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# HARD X-RAY IMAGING OF A SOLAR LIMB FLARE WITH THE X-RAY TELESCOPE ABOARD THE *HINOTORI* SATELLITE

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## ABSTRACT

An intense solar X-ray burst occurred on 1981 April 27 at the solar limb. The X-ray images of this burst were observed with the hard X-ray telescope (17–50 keV) aboard the satellite *Hinotori*. The centroid of images was located in the corona $1.4 \times 10^4$ km above the photosphere throughout the increasing phase (about 15 minutes) of this strong burst without much change in its size of about 20″ (FWHM). A weak subordinate source $5 \times 10^4$ km apart from the main source was also located in the corona $3 \times 10^4$ km above the photosphere, and it exhibited a change in relative intensity.

This observation has given the first image of a strong coronal hard X-ray source, showing the height structure of a solar hard X-ray flare. The present observation gives a strong constraint on the theoretical model of solar flares, in that a very stable isolation of high-temperature plasma ($\sim 10^8$ K) in the corona is required.

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

## I. INTRODUCTION

Observations of the source structure and its time variation of solar hard X-ray bursts are very important in understanding the mechanism of initial energy release and subsequent evolution of high-energy electrons in the flare plasma. The first observation (30–60 keV) was made by Takakura *et al.* (1971) with a balloon-borne modulation collimator. The observed one-dimensional source size was 1′ or less, which was remarkably smaller than the relevant large Hα flare of 3′. From 1980 to 1981, X-ray images were obtained with the hard X-ray imaging spectrometer (HXIS) aboard the *Solar Maximum Mission* (*SMM*) satellite. The X-ray images (16–30 keV) derived for three relatively strong events (Hoyng *et al.* 1981*a*,*b*; Machado, Duijveman, and Dennis 1982) revealed double structure in the impulsive phase and an elongated single source at the later phase. Such a structure has been interpreted as the footpoints of coronal loops or arcade, while the source in the later phase has been located near the top of the same loops as the source of softer X-rays.

The Japanese solar X-ray satellite *Hinotori* was launched on 1981 February 21. The hard X-ray telescope, SXT, installed in this satellite is designed to observe the images of solar hard X-ray bursts in a band typically 20–40 keV with high angular resolution, moderate time resolution, and a wide field of view. Among a number of observed events, an intense X-ray flare which occurred on 1981 April 27 at the solar west limb gave us the first chance to see the height distribution of the hard X-ray source. The X-ray images described in § III show direct evidence for a strong hard X-ray source confined steadily in the corona for at least 15 minutes.

## II. INSTRUMENTATION

The SXT consists of a pair of almost identical modules, SXT-1 and SXT-2. Each module consists of a bi-grid modulation collimator with a NaI(Tl) X-ray detector and an optical solar aspect sensor, SXA. The optical axis of the telescope is parallel to the spin axis of the satellite with a sufficiently wide field of view to cover the whole solar disk. The SXT collimator casts on the sky a number of periodic transmission bands separated by 2′.158. An X-ray source in the field of view is scanned by the transmission bands almost linearly at a position angle. The angle changes gradually according to the rotation of the satellite, with a period of 16–19 s. The spin axis is automatically controlled to remain 1°.2 ± 0°.5 off the center of the solar disk. A complete set of position angles is available with each SXT in every half rotation. Since the two collimators are mounted with their grids perpendicular to each other, a quarter rotation is sufficient to have all position angles if both are used together. The beamwidth (FWHM) is 38″ ± 2″ for SXT-1 and 28″ ± 2″ for SXT-2. The multidirectional linear scans thus obtained are used to synthesize a two-dimensional image of the hard X-ray source mathematically.

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### *a*) *SXT*

The modulation collimator consists of two grid plates 445.6 mm apart, and each plate is formed by a stack of 12 sheets of photo-etched brass grid that is 50 $\mu$m in thickness. The thickness of each plate sets an upper limit on the X-ray energy of about 50 keV for the imaging of the source. In order to minimize thermal deformation, the collimators are wrapped in a passive thermal barrier, and the active thermal control is provided by electric heaters attached to the grid plates. The in-orbit performance of the collimators has been confirmed by Makishima (1982), using a compact image of a solar flare that occurred on 1981 April 2. The roundness of the beam pattern is found to be less than 7″ in Gaussian FWHM equivalent.

The NaI scintillator is 113 cm$^2$ in effective area and 3 mm in thickness. Two aluminum filters, of 27 mg cm$^{-2}$ and 162 mg cm$^{-2}$, are set in front of each SXT in order to reduce the flux of soft X-rays to avoid the pulse pileup. The thicker filter contains a small hole (1% in area) to pass a small amount of soft X-rays. Thus an effectively flat energy response (for a standard flare X-ray spectrum) down to about 5 keV is achieved. The in-orbit calibration of energy range is made with 22 keV line of $^{109}$Cd.

### *b*) *Mapping*

The *Hinotori* aspect system includes a pair of optical Sun sensors (SXA), Earth horizon sensors, and three-axis geomagnetic sensors. The accuracy of the resulting absolute position of the centroid of a typical X-ray image thus derived is about 7″ in radial distance from the solar center and 1° in the azimuthal angle measured from the solar north pole (Tsuneta 1983).

The synthesis of a two-dimensional image from one-dimensional scans for multiple position angles was reviewed by Oda *et al.* (1976). In the present case, the synthesis is made by using the "maximum entropy method" (Gull and Daniel 1978; Willingale 1981). The resulting spatial resolution of the X-ray image is about 10″.

### *c*) *Spectrometer*

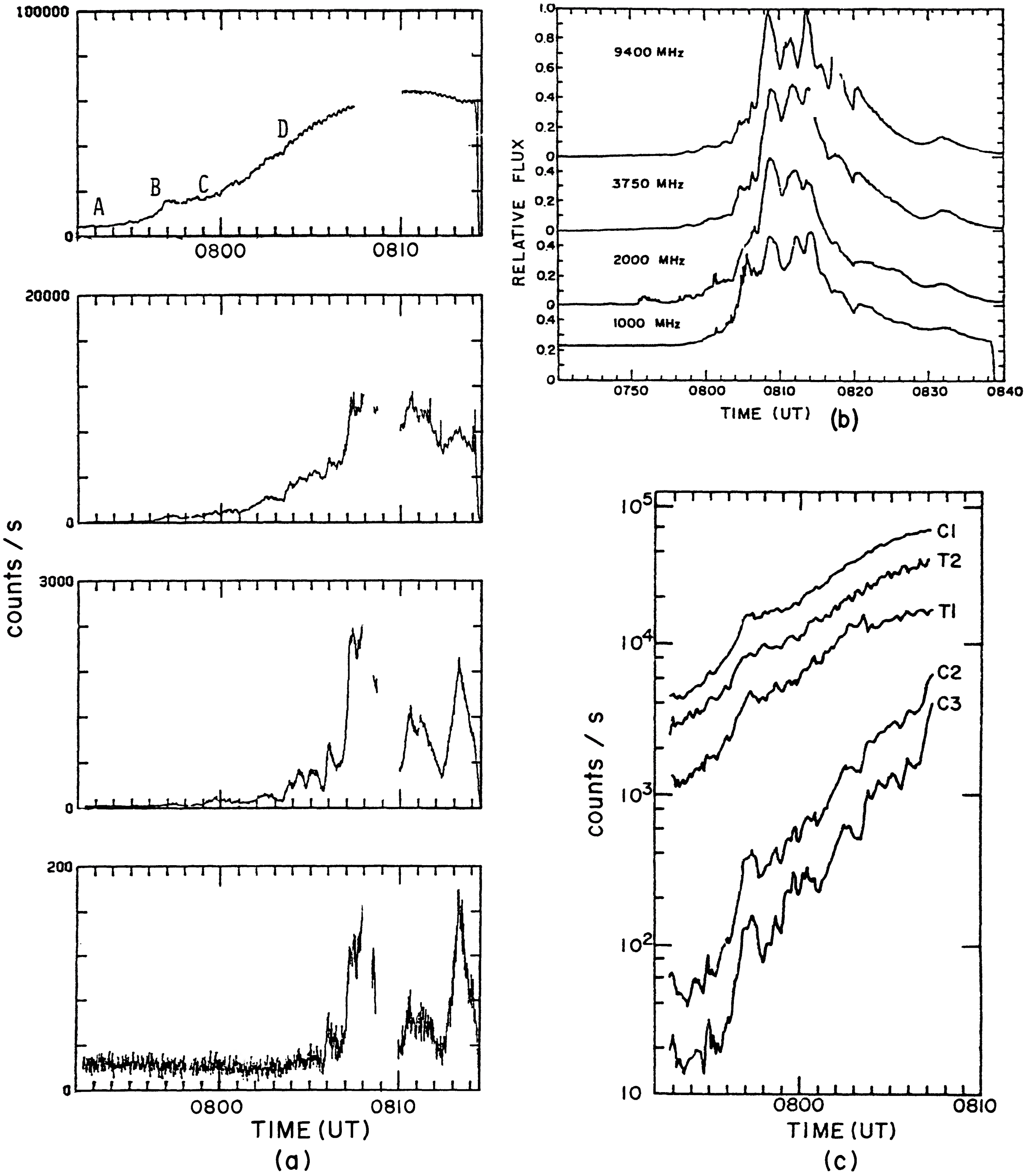
The hard X-ray monitor spectrometer (HXM) is also installed in the satellite (Ohki *et al.* 1982). It consists of an NaI scintillator which covers 17–360 keV over seven energy bands (17–40, 40–50, 50–67, 67–101, 101–152, 152–235, and 235–360 keV). The effective area of the detector is 39 cm$^2$, and a thick aluminum filter of 432 mg cm$^{-2}$ is adopted to avoid pulse pileup. The time resolution is 7.8 ms for the lowest energy band (17–40 keV) and 125 ms for the other bands. The in-orbit calibration of the energy range is made with 22 keV and 88 keV lines of $^{109}$Cd. No appreciable shift of the energy ranges compared with preflight values has been detected. A comparison of burst spectra simultaneously observed with the HXM and spectrometers aboard *SMM* and *International Sun-Earth Explorer 3* (*ISEE 3*) has been made.

## III. OBSERVATIONAL RESULTS

A large X-ray flare classified as X5.5 on the *GOES* satellite scale was recorded with the HXM from 0750 UT to 0815 UT on 1981 April 27. Since no H$\alpha$ disk flare is reported, the flare is supposed to be occulted by the solar limb. The X-ray time profiles obtained with the HXM in four energy bands are shown in Figure 1*a*. The time variation only in the lowest energy band is gradual after 0803 UT compared with the other bands. This gradual profile could be attributed mostly to the saturation in amplifier because of the extremely high flux of this event and partly to a superposition of the softer gradual component from the hot plasma with a temperature of $4 \times 10^7$ K (K. Tanaka, private communication) derived from soft X-ray spectrometer (SOX) aboard the *Hinotori*. A strong radio burst associated with this event was observed at Toyokawa. Its time profiles are shown in Figure 1*b*. The radio spectrum at the time of peak flux showed a monotonic increase with frequency at least up to 35 GHz (14380 SFU, Bern; *Solar Geophysical Data*), which implies a negligible effect of solar limb occultation of the radio source, since the radio emissions at the high frequencies originate from lower altitudes.

Some of hard X-ray images obtained with SXT-2 in a nominal energy band of 17–50 keV are shown in Figure 2. The images obtained with SXT-1 in a nominal energy band of 26–50 keV are similar. The time profiles of SXT-2 and SXT-1 after averaging the modulation phase for 8.125 s (about a half rotation) are shown in Figure 1*c* together with the time profiles of the lower three bands of the HXM. The time profile of SXT-2 is quite similar to that of C1 (17–40 keV). Progressive hardening of the photon spectrum with time can be seen. The times for the snapshots (8 s each) in Figure 2 are indicated by A, B, C, and D in Figure 1*a*. After about 0807 UT, SXT observation was terminated due to the limit of recorder capacity. As can be seen in Figure 2, the core of the hard X-ray source is located in the corona about $1.4 \times 10^4$ km above the photosphere throughout the observation. Another weak, extended subordinate source most clearly seen in Figure 2*b*, with a maximum brightness of about 10% of the main source and located $5 \times 10^4$ km apart from the main source and $3 \times 10^4$ km above the photosphere, persisted throughout the observation, though it is relatively weaker in the other phases.

A loop prominence system was observed above the west limb at the later phase of this event from 0758 UT at the Purple Mountain Observatory, Beijing Observatory, and Yunnan Observatory in China. Two H$\alpha$ mounds were located below the main and subordinate



(a) (b) (c)

FIG. 1.—(*a*) Hard X-ray time profiles of the flare of 1981 April 27, obtained with the HXM in four energy bands. Energy ranges (keV) are 17–40, 40–67, 67–152, and 152–359, respectively, from top to bottom. In the top panel, small ripples on the time profile are due to spin modulation, and a gap between 0807 to 0810 UT is due to calibration. (*b*) Microwave burst observed at Toyokawa (courtesy of Dr. S. Enome). At 1000 MHz, the decrease of flux to zero at about 0838 UT is due to sunset. The peak fluxes of the burst are 13,000, 5250, 2100, and 400 SFU, respectively, from top to bottom. (*c*) Hard X-ray time profiles averaged for 8.125 s (about a half rotation):T1, SXT 1; T2, SXT 2; C1, 17–40 keV (HXM); C2, 40–50 keV (HXM); C3, 50–67 keV (HXM).

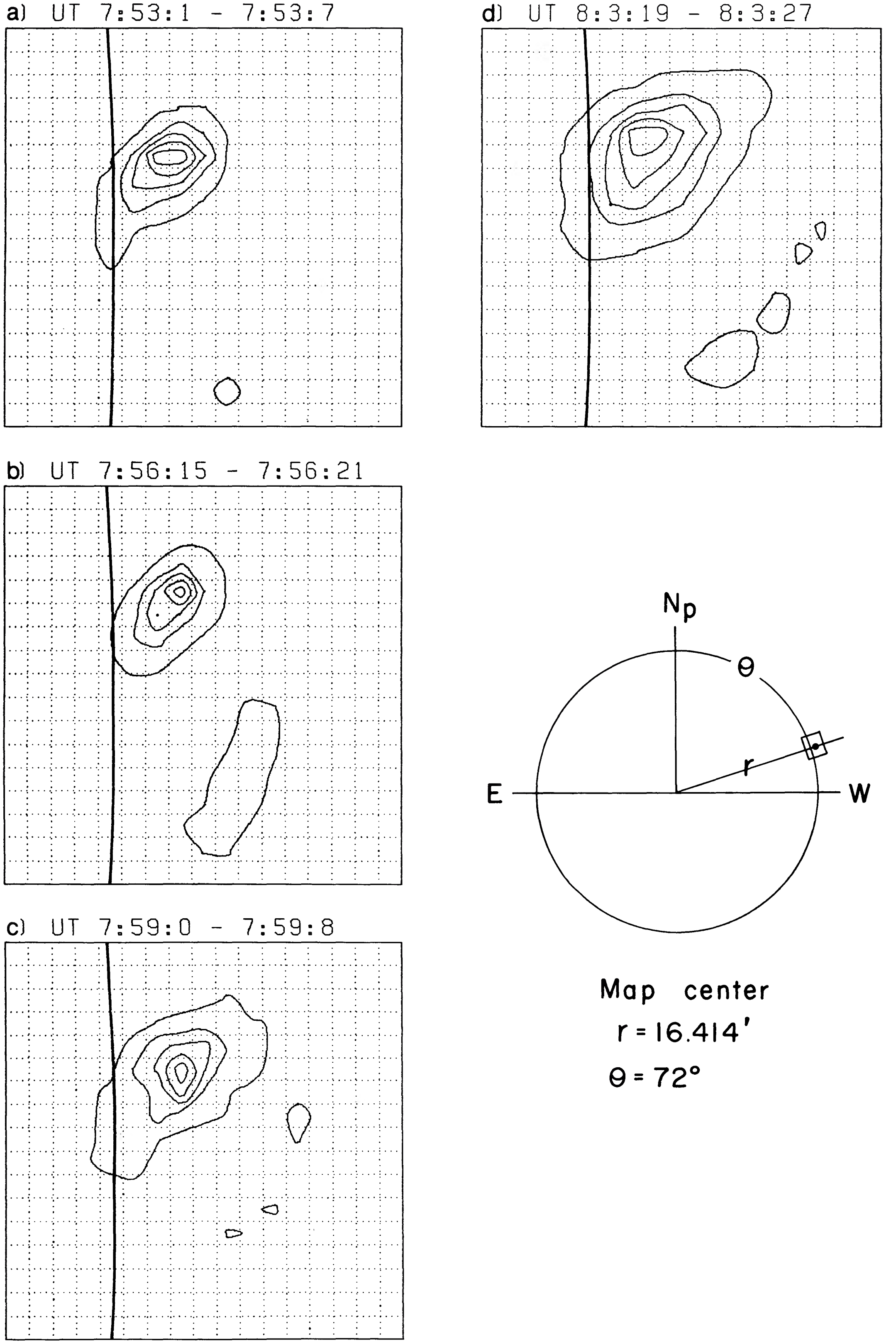


FIG. 2.—Hard X-ray images at times (*a*) A, (*b*) B, (*c*) C, and (*d*) D as marked in Fig. 1. Energy range is a nominal value. One cell equals 7.″615. The field of view of the X-ray maps is 2.158 × 2.158 $\text{arcmin}^2$. The minimum contour is 0.55, each step of the contours is 2, and the peak brightness is 10. The solar optical west limb is indicated by a curve.

X-ray sources at 0758.2 UT. For the observations after 0830.6 UT, an H$\alpha$ loop was located between the two hard X-ray sources (Li and Cao 1983).

## IV. DISCUSSION AND CONCLUSION

The hard X-ray images shown in this *Letter* have revealed the height structure of a strong hard X-ray source located in the corona. The coronal source consisted of two sources. The main source was steady with the size of about 20″ in FWHM, and the subordinate source exhibited variable intensity relative to the main source. Both sources were located in the corona without any evidence of an appreciable chromospheric source throughout the observation. This is the first image of a strong coronal hard X-ray source, though some evidence of a coronal source has been reported (Frost and Dennis 1971; Hudson 1978; Kane *et al.* 1979, 1982).

It is improbable that an impulsive phase of the present X-ray burst was not observed due to the occultation of the relevant source near the chromosphere, since no appreciable impulsive peak was recorded before 0803 UT in microwaves even at 1 GHz, as shown in Figure 1. The longitude of the flare is estimated to be 0°–5° behind the west limb from the extrapolation of disk flares occurring in the same active region in the previous 2 days. Thus the occultation height would be $3 \times 10^3$ km or less.

The main source would be the loop itself viewed face-on or the cross section of a larger loop viewed edge-on. Another, less probable configuration is that the main source is a small portion of a large loop connected to the subordinate source, since the two sources show independent time variations in X-ray intensity. Probably the two sources are independent loops as inferred from the H$\alpha$ loop prominence system observed at Chinese observatories.

The X-ray photon spectra obtained with the HXM fit better to power laws (with exponents of 8–6) than to isothermal spectra, especially after 0803 UT (D in Fig. 1*a*). The $\chi^2$ values for the power-law and the isothermal fits are, respectively, 7 and 8 at B, and 11 and 120 at D. If we adopt an isothermal fitting for simplicity, the electron density in the X-ray source from A to D must lie in the narrow range from $2 \times 10^9$ to $4 \times 10^9$ cm$^{-3}$ with temperatures of $8.0 \times 10^7$ K at A and B, and $1.3 \times 10^8$ K at C and D. The conduction cooling time is only of the order of 30 s even if the heat conduction is limited by thermal ion velocity for $10^7$ K. Therefore, the bottling up of the hot plasma in the corona at least for 15 minutes during the increasing phase of a flare presents a difficult theoretical problem.

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