of the sun, was in full view of the PVO instrument, but was partially occulted from the ISEE-3 line of sight. Note that only the gradual burst starting at ~0655 UT in the PVO record is present also in the ISEE-3 record. The large impulsive burst at ~0703 UT was almost completely occulted from the ISEE-3 line of sight.

The X-ray spectra for flares 1 (Figure 2), 2 (Figure 3), and 3 through 5 (Figure 4), are presented, following. The spectrum for flare 1 (5 October 1978) has been revised on the basis of the extensive detector calibration described by Kane *et al.* (1982). In the case of flare 2 (14 September 1978), a preliminary X-ray spectrum is shown for the first major maximum. The ratio $r(E, h_{\min})$ of the occulted to unocculted X-ray fluxes is computed for photon energies E ~150 keV and ~350 keV from the spectra such as those shown in Figures 2, 3 and 4. The values obtained are listed in Table I.

3. VARIATION OF THE X-RAY SOURCE BRIGHTNESS WITH ALTITUDE AND X-RAY ENERGY

Since the altitude structure of the impulsive and gradual hard X-ray sources could be quite different, it is important that the ratios r of the occulted to unocculted X-ray fluxes be computed separately for impulsive and gradual X-ray components. Also, since the flux ratio could depend on the energy of the observed X-ray emission, the ratios need to be computed separately for different values of the photon energy E, such as 150 keV and 350 keV. In constructing Table I, both of the above requirements have been taken into account.

Figure 5 shows the variation of the occulted to unocculted X-ray flux ratio $r(E, h_{\min})$ with the occultation altitude $h_{\min}$ and photon energy E. Note the break in the scale for altitude $h_{\min}$. Two values of E are considered in Figure 5, viz., 150 keV and 350 keV. The variation of r is shown separately, left and right, for impulsive and gradual X-ray bursts, respectively.

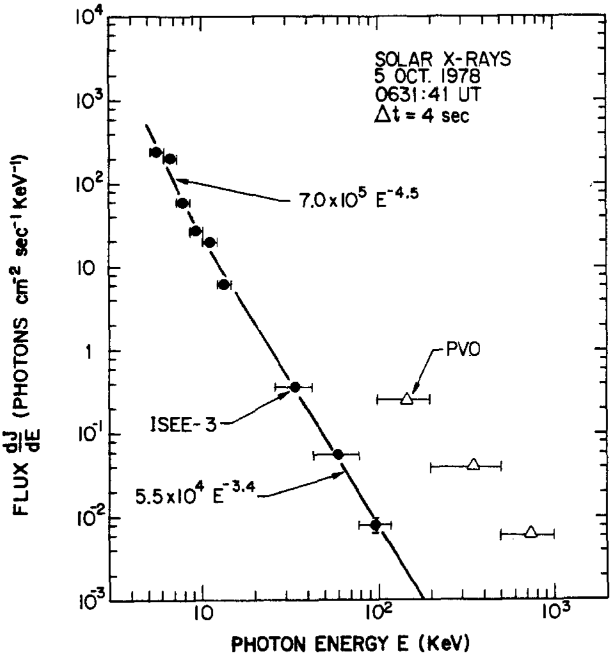

Figure 2. The X-ray spectra observed by the ISEE-3 and PVO instruments at the maximum (~0632 UT) of the impulsive hard X-ray burst on 5 October 1978.

In Figure 5 (left), flares 2, 3 and the impulsive part of flare 4 are included. These three flares occurred in the same active region within a period of six hours, and hence the altitude structure of the X-ray source may be considered essentially similar in the three flares. Flare 1, in which the coronal source was observed, is also shown for comparison. However, this flare occurred almost one year before the flares 2, 3 and 4, and hence may have a somewhat different altitude structure for the X-ray source. Similar remarks apply to Figure 5 (right), where flare 2 and the gradual part of flare 4 are included. In what follows, we discuss the two parts of Figure 5 as if they presented representative observations for a single flare.

(a) Impulsive X-Ray Source

An examination of Figure 5 (left) indicates two principal characteristics of the impulsive X-ray source:

1. The source brightness decreases with increasing altitude h above the photosphere. The decrease in brightness is most rapid as h increases from ~1000 km to ~3000 km. About 95% of the total ~150 keV X-ray emission originates at altitudes $h \lesssim 2500$ km.
2. In the 100 - 500 keV range, the X-ray source brightness at altitudes $h \lesssim 2000$ km does not vary significantly with the photon energy E. At $h \sim 2500$ km, the ~150 keV X-ray emission seems to decrease more rapidly with increasing altitude than the ~350 keV X-rays. This energy dependence is, however, reversed at coronal altitudes.

(b) Gradual X-ray Source

Figure 5 (right) shows the relatively limited observational information available for the gradual X-ray source. A comparison with the altitude dependence of the impulsive source (solid curve) indicates the following:

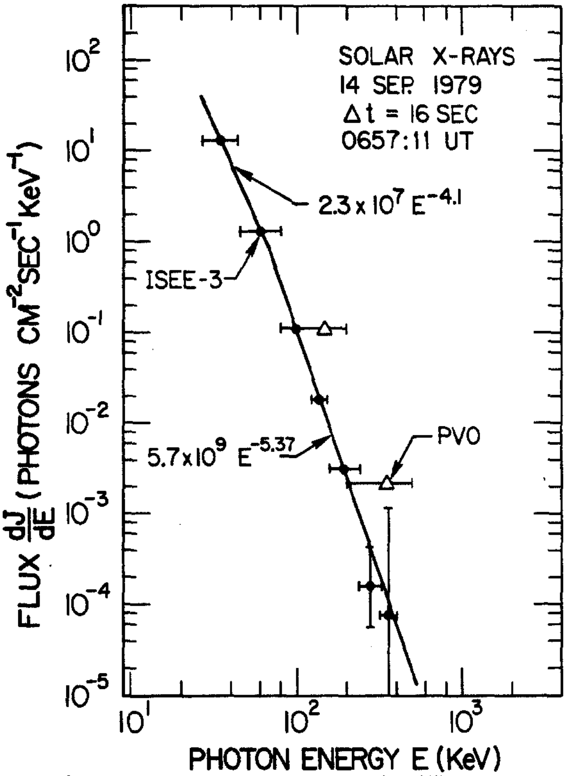

Figure 3. The X-ray spectra observed by the ISEE-3 and PVO instruments at the first maximum (~0657 UT) of the gradual hard X-ray burst on 14 September 1979.

1. For a gradual source, the decrease in brightness with increasing altitude is much less rapid than that for the impulsive source. Hence, the effective height of the gradual source is larger than that for the impulsive source. However, at least in the case of a gradual burst preceded by a large impulsive burst, $\gtrsim$70% of the 100 - 500 keV photon emission originates at altitudes $h \lesssim 2500$ km.
2. In the 100 - 500 keV range, the rate of decrease in the X-ray source brightness with increasing altitude is larger for higher energy photons.

4. EVOLUTION OF THE X-RAY SOURCE WITH TIME

The hard X-ray bursts associated with flares 2 and 5 were relatively large in magnitude as well as duration. It was therefore possible to measure the time variation of the flux ratio $r(E, h_{min})$ for a fixed value of h_{min} and two values of E, viz., ~150 keV and ~350 keV. The results for flare 5 (5 November 1979, ~2347 UT) and flare 2 (14 September 1979) are shown in Figures 6 and 7, respectively. It is important to note that, unlike flare 5 (Figure 6), in which the small gradual burst was preceded by a large, impulsive burst, flare 2 (Figure 7) produced primarily a large gradual burst.

For ~150 keV X-rays, the most important feature in Figure 6 is the increase in the value of r by a factor of ~6 as the character of the X-ray burst changes from impulsive to gradual. This effect can also be seen in ~350 keV X-ray emission, although its magnitude is smaller. The overall variation of r with time is very similar at the two photon energies.

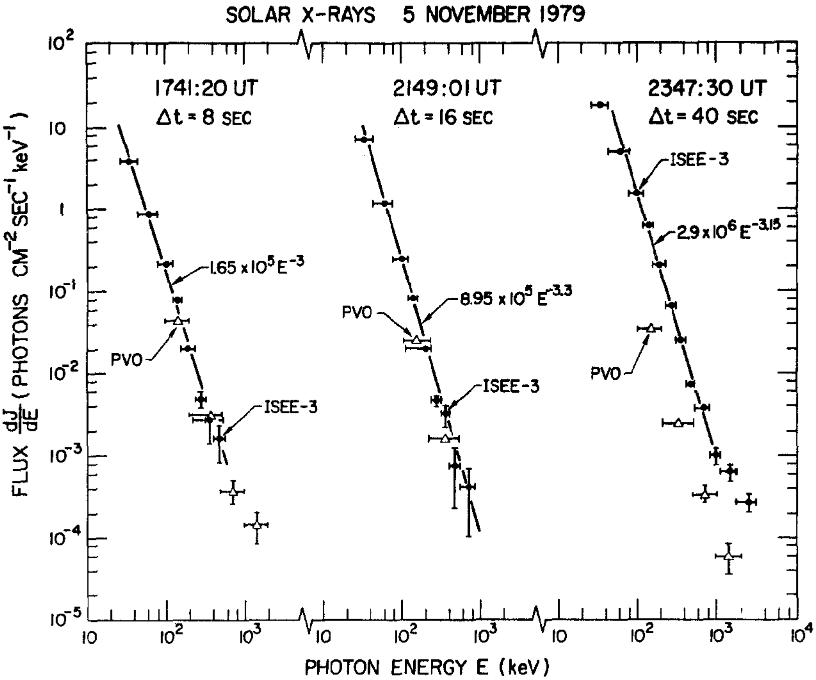

Figure 4. Total event X-ray spectra observed by the ISEE-3 and PVO instruments at the times of three flares on 5 November 1979. After the first flare (~1741 UT), which was in full view of both the ISEE-3 and PVO instruments, within a period of six hours there occurred two additional flares in the same active region which were successively more and more occulted from the PVO line of sight (Kane *et al.*, 1982).

In the gradual burst of flare 2 (Figure 7), the variation of r with time is quite different for ~150 keV and ~350 keV photons. At the time of the first maximum t_{max} (~0656:50 UT), the value of r at ~150 keV is larger than that at ~350 keV only by a factor $\lesssim 2$. As time progresses, the value of r at ~150 keV increases gradually from ~0.1 to ~0.27 and remains at that value for the remainder of the burst. On the other hand, at ~350 keV, r decreases more or less continuously with time from a value of ~0.06 to ~0.01. An examination of the time-rate profile (Figure 1) shows that, whereas the unocculted X-ray spectrum at PVO was gradually hardening with time, the partially occulted spectrum at ISEE-3 was either softening or relatively constant during the interval 0657-0700 UT. Thus, it appears that the energetic electron populations in the coronal and lower altitudes X-ray sources were not well correlated during this flare.

5. COMPARISON WITH THE FLARE MODELS

We now compare the above observations with the characteristics of the hard X-ray source predicted by the different models of the flare emissions (Kane, 1974, 1981). The observed low altitude of the principal part of the *impulsive* hard X-ray source rules out theoretical models requiring a high altitude (low density) X-ray source such as the non-thermal thin target model (Datlowe and Lin, 1973) and the thermal model with adiabatic compression and expansion of a magnetically-confined plasma (Crannell *et al.*, 1978). On the other hand, the non-thermal thick target model (Brown, 1971; Hudson, 1972) and possibly the dissipative thermal model (Brown *et al.*, 1979), which is similar to the thick target model at high photon energies (Emslie, 1980; Brown and Hayward, 1981), are consistent with the observed low altitude of the impulsive X-ray source. The observed variation of the source brightness with altitude above the photosphere is roughly similar to that expected from a thick target model, in which a beam of

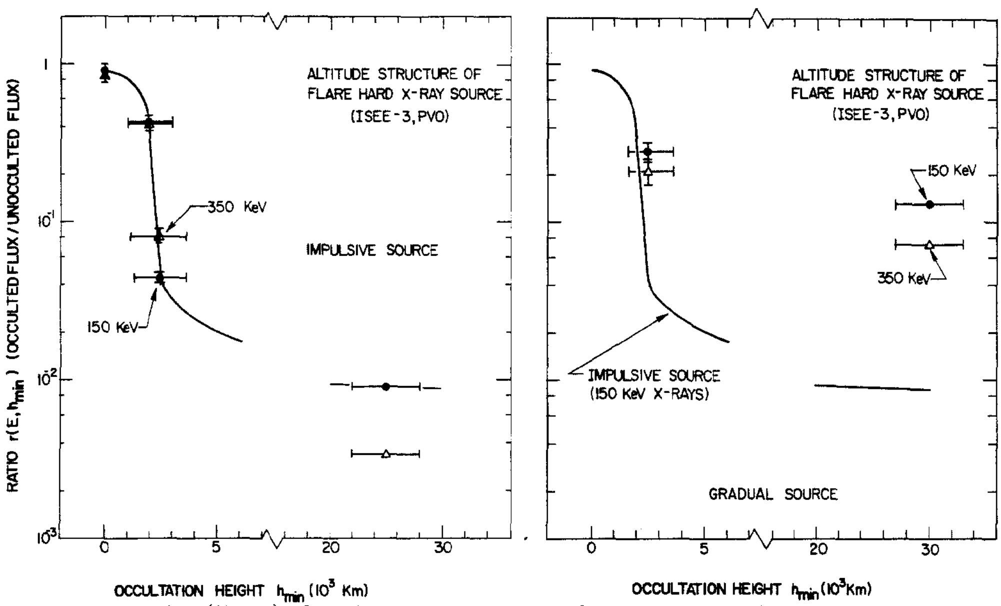

Figure 5. The ratio $r(E, h_{min})$ of occulted to unocculted X-ray flux plotted against the minimum altitude h_{min} observable from the occulted spacecraft. Observed values of r for two values of the photon energy E, viz., ~150 keV and ~350 keV, are presented. Two types of sources are considered: (left) impulsive source, (right) gradual source. The solid line at left representing the ~150 keV impulsive source is reproduced at right for comparison.

energetic electrons, accelerated in the corona, moves downwards towards the photosphere (Brown and McClymont, 1975). However, the observations are not in agreement with the predicted $\sim E^{-\alpha}(\alpha = 1.5 - 2)$ dependence of the occulted to unocculted X-ray flux ratio $r(E, h_{min})$ on the photon energy E. For ~150 keV and ~350 keV X-rays, we expect $R(h_{min}) = r(150, h_{min}) / r(350, h_{min}) \approx 3.6 - 5.4$. From Table I and Figure 5 (left), we find that the observed values of R are much smaller. For $h_{min} \lesssim 2500$ km, $R \lesssim 1$. Although some of this disagreement could be due to factors, such as the detailed shape of the magnetic field, which have not been taken into account here, it seems more likely that the X-ray source is not homogeneous and continuous in altitude, as assumed in a simple thick target model. The impulsive hard X-ray emission probably originates in many individual sources distributed in altitude, the sources at lower altitudes being, in general, brighter than those located at higher altitudes. Such a distribution could result, for example, from the multi-layer trapping of precipitating electrons if there are inhomogeneities in the magnetic field and electron pitch angle distribution. The individual X-ray sources are not likely to be hot thermal kernels (cf. Brown *et al.*, 1980) because of the very high temperatures required by the high energies of emitted photons. It seems more likely that the X-ray sources are non-thermal and are produced by acceleration and/or trapping of energetic electrons in small "kernels" along the magnetic field. Such a source structure would be consistent with the relatively low observed directivity of the hard X-ray emission (Kane *et al.*, 1980).

The gradual hard X-ray source is often assumed to be located in the corona, where the ambient density is $\lesssim 10^8$ cm^{-3} (cf. Brown and Hoyng, 1975; Stewart and Nelson, 1980). Such an assumption is not consistent with the observations. A substantial fraction of the total gradual hard X-ray emission seems to originate at much lower altitudes. At a given altitude, the relative brightness of the gradual source is greater than or equal to the relative brightness of the impulsive source. This could be due to an enhancement in the ion density caused by "chromospheric evaporation" during the impulsive phase, a plausible explanation, especially for

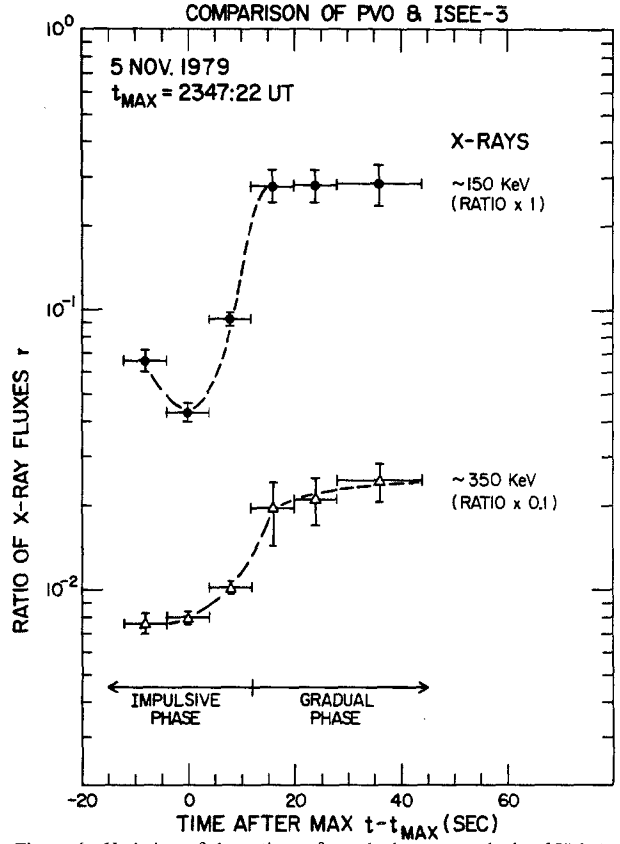

Figure 6. Variation of the ratio r of occulted to unocculted ~150 keV and ~350 keV X-ray fluxes with time during the 5 November 1979 (~2347 UT) flare. Note the large increase in r as the character of the X-ray burst changes from impulsive to gradual.

flares in which a large impulsive X-ray burst can be clearly identified. However, in cases such as flare 2, in which the hard X-ray emission is mostly gradual, it is unlikely that chromospheric evaporation plays a significant role. It appears that, at least during a gradual burst, both chromospheric and coronal hard X-ray sources are present, as would be expected, for example, from a partial precipitation model (Kane, 1974; Melrose and Brown, 1976). In such a model, energetic electrons are continuously injected into a "leaky" magnetic trap from which some electrons precipitate into the chromosphere.

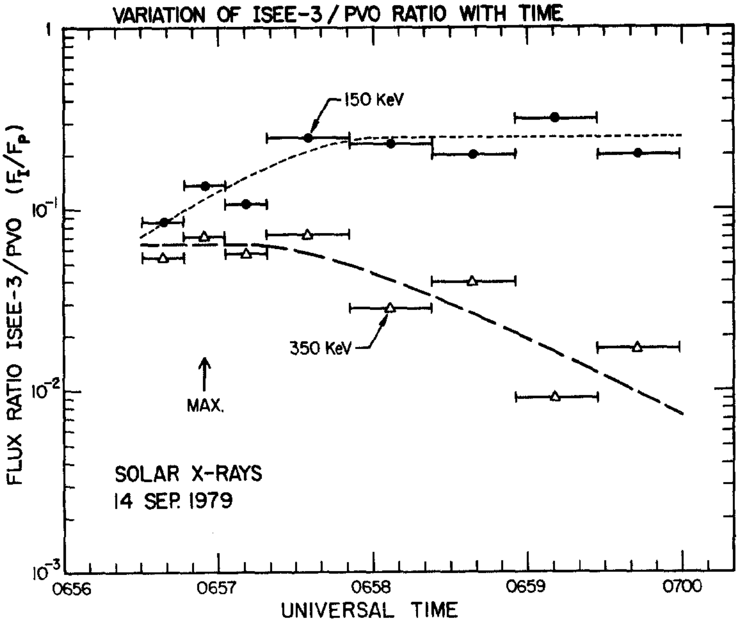

Figure 7. Same as Figure 6, but for the gradual X-ray burst on 14 September 1979. See text for details.

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DISCUSSION

J. C. Henoux: I don't think the lack of directivity implies that the thick target emission does not explain your observations. Computations by Bai and also by myself show that, even for electron beam X-ray emission, photospheric Compton backscattering greatly reduces the directivity.

S. R. Kane: Your assertion is true only for low energy (<100 keV) photons. Since the relative effect of Compton backscattering tends to decrease with increasing photon energy, stereoscopic measurements of 500 - 1000 keV X-rays can provide a measure of the true directivity of the hard X-ray source.

J. C. Brown: The energy dependence of the flux ratio in the later stages of the Sept. 14, 1979 event is, in a sense, expected in a thick target model, *i.e.*, the 350 keV ratio is lower. I would expect the energy dependence of the ratio in this case to be about E^{-2}, so that the 350 keV ratio should be about 5.1 times smaller than the 150 keV ratio, much as you observe.

S. R. Kane: Yes, it certainly seems that way. I wonder if it is a large density enhancement or some other effect that makes the hard X-ray source look like a thick target source up to heights $\gtrsim$ 30000 km.

H. S. Hudson: It does not seem worthwhile to try to draw general conclusions! You have only three of your excellent stereo observations, and there were only three single-spacecraft occultations reported during the last solar maximum. In particular, the May 12, 1981, HINOTORI event described by Mr. Tsuneta appears to have a much greater extent in height.

S. R. Kane: I agree that we should not draw general conclusions from only three events. We hope to observe some more events and see if these conclusions are still true. As regards the HINOTORI measurements, I do not know what the assigned height corresponds to: is it the geometrical center of the source, or the most intense part, or something else? I hope that we will find a common event so that we may compare the two sets of measurements.

G. A. Doschek: I believe we have soft X-ray spectra for the 5 Nov. 1979 flare you discussed. It may be interesting to compare these data with the ISEE data.

S. R. Kane: Yes! We should certainly compare the two data sets.