Yohkoh OBSERVATIONS OF FLARES WITH SUPERHOT PROPERTIES

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Solar flares, almost as their defining property, fill coronal magnetic flux tubes with hot plasma. When the temperature of a significant fraction of this plasma exceeds about 30 $\times$ 10^6K, we call the event "superhot", following the initial observation of the hard X-ray continuum of such an event by Lin *et al.* (11). The *Yohkoh* observations include many examples of similar events, of which three have been published thus far. This paper reports a survey of the *Yohkoh* observations, based mainly on the hard X-ray spectra obtained by the HXT instrument. While comprehensive conclusions will not be possible until the survey includes the *Yohkoh* imaging observations, we make tentative suggestions here about the nature of flares with superhot properties.

INTRODUCTION

Pioneering observations with high spectral resolution (11) showed that the hard X-ray continuum of a solar flare may contain an apparently isothermal component at a temperature considerably exceeding that of the associated soft X-ray source. This hottest component of thermal flare plasma may be that part most closely related to the heating mechanism, but further study has been difficult because of the absence of definitive high-resolution hard X-ray spectra. The superhot component could essentially form a bridge between the inherently non-thermal energy release of a solar flare, and its thermal consequences. Tsuneta *et al.* (20) suggest, for example, that flares with spectral properties similar to that of Lin *et al.* may result from intrinsically thermal energy release, rather than the usual non-thermal energy release involving strong particle acceleration.

The *Yohkoh* data (18) provide our most comprehensive observations yet of superhot sources, since they combine hard X-ray continuum spectroscopy and imaging, soft X-ray imaging, and soft X-ray emission-line spectroscopy, including spectroscopy in the FeXXVI emission lines. Figure 1 shows the thermal responses of the different instruments on board *Yohkoh*.

FIG. 1. Responses of the different detectors on board *Yohkoh*, as functions of temperature. The calculations assume an isothermal source with Mewe atomic-physics tabulations (12), with assumptions about abundances and ionization equilibrium. The dotted lines refer to emission at the formation temperatures of the resonance lines. The HXT responses are normalized to the values at 10^8K.

Thus far only three superhot events observed by *Yohkoh* have been described in the literature (Appendix B). This paper begins a broader survey, starting with a list of FeXXVI events compiled by Pike *et al.* (15). The FeXXVI lines require high temperatures to excite them. According to Figure 1, the low-temperature branch of the FeXXVI contribution function almost exactly matches that of the HXT low-energy channel. The Pike *et al.* list of 75 events is therefore a good starting point, although we note that instrumental effects restrict the numbers. In any case, the *Yohkoh* data show that FeXXVI emission or "Type A" behavior (19) is relatively common. We study these events using the hard X-ray spectral evolution seen in the four broad-band energy channels of the *Yohkoh*/HXT instrument. This paper represents a progress report for a fuller survey, which would include the hard and soft X-ray images from *Yohkoh*.

In this paper we use certain properties of the hard X-ray spectral evolution to show the superhot nature of an event: high apparent temperatures (above 30×10^6K), smooth time profiles, and the characteristic pattern of joint variation of temperature and emission measure seen in thermal sources at lower temperatures (7). These conditions do not unambiguously establish the thermal nature of a source, but the smooth time profile and cooling pattern are not found in impulsive-phase non-thermal sources (4), and the cooling pattern is not found in gradual coronal sources (6).

BACKGROUND

The appearance of hot plasma in the solar corona is nowadays almost the defining property of a solar flare. Soft X-rays and Hα emission occur in a one-to-one relationship, except for limb flares where occultation confuses the relationship; the effective temperatures of flare X-ray plasmas distinguish them clearly from ordinary active-region loops. Soft X-ray emission from a

FIG. 2. A superhot flare observed by *Yohkoh*/HXT on 6 September 1992 (Pike #52). Left, time profiles of the two lowest energy channels of HXT, 14-23 keV and 23-33 keV. Right, the hardness ratio of these two channels plotted against the rate in the low channel. After the clearly-defined impulsive phase, the spectrum radically softens, the time profile becomes smooth, and the flux decays smoothly. After the dotted line (left) and below it (right) the apparent temperature drops below about 35 × 10^6K.

flare occurs in a set of one or more magnetic flux tubes and develops late in the flare process. The Hα emission tends to occur at the chromospheric footpoints of the magnetic loops. This picture is oversimplified but adequately represents the important part of the phenomenology.

The bulk of the emission measure typically falls in the range 10-20 × 10^6 K, although lower peak temperatures occur in flare-like structures outside active regions *e.g.* (1). The temperature of the hot flare plasma typically reaches a maximum before the emission measure (or the flux) does, *e.g.* (5). This pattern of spectral evolution clearly distinguishes thermal X-ray sources from the non-thermal (hard) impulsive bursts, which tend to show a symmetrical soft-hard-soft spectral evolution (8).

Similar behavior (hot first, then bright) also characterizes the superhot component (11). Figure 2 shows a *Yohkoh* flare with superhot characteristics. In this case HXT photometry in the 14-33 keV range showed temperatures above 30 × 10^6 K, while GOES temperatures did not exceed 16 × 10^6 K. The ratio of emission measures of the two "components", although this is unlikely to be the correct way to describe the broad distribution of differential emission measure, is about 10 in this case.

We normally allow for the possibility of a distribution of temperatures in a given observation via the concept of the differential emission measure (for a recent discussion in the context of moving plasmas, see (13). There are two distinct ways in which a distributed emission measure can occur. First, in an optically-thin medium a given observational line of sight may include radiation from physically distinct plasmas at different temperatures. Second, the plasma itself may be homogeneous but have a non-Maxwellian particle velocity distribution. This is a transient situation, expected to prevail during heating. The time scale for thermalization can be estimated from Coulomb collision theory (21):

$$\tau_{ee} = 5.5 \times 10^6 T_6^{1.5}/n \ \ sec,$$

where T_6 represents the minority electron temperature in MK, n the ambient density, cm^{-3}, and τ_{ee} the electron energy-exchange time with an assumed background component at a much lower temperature. For $T_6 = 40$, τ_{ee} ranges from 20 sec to 2 msec for densities in the range 10^8-$10^{12}cm^{-3}$. These times may be long enough to permit a non-Maxwellian electron distribution function to exist, especially if the particle heating occurs in a low-density domain and on the rapid time scales recently discovered in solar flares (2).

Yohkoh/HXT HARD X-RAY PHOTOMETRY

The *Yohkoh*/HXT instrument is designed to image hard X-ray sources (9). It also has provided the best broad-band photometry to date. The photometry is good because the imaging function of HXT dictated the use of many (64) small, independent detectors, each with a peak exposed area of about 2 cm^2. Thus the counting rate does not become large even in a major event, and saturation problems such as pulse pile-up are minimized. The total detector area is large, for photometric purposes ~55 cm^2, to provide good photon statistics for image reconstruction. In addition, imaging requires careful detector gain stabilization (gain is defined here as $d(PH)/d(h\nu)$, where PH represents the pulse height in the detector electronics, and $h\nu$ the photon energy). With these advantages HXT can do precise photometry over a wide dynamic range. There is normally a telemetry-imposed restriction on the number of energy channels of four (Low, M1, M2, High: nominally 14-23-33-53-93 keV) in the normal mode of operation.

Appendix A describes the modeled response of the four HXT energy channels to thermal sources (*cf.* Fig. 1). It is important to note that the HXT entrance windows are thin enough to permit substantial response even at "normal" flare temperatures of 15-20 × 10^6K, so it is not surprising that most flares show thermal characteristics at least in the 14-23 keV channel.

The recognition of a thermal source from HXT data alone is inherently ambiguous, since the two-channel comparison that determines a temperature could as easily be used to fit a power-law distribution. It is not enough to note that a thermal spectrum of 30 × 10^6 K corresponds to an implausibly soft non-thermal spectra (the equivalent power-law index $\gamma \sim h\nu/kT$, so that for HXT energies we would have $\gamma \sim$ 8-10). There is no theoretical reason not to have

TABLE 1. *Yohkoh*/HXT spectra of flares in the Pike *et al.* list

Property	Number of events
Number with superhot properties	~46/64
"Good" events	33
Number with >5% "superhot" emission measure	13/33
Number with $T_{M1/Low}$ > 30 MK	26/33

such distributions even though they do not occur at higher energies in normal impulsive-phase spectra (4). Therefore in identifying superhot plasmas we also make use of the spectral time evolution. The normal pattern of impulsive-phase hard X-ray spectral evolution is the soft-hard-soft variation (8). As noted above, thermal plasmas may tend instead to show a pattern of cooling with time, or if the heating phase is included, then an open loop pattern.

SURVEY FOR SUPERHOT PROPERTIES

The preliminary survey presented here starts from the Pike *et al.* list of FeXXVI flares observed by *Yohkoh* (15). This list includes the three prominent examples described in Appendix B, but we note that this does not represent a complete survey because of detector saturation and other effects,

For each of the events in the Pike *et al.* list, we have examined (i) the thermal fits to HXT photometry (*i.e.*, non-imaging), (ii) the HXT and GOES light curves, and (iii) the joint variation of HXT spectral hardness ratio with respect to flux. Table 1 presents the results of estimates of the thermal parameters, which were carried out in an interactive manner for background selection and time range. We find that most events in the Pike *et al.* list do exhibit superhot characteristics, as inferred from the HXT photometry. We find many cases (*e.g.*, the one shown in Figure 2) in which the two HXT temperatures match reasonably well, and some in which they do not. In the latter cases the temperature derived from the M2/M1 ratio, at a representative energy of 33 keV, is normally higher than the temperature derived from the M1/Low ratio, at a representative energy of 23 keV.

The *Yohkoh*/HXT data show events similar in spectral behavior to the original Lin *et al.* event, namely the appearance of isothermality over the range of photon energies detected. We interpret this to mean that, in such events, a truly Maxwellian particle energy distribution dominates, and that the apparent differential emission measure (*i.e.*, that resulting from line-of-sight averaging) has a well-defined upper-limit temperature. These events tend strongly to show time variations of thermal types, in the sense of the loop seen in Figure 2.

FIG. 3. Results of the survey of hard X-ray spectral properties of the Pike *et al.* list (15) of FeXXVI flares observed by *Yohkoh*. Left, the distribution of temperatures (solid line, the HXT M1/Low hardness-ratio temperature; dotted line, the simultaneously observed temperature from GOES; right, the distribution of ratios of emission measures between the hard X-ray source and the GOES sources. Both of these distributions are for 33 of the 75 Pike events matching the criteria described in the text.

CONCLUSIONS

From the *Yohkoh* observations, we find abundant evidence that superhot temperatures occur. The Pike *et al.* list of 75 members, a lower limit, represents a substantial fraction (on the order of 10%) of all the flares that triggered *Yohkoh* flare mode during the interval. Do the events showing this phenomenon constitute a separate *class* of flares, as it appeared from *Hinotori* (19)? Do the observations even suggest the existence of a physically distinct *component*, as suggested by Lin *et al.*? The answers to these two questions are "probably not", even though the superhot phenomenon is observationally distinctive when it occurs. In two of the three events already published (Table 1, Appendix A), the superhot characteristics appear in a physically distinct structure.

The present work deals mainly with a survey of the morphology of the hard X-ray spectral evolution in the Pike *et al.* list of 75 FeXXVI events. A future more comprehensive work will include image properties, which are available both from SXT and from HXT. We summarize our present results as follows:

- The occurrence of FeXXVI emission lines (15) is a good guide to the presence of superhot characteristics in the hard X-ray spectrum.
- The superhot sources behave like normal hot plasmas in solar flares, except for having higher temperatures.
- The differential emission measure of the superhot sources may abruptly

drop at a relatively low temperature, say 30×10^6K, but in some cases it clearly extends much higher.

These observations are consistent with the notion that, at least sometimes, the superhot characteristics represent the thermalization of a plasma whose electron distribution function has been driven out of equilibrium. In other cases, the superhot source may be relaxed but seen together with normal flare sources (line-of-sight effect), thus giving the appearance of a broad differential emission-measure distribution. The survey described here could not easily distinguish these two alternatives, but the future survey using images may be able to help further. There is always the possibility that these superhot properties result actually from non-thermal particles mimicking thermal behavior. The nature of the particle distribution function is difficult to determine from remote-sensing observations.

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APPENDIX A. *Yohkoh*/HXT THERMAL RESPONSE

Figure A1 (left) summarizes the spectral response of the HXT instrument, based upon detailed calculations performed by M. Inda-Koide. These calculations include the detailed material properties of the detectors, entrance windows, and housings, plus allowance for detector resolution spreading and K-photon escape. Each of the 64 subcollimators views a different part of any given source, due to the modulation collimators that provide the imaging response. Accordingly each will have a different total counting rate, and the measurement of total hard X-ray flux at any given instant may have an uncertainty on the order of $1/\sqrt{64}$ or about 10%.

We have taken these probability functions and convolved them with model thermal spectra (12) for isothermal sources at different temperatures. From the convolved counting rates, the ratio of counts in any adjacent pair of energy channels determines a temperature and an emission measure. Figure A1 (right) shows these "hardness ratios" for the three independent pairs of adjacent channels. Note that the thermal hardness ratios are much smaller than the hardness ratios rsulting from power-law spectra: HXT was designed to have hardness ratios of approximately unity at number spectral index $\gamma = 2$.

APPENDIX B. THREE *Yohkoh* SUPERHOT EVENTS

Three *Yohkoh* events with superhot properties have already been presented in the literature (Table 2). The published analyses include image morphology. We describe these briefly here.

FIG. A1. Left, the responses of the four HXT broad-band channels (Low, 14-23 keV, dots; M1, 23-33 keV, dashes; M2, 33-53 keV, dot-dash; and High, 53-93 keV, solid). Right, the variation of hardness ratios with temperature: Med1/Low, solid; Med2/Med1, dots; High/Med2, dashes.

TABLE 2. Three previously reported superhot events

Date	T_{HXT} [a]	Spatial Pattern	Reference
16 Dec 1991	35	Legs	(3)
6 Feb 1992	35	Separate	(10), (17)
21 Aug 1992	40	Separate	(14)

[a] MED1/LOW channel ratio, effective energy ~23 keV, evaluated at end of impulsive phase.

16 December 1991, Pike #10 (3). The light curves show a distinct second phase, during which the HXT and FeXXVI temperatures matched. The HXT images showed a loop with bright footpoints, but there unfortunately were no SXT data. Culhane *et al.* suggested that the superhot component in this case could be identified with the legs of the loop, filled with the heated and upward-flowing material ablating from the chromosphere.

6 February 1992, Pike #25 (10); (17). The superhot signatures occurs later in time by several minutes than a more normal flaring loop. The HXT images clearly define the superhot location to be a separate structure. The SXT image sequence gives the appearance of gradual filling from one leg during the source evolution.

21 August 1992, Pike #47 (14). The superhot source appears in a separate loop following a more normal event, in a pattern possibly similar to that of the 6 Feb. 1992 event. The temperatures determined by SXT filter photometry clearly define the superhot location to be a separate longer loop structure in this case.

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