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SOLAR FLARE IRON Kα EMISSION ASSOCIATED WITH A HARD X-RAY BURST

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ABSTRACT

An exceptionally intense iron Kα emission associated with a hard X-ray burst was observed by the Bragg crystal spectrometer aboard *Hinotori*. High-resolution continuum spectra from 1.5 to 12.5 keV and hard X-ray spectra from 18 to 400 keV of this flare were obtained, respectively, by the gas scintillation proportional counter and the scintillation counter aboard *Hinotori*. They show a remarkable power-law photon distribution extending from below 10 keV to above 100 keV in the early phase of the flare. We attribute the intense Kα emission in the early phase to fluorescence of photospheric neutral iron by the power-law X-ray flux that extends down to the K-shell ionization threshold at 7.1 keV. On the other hand, the gradually increasing Kα emission after the decay of the hard X-ray burst can be explained by fluorescence due to the X-ray flux of thermal origin. We discuss the relation between the Kα emission due to the hard X-ray fluorescence and the Kα emission by thick-target electron impact.

The implications of the low-energy power-law distribution for the flare energetics are also discussed.

Subject headings: Sun: flares — Sun: spectra — Sun: X-rays — X-rays: bursts

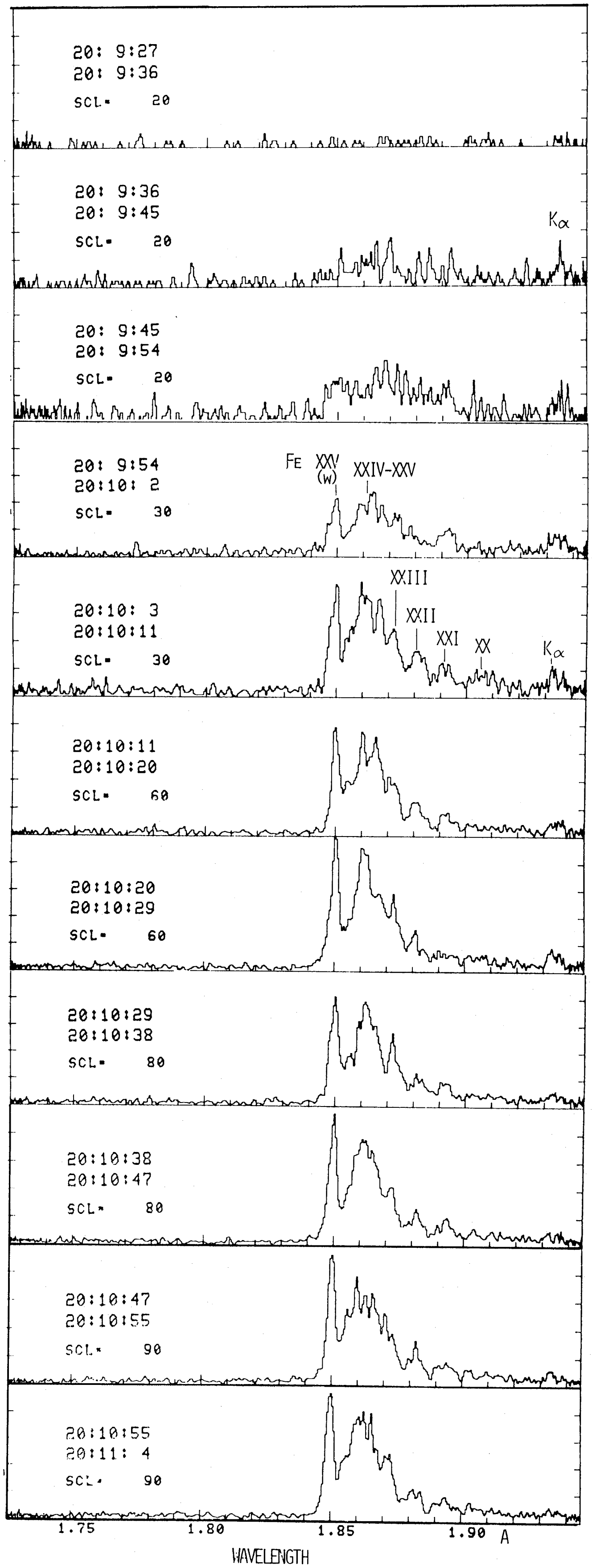
I. INTRODUCTION

The rotating Bragg crystal spectrometers (SOX) on the Japanese solar maximum satellite *Hinotori* have obtained high-resolution spectra in the soft X-ray range 1.75–1.95 Å from many flares (Tanaka *et al.* 1982*a*; Tanaka *et al.* 1982*c*; Moriyama *et al.* 1983). This wavelength range contains lines from a wide range of ionization stages of iron extending from Fe II to Fe XXVI. One of the controversial problems in this spectral range concerns the radiation mechanism of Kα emissions at 1.936 Å and 1.940 Å. The Kα photons are radiated after the removal of a K-shell electron. Two mechanisms have been suggested for this K-shell ionization. One is the fluorescence of photospheric neutral iron by irradiation of the soft X-rays above the ionization threshold energy 7.1 keV (Neupert *et al.* 1967; Bai 1979), and the other is electron impact ionization by nonthermal electrons, which also emit the hard X-rays (Acton 1965; Phillips and Neupert 1973).

Weak and long-lasting Kα emission from solar flares has been reported in many observations (Neupert *et al.* 1967; Doschek *et al.* 1971; Grineva *et al.* 1974; Feldman, Doschek, and Kreplin 1980; Culhane *et al.* 1981; Tanaka *et al.* 1982*c*). From the close temporal correlation between Kα and soft X-ray intensities and limb weakening of Kα emission, a fluorescence origin has strongly been suggested by several authors (Doschek *et al.* 1971; Tomblin 1972; Feldman, Doschek, and Kreplin 1980; Culhane *et al.* 1981; Tanaka *et al.* 1982*c*). On the other hand, a search for transient Kα radiation temporally correlated with the hard X-ray burst has been pursued to detect electron-impact Kα, and thereby to provide evidence for electron beaming. Culhane *et al.* (1981) reported a case of impulsive Kα radiation among the results from the bent crystal (Ge) spectrometers aboard *SMM*. The LiF crystal spectrometer aboard the *Tansei IV* satellite has detected several cases of enhanced Kα emission in the initial phase of flares associated with the microwave bursts (Tanaka 1980). From the SOX observation which uses a flat SiO_2 crystal we have obtained so far a few cases of exceptionally intense Kα emission in the initial phases of impulsive flares. Tanaka *et al.* (1983) have given preliminary results for the most striking case. In this paper we present a detailed analysis of this transient Kα emission using various observations made by *Hinotori*. The observations include the line spectrum data obtained by SOX and continuum spectra obtained by the soft X-ray spectrometer (FLM, Inoue *et al.* 1982) and the hard X-ray spectrometer (HXM, Ohki *et al.* 1982). We conclude that the intense Kα emission associated with the hard X-ray burst is produced by the fluorescence of the hard X-ray flux, which extends down to 7 keV.

II. OBSERVATION

Intense Kα emission was observed in the initial phase of a flare that occurred at 20:09:30 UT, 1981 July 28, near the disk center (S10 W18). The flare showed a very impulsive hard X-ray burst with high flux (10^8 $[h\nu]^{-4}$ photons cm^{-2} s^{-1} keV^{-1} at the peak), but the soft X-ray flux was unusually low (X-ray class M3.4). Figure 1 shows the time sequence of the soft X-ray line spectra in the 1.75–1.95 Å region obtained by the lower resolution Bragg spectrometer. The Kα emission in the first few frames shows remarkably high counts relative to the lines from highly ionized stages of iron compared with the later phases. In the first recognizable spectrum, the peak of the Kα line is comparable to the prominent feature at 1.87 Å, consisting of blended lines from Fe XXIII. As the peak shifts from 1.87 Å to 1.85 Å (the resonance line from Fe XXV), the Kα emission relative to the peak decreases. In Figure 2 the intensity-time profile of residual Kα emission is compared with the intensity-time profiles of the Fe XXV resonance line (w) and the hard X-ray burst in the 18–44 keV range. The ratio of Kα to the w line decreases from more than 1 to 0.08, which is a value



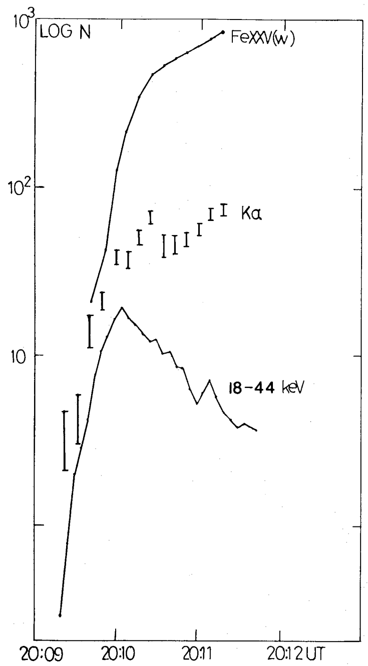


FIG. 2.—Intensity-time profiles of the 1981 July 28 flare are shown. *From top to bottom*, the Fe XXV resonance line (w), the iron Kα line, the hard X-ray flux in the 18–44 keV range (arbitrary scale). Error bars in the Kα line indicate $\pm\sigma$ levels.

commonly observed in other flares. The Kα time profile shows a hump slightly after the peak of the hard X-ray burst, while the resonance-line time profile shows a smooth increase.

The continuum spectra from 1.5 keV to 400 keV are shown in Figure 3; the spectrum from 1.5 keV to 12.5 keV is divided into 128 channels, obtained every 4 s by the gas (Xe) scintillation proportional counter (FLM), and the spectrum from 18 keV to 400 keV is obtained every 125 ms by the NaI(Tl) scintillation counter (HXM) aboard *Hinotori.* The gas scintillation proportional counter achieves energy resolution that is twice as good as that of a conventional proportional counter, i.e., 10% at 6 keV, resolving the prominent emission of blended iron lines at 6.7 keV and the weak emission of nickel at 7.6 keV. This resolution enabled us to analyze the pure continuum spectra below 8 keV. The relative intensities between the two spectrometers are calibrated to better than a factor of 2. The absolute fluxes of total iron line emission at 6.7 keV as obtained by the SOX and the FLM agreed within 50%.

Figure 3 indicates that the continuum from 7 keV to 150 keV is remarkably well represented by a power-law spectrum. The straight lines in Figure 3 represent the best power-law fit for the hard X-ray region above 44 keV. This distribution also nicely fits the continuum below 12.5 keV in the period from 20:09:09 to 20:09:42 UT. After 20:09:42 the power-law photon distribution tends to have a break around 70 keV, with the spectral index changing, typically, from 3.9 to 4.1 as energy increases, but the power-law distribution with the same index prevails in the range from 70 keV to below 9 keV. The

FIG. 1.—Time sequence of iron line spectra for the 1981 July 28 flare obtained by the low-dispersion SiO_2 Bragg spectrometer on *Hinotori.* Spectra from the original time resolution (9 s) are shown. The scan period (UT) and full count scale (SCL) of each spectrum are shown. The SCL refers to a count rate per bin (note that the spectral bins become smaller toward the edges of the spectrum, increasing the sensitivity in the rotating Bragg spectrometer).

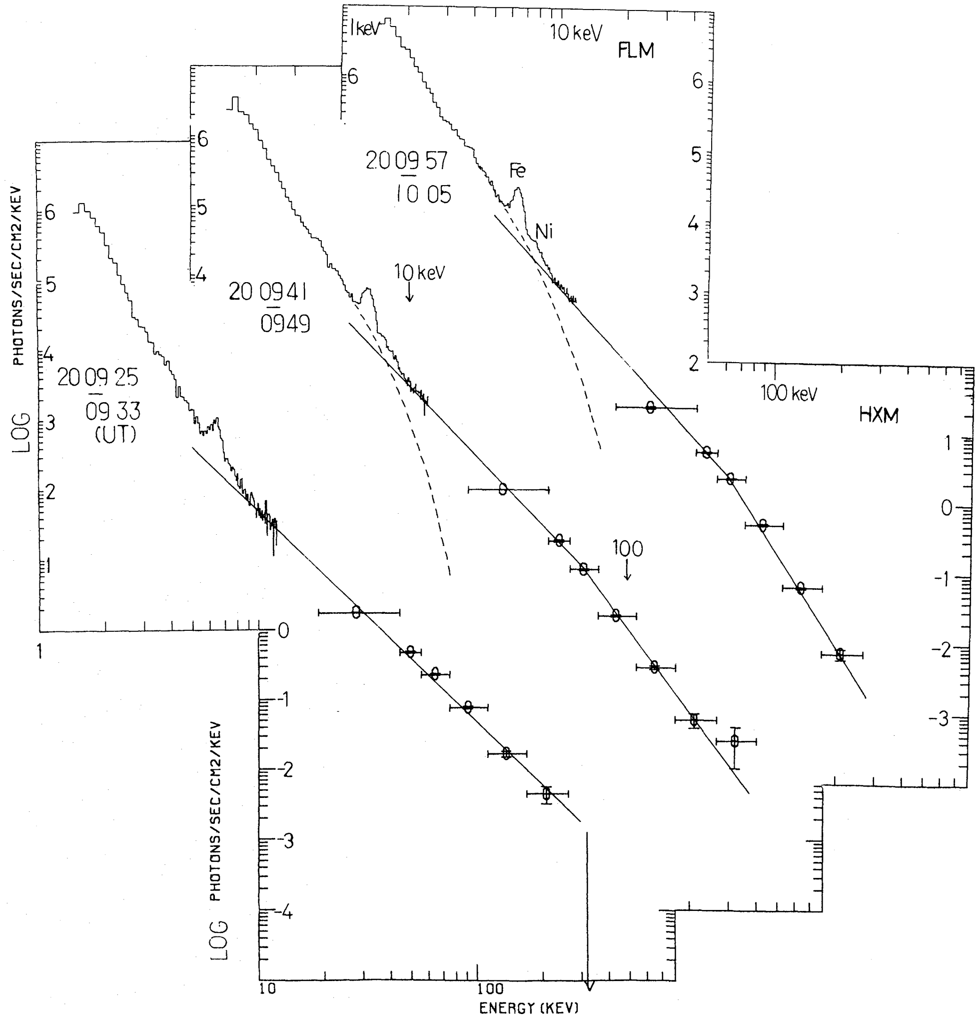


FIG. 3.—Continuous spectra of two regions, 1.5–12.5 keV and 18–400 keV, at three different times during the 1981 July 28 flare. Fe line (6.7 keV) and Ni (7.6 keV) are resolved from the continuum. Straight lines represent the best fit power-law distribution for $E > 44$ keV. This distribution also fits the lower energy region below 12 keV. Dashed lines indicate the thermal bremsstrahlung spectrum expected from the emission measures and temperatures derived from the line spectra (Table 1).

spectral index varies from time to time in the range from 3.42 to 4.4. The earliest spectra show a smaller index, but the time variation is not always monotonic. The scintillation proportional counter became seriously affected by pulse pile-up effects due to the high count rate after 20:10:15 UT. Most flares analyzed by Watanabe, Tanaka, and Matsuoka (1982) and Watanabe *et al.* (1983) show exponential spectra below 10 keV. These flares show, however, less prominent hard X-ray bursts than the present case, so that the power-law component, if any, may be veiled by the dominant thermal spectra below the 10 keV region.

III. RESULT

Theoretical analyses of the fluorescence emission of the Kα line have so far been aimed at the X-ray source of thermal origin. However, the general formulation obtained by Bai (1979) can be used to evaluate the Kα emission due to a hard X-ray burst with a power-law spectrum. The fluorescence Kα emission is calculated by

$$I(\mathrm{K}\alpha) = \Gamma f(\theta) I(7.1\ \mathrm{keV})/(1 + \alpha)\,, \qquad (1)$$

where Γ is the integrated fluorescence efficiency defined as the ratio of Kα flux to one-half of the X-ray flux above the threshold energy 7.1 keV, $I(7.1\ \mathrm{keV})$; $f(\theta)$ is the dependence of the Kα intensity on the heliocentric angle θ of the flare location; and α is an albedo correction factor for the back-scattering effect in the X-ray continuum. Bai obtained the dependence of the fluorescence efficiency on the photon energy by a Monte Carlo calculation and showed values of Γ as a function of temperature for thermal bremsstrahlung. We have evaluated Γ for the observed power-law photon distribution by adopting Bai's Monte Carlo results. The value of Γ for a spectral index 4.2 and source height 0 km, for example, is found to be 0.027, which is equal to Γ for $kT = 3.3$ keV in the case of a thermal X-ray source. The dependence of Γ on the X-ray source height is simply determined by the solid angle subtended by the photosphere at the flare height.

The evaluated Kα intensity due to hard X-ray fluorescence is compared with observations in Figure 4. The rising part of the observed intensity up to the hump is well reproduced by the calculation made for a zero source height. The hump

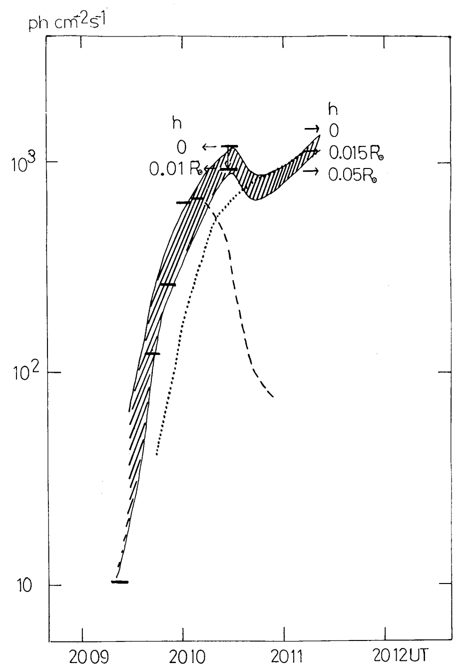


FIG. 4.—Comparisons of the observed Kα intensity (*shaded portion*) with various predicted Kα intensities. Bars show the fluorescence Kα emission due to the observed power-law hard X-ray burst. After 20:10:15 UT, observation by the gas counter is seriously affected by the pile-up effects, and no data are shown. The dashed line shows the fluorescence Kα emission during this period as estimated from the extrapolation of the higher energy (>18 keV) hard X-ray spectrum. The dotted line shows the fluorescence Kα emission due to thermal soft X-ray flux, which is derived from the line spectral analysis. The three levels at 20:11:20 UT are cases in which the soft X-ray source is located at three different heights.

at 20:10:15 UT is better fitted for the case of $h = 0.01\ R_\odot$ (7000 km) above the limb, although the pulse pile-up effect in the continuum detector makes this comparison a little unreliable. For the data after 20:10:30 UT, no continuum data are available in the 7 keV region because of the pile-up effect, and the intensity was evaluated based on the power-law spectra extrapolated from the higher energy region above 18 keV (shown by dashed line). It decreases rapidly as the hard X-ray burst decays, while the observed intensity increases in the same period.

After the initial phase the fluorescence due to the thermal soft X-ray flux may be dominant. We have evaluated this component from the soft X-ray flux I(7.1 keV) derived from the emission measure and temperature from line spectra. Temperatures were obtained from the comparison of the observed spectra of 1.85–1.90 Å with the theoretical spectra, which have been synthesized from the line data by Bely-Dubau *et al.* (1982) and Doschek, Feldman, and Cowan (1981) under the assumption of ionization equilibrium as given by Jacobs *et al.* (1977). The theoretical spectra synthesized to the same resolution as the crystal spectrometer are shown in Tanaka *et al.* (1982*b*). The derived temperatures and emission measures are shown in Table 1. The fluorescence Kα emission due to the thermal X-ray flux is plotted in Figure 4 (*dotted line*) and explains well the observed Kα emission after the hump, or after the hard X-ray burst decays if we assume an X-ray source height of $h = 0.015\ R_\odot$. On the other hand, this component is lower by a factor of 3 than the fluorescence due to the hard X-ray burst or the observed Kα emission in the early

TABLE 1

TEMPERATURES AND EMISSION MEASURES OF THE THERMAL PLASMA OBTAINED FROM LINE SPECTRA

Time (UT)	T (10^6 K)	Log $n_e^2 V$ (cm^{-3})
20:09:36–20:09:54	15.4	48.1
20:09:54–20:10:11	16.8	48.7
20:10:11–20:10:29	17.3	49.0
20:10:29–20:10:47	17.8	49.0
20:10:47–20:11:04	18.8	49.0
20:11:04–20:11:22	19.4	49.0

phase. Therefore, the whole temporal behavior of Kα is explained by the superposition of the fluorescences from the power-law spectrum and from the thermal X-rays, which, temporally, behave similarly to the hard X-ray burst, and the soft X-ray high-temperature emission line, respectively. Since the two contribution curves cross at 20:10:20 UT, the observed hump may be explained as the effect of the superposition. The thermal X-ray continuum expected from the obtained emission measures and temperatures derived from the line spectra are shown by dashed lines in Figure 3. In the early phase the thermal X-ray spectrum in the energy range 7–10 keV is lower than the observed power-law spectrum, consistent with the above explanation.

The absolute value of the predicted fluorescence Kα emission depends on the height of the X-ray source and on the iron abundance. With the adopted abundance, i.e., $n(\mathrm{Fe})/n(\mathrm{H}) = 4 \times 10^{-4}$ (cf. Culhane *et al.* 1981) the X-ray source height is found to be 0 km for the fluorescence due to the hard X-ray burst in the early phase and about 10,000 km ($0.015\ R_\odot$) for the fluorescence due to the thermal X-rays in the later phase. At the intermediate phase (near the hump) the height is found to be 7000 km. Although the absolute source height cannot be discussed because of the uncertainty in the iron abundance, this variation is consistent with a model in which the hard X-ray burst originates at the footpoint of the loop, while later soft X-rays originate near the loop top.

IV. DISCUSSION

The present results show that a power-law photon distribution of a hard X-ray burst extending in energy below 10 keV can produce intense fluorescence Kα emission in the impulsive phase of a flare. The low-energy power-law spectrum may have been revealed in this flare because the soft X-ray thermal spectrum was suppressed because of an unusually small emission measure of the thermal plasma in comparison to a high flux in the hard X-ray burst. In the later phase of this flare, fluorescence due to soft X-rays of thermal origin dominates, as is usually observed almost throughout the entire flare in other cases. Among about 30 flares we have analyzed so far, at least one other case that fits the present explanation has been found. Several other impulsive flares showed considerable enhancement of Kα emission relative to the resonance line at 1.85 Å, restricted to only a few spectra in the initial phases; this suggests Kα emission associated with the hard X-rays. It is obvious that the detection of such Kα emission in more cases with more clarity would require a substantial increase in spectrometer sensitivity. This is supported by the fact that a LiF crystal which possessed much more sensitivity than the present SiO_2 crystal detected more evident Kα enhancement in the initial phases of flares, even though the spectral resolution was relatively poor (Tanaka 1980).

The presence of a low-energy nonthermal component below 10 keV has been reported by Kahler and Kreplin (1971), using the data from a proportional counter which could not resolve well the iron line around 7 keV. The present observation has confirmed this firmly by distinguishing the line components from the background continuum.

Recent hard X-ray imaging observations from *SMM* (Hoyng *et al.* 1981) and from *Hinotori* (Tsuneta *et al.* 1983; Ohki *et al.* 1983) have revealed that the impulsive hard X-ray burst is emitted at low heights, presumably from the footpoints of a loop. These observations, together with the stereoscopic observation using two spacecraft (Kane *et al.* 1982), have strongly suggested thick-target emission for the hard X-ray burst as the electrons precipitate in a beam into the lower, denser atmosphere. It is of interest to ask whether the electron-impact Kα emission due to the precipitating electron beam is comparable to the fluorescence Kα emission due to the hard X-rays. To evaluate the Kα emission due to collision impact, a thick-target Kα radiation theory is required. So far the published calculation is based on the thin-target assumption (Phillips and Neupert 1973). Recently, Emslie and Phillips (1982) have developed a thick-target Kα theory and have kindly provided us the result before publication. They predict the Kα emission as a function of overlying column density at the top of the target neutral iron, for various values of the hard X-ray spectral index. Their result shows, for example, that the thick-target Kα emission for $\gamma = 4$ is much lower than $10^{-4.7}$ A photons s^{-1} (thin-target limit), e.g., $10^{-5.2}$ A for a column density of $10^{19.5}$, when the observed hard X-ray spectrum is equal to $A(h\nu)^{-\gamma}$ photons cm^{-2} s^{-1} keV^{-1}. On the other hand, the Kα emission due to hard X-ray fluorescence for the same hard X-ray spectrum is estimated to be $10^{-4.5}$ A for $h = 0$ km. Generally, if we compare thick-target Kα emission with the fluorescence Kα as predicted from the hard X-ray burst of the same spectral index, the electron-impact Kα emission always turns out to be smaller than the fluorescence Kα emission from the disk center, unless the spectral index is lower than 3.5. This suggests that the Kα emission associated with hard X-rays can mainly be explained by fluorescence for the present flare and perhaps for most flares, even if the electron beam does exist. A better possibility for detecting impact Kα emission would be in a flare in which a very intense hard X-ray burst of spectral index lower than 3.5 occurs. A search for such an event is in progress.

This observation raises a problem concerning the energetics of the electron beam which extends to low energy. The total energy deposition of the electrons in this flare as calculated from the formula of Hudson, Canfield, and Kane (1978) amounts to 1.5×10^{32} ergs for a low-energy cutoff equal to 7 keV. This may be compared with the total energy of the thermal plasma $(3kN^2VT/N)$, 10^{30} ergs, which is derived assuming an electron density (N) equal to 10^{11} cm^{-3} (Dere *et al.* 1979). The energy deposited by electrons of $E > 35$ keV is sufficient to explain this thermal energy. Therefore, we must consider where the excess deposited energy has gone. Since the low-energy electrons of $E < 10$ keV are stopped at a column density of less than 10^{19} cm^2, most of the energy is released around the top of the transition region in the quiet atmosphere. This energy may be radiated in the UV region. However, according to the comprehensive estimation of a well-studied *Skylab* flare by Canfield *et al.* (1980), the total radiated energy in the UV region is at most 10 times larger than the radiated energy in the X-ray region. The latter does not exceed the total energy of the thermal plasma. Thus it seems difficult to believe that this enormous energy input is converted to the radiation energy in the UV and X-ray regions. One possibility would be that this intense energy input cannot be released by local energy transport mechanisms but goes into explosive bulk motions which may be observed as shocks and spray.

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