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OBSERVATIONS OF THE HARD X-RAY SPECTRUM OF THE IMPULSIVE PHASE OF SOLAR FLARES

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ABSTRACT

The impulsive solar hard X-ray spectrum provides a direct diagnostic on the impulsive energy release of the flare. The data from the hard X-ray (14–342 keV) spectrometer on *OSO 7* have been examined for events covering a wide energy range to determine the photon spectrum more precisely. This resulted in a sample of 38 events. The data have been fitted with either single- or double-power laws, and with an exponential spectrum, as from thermal bremsstrahlung. The χ^2 statistic between two-parameter fits strongly favors the exponential fit, particularly at peak intensity when the widest energy range is sampled. This result supports a single-temperature thermal source of the impulsive solar hard X-rays with temperatures in the range 4.7–31 keV and emission measures in the range 8.4×10^{43}–6.0×10^{46} cm^{-3}. The temperature reaches a single maximum and then rapidly decays, but the emission measure usually increases throughout, even after temperature maximum, for data with 10 s resolution.

Subject headings: plasmas — Sun: flares — Sun: X-rays

I. INTRODUCTION

The impulsive hard X-rays ($h\nu \gtrsim 15$ keV) provide a relatively direct diagnostic on the impulsive energy release of the solar flare. The hard X-ray (HX) time history can be compared with other flare phenomena and the energy flow deduced under an assumed flare model which includes the distribution of the electrons producing the hard X-ray emission (e.g., Lin and Hudson 1971). The uniqueness of the electron distribution inferred from the photon spectrum may be questionable (Brown 1975), but an accurate determination of the impulsive HX flare spectrum over a wide energy range with good energy resolution helps reduce this ambiguity. The nature of the inferred electron spectrum provides a critical criterion for solar flare theories. This *Letter* describes the shape of the hard X-ray spectrum during the impulsive phases of many solar flares well observed by *OSO 7*, and interprets the spectra in terms of flare models.

The first measurement of the HX spectrum by Peterson and Winckler (1959) consisted of but two data points which the authors provisionally characterized as due to bremsstrahlung by nonthermal electrons. Chubb, Kreplin, and Friedman (1966) have commented that the data could equally well be fitted by a thermal bremsstrahlung spectrum from a very high-temperature ($\sim 10^8$ K) plasma. The bulk of the HX spectral reports to date use the convenient power-law characterization, although a spectral break in the 60–100 keV range (Frost 1969; Kane and Anderson 1970; Frost and Dennis 1971; van Beek 1973) sometimes is needed. Such a spectral break can be produced by a high-energy ($\gtrsim 100$ keV) cutoff in the electron distribution (Kane and Anderson 1970) or by the directivity of the bremsstrahlung emission process for anisotropic electron beams (Petrosian 1973). Although other physical explanations exist, the spectral breaks might also be only an artifact of the attempt to describe a curve (as on a plot of the logarithm of the photon flux versus the logarithm of the photon energy) with two straight lines. The resolution of these ambiguities bears directly on the question of the existence of nonthermal processes during the impulsive energy release in solar flares.

Kahler (1975) and Švestka (1976) have reviewed the literature and find the reports of observed power-law spectra and rapid temporal variations are much more favorable to nonthermal models. Further, Kahler (1971) has offered substantial reasons to doubt that a thermal plasma of the required temperature could be formed on the Sun, and, if it were somehow formed, it would require an excessive amount of energy to exist for the observed duration of HX bursts. On the other hand, Chubb (1970) and Milkey (1971) have pointed out that an observed true power-law spectrum can be produced by a distribution of temperatures with different emission measures. Also, Kahler's (1971) analysis need not apply (Kahler 1975; Elcan 1975) in the presence of the plasma turbulence expected near the site of magnetic field reconnection or current disruption.

This work uses the extensive data set from the UCSD solar spectrometer (Datlowe, Elcan, and Hudson 1974) on *OSO 7* to determine the spectral shape of the incident photon spectrum. This instrument had better energy resolution than other experiments and the work reported here constitutes the first detailed analysis of the spectral shape from the *OSO 7* data.

II. THE DATA

The data come from the UCSD solar X-ray instrument on board *OSO 7* (Datlowe, Elcan, and Hudson 1974). The data set has been extended to cover 1971

October to 1973 February. The set now consists of approximately 400 HX bursts with some 3600 spectra (representing 10.24 s integrations) characterized by power-law fits essentially over the limited energy range 14–46 keV. The lowest-energy scintillator channel (11–14 keV) usually has significant counts due to the high-energy tail of the low-temperature ($kT \sim 1$–2 keV) plasma present in all flares and has therefore been omitted from all HX fits. These limited-energy HX fits usually do not have enough statistical power to choose between best-fit power law and best-fit exponential spectra. The single-power-law fits were therefore extrapolated to higher energies to determine which bursts were likely to have solar flux above background in the higher-energy channels, thus allowing a better determination of the HX spectrum. The resulting sample of 86 bursts was therefore biased toward larger fluxes and flat power-law indices, although no explicit restrictions were placed on the power-law index. In fact, only 38 of the 86 events contained spectra with more than four channels above background, and these 38 flares constitute the data set for this work.

III. DETECTOR AND BACKGROUND MODELS

Comparing the assumed spectral distributions with the observed data requires an accurate detector model. The model used here takes into account in detail the effects of spacecraft rotation, aluminum entrance window, iodine K X-ray escape, efficiency, channel energy calibration, and energy resolution on the scintillator's response to power-law and exponential photon spectra. The energy resolution, FWHM $= 1.06\,E^{0.55}$, is similar to that of the HX spectrometer on *TD 1A* (van Beek 1973) and is about one-fifth as broad as that on *OSO 5* (Crannell *et al.* 1978) at 60 keV. The model calculations result in spectral parameter-dependent conversion factors from the assumed photon distribution to pulse-height channel counts. These factors are calculated to better than 1% numerical accuracy, typically 0.1%.

Below about 46 keV the cosmic X-ray diffuse component determines the detector background counting rate, while above this energy the local radiation environment at the satellite's geomagnetic latitude dominates. For each flare the background in each channel was measured during long samples both before and after the flare, and then linearly interpolated. Without this interpolation, errors of over 300% in the background could occur in the channels above 100 keV, mainly because of slow variations due to geomagnetically trapped particles, cosmic rays, and aurorae. Such an error, if uncorrected, would usually affect only the top two channels, as all lower channels contain several times their background counts during a flare. When an interval was not available, either a sample from an adjacent orbit was substituted or a constant background was assumed. This background is added to the assumed solar photon spectrum, after the latter has been transformed via the detector model, for the parameter fitting.

IV. PARAMETER FITTING

The two mathematical forms used to represent the photon flux distribution $F(E)$ are:

Power law:

$$F(E) = A_{20}(E/20)^{-G_1}\,, \quad E \leq E_M\,;$$
$$= AE^{-G_2}\,, \quad E > E_M\,.$$

Exponential:

$$F(E) = 2 \times 10^{-42} S(kT)^{-0.5} E^{-1}$$
$$\times \exp(-E/kT) g(E, kT) \text{ photons s}^{-1} \text{ cm}^{-2} \text{ keV}^{-1}\,.$$

The units are photon energy E, matching energy E_M, and kT in keV, S in cm^{-3}, and the Gaunt factor g dimensionless (Karzas and Latter 1961). The exponential spectrum resembles the bremsstrahlung spectrum expected from an isothermal plasma, but neither of these forms explicitly takes into account the possible modification of the source X-ray spectrum due to the solar albedo. They are thus intended only to represent the photon flux distributions which might produce the observed data.

A computer algorithm finds the self-consistent parameters which produce the minimum χ^2 error between the observed pulse-height channel counts and the expected counts from the assumed photon distribution and background (see Lampton, Margon, and Bowyer 1976). The program determines the best-fit single-power-law parameters over the 14–46 keV range (3 channels) and also the best-fit single-power law over all channels above background. Spectral breaks are found by extrapolating the low-energy fit to determine the first two consecutive channels to fall significantly below the extrapolation. A second power law is best fitted from these channels upward in energy, and the intersection of the two power laws determines the matching energy E_M. Since determining a spectral break meaningfully requires at least two channels in each fit, E_M is required to be in the range 30–100 keV. This well-tested algorithm finds any downward spectral breaks that produce a meaningful reduction in the total χ^2 for a given spectrum (Elcan 1978). When E_M would have been outside this range, the best-fit single-power law over all channels is used. The program then finds the best exponential fit over all channels above background.

V. MORPHOLOGY

Two sample events typify the data set. Figure 1 shows the time histories of the fluxes of hard (21–32 keV) and soft (5.1–6.6 keV) X-rays for the event at 10:01 UT on 1972 March 7. Spectra were determined for the times indicated by the letters *A*–*F* beginning at 10:01:14 UT and continuing on 10.24 s intervals. The spectra at the 21–32 keV flux peak (interval *D* at 10:01:45 UT) are shown for the two-power-law best fit in Figure 2*a* and for the exponential best fit in Figure 2*b*. Plots for intervals *C* and *E* are similar. The χ^2 statistic strongly favors the exponential fit over the full energy range compared with a single-power law.

Table 1 shows the best-fit parameters for the event

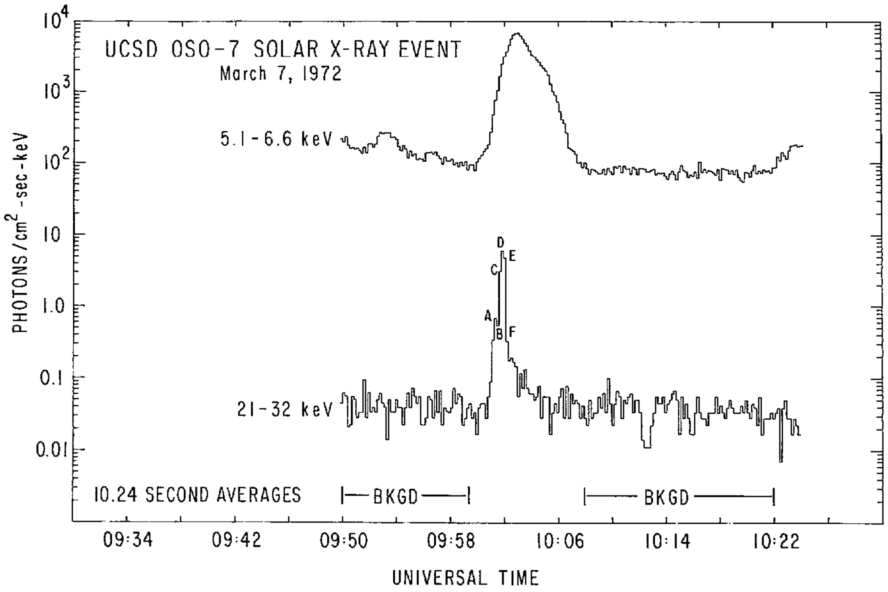

FIG. 1.—Hard (21–32 keV) and soft (5.1–6.6 keV) X-ray fluxes from an N subflare at 10:01 UT on 1972 March 7, located at S10 E10. Each point represents a 10.24 s average. Intervals *A–F* were analyzed, using 09:50–10:00 and 10:08–10:22 as background (BKGD).

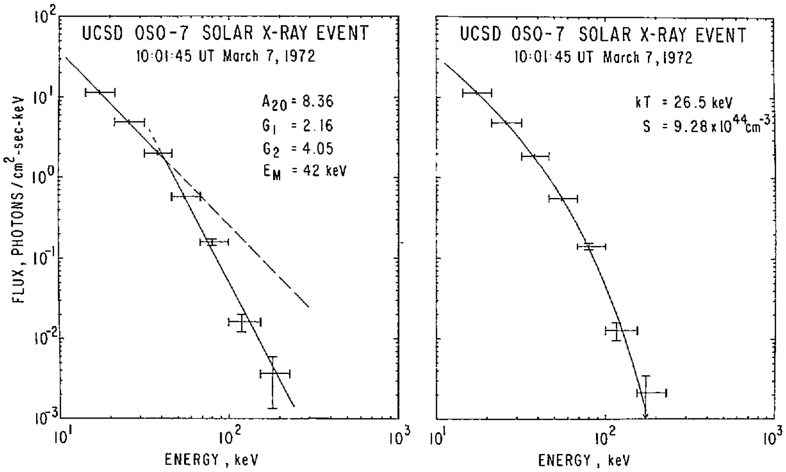

FIG. 2.—(*a*) The hard X-ray spectrum at 10:01:45 UT for the flare shown in Fig. 1 as characterized by two power laws, which intersect at 42 keV. The best-fit lower-energy slope is -2.16 and the upper-energy slope is -4.05. The value of χ^2 was 9.63 for 3 degrees of freedom. (*b*) The same spectrum as in (*a*), but interpreted as thermal bremsstrahlung from a single-temperature plasma with $kT = 26.5$ keV and emission measure $S = 9.28 \times 10^{44}$ cm^{-3}. The value of χ^2 was 5.95 for 5 degrees of freedom.

TABLE 1

PARAMETERS OF HARD X-RAY BURST AT 11:37 UT ON 1972 MARCH 5

Time	$S \times 10^{44}$(cm^{-3})	kT(keV)	G_1	G_2	A_{20}
11:37:02..............	4.18	7.80	4.20	*	0.61
11:37:12..............	6.45	14.0	3.03	4.80	3.00
11:37:22..............	12.9	16.1	2.97	4.84	7.22
11:37:33..............	19.2	18.7	2.72	4.31	12.7
11:37:43..............	21.7	20.4	2.67	4.37	15.7
11:37:53..............	39.8	9.16	4.06	4.99	8.40
11:38:03..............	61.7	6.81	5.18	*	5.63
11:38:14..............	69.2	6.48	5.58	*	5.51

* $E_M < 30$ keV; G_1 is best-fit slope over all channels.

at 11:38 UT on 1972 March 5 (not shown), which had a longer duration. The lower-energy power-law slope G_1 tended to follow a soft-hard-soft pattern as described by Kane and Anderson (1970), although often only the hard-soft portion is seen (Datlowe, Elcan, and Hudson 1974), perhaps because of the longer integration time. The parameter G_2 varied similarly, over a smaller range. The parameter kT varied in a manner suggestive of a rising and falling temperature, which would account for the soft-hard-soft pattern of the parameter G_1. As typified by this event, the emission measure S usually increased continuously, even after the temperature maximum. This behavior mimics that of the low-temperature SX plasma (Datlowe, Hudson, and Peterson 1974), although the energy ranges, time scales, and magnitudes are different.

For all events in the data set, the shape parameters ranged as follows: $2.85 \leq G_1 \leq 6.8$ (single-power-law fits); $1.8 \leq G_1 \leq 4.4$ and $3.0 \leq G_2 \leq 7.2$ (double-power-law fits); and $4.7 \leq kT \leq 31$ keV (exponential fits). The normalization parameter S fell in the range 8.4×10^{43}–6.0×10^{46} cm^{-3}. When the two-power fit was allowed by the restrictions on E_M, the matching energy lay in the range 30–46 keV. No upward breaks were observed on plots like that in Figure 2*a* in the 30–100 keV range. Of the 38 events, 28 were better characterized by the exponential fit, or double-power law at peak intensity. The χ^2 statistic strongly favored the exponential form over the single-power law. The exponential and double-power law were about equally satisfactory overall, despite the latter's ability to cover up unknown systematic errors. Two were better fitted by a single-power law, and eight were satisfactorily fitted by either an exponential or single-power law. Nine of the latter 10 events were steep ($G_1 > 4$, usually >5) and had no more than five channels above background. Spectra in all but one event with six or more channels ($E \gtrsim 100$ keV) above background were better fitted by the exponential.

VI. CONCLUSIONS

The shape of the solar hard X-ray flare photon spectrum has been reliably determined in a statistically consistent manner with data free from known instrumental defects. The slope of the HX spectrum usually steepened with increasing photon energy faster than a single-power law. The spectrum was then better fitted by an exponential or two power laws, particularly at peak flux. Although the fitting algorithm allowed the two-power law matching energy to be up to 100 keV, the highest E_M determined was only 46 keV. Reports of E_M near 80–100 keV (Frost 1969; Kane and Anderson 1970; Frost and Dennis 1971) and near 60 keV (van Beek 1973) may not be in disagreement (despite differences in burst sizes), as these authors used a different goodness-of-fit criterion which will bias E_M toward higher values. The solar plasma temperatures inferred from the kT parameter lay generally below those reported by Crannell *et al.* (1978), and considerably below those required to produce the observed isotopic composition of solar cosmic rays in the manner suggested by Colgate, Audouze, and Fowler (1977). Hot ($kT \gtrsim 100$ keV) spots with low emission measure ($\lesssim 10^{43}$ cm^{-3}) were not ruled out, however.

The good fit of the exponential spectrum, particularly at peak flux, supports a single-temperature thermal interpretation of the impulsive solar hard X-rays. Mätzler *et al.* (1978) have also found good agreement with the single-temperature model for two events reported in Crannell *et al.* (1978). Such high temperatures plausibly could occur on the Sun (Elcan 1975) via plasma turbulence (Friedman and Hamberger 1969) or via adiabatic compression (Chubb 1970). However, the observed increase of the emission measure after temperature maximum argues against the adiabatic compression mechanism. This work supports the speculation of Chubb *et al.* with data covering a wide energy range and free from known systematic defects. The thermal model certainly cannot be dismissed on the basis of the hard X-ray spectral shape (cf. Švestka 1976). The possible thermal electron distribution producing the observed hard X-rays should be included in calculations of energy flow in the solar flare, as, for example, was done by Davis and Rogerson (1977).

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